Faculty of Science and Engineering
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Alkali Pozzolan Cement for Integral Sustainability

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made. This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

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Abstract

This thesis presents the design and development of an alternative cement that meets the criteria for 'integral sustainability'. The developed alternative cement was named 'Alkali Pozzolan Cement' (APC for convenience), since the research started with a preliminary cementitious mixture comprising alkali and pozzolanic materials. The term 'integral sustainability' implies an integration of a number of sustainability aspects; i.e. the integration of not only the aspects related to ecological sustainability, but also those of technological sustainability, economical sustainability and social sustainability. Hence, the aim of the research is 'to investigate the design and development of Alkali Pozzolan Cement (APC), comprising non-hazardous chemicals, which can be cured under normal conditions, stored as a dry powder, and conforms to integral sustainability'.

This research is related to engineering as well as integral philosophy. Hence, the positivist paradigm, which is the standard research paradigm commonly used in science and engineering, could not be employed alone. Therefore, an integrated research methodology suitable for this research was developed by combining positivist with non-positivist paradigms. Three approaches were adopted for the purposes of investigations: the technological sustainability of APC was investigated through experimental methods; the ecological and economical sustainability of APC were investigated through numerical computations; the social sustainability was investigated through social surveys.

Experimental investigations started with a basic APC mixture consisting of lime and fly ash. Two critical issues were identified, namely the slow activation of fly ash particles and the slow hardening process. In order to resolve these critical issues, an activating material (Na_2SO_4) and scaffolding material (Ordinary Portland Cement) were added. The experimental program was extended with the introduction of different pozzolanic materials, different proportions of raw materials and different curing conditions (air, heat, steam and water curing). Structural properties were investigated in terms of the compressive strength. The microstructural properties were investigated using microstructural techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDS) and thermal analysis

(TG, DTG, DTA and DSC). The results obtained for APC mixtures were also compared with results for High Volume Fly Ash (HVFA) cement and Ordinary Portland Cement (OPC) mixtures. The durability properties of APC were investigated using several important durability tests, namely, water absorption, acid attack, chloride ion penetration and carbonation.

Investigations related to the ecological sustainability of APC were carried out using computations based on the results of the experiments, and also embodied energy and CO_2 emission values given in reliable data bases, and compared with those of HVFA and OPC. Investigations related to the economic sustainability of APC considered the market prices of constituting materials, and they too were compared with those of HVFA and OPC. Explorations of social concerns of APC were done by presenting information related to APC to survey respondents in various contexts and determining their concerns regarding those.

Next, information related to technological, economical, ecological and social sustainability were integrated using the two integral sustainability frameworks that were developed in this research. The first framework was used to investigate the overall integral sustainability of APC, while the second framework was employed to demonstrate the certainty/uncertainty of the aspects related to APC, based on variability and sensitivity of entities, in order to improve/maintain the integral sustainability of APC.

Finally, the findings of the research were summarized and recommendations for future research presented. It can be concluded that APC is a reasonably good alternative to OPC since it does not need water curing, and that its compressive strength is much higher than that of the HVFA tested (incorporating a similar percentage of OPC). When aspects related to integral sustainability are considered, it can be concluded that objective aspects are moderately satisfactory, while inter-objective aspects are highly satisfactory; moreover, the subjective aspects are satisfactory while inter-subjective aspects are moderately satisfactory.

List of Publications

Published journal articles already derived from Chapters

Chapter 3

Kulasuriya, Chandana, Vanissorn Vimonsatit, WPS Dias and P De Silva. 2014. "Design and Development of Alkali Pozzolan Cement (APC)." *Construction and Building Materials* 68: 426-433.

Chapter 8

Kulasuriya, Chandana, Priyan Dias and Vanissorn Vimonsatit. 2014. "Integral Sustainability of Alkali Pozzolan Cement." *Journal of Integral Theory & Practice* 9(1).

Unpublished manuscripts being derived from Chapters

Chapter 2

Kulasuriya, Chandana, Priyan Dias and Vanissorn Vimonsatit. "Development of Integral Research Paradigm for Techno-Philosophical Multi-Paradimatic Researches".

Chapter 4

Kulasuriya, Chandana, Vanissorn Vimonsatit, WPS Dias and P De Silva. "Structural and Microstructural Properties of Alkali Pozzolan Cement (APC)".

Chapter 5

Kulasuriya, Chandana, Vanissorn Vimonsatit and WPS Dias. "Durability Properties of Alkali Pozzolan Cement (APC)".

Chapter 9

Kulasuriya, Chandana, Priyan Dias and Vanissorn Vimonsatit. "An Investigation of Individual and Social Concerns of Alkali Pozzolan Cement (APC) in Different Contexts".

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Abbreviations and Acronyms

APC	Alkali Pozzolan Cement
C-A-S-H	Calcium Aluminium Silicate Hydrate
C-S-H	Calcium Silicate Hydrate
DSC	Differential Scanning Calorimeter
DTA	Differential Thermal Analysis
DTG	Derivative Thermogram
EDS	Energy Dispersive Spectroscopy
HVFA	High Volume Fly Ash
LVFA	Low Volume Fly Ash
N-A-S-H	Sodium Alumino Silicate Hydrate
OPC	Ordinary Portland Cement
SEM	Scanning Electron Microscopy
TA	Thermal analysis
TG	Thermogravimetry
TGA	Thermo Gravimetric Analysis
XRD	X-Ray Diffraction

1 Introduction and Formulation of the Research

What is Research?

"Research is to see what everybody else has seen, and to think what nobody else has thought".

Albert Szent-Györgyi
(Winner of Nobel Prize for Medicine in 1937)

Overview

This chapter presents the overall idea and framework of the research on the development of Alkali Pozzolan Cement (APC) for integral sustainability. First, it explores the historical development of the concept of 'sustainability' over the modern, post-modern and post-postmodern eras, with special reference to sustainable buildings. Then it gives an overview of 'integral theory', which is one of the latest philosophical paradigms, and introduces the concept of 'integral sustainability', with reference to sustainable buildings. Thereafter, the formulation of the research is presented. When formulating the research, the broad concept of 'sustainable buildings' is narrowed down to 'sustainable building materials', and in that context, an alternative cement called 'Alkali Pozzolan Cement' (APC), which has been developed in this research, is introduced. Next, the objectives, scope and significance of the research are presented. Finally, an overview and 'map' of the thesis is given.

Keywords: *Alkali Pozzolan Cement, modernism, post-modernism, post-postmodernism, integral theory, integral sustainability*

1.1 Introduction to Sustainable Cements

Conventional cement, which is commonly known as Ordinary Portland Cement (OPC), is one of the most widely used materials in building construction. To produce 1 tonne of OPC, approximately 1.7 tonnes of non-fuel, non-renewable raw materials and 3.3 to

6.3 Giga Joules of energy are required. Further, during the production of 1 tonne of OPC, approximately 1 tonne of carbon dioxide, which is a greenhouse gas that contributes to global warming, is released into the atmosphere (Van Oss and Padovani 2002; Oss and Padovani 2003). Kumar and Naik (2010) reported that, according to World Energy Commission (WEC) statistics, the energy consumption in cement production is about 2% of global energy consumption. When emissions are considered, the carbon dioxide released from the cement industry is over 5% of the total anthropogenic carbon dioxide emissions (Hendriks et al. 1998). Therefore, OPC has become a threat to the sustainability of the planet. Hence, there is a great need to minimize the use of non-sustainable OPC, and to develop ‘sustainable cements’. Here the term ‘sustainable cements’ refers to cements that can be manufactured and used with less adverse impact on the sustainability of the planet. Given this background, this research investigates the possibility of developing a sustainable cement utilising a dry form of alkali materials and pozzolanic materials, called ‘Alkali Pozzolan Cement’ (APC), within the context of this research.

1.2 Historical Development of Discourse of Sustainability

As mentioned above, this research investigates the feasibility of developing a sustainable cement. However, within the context of this research, the term ‘sustainability’ is used not only to refer to ‘ecological sustainability’, but also to ‘integral sustainability’, which can be briefly described as a condition that integrates many sustainability aspects such as ecological, economic, social and technological. Obviously, the development of an alternative cement is a technological procedure. However, ‘integral sustainability’ is a philosophical concept that constitutes many narratives such as historical, cultural, sociological and economic ones. Accordingly, this research can be described as an integration of technological and philosophical investigations. Hence, the purpose of this chapter is to establish a solid foundation for this techno-philosophical, multi-paradigmatic research. The following sections of this chapter first present the evolution of the philosophy of integral sustainability; this is followed by the formulation of this research on integral sustainability.

It is reported that, during the 'age of reason' (around 17^{th} century), Francis Bacon, who is considered as the father of the modern science, advocated human power over nature for 'human benefit', suggesting that nature be treated as feminine and tortured through mechanical interventions (Merchant 1983). This implies the 'value-free' attitude with regard to nature and women in that era. This intensified during the 'Age of Enlightenment' (around 18^{th} century), where the mission became the full-scale utilisation of global natural resources (Vehkamäki 2005). Subsequently, the concept of 'sustainability' (German term '*Nachhaltigkeit*') was introduced by the German nobleman Hans Carl von Carlowitz in 1713, who argued against the short-term profit-exploitation of forests (Grober 2007; Robin, Sorlin and Warde 2013). Further, Romanticism emerged as a reaction to the scientific rationalization of nature during the Enlightenment; and the ideas of the Romantics led to movements for environmental conservation (Environmental History Resources 2015). Accordingly, the discourse of sustainability has been developed over 300 years influenced by various contemporary movements, and has been defined in many ways. Among those, the definition given in the Report of the World Commission on Environmental and Development (WCED), commonly known as the 'Brundtland Report' (Brundtland 1987), is one of the most popular definitions. It states that "*Sustainable development is development that meets the needs of present without compromising the ability of future generations to meet their own needs*".

The 'Policy Research Brief on Environmental Valuation in Europe' complied by Cambridge Research for the Environment (CRE) had identified the following three spheres of sustainability (CRE Policy Research Brief 2000).

1. Biomedical sustainability
2. Material sustainability
3. Aesthetic sustainability

Biomedical sustainability can be described as maintaining the health of the environment for living beings; this is integrated with preserving water, air and atmospheric temperature (i.e. not leading to air, water and land pollution) while material sustainability can be described as preserving the resources of nature (i.e. not leading to resource depletion). Aesthetic sustainability can be defined as maintaining the aesthetics of the environment, i.e. not leading to visual pollution (Kulasuriya 2003).

With time, the concept of 'sustainability' has penetrated many fields. In the domain of Civil and Building Engineering, it has given rise to another new concept called 'sustainable buildings'. The meaning of the term 'sustainable buildings' is not limited to the literal meaning of the term, i.e. buildings that are sustainable or last long. Instead, it has to be understood within the context. Accordingly, the term 'sustainable buildings' can be defined as buildings that can be constructed and operated with less adverse impacts on the sustainability of the planet. Similarly, 'sustainable building materials' can be defined as building materials that can be manufactured and used with less adverse impact on the sustainability of the planet. In this context, materials that can be manufactured from fewer non-renewable resources and that can be reused or recycled, have added importance. The Organisation for Economic Co-operation and Development (OECD) actively promotes sustainable buildings (OECD Policy Brief 2003). John, Clements-Croome and Jeronimidis (2005) reported that the OECD Project identified the following five objectives of sustainable buildings.

1. Resource efficiency
2. Energy efficiency
3. Pollution prevention
4. Harmonising with environment
5. Integrated & systematic approach

Through the passage of 'the past to the present' (and to the future), the discourse of 'sustainable buildings' has been influenced by modernism, post-modernism, and now 'post-postmodernism' as well. Within this discourse, it is important to understand the use of the Latin term 'post' (meaning 'after') in this context. It does not mean that the post-modern era has begun after the death of the modern era. It only means that the modern era began first, and thereafter the post-modern, while the modern era continues. In other words, modernism emerged first and thereafter post-modernism, while modernism continues. Similarly, post-postmodernism has emerged subsequently, but modernism as well as post-modernism still continues. This is graphically depicted in **Fig. 1.1**.

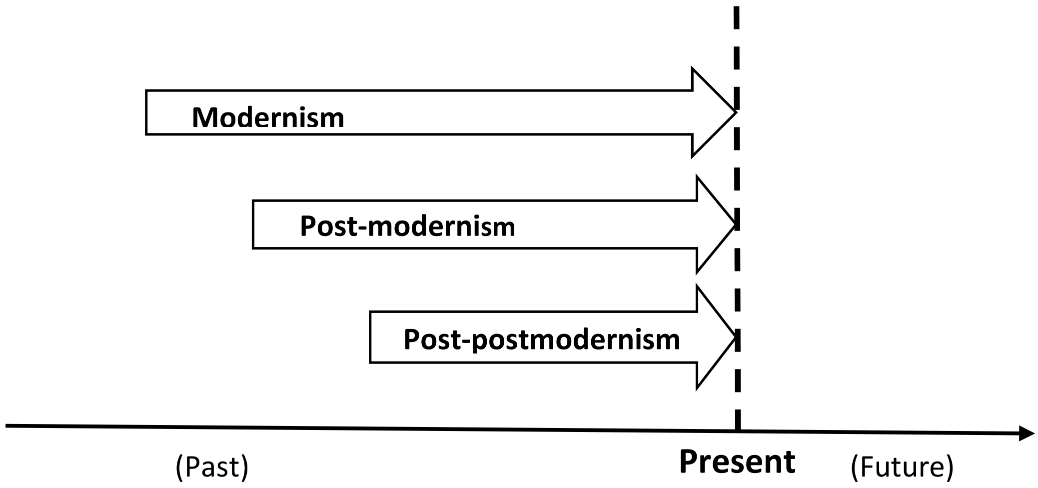

Fig. 1.1 Graphical Depiction: Modernism to Post-postmodernism

Modernism and discourse of sustainable buildings

Within the modern movement, a family of philosophical paradigms that positively affirmed science and the 'scientific method' were identified as positivism. Positivism has become dominant under the modern movement; hence, sometimes the term 'modernism' implies positivism. According to positivism, there is one and only one reality, which is external, objective and tangible (Lincoln and Guba 1985). Therefore, reality is reduced to quantitative, testable and objective knowledge. Accordingly, within the modern paradigm, the discourse and research on sustainable buildings focuses mainly on the consumption of physical and quantifiable entities such as resources and energy, which are external, objective and material aspects.

Post-modernism and discourse of sustainable buildings

The basic assumptions of modern science were challenged by the findings of two Nobel Prize winners in physics, namely, Werner Heisenberg and Niels Bohr. It is impossible to determine both the momentum and position of a subatomic particle at the same time; and also particles are altered when they are observed. This implies that there are cases where the observations are not independent of the observer. These findings challenged the fundamental assumption of modern science which says that the observations are always independent of the observer (Crotty 1998). In other words, there can be instances where observations are not 'objective' as asserted in modern science. While 'objectivity' in modern science was challenged by quantum physicists, the modern worldview (positivist worldview) of 'single-objective reality' was questioned by philosophers. Finally, as a reaction to the modern movement, post-modernism emerged in the latter part of the last century, and it rejected all fundamental principles of modernism (Huckle and Martin 2001). Accordingly, it rejected the modern world view of a single objective reality and recognized multiple realities. As a result, the discourse on sustainable buildings, which was limited to 'objective reality' within the modern movement, has traversed to many other realities. The concerns regarding ecological systems, social systems and aesthetics could be a result of that.

Post-postmodernism and discourse of sustainable buildings

Post-modernism 'deconstructed' the grand narrative or single reality of modernism and created a room for multiple realities. However, the stand of the 'rejection of grand narrative' might have prevented the integration of multi-narratives to form a meaningful whole. Hence, a need for a framework to integrate multiple realities for holistic perspective was recognised; and finally post-postmodernism emerged from post-modernism. 'Integralism' or 'Integral Theory' is one of the major philosophical paradigms that have emerged in the post-postmodern era. Integral theory not only recognises multiple realities, but also integrates those realities (Esbjörn-Hargens 2009). Thus, Integral Theory has opened a space for the discourse on sustainable buildings to recognise many realities and to integrate them.

1.3 Overview of Integral Theory

According to Integral Theory, any issue can be linked to the four irreducible realities, which are subjective realities, inter-subjective realities, objective realities and inter-objective realities; and these realities are assigned to the upper left (UL), lower left (LL), upper right (UR) and lower right (LR) quadrants of the tetra-quadrant framework respectively (Esbjörn-Hargens 2009; Wilber 1996) as graphically depicted in **Fig. 1.2**.

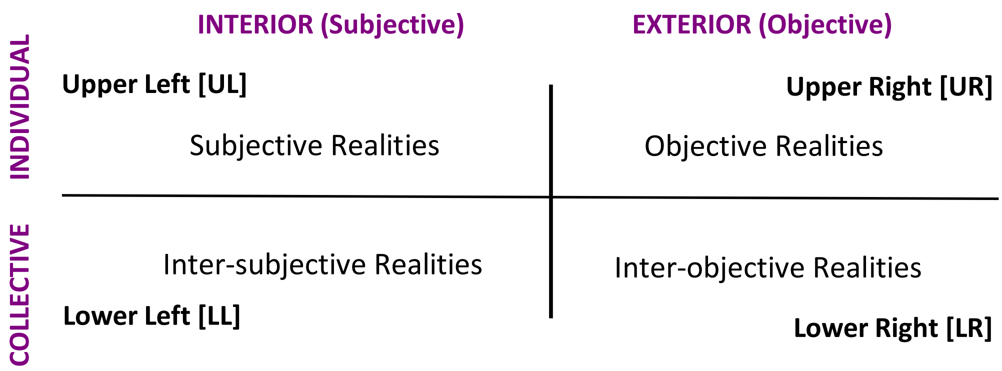

Fig. 1.2 Tetra-quadrant Framework

This tetra-quadrant framework can be expanded into a more comprehensive model by including all development levels, lines, states and types; hence, it is often referred to as an 'All Quadrants All Levels framework', or AQAL tetra-quadrant framework (DeKay 2011).

According to the tetra-quadrant framework, any issue can be viewed through four lenses, namely subjective, inter-subjective, objective and inter-objective. Also it is capable of accommodating different stances of the subjective vs objective debate. One such stance is that ideal forms of subjective and objective are not mutually exclusive binary oppositions, but only two extremes of a continuum; hence, all practical issues have subjective as well as objective components. Dias (2010) argues that the notion that subjectivity and objectivity are polar opposites is an archetype of the modern period. His argument implies that objectivity and subjectivity can exist not only in contrast but also in harmony.

More importantly, the integral framework provides a platform to integrate alternative paradigms of knowledge. An eminent philosopher and a critic of modern science, Paul Feyerabend has argued that the belief that the scientific paradigm is superior to other paradigms of knowledge is baseless, since science does not possess features to make such a conclusion (Chalmers 1999). Dias (2010) argues that even though science is more objective than religion, like religion, science too has indispensable subjective elements. For example, both science and religion are arguably underpinned by 'faith', even though this is not immediately discernible.

1.3.1 Application of Integral Theory in Related Fields

The multi-reality, multi-paradigm space unveiled by Integral Theory has been used by many researchers for the advancement of many fields. DeKay and Guzowski (2006) employed Integral Theory when developing a model for integral sustainable design explored through day lighting; while Pavez, Gonzalez and Alarcon (2010) investigated the possibility of improving the effectiveness of new construction management technologies and philosophies using Integral Theory. Robledo (2013) adopted Integral Theory in management research, while Cardoso and Ferrer (2013) used Integral Theory to develop a management model. Brown (2004) used Integral Theory to explore integral sustainable development.

1.3.2 Integral Theory for Sustainable Buildings and Building Materials

DeKay (2006) applied the concept of 'Integral Sustainability' in architecture by recognising aspects related to the four quadrants of the tetra-quadrant framework. In his study, he considered the aspects related to UR, LR, LL and UL quadrants under technological sustainability, ecological sustainability, cultural sustainability and the individual's sustainability consciousness. He argued that most high performance design approaches collapse reality into the UR quadrant, while green or ecological approaches collapse it into both UR and LR quadrants of the tetra-quadrant framework. In this context, when one reality is collapsed into another, the dimension associated with the former cannot be seen; hence, it is called a 'flat land' view as shown in **Fig. 1.3** (DeKay 2006, 2011).

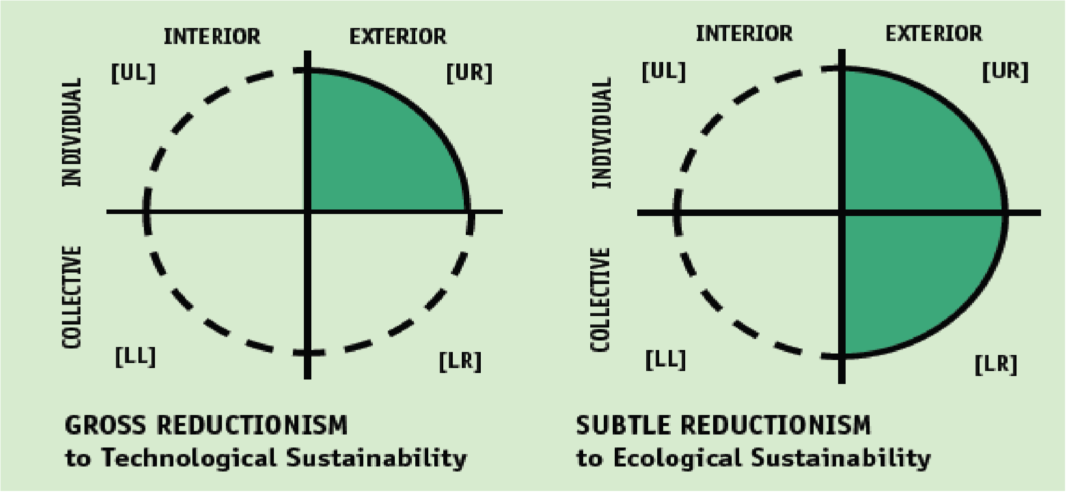

Fig. 1.3 Flatland Sustainability (DeKay 2011)

Kulasuriya and Vimonsatit (2012) proposed a method of designing integrally sustainable structures by starting with four conceptual design goals, namely objectively sustainable, inter-objectively sustainable, subjectively sustainable and inter-subjectively sustainable. These sub-goals are to be further decomposed and suitable weights assigned according to their importance. By adopting this method, the above mentioned 'flat-land solutions' can be avoided.

1.4 Formulation of the Research

As mentioned previously, conventional cement, which is commonly known as Ordinary Portland Cement (OPC), has become a threat to the sustainability of the planet. Now, the future challenge for the cement industry is to develop alternative cements using alternative materials (Schneider et al., 2011). Accordingly, much research is being carried out to develop alternative cements. Such research is focused mainly on technological and ecological aspects, which fall into the right hand side quadrants of the tetra-quadrant integral framework. However, according to both Integral Theory and contemporary discourses, considerations of individual as well as social aspects regarding common activities and products are of paramount importance. If expressed in Integral Theory terminology, it is imperative to conduct research on alternative cements that covers not only technological and ecological aspects, but also individual and social aspects, which fall into the left hand side quadrants of the tetra-quadrant integral framework. It is evident from the literature that research studies on alternative cements that cover all the four quadrants are either rare or non-existent; hence, there is a research gap to be filled.

A comprehensive literature review on alternative cements is given in Chapter 3. According to the review, the research on alternative cements can be broadly categorised into three groups. The first category involves partial replacement of OPC by pozzolans, which is commonly known as research on blended cements. The second category involves activation of pozzolans by alkali solutions such as NaOH and Na_2SiO_3, which comprises research studies on geopolymers. The third category - the research on hybrid alkaline cements - is a combination of the previous two. The first category focuses on development of dry cementitious powders, but the replacement of OPC by pozzolan is normally less than 40%. The second category normally uses hazardous chemicals such as NaOH and also requires elevated temperature curing. The third category, namely 'hybrid alkaline cements', has overcome the requirement of elevated temperature curing, but still involves the use of hazardous chemicals such as NaOH; further, the product is not a dry cementitious powder, but a wet binder. Accordingly, there is a research gap requiring an investigation into the possibility of developing a type of cement that satisfies the following requirements:

1. Utilization of over 50% pozzolanic materials and/or less than 50% of OPC
2. Use of non-hazardous chemicals
3. Eliminating the requirement of elevated temperature curing
4. Storage in dry form
5. Ensuring integral sustainability

Considering the above requirements, the aim of the research was tentatively formulated as follows:

> '*To investigate the design and development of an alternative cementitious mixture, constituted of non-hazardous chemicals that can be cured under ambient conditions and stored as a dry powder, ensuring integral sustainability'*.

In the context of this research, the developed alternative cement is called 'Alkali Pozzolan Cement', since the main constituent materials of the initial mixtures are in a dry form of alkali materials and pozzolanic materials; and the abbreviated form APC is used for convenience. The cementitious mixture used for comparison purposes is High Volume Fly Ash (HVFA) cement; and the mixture used for reference is Ordinary Portland Cement (OPC).

Accordingly, the aim of the research was re-worded as follows:

> *'To investigate the design and development of 'Alkali Pozzolan Cement' (APC), which is constituted of non-hazardous chemicals that can be cured under ambient conditions and stored as a dry powder,*

and to establish its integral sustainability; and also to compare APC with High Volume Fly Ash (HVFA) Cement with reference to Ordinary Portland Cement (OPC)'.

Accordingly, the three key terms related to the cementitious mixture are 'non-hazardous', 'ambient curing' and 'dry cement powder'; and the central theme of the whole research is 'integral sustainability'.

1.4.1 Research Development Framework

From an 'integral sustainability' viewpoint, in order to develop Alkali Pozzolan Cement (APC) for integral sustainability, it is essential to achieve the 'four quadrant sustainability' of the integral sustainable framework. That is, objective, inter-objective, subjective and inter-subjective sustainability have to be achieved. Further, they have to be addressed from the development stage of the APC. The process covers not only the objective properties of APC and its ecological impact, but also individual and social concerns. In other words, individual and social concerns about APC have to be addressed even before APC is properly developed and introduced to the public. This requirement produces a significant challenge: "*how can individual and social concerns about a product be investigated when that product has yet to be fully developed?*" The strategy that can be adopted is an 'implementation of a cyclic process', instead of a 'linear process', as illustrated in **Fig. 1.4**.

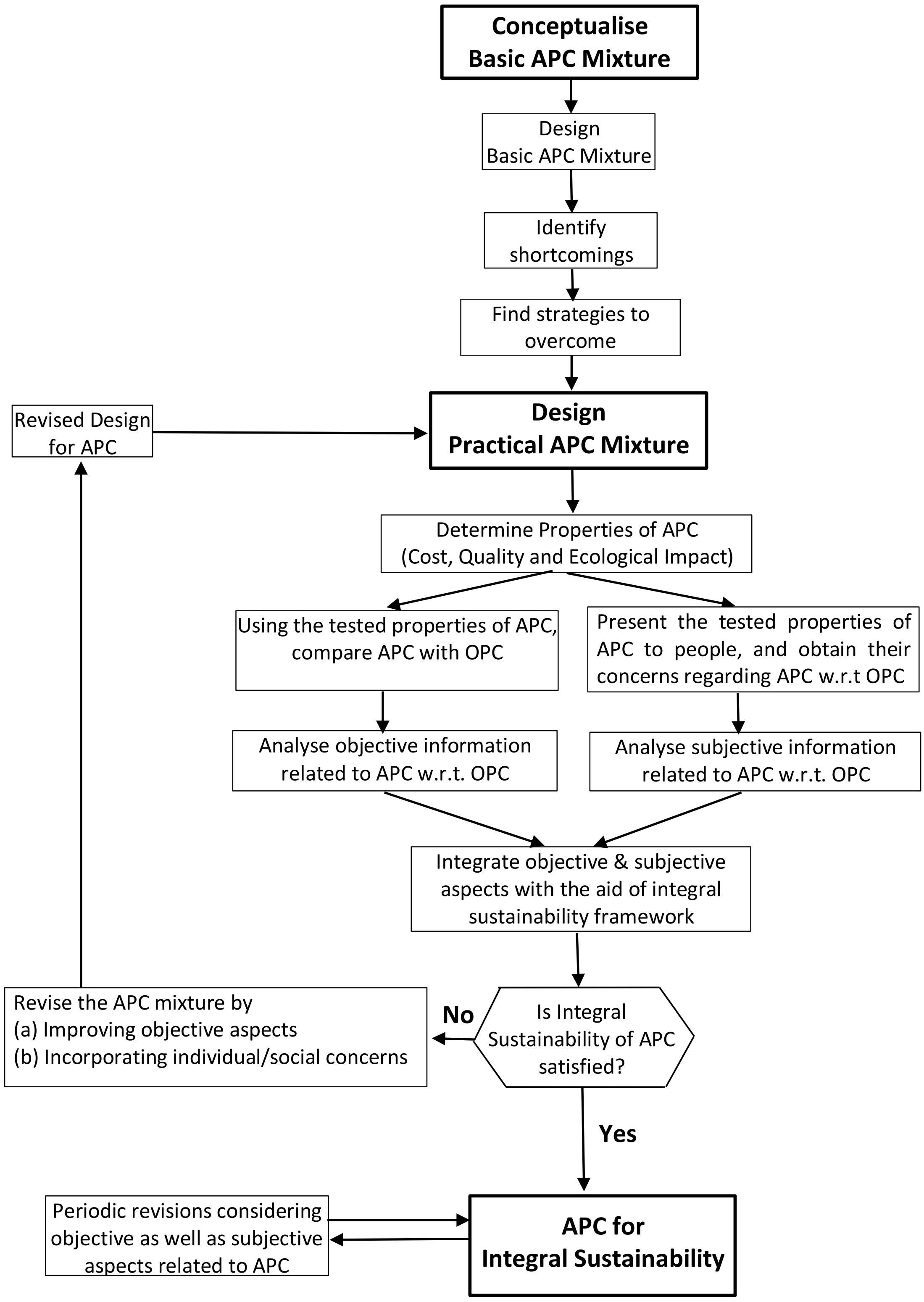

Fig. 1.4 Development of APC for Integral Sustainability

Fig 1.4 illustrates the process of developing APC for integral sustainability. The first step of developing APC is the 'conceptualisation of basic APC mixture'. After that, the basic APC mixture is produced and its shortcomings are experimentally identified. Then strategies are found to overcome those shortcomings, and the first practical APC mixture is designed and developed. Thereafter, properties of this practical APC mixture are experimentally determined, and based on the results, rough assessments are made of the quality, cost and ecological impact of APC. This information related to APC is used for two parallel investigations. One is to compare the objective properties of APC with respect to HVFA and OPC. The other is to present those properties of APC to people and obtain their subjective concerns about APC with respect to HVFA and OPC. After that, both subjective and objective information are analysed using suitable methods. In the next step, findings of both objective and subjective information related to APC are integrated with the aid of an integral sustainable framework. Then, it must be ascertained whether the developed APC can be accepted as an integrally-sustainable cement. If the developed APC cannot be accepted, then it has to be revised by improving properties and/or incorporating individual and social concerns. The revised APC mixture has to undergo the same process again. As this cycle process continues, more and more properties of APC are investigated with greater accuracy. Hence, more specific information can be presented to people, and in return more focused concerns can be obtained from them. Accurate information about the properties of APC and focused concerns about APC from people will help to assess the integral sustainability more accurately (or on more certain grounds), and also to refine it further. Finally, by the time APC is developed to the required level of integral sustainability, all the relevant requirements including the approvals of standards institutions and market research endorsements should have been covered. However, according to the integral sustainability philosophy, the process does not stop there. Periodic revisions considering objective and subjective aspects related to APC are essential in order to maintain the integral sustainability of APC.

As described in the above paragraph, the process of developing APC for integral sustainability is essentially a repetitive, cyclical process. However, the aim of this research is not to produce the final APC mixture, by adopting the repetitive process; but only to demonstrate an investigation of the development of APC for integral sustainability. Hence, only one cycle was adopted in order to achieve the objectives of this research.

1.5 Aim and Objectives of the Research

The main aim of the research was '*to investigate the design and development of 'Alkali Pozzolan Cement' (APC), which is constituted of non-hazardous chemicals, that can be cured under ambient conditions and stored as a dry powder, and to establish its integral sustainability; and also to compare APC with High Volume Fly Ash (HVFA) Cement with reference to Ordinary Portland Cement (OPC)'.*

The main aim stated above was decomposed into the following objectives.

1. To design APC with alkali materials, pozzolanic materials and other non-hazardous materials to yield satisfactory compressive strength, and compare it with HVFA with reference to OPC (details of which are presented in Chapter 3).

2. To investigate structural and microstructural properties of APC, and compare them with those of HVFA with reference to OPC (details of which are presented in Chapter 4).

3. To investigate durability properties of APC, and compare them with those of HVFA with reference to OPC (details of which are presented in Chapter 5).

4. To investigate economic aspects with respect to 'ecological cost' and 'financial cost' of APC, and compare them with those of HVFA with reference to OPC (details of which are presented in Chapter 6).

5. To bring together all the aspects considered above (technological aspects with respect to structural and durability properties as well as economic aspects with respect to ecological and financial economy) of APC, and compare them with those of HVFA with reference to OPC (details of which are presented in Chapter 7).

6. To develop frameworks to investigate integral sustainability of APC, and compare it with that of HVFA with reference to OPC (details of which are presented in Chapter 8).

7. To investigate individual and social concerns (subjective and inter-subjective concerns, according to integral theory terminology) about the integral sustainability of APC (details of which are presented in Chapter 9).

8. To employ the two frameworks developed during the research to integrate all the aspects related to APC in order to investigate the degree of integral sustainability of APC, and to identify the aspects to be improved to achieve/maintain integral sustainability of APC (details of which are presented in Chapter 10).

1.6 Methodology

The objectives indicated in Section 1.5 are diverse in nature. Objectives 1, 2 and 3 are related to properties of APC, which have to be investigated through experimental research methods. Objective 4 is related to financial cost and ecological cost, involving both market research and ecological cost assessments. Objective 5 involves the comparison of properties of APC with those of HVFA and OPC, which can be done using numerical and/or statistical methods. Objective 6 involves the development of a conceptual framework which is a theoretical procedure. Objective 7 is about individual and social perceptions, which have to be investigated by adopting social research methods. The last objective, Objective 8, involves the investigation of integral sustainability of APC using the developed frameworks. In order to achieve the objectives of this research, an integrated research methodology had to be developed; this is presented in Chapter 2.

1.7 Scope of the Research and Limitations

As mentioned previously, the main aim of the research was to investigate the development of Alkali Pozzolan Cement (APC) for integral sustainability. Accordingly, it was essential to achieve sustainability of APC with respect to all four quadrants of the integral sustainable framework, namely objective, inter-objective, subjective and inter-subjective sustainability. Each of the above quadrants involves a large number of aspects; hence, it was impossible to incorporate all of them. Therefore, only some aspects were selected for consideration.

When technological aspects related to cement are considered, there are many important structural and mechanical properties such as compressive strength, consistency, setting time and soundness; and durability properties such as permeability, sorptivity, water absorption, carbonation, sulphate attack and sulphuric acid attack. Investigations of cement products are normally done using samples made of hardened cement paste, mortar and concrete. However, in the initial stage of development of a new cement, it is more logical to use hardened cement paste, since it is the basic binding material of mortar and concrete. Where properties are concerned, it is also rational to consider the primary structural property which is compressive strength, and primary durability properties such as water absorption, carbonation, sodium chloride penetration and sulphuric acid attack.

When ecological aspects related to cement are considered, in order to assess the total environmental impact, it is necessary to perform Life Cycle Assessments (LCA), which is an approach used to identify/compare the environmental impacts of the production, marketing, transport, distribution, operation and disposal of the product throughout the whole life cycle, or 'cradle-to-grave' life of the product (Environmental Justice Organizations 2014). There are many LCA parameters related to building materials such as material usage, embodied energy, CO_2 emissions, air pollution, solid waste generation and water pollution (Canadian Architect 2014). However, in this research, only embodied energy and CO_2 emissions were considered, as they are the two primary parameters.

When individual and social concerns about APC were investigated, the findings of the initial stage of the research were presented to various individuals, and their concerns regarding eight selected important aspects were generated. The social surveys were conducted only in three contexts: Australia, America and Sri Lanka.

In addition, when conducting the research, there were limitations regarding materials, equipment and climate. Material limitations are related to the availability of materials in Western Australia. Limitations regarding equipment are due to the institutional availability of equipment for preconditioning and testing specimens. Limitations regarding climate were associated with differences in local temperature and relative humidity during different seasons of the year. The first stage of the experiments was conducted under ambient conditions during winter, where the local temperature and relative humidity were 0°C – 25°C and 45 - 55% respectively. However, the subsequent experiment stages were conducted in controlled conditions, where the temperature and relative humidity were 20°C – 25°C and 70 - 75% respectively.

In the initial stage of developing a new cement, it is more logical to use hardened cement paste, as it is the basic binding material in mortar and concrete. Hence, for the development of APC in this research, it was decided to use a hardened cement binder. Therefore, it should be noted that the findings of this research are mainly applicable to binder systems, and might not be directly applicable to mortar and concrete systems.' Investigating this applicability is one of the recommendations made for future research.

In conclusion, the scope of the research is limited to the abovementioned selected properties of APC paste under the stated conditions; individual and social concerns are also limited to specific contexts. These are described in detail in the methodology section of each chapter.

1.8 Significance of the Research

The significance of this research can be described in relation to three spheres: general, specific and distinctive.

General Significance

Conventional cement, which is commonly known as OPC, has issues related to ecological sustainability, and thus there is a general need to minimize the use of OPC. Consequently, an investigation of the development of Alkali Pozzolan Cement (APC), which is an alternative cement, has a general significance.

Specific Significance

Contemporary research on alternative cements can be broadly categorised into three groups, namely, researches on blended cement, geopolymer binders and hybrid alkaline binders. The limitation of blended cement is related to the replacement level of OPC by pozzolan, which is normally less than 40%. Issues related to geopolymer binders concern the need for elevated temperature curing, use of hazardous chemicals such as NaOH, and the product being a wet binder, which cannot be stored in dry form. Hybrid alkaline binders have overcome the need for elevated temperature curing, but still use hazardous chemicals such as NaOH; further, the product is not a dry cementitious powder, but a wet binder. Hence, there is a specific need to develop an alternative cement which utilises a higher percentage of fly ash, is constituted of non-hazardous chemicals, can be cured under ambient conditions, and can be stored as a dry powder. Subsequently, this research on APC, which investigates the development of an alternative cement that satisfies the above requirements, has a specific significance as well.

Distinctive Significance

Even though much research is being carried out to develop alternative cements, such studies tend to be focused mainly on technological and ecological sustainability. However, according to contemporary discourses, considerations of the social and cultural aspects of research projects are of paramount importance. This research on APC is focused not only on technological and ecological sustainability, but also on the social and cultural aspects of the integral sustainability framework; hence, it also has a distinctive significance.

1.9 Structure of the Thesis

The thesis consists of 11 chapters including this chapter, which is the introductory chapter. Chapter 2 describes the philosophical underpinnings of different research methodologies adopted in this research. Chapters 3 to 10 are related to the eight research objectives stated in Section 1.5. Chapters 3, 4, 5, 8 and 9 were written as semi-independent manuscripts, and therefore contain literature reviews relevant to those chapters; and there is no separate chapter for the literature review. The key focus points of each chapter are outlined in **Table 1.1**.

Table 1.1 Key focused points in Chapters

Chapter No	Title	Topics Covered
1	Introduction	-Historical development of the concept of sustainability -Introduction to Integral Theory -Introduction to the research -Research objectives -Thesis structure
2	Search for Research Methodology	-Major research paradigms -Development of an integrated approach -Research methods for objective inquires -Research methods for subjective inquires
3	Design of Alkali Pozzolan Cement (APC)	-Design of 'Basic APC mixture' -Design of 'Practical APC mixtures'
4	Structural and Microstructural Properties of APC	-Compressive strength test -X-Ray Diffraction (XRD) -Scanning Electron Microscopy (SEM) -Energy Dispersive Spectroscopy (EDS) -Thermal Analysis (TG-DTG, DTA, DSC)
5	Durability Properties of Alkali Pozzolan Cement (APC)	-Water absorption test -Sulphuric acid attack test -Carbonation test -Chloride iron penetration test
6	Ecological and Financial Cost of APC	-Ecological cost : embodied energy and CO_2 emission -Financial cost
7	Cross-comparison: APC and HVFA with OPC	-Comparison of compressive strengths -Comparison of durability properties -Comparison of ecological cost -Comparison of financial cost
8	Development of Frameworks to Access 'Integral Sustainability' of APC	-Integral sustainability map -Modified two-dimensional tetra quadrant Framework -Newly developed three-dimensional octa-octant framework -Application of the modified integral frameworks

9	Individual and Social Concerns of APC	-Generation of individual and social concerns about APC -Analysis of individual and social concerns about APC
10	Integral Sustainability of Alkali Pozzolan Cement (APC)	-Integrating subjective and objective aspects of APC -Assessment of integral sustainability of APC. -Identifying the certain/uncertain aspects of APC
11	Conclusions and Recommendations	-Summary and conclusions drawn from chapters -Overall research summary and conclusions -Originality of the Research -Recommendations for future research

1.10 Conclusions

This research can be broadly described as the development of Alkali Pozzolan Cement (APC) for integral sustainability; it can be considered as an integration of technological and philosophical investigations. The purpose of this chapter is to lay a foundation for the presentation of this techno-philosophical research. The summary and the conclusions drawn from this chapter are given below.

1. Through the passage of 'the past to present' (and to the future), the discourse of 'sustainability' has been influenced by modernism, post-modernism, and now 'post-postmodernism'. 'Integral Theory' is one of the major philosophical paradigms in the post-postmodern era; and the concept of 'integral sustainability' emerged from it.

2. The main aim of the research arising out of general, specific and distinctive needs was to develop 'Alkali Pozzolan Cement' (APC), which is constituted of non-hazardous chemicals, which can be cured under normal conditions, which can be stored as a dry powder, which confirms integral sustainability'.

3. To achieve the above mentioned main aim, it was decomposed into 8 objectives. Some of those objectives are technological in nature while others are philosophical. Hence, it was recognized that different methods had to be adopted to achieve the objectives.

4. The significance of this research was discussed under three spheres: a general sphere, specific sphere and distinctive sphere. Since this research addresses the general requirement of minimising the use of OPC by developing an alternative cement, it has a general significance. Moreover, as it searches for strategies to satisfy the specific requirement of developing a dry powder form of an alternative cement that is constituted of non-hazardous chemicals, it has a specific significance as well. In addition, as it focuses not only on technological and ecological sustainability, but on other aspects related to integral sustainability, it also has a distinctive significance.

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2 Search for Research Methodology

> *"What we observe is not nature itself, but nature exposed to our method of questioning"*
>
> ***Werner Heisenberg***
> *(Winner of Nobel Prize for Physics in 1932)*

Overview

This chapter presents the process of developing a research methodology to be adopted in this research on Alkali Pozzolan Cement (APC) for integral sustainability. Firstly, it explains that this research deals with both objective and subjective realities, namely, properties of cement, ecological impact and social concerns regarding cements. Then, it emphasises the necessity of adopting a research methodology that recognises both types of realities. After this, it briefly describes various research paradigms and their domains. The positivist paradigm is a widely employed paradigm in the domain of engineering, but there are limitations of extending it to other domains such as that of social research. Hence, it is proposed to integrate positivist and non-positivist paradigms to overcome those limitations. Finally, the chapter presents an integrated research approach, by integrating 'scientific method' with 'grounded theory', in order to achieve the goal of this research.

Keywords: *scientific method, positivist paradigm, non-positivist paradigms, critical theory, interpretive paradigm, grounded theory*

2.1 Introduction

As described in Chapter 1, the integral theory not only recognises objective realities, but also subjective realities in individual and collective forms. Hence, this research on 'Alkali Pozzolan Cement (APC) for integral sustainability' also deals with both objective and subjective realities in individual and collective forms. Therefore, it is essential to employ a research methodology that provides room to employ different methods to investigate aspects related to objective and subjective realities. Here, the terms 'methodology' and 'methods' are used with specific meanings, even though these terms are commonly used inter-changeably. The term 'method' refers to techniques and procedures (experiments, statistical approaches, theoretical procedures, questionnaire surveys, interviews and numerical approaches) used when conducting a research, while the term 'methodology' refers to the 'science of methods' or 'study of methods' that provide a systematic way of conducting a research, including the choice of suitable methods and procedures (Rajasekar, Philominathan and Chinnathambi 2006).

This research on the development of APC for integral sustainability involves not only investigations of material properties, but also investigations of ecological impact, cost analysis, individual and social concerns; and it can be graphically depicted using the integral sustainability framework shown in **Fig. 2.1**.

SUBJECTIVE INQUIRIES Investigation of individual concerns	**OBJECTIVE INQUIRIES** Investigation of material properties Cost Analysis
INTER-SUBJECTIVE INQUIRIES Investigation of social concerns	**INTER-OBJECTIVE INQUIRIES** Investigation of ecological impact

Fig. 2.1 Integral Sustainability Investigations

As illustrated in **Fig. 2.1** different investigations fall into different quadrants of the integral sustainability framework. However, a single integral research paradigm that can be employed for the four quadrant investigations has not yet been fully developed, even though several researchers have been working on it. For example, Thomas (2004) conceptualized an integrated research approach applicable to social work. However, the models which have been developed for specific research studies cannot be employed in this research of integral sustainability of APC, as the scope is different. Further, it seems that a research methodology that can be employed for a research related to engineering and integral theory has never been established. Hence, the development of a suitable methodology for this research became the first research objective.

When developing a suitable research methodology, it is useful to explore different research paradigms and their limitations. Then, by integrating appropriate paradigms, an integrated research methodology can be developed and adopted in this research on the integral sustainability of APC. The following section describes various research paradigms.

2.2 Research Paradigms

The research methodology is guided by epistemology, ontology and axiology, which are three branches of philosophy (Belbase 2008). Epistemology deals with the inquiry of '*how people know what they know'*, while ontology deals with the inquiry of '*what would be the nature of things we seek to know*'. Axiology deals with '*norms and values related to methodology adopted*'. Therefore, methodology, along with epistemology, ontology and axiology constitute the 'research paradigm', which is graphically depicted in **Fig. 2.2.**

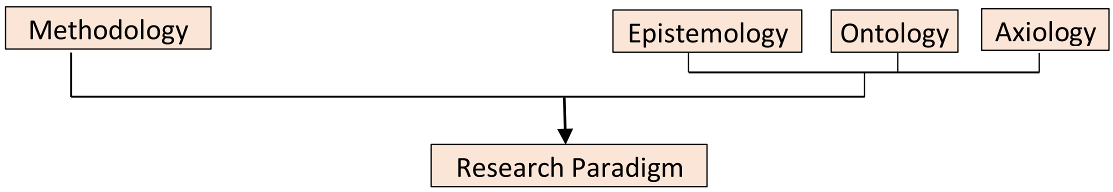

Fig. 2.2 Research Paradigm

Guba and Lincoln (1994) define a paradigm as "*the basic belief system or worldview that guides the investigator, not only in choices of method but in ontologically and epistemologically fundamental ways*". In other words, a paradigm can be simply described as a framework that guides the whole research process (Willis, Jost and Nilakanta 2007).

The research method commonly adopted in science and engineering research is the 'scientific method', which is guided by 'empirical methodology' (commonly known as scientific methodology) which belongs to the 'positivist paradigm'. The positivist paradigm affirms that there is one and only one reality, and it exists outside of ourselves, and is independent of our knowledge of it. That is, the positivist paradigm asserts the existence of a single 'objective reality' (Lincoln and Guba 1985). However, the stance of a single objective reality was challenged by the findings of two Nobel Prize winners in physics, namely, Werner Heisenberg and Niels Bohr. According to Niels Bohr, at the sub-atomic level, there is no objective reality as such, but the observer creates the reality he observes; observations are observer-dependent and context-dependent (Barukcic 2010). It is true that the above findings are related to the sub-atomic level, but it indicates that there are situations where the stance of 'objective reality' is not valid. In other words, it proves that the scientific paradigm is not a universally valid paradigm. In this background, two recent philosophers of science, Paul Feyerabend (1924-1994) and Thomas Kuhn (1922-1996) further explored the nature of scientific method. Paul Feyerabend disclosed the limits of a single prescriptive scientific method (Morrison et al. 2008; Sataty 2013; Essien and Umotong 2013). Thomas Kuhn's description of 'competing paradigms' of science suggests that science is not fully objective (Kuhn 1970). Kuhn's notion of 'relativity of knowledge' challenges positivist stance that the world is real and the truth of it can be uncovered by experimental and theoretical inquiry (Dias 2008).

Hence, the scientific method and positivist paradigm was contested not by non-scientists, but by eminent scientists. Moreover, the application of scientific method in social research was questioned by researchers of sociology. All those developments paved the way for the emergence of non-positivist paradigms; and the main differences between two types of paradigms can be summarised as follows (Lane 2009; Lincoln and Guba 1985):

1. The positivist paradigm affirms that the researcher is independent from the research, but according to non-positivist paradigms, the researcher is not independent but inter-dependent with the research.

2. The positivist paradigm asserts that reality is singular and objective (There is one reality 'out there'; and it is tangible). However, according to non-positivist paradigms, there are multiple realities that are constructed by people (subjective) and among people (inter-subjective).

3. According to the positivist paradigm, a research can be value-neutral and unbiased; but according to non-positivism, a research is inherently value-bound and biased, and knowledge is never neutral.

Positivist as well non-positivist paradigms can be broadly assigned to three categories, namely, modernism, post-modernism and post-postmodernism (Belbase 2008). As described in Chapter 1, modernism asserts a single reality, while post-modernism is an umbrella term to cover paradigms that assert multiple realities. The agenda of post-postmodernism is not only to accept multiple realities, but also to integrate them. Accordingly, positivism which assumes a single reality falls under modernism, while research paradigms such as interpretivism and critical theory that assume multiple realities fall into post-modernism. In addition, there are many other alternative approaches and research methodologies such as constructivism, hermeneutics, phenomenology, ethnography and grounded theory, which have roots in the interpretive paradigm (Higgs and Titchen 1995). As they too recognize multiple realities and/or subjective reality, they too fall under post-modernism. However, those have unique features too. For example, while constructivism accepts multiple realities, in addition it asserts that those realities are only our constructions (Forney 2004). Those sub-paradigms are not described here as it is beyond the scope of this chapter. 'Grounded theory', which is a relatively new paradigm, has traversed through post-positivism, constructivism and finally acquired post-modern status (Annells 1996). Integral theory, that has an integrated approach, falls into the category of post-postmodernism (Belbase 2008). The positivist paradigm and some of the major non-positivist paradigms which are related to this research are summarized in **Table 2.1.**

Table 2.1 Categories of Research Paradigms

Modernism (Single reality)	**Post-modernism** (Independent multiple realities)	**Post-postmodernism** (Integrated multiple realities)
Positivism	Interpretivism/Constructivism Critical theory Grounded Theory	Integral theory
NOTE: Other paradigms such as hermeneutics, phenomenology and ethnography, which have roots in the interpretive paradigm that recognizes multiple realities and/or subjective reality too fall under post-modernism.		

2.2.1 Positivist Paradigm

The term ‘positivist’ had been derived from the term ‘posit’, which means ‘assume as fact for reasoning’ (Crotty 1998). Positivism asserts that there is one reality ‘out there’, and it is tangible. Further, reality can be separated into parts and can be studied independently; and the observer can be separated from the observations. The observations are independent of the observer and of the context (under appropriate circumstances and conditions); hence, the truth in one context can be generalised to other contexts as well. The results of an inquiry are free from the influence of any value system (i.e. the results are unbiased) (Lincoln and Guba 1985).

Even though the positivist paradigm had been developed for the natural and physical sciences, later it was adopted by social science research as well. Currently, it is a major research paradigm that has been adopted in natural science as well as social research.

2.2.2 Interpretive Paradigm

The interpretive paradigm was developed in response to the criticism of using the positivistic paradigm in social sciences. For example, in a research on the investigation of crimes, a positivist would simply define the ‘crime’ and measure the ‘crime’ using quantitative methods, but an interpretivist would argue that first the researcher needs to understand what people mean by ‘crime’ in the given context (Abbott 2010). According to the interpretive paradigm, the reality (or ‘what we know’) is constructed through meanings and understandings developed over time experientially in social and cultural contexts. The reality cannot be separated from our knowledge of it (that is, subject and object separation is not possible). All interpretations depend on the context or situation and time (Cohen and Crabtree 2006b). Accordingly, there is no single reality; instead, there are multiple constructed realities. Additionally, the interpretivist does not attempt to make general claims from the findings, instead attempts to provide only descriptions about particular contexts (Forney 2004).

2.2.3 Critical Paradigm

Critical Theory asserts that all knowledge is historical and biased; hence 'objective knowledge' is illusory. The objective-subjective distinction is a socially constructed concept, but not a natural fact. Critical theorists have shown that the 'so-called' objective practices are not really objective but most subjective. The 'so-called' subject-object distinction provides identity protection and privileges for powerful groups in the society as well as in the research community. This has created false beliefs about quantitative and qualitative research. If the subject-object dualism is eliminated, then the substances in both quantitative and qualitative research methods can be seen as historically produced, socially shared, and general to a social group. The critical theory approach is a reflective dialogic method. Critical and reflective debates encourage the researcher and the participant to question the 'natural' state and challenge the mechanisms that maintain it. Hence, critical theorists do not just describe and interpret a situation; they try to change the situation for the better (Cohen and Crabtree 2006a). According to the critical paradigm, merely interpreting situations and remaining passive about the issues is considered as 'intellectual dishonesty' (Belbase 2008).

2.2.4 Integral Paradigm

Integral Theory not only recognises multiple realities, but also integrates them. A fully-fledged integral research paradigm has not yet been established, but relevant research methodologies are in the process of being developed (Belbase 2008). Since the main agenda of the integral research paradigm is to adopt an integrated approach in conducting research, the positivistic paradigm may have to be integrated with relevant post-modern paradigms in order to develop integral research paradigms.

2.3 Development of an Integrated Approach

As illustrated in **Fig. 1.4** of Chapter 1, the development of APC for integral sustainability is a cyclical process. During each cycle, objective aspects as well as subjective concerns of people have to be investigated and addressed. Obviously, the most suitable paradigm to investigate objective aspects is the positivist paradigm; and this can be adopted in each cycle, from the beginning, without any issue. However, the positivist paradigm is not the most suitable paradigm for investigating subjective concerns; instead, a non-positivist paradigm such as the interpretive paradigm would be more suitable. Using such a paradigm, it is possible to generate people's inner concerns and feelings about 'familiar commodities'. However, in the first round of the development of APC, where APC has not been introduced to people, the interpretive paradigm cannot be adopted in a strict sense, since APC is not a familiar commodity to people. Hence, a different strategy has to be adopted to generate people's concerns. One such strategy is to present the properties of APC to people, make them aware of those properties of APC, and obtain their subjective concerns about APC by adopting a positivist paradigm coupled with the interpretive paradigm.

When selecting paradigms for a research on integral sustainability, the historical development of the concept of integral sustainability cannot be forgotten. The concept of 'sustainability' has been a popular topic for many decades. Hence, the concept of 'integral sustainability' has emerged as a critique to conventional concept of 'sustainability', highlighting the non-integration of all the aspects related to sustainability. Hence, it implies the necessity of a critical debate with society regarding shared meanings and values related to the concept of sustainability. In other words, a research of this nature demands a 'critical paradigm', which uses a 'reflective dialogic method' as well. However, the application of a critical paradigm becomes meaningful only after introducing APC to people, but not at the initial stage of the research. Hence, in the initial APC development stage,, the critical paradigm has to be omitted.

Considering all the above, a comprehensive research framework was developed for this research regarding the design and development of APC for integral sustainability, and is illustrated in **Fig. 2.3**.

SUBJECTIVE INVESTIGATIONS	**OBJECTIVE INVESTIGATIONS**
Interpretive Paradigm *-to Investigate individual concerns* Positivist/Post-positivist Paradigm *-to Investigate trends of individual concerns* Critical Theory Paradigm *-to initiate a critical debate with individuals in order to achieve integral sustainability*	Positivist Paradigm *-to Investigate material properties and cost*
INTER-SUBJECTIVE INVESTIGATIONS	**INTER-OBJECTIVE INVESTIGATIONS**
Interpretive Paradigm *-to Investigate social concerns* Positivist/Post-positivist Paradigm *-to Investigate trends of social concerns* Critical Theory Paradigm *-to initiate a critical debate with individuals in order to achieve integral sustainability*	Positivist Paradigm *-to Investigate ecological impact*

Fig. 2.3 Integral Research Framework

The research framework illustrated in **Fig. 2.3** is the comprehensive framework that covers all the aspects of the research, and that can be adopted from beginning to end in developing APC for integral sustainability. However, this thesis focused only on the initial stage of the research. Hence, it was decided not to employ the critical theory paradigm. However, it was decided to employ 'grounded theory', a paradigm which has roots in the interpretive paradigm, instead of employing the pure form of the latter. Hence, the integrated approach used in this research consisted of the positivist paradigm and grounded theory, which employs quantitative as well as qualitative research methods.

2.3.1 Research Methods to be adopted for Objective Inquiries

Objective aspects include the structural, microstructural and durability properties of cement, the ecological impact of cement, and the cost of producing cement, which are quantitative information. Hence, the positivist paradigm with quantitative techniques is used to analyse this information. However, when an entity is measured, instead of single-value measures, spread-value measures are taken into account to determine statistical mean and variability. Investigation of these entities involves different methods, which are comprehensively described under the methodology sections of the chapters that focus on the objective aspects. However, they are briefly described below.

Structural, Microstructural and Durability Properties of APC

The structural, microstructural and durability properties of cement are investigated using experimental methods. Different dry cementitious mixtures are mixed with different water quantities, and samples are cured under different conditions. The structural properties are investigated based on the compressive strength using destructive testing; while microstructural properties are investigated using microstructural techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), Energy Dispersive Spectroscopy (EDS) and thermal analysis (TA).

To determine compressive strength, a number of test samples are tested and statistical methods are adopted to determine mean strengths. Moreover, factorial analysis and Analysis of Variance (ANOVA) are performed to investigate the variations of strengths caused by different treatments and whether or not the effects of different treatments are significant. When it comes to microstructural techniques, the cost involved is relatively high; hence, only one sample from each mixture is selected, and statistical techniques cannot be employed. Thus, when selecting the samples, representative samples have to be carefully selected. When durability properties are tested, a number of samples from each mixture are tested and mean values computed. In addition, sensitivity measurements such as sensitivity to water/cement ratio, and sensitivity to curing are computed using the results. Moreover, in order to take 'uncertainty' into account, the variabilities of measures are computed.

Ecological impact of APC

The ecological impact of cementitious mixtures can be computed based on the results of the experiments and also on embodied energy and CO_2 emission values given in reliable data bases. When searching for the embodied energy and CO_2 emission values of raw materials, instead of depending on a single source, data are extracted from a number of reliable sources. Using those values, the statistical mean and variability values of embodied energy and CO_2 emissions of different cementitious mixtures are computed. The mean and variability values are used in order to assess the 'uncertainty' of measures.

Cost of producing APC

The costs associated with producing cementitious mixtures are computed based on market prices of constituent materials. Instead of prices from a single supplier, market prices of different suppliers are obtained. Using these prices of constituent materials, mean cost of producing different cementitious mixtures are computed with cost ranges and variability values.

Degree of Certainty/ Uncertainty of Objective Aspects

The degree of certainty/uncertainty of objective aspects related to cement is mainly due to the randomness of data, which is reflected by the 'variability of data' (variability = range of data/mean of data). The process of identifying certainty/uncertainty of objective aspects, based on variability values, is described in detail in Chapter 10.

2.3.2 Research Methods for Subjective Inquiries

Subjective aspects related to cement (that is, individual and social concerns) are investigated using both positivist and non-positivist paradigms. Individual and social concerns can be generated through a questionnaire having close-ended as well as open-ended questions. However, as mentioned previously, when people are unfamiliar with the cement, the properties of the cement have to be presented to people and their subjective concerns about cement have to be generated. The uses of close-ended and open-ended questions are briefly described below.

Use of close-ended questions

There are two problems associated with close-ended questions when used to investigate social responses.

1. Rigidness in generating responses
2. Rigidness in analysing responses

The rigidness of generating responses and the rigidness of analysing responses can be minimised by adopting the strategies described below.

Minimising Rigidness in Generating Responses

When close-ended questions are used to generate responses, participants can select a response only from the choices given under the question; hence, this limits the respondent's voice. This is even worse when the question is a Yes/No type of question. However, to minimize the above rigidness, respondents can be given multiple choices in the form of linguistic labels such as 'very low', 'low', 'moderate', 'high', 'very high' to cover the whole spectrum.

Minimising Rigidness in Analysing Responses

Even though the rigidness of responses is minimised by using linguistic labels as mentioned above, when analysing them, normally those responses are considered as separate categories and added together. Thereafter, statistical methods are employed to determine mean and variability. However, in reality, human preferences do not have clear-cut boundaries; their boundaries are fuzzy and will be 'overlapping areas' between them. This fact is not reflected when 'categorising' is done according to a step scale, and the rigidness of analysis is not ameliorated. Hence, the strategy suggested by Dias (1999) can be adopted to mitigate the rigidness in analysing. Instead of representing the responses (which are in the form of linguistic labels) as a 'step scale', they are converted to a fuzzy scale where the boundaries are fuzzy. Then the analysis is done using fuzzy techniques, and the results converted back to linguistic labels 'very low' to 'very high' with fuzzy support for each. By adopting this strategy, the fuzzy nature of human preferences can be incorporated during the analysis stage as well. The analysing process is not described here, as it is beyond the scope of this chapter (An example of a representation of a fuzzy scale is given in Section 8.6.1.2; and the process of analysis using 'fuzzy techniques' is demonstrated in Section 9.4.1).

Use of open-ended questions

Open-ended questions give participants complete freedom to express their concerns and feelings. Hence, it is possible to generate their subjective concerns and 'feelings', and analyse them using qualitative techniques. Therefore, as illustrated in the integral research framework given in **Fig. 2.3**, the interpretive paradigm can be adopted to investigate subjective inquiries. The purpose of using open-ended questions is to identify the concerns that are related to (or grounded in) the context. Hence, grounded theory techniques are used in the analysis. The analysis process is not described here as it is beyond the scope of this chapter (the process of analysis using 'grounded theory techniques' is demonstrated in Section 9.4.2).

Degree of Certainty/ Uncertainty of Subjective Aspects

The degree of certainty/uncertainty of subjective views regarding an aspect is mainly due to fuzziness about the perceptions regarding the aspects. Fuzziness of perception can be assessed by computing the 'degrees of identity' of aspects (described in Chapter 9), and by examining the 'magnitude' and 'width of spread' of 'degrees of identities'. The process of identifying certainty/uncertainty of subjective aspects is described in detail in Section 10.4.2.

2.4 Conclusions

This research on 'Alkali Pozzolan Cement (APC) for integral sustainability' deals with both objective and subjective aspects related to APC. Hence, it is essential to adopt a research methodology that recognizes objective as well as subjective aspects. Thus, it was necessary to develop a methodology for this research, which is related to engineering and integral theory. The development of an integrated research methodology has been presented throughout this chapter, and the conclusions drawn are summarized below:

1. The research method commonly adopted in science and engineering research is the 'scientific method', which is guided by 'empirical methodology'. This method belongs to the 'positivistic paradigm', which positively affirms that there is one and only one reality, and it is totally objective. Hence, within the positivist paradigm, there is no room for socially and culturally constructed multiple realities and to understand/investigate differences in subjective meanings. Therefore, positivist research paradigm cannot be used alone for this research on integral sustainability of APC.

2. Non-positivist paradigms reject the stance of single objective reality, and accept the existence of multiple paradigms that are socially and culturally constructed. Hence, non-positivist paradigms are useful for understanding/investigating differences in subjective meanings. However, within non-positivist paradigms, there is no room for objective entities. Therefore, non-positivist paradigms also cannot be used alone for this research on integral sustainability.

3. Combining the positivist paradigm with non-positivist paradigms, an integrated research approach was developed to be employed in this research, which includes both quantitative and qualitative research methods.

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3 Design of Alkali Pozzolan Cement (APC)

Overview

This Chapter presents the preliminary design and development of Alkali Pozzolan Cement (APC), a non-hazardous dry cement powder that needs only ambient temperature curing in order to achieve strength. The design process began with a basic APC mixture consisting of fly ash and lime. However, two critical issues, namely, slow pozzolanic reaction and slow hardening process were noted. Addition of activating materials (Na_2SO_4) improved pozzolanic reaction, yet hardening process was not improved significantly. In order to 'scafold' the mixture till it gets hardened, Ordinary Portland Cement (OPC) was added as a scaffolding material. Accordingly, the final APC mixture was defined as a mixture of alkali materials, pozzolanic materials, activating materials and scaffolding materials. This chapter presents strength development of basic, activated, scaffolded and final APC mixtures up to 28 days, under ambient curing and elevated temperature curing conditions. A full factorial analysis performed on the results of the APC mixtures, considering the effect of age, activation (with Na_2SO_4), scaffolding (with OPC) and elevated temperature curing (15 hours at 60^o C) on the strength. SEM, EDS and XRD investigations were employed to explain variations in strength.

Keywords: *Alkali Pozzolan Cement, lime, fly ash, activation, scaffolding, curing regimes, compressive strength, factorial analysis, microstructure.*

3.1 Introduction

'Alkali Pozzolan Cement' (APC) is an alternative cement developed in this research. The design and development of practical APC mixtures and investigation of their properties were done through a number of stages. In the first stage, constituent materials and their proportions to achieve practical APC mixtures were investigated, and they are presented in this chapter.

The design of APC was based on the findings of past and contemporary research on supplements or alternatives to Ordinary Portland Cement (OPC). Accordingly, the following sections first present the literature review on alternative cements and thereafter the formulation of APC.

The research on supplements or alternatives to OPC can be divided into two broad categories, namely ‘partial replacement of OPC by pozzolans’ and ‘activation of pozzolans’. The sources of these pozzolans could be industrial (fly ash, silica fume, ground granulated blast-furnace slag, red mud), agricultural (rice husk ash, sugar cane bagasse ash) or natural (volcanic ash) (Allahverdi and Ghorbani 2006a; Cordeiro et al. 2008; Helmuth 1987; Malhotra and Mehta 1996; Payá et al. 2002; Rashid, Molla and Ahmed 2010; Ribeiro, Labrincha and Morelli 2011; Shi and Day 2000b). The motivation for finding supplements or alternatives to OPC is to reduce the energy costs and carbon emissions associated with the production of OPC, and also to profitably use pozzolans, many of which are by-products or wastes. These motivations result in environmentally friendly binders.

Research in the first category, i.e. ‘partial replacement of OPC by pozzolans’, has resulted in dry blended cement powders. Kumar, Kumar and Mehrotra (2007) partially replaced OPC by fly ash up to 35% and concluded that the typical range was 15-25%, and strength would decrease after that. Oner and Akyuz (2007) added ground granulated blast-furnace slag (GGBS) to cement (from 0 % to 60% of total binder content) for preparing concrete samples and found that the optimum GGBS percentage was about 55% of the total binder content; while Malagavelli and Rao (2010) replaced cement by 40% to 60% of GGBS and also replaced sand by 0% to 30% of crusher dust for preparing concrete and concluded that 50% replacement of GGBS is a practical option. Katkhuda, Hanayneh and Shatarat (2009) varied the silica fume percentage from 0% to 25% of binder content and found optimum percentages of 15-20% at water/cement ratios of 0.26 to 0.34 for the strength of lightweight concrete specimens. Rashid, Molla and Ahmed (2010) replaced OPC by rice husk ash in steps of 5% from 10% to 30%, and tested mortar samples up to 700 days; they found that 20% replacement is appropriate where both short term and long term compressive strengths are concerned.

Hence, the optimum OPC replacement percentages depend on the type of pozzolan used, but are generally below 40%, except for ground granulated blast-furnace slag. At these optima, the strengths achieved are expected to equal or exceed that of the corresponding OPC mixtures, especially at ages greater than 56 days.

Research in the second category, i.e. ‘activation of pozzolans’, involves different activating and curing methods and generally results in wet binders. Shi (2001) says that thermal, mechanical or chemical activation can be used. Li et al. (2000) described the process of activation as the breaking down of glass phases of fly ash particles. Shi and Day (2000b, 2000a) studied the activation of cementitious paste made with 20% hydrated lime and 80% natural pozzolan using four different chemical activators, namely sodium sulfate, flake calcium chloride, hemihydrate gypsum and sodium chloride, cured at 50°C till the test date. They recommended 4% as an activator percentage suitable for sodium sulfate or calcium chloride. Allahverdi and Ghorbani (2006a) too studied the activation of cementitious paste made with 30% hydrated lime and 70% natural pozzolan using sodium sulfate, calcium chloride, sodium chloride, sodium hydroxide, sodium carbonate and Ordinary Portland Cement (OPC) added separately and cured for 15 hours at 50°C. In the cases of sodium sulfate and calcium chloride, strength increased significantly at percentages from 2% to 6%, while the other four additives gave relatively low strengths. Fan et al. (1999) prepared ‘activated fly ash’ (AFA) by mixing fly ash and calcium hydroxide in a weight proportion of 6:1, adding 3.91% of Na_2SiO_3, grinding the mixture and drying at 120° C. They had then replaced OPC by up to 15% with AFA and obtained compressive strengths of around 50 MPa. Katz (1998) emphasized the need for elevated temperature in activating fly ash by NaOH.

In all the methods mentioned above, the ultimate goal is to improve the formation of cementitious hydrated products by activating pozzolanic materials. Geopolymer mixtures are obtained by using alkali solutions to activate pozzolanic materials, the main cementitious compounds obtained being alkali-aluminosilicates (Al Bakri et al. 2011). Davidovits (2011) produced a geopolymer liquid binder using metakaolin and soluble alkali silicate in 1975. Rangan and Hardjto (2005) were able to achieve a high strength of 70 MPa in 7 days from geopolymer concrete prepared by using fly ash, sodium silicate solution and sodium hydroxide solution, cured for 24 hours at 90°C.

Mandal and Majumdar (2009) were able to achieve 47 MPa at 28 days from mortar specimens prepared using fly ash and the same alkali solutions cured at 60°C for 48 hours; however, the maximum strength obtained at room temperature was only 5 MPa. Their results imply the necessity of elevated temperature curing. Rostami and Brendley (2003) introduced a new cementitious binder called Alkali Ash Material (AAM), the constituent materials of which are the same as geopolymer material. They obtained strengths over 100 MPa by curing AAM concrete samples for 24 hours at 70°C, 80°C and 90°C. It can be concluded that activated pozzolan mixtures would give much better results when specimens are cured at elevated temperatures.

The term 'hybrid alkaline cement' is now being used for mixtures that involve both OPC replacement and pozzolan activation. This can be considered a hybrid or even third category of research. Garcia-Lodeiro, Fernández-Jiménez and Palomo (2013) selected a 'hybrid cement' that contained 70% fly ash and 30% OPC and activated it by NaOH and Na_2SiO_3 solutions, resulting in a strength of 30 MPa at 28 days. Shi, Jiménez and Palomo (2011) too used a hybrid cement that contained 70% fly ash and 30% OPC, from which three different mixtures were obtained by mixing with water, sodium silicate solution and sodium hydroxide solution. This had resulted in 28 day strengths of 29 MPa, 25 MPa and 37 MPa respectively. It can be concluded that 'hybrid alkaline cements' can yield reasonably high strengths even at room temperature.

In summary, the first category that involves dry blended cements has a limitation related to the replacement percentages (limited to 40% or less in most cases), whereas the second category that often requires wet cementitious binders has a disadvantage because of the need for elevated temperature curing. The third category, namely 'hybrid alkaline cement', has overcome those limitations. This research on development of an alternative cement too can be considered within the paradigm of hybrid cement. However, this research also tries to improve on some of the shortcomings of the above third category systems, for example the fact that they are wet formulations that use hazardous chemicals such as NaOH. The research reported here also has a somewhat different conceptual framework, outlined below.

The success of the first category research is due to the pozzolanic replacements reacting with the calcium hydroxide which is released during OPC hydration (Payá et al. 2002).

Hence the idea of directly using calcium hydroxide (i.e. slaked lime) as an alkaline material to activate a pozzolan (primarily fly ash) can be explored. Fly ash is chosen over other pozzolans because it is by far the most commonly available pozzolanic material in Western Australia and worldwide; it is also a by-product. This will generate a system that is a lime-pozzolan mix (i.e. a second category system). Since these systems require activation, a range of activators is tried in order to improve the reaction between fly ash and lime; elevated temperature curing is also resorted to. However, it is also proposed that a proportion of fast reacting OPC could result in 'scaffolding' that would enable better void filling in the alkali-pozzolan system. Note that the OPC is not meant as a source for free lime released through hydration, since lime is already present initially. The addition of OPC results in a third category system, which is called 'Alkali Pozzolan Cement' (APC) in this research. The term 'alkali' in general usage refers to basic (as opposed to acidic) materials, and in this research the term 'alkali' covers basic compounds of calcium as well as sodium, present or created in the mixture. The term 'pozzolan' refers to the fly ash, and the use of the noun rather than the adjective 'pozzolanic' conveys the idea that the pozzolan percentage is significant. The term 'Alkali Pozzolan Cement' is broad enough to cover the OPC used as well, since the term 'pozzolanic cement' is also used for blended cements manufactured by mixing fly ash and OPC.

3.2 Aim and Objectives

This chapter presents the first stage of the research on design and development of Alakali Pozzolan Cement (APC). Accordingly the main aim the research component presented in this chapter is to investigate the design and development of practical APC mixture. This main aim was decomposed into following objectives.

1. To arrive at the formulation of a 'non-hazardous dry cement powder' that contains significant amounts of by-product pozzolan but yields strengths comparable to OPC mixtures.
2. To study the relative and combined effects of chemical activation, scaffolding by OPC, elevated temperature curing and age, on the strength development of APC, or specifically, in this case a slaked lime – fly ash cement mixture.

3. To seek explanations for the above effects through microstructural investigations, namely, XRD, SEM and EDS.

Experimental methods were adopted to achieve the above objectives, and described in the following sections.

3.3 Materials, Methods and Experimental Program

In the experimental program, different APC mixtures were classified as 'basic', 'reference' and 'comparable' mixtures, to reflect the purpose of the mixes. The basic mixture contained only fly ash and lime; the reference mixture was pure OPC; while the comparable mixture contained a high volume of fly ash combined with OPC. Other mixtures were activated APC, scaffolded APC and an APC mixture that was both activated and scaffolded. The details of the material constituents and other admixtures used in the experiments are described in the following sections.

3.3.1 Materials

The pozzolanic material used in the mixtures was Class F fly ash, which had 51.6% SiO_2, 27.6% Al_2O_3 and 1.6% CaO. The other 19.2% contained mainly Fe compounds. The alkali material used was a fine lime powder available in the market and derived from quicklime via grinding and slaking. Hence it can be considered a mixture of quicklime and hydrated lime. The CaO content (whether as CaO or $Ca(OH)_2$) was 56.5%; hence for preliminary calculations, the lime content was assumed as 60%. The lime powder also contained small amounts of MgO (3.6%), SiO_2 (2.3%) and Al_2O_3 (0.5%). The other 37.1% contained mainly moisture and compounds of Fe, K, Na, S and Sr in small percentages. The Ordinary Portland Cement (OPC) used was the General Purpose OPC available in Western Australia; it typically contains 63.6% CaO, 21.1% SiO_2 and 4.7% Al_2O_3. The other 10.6% contains mainly Fe_2O_3, MgO and SO_3. The activating chemicals used were fine powder form of Na_2SO_4 and Na_2SiO_3. Finley ground Na_2SO_4 is shown in **Fig. 3.1**.

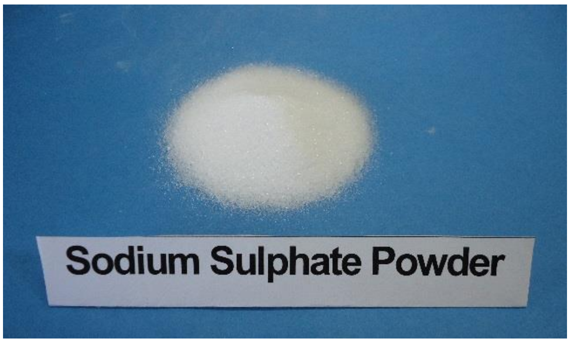


Fig. 3.1 Sodium Sulphate Powder

3.3.2 Basic, Reference and Comparable Mixtures

When preparing the APC, since differing percentages of pozzolan and lime can be mixed together, the common form 'APCr' is used to identify a mixture, where 'r' indicates the percentage of pozzolan in the mixture. Thus, since the APC mixture described in this chapter contained 70% fly ash and 30% lime (see below for justification), it is termed APC70. It should be noted that similar research studies have been carried out by other researchers using different pozzolanic materials and lime percentages in the range of 20%-30% (Allahverdi and Ghorbani 2006b; Fan et al. 1999; Shi and Day 2000b, 2000a)

In order to determine the quantities of material needed to complete the reaction in the basic APC mixture, the method used by Helmuth (1987) was used as a guide. SiO_2 in fly ash reacts with CaO and water to form Calcium Silicate Hydrate (CSH), the approximate chemical formula of which is $CaO.SiO_2.nH_2O$. As per Helmuth (1987) , the average CaO to SiO_2 molar ratio in CSH after complete reaction, is taken as 1.0. The equivalent CaO to SiO_2 weight ratio is 0.93. In addition, Al_2O_3 in fly ash, along with SiO_2, reacts with CaO and water to form 'gehlenite hydrate', the approximate chemical formula of which is $2CaO.Al_2O_3.SiO_2.\ 8H_2O$. Gehlenite hydrate has a CaO to (SiO_2 + Al_2O_3) molar ratio of 1.0. The equivalent CaO to Al_2O_3 weight ratio is 0.55. Fly ash used in experiments contains 51.5% of SiO_2 and 27.6% of Al_2O_3. The percentage of CaO in fly ash is 1.5% and thus can be neglected. Accordingly, the quantity of CaO required for complete reaction with fly ash can be calculated as 0.93x51.5% + 0.55x27.6% = 0.630kg of CaO per kg of fly ash, or 1.59 kg of fly ash per kg of CaO. It was assumed that commercially available lime contains around 60%

of CaO (see Section 3.3.1). Thus, 1.05 kg of lime is needed to react with 1 kg of fly ash. Accordingly, the ideal composition of the fly ash–lime mixture would be 48.8% fly ash and 51.2% lime. However, formation of hydration products around the fly ash would preclude the consumption of all the fly ash (just as in OPC hydration). Hence more fly ash than theoretically needed would be required to ensure that there is a sufficient quantity of fly ash to react with the lime. Based on the above calculations and considerations, the 'basic' APC mixture selected was a mixture of 70% fly ash and 30% lime, or APC70. This is labelled Mixture B1.

A reference mixture that contained 100% OPC was also used (Mixture R1), as was a comparable mixture that contained 70% fly ash and 30% OPC (Mixture C1). This combination was used for the 'comparable' mixture, because it is probably the largest percentage of fly ash that can be envisaged for 'high volume fly ash' (HVFA) mixtures, containing significantly more fly ash than the typical 25% (Kumar, Kumar and Mehrotra 2007) ; also, it can be seen as a cement where OPC is substituted for the lime in the APC70 mixture.

3.3.3 Activated and Scaffolded Mixtures

Li et al. (2000) state that fly ash can be activated by breaking down the glass phases of fly ash particles through an increase in the alkalinity of the mixture. The common method of increasing alkalinity is by adding a NaOH solution. However, NaOH is considered a hazardous chemical and hence its use is at variance with the aim of this research of producing a 'non-hazardous dry cement powder'. Therefore, it was sought to increase the alkalinity indirectly by using the activators Na_2SO_4 and Na_2SiO_3, which are not as hazardous as NaOH. Na_2SO_4 was selected as it was used to successfully activate fly ash by other researchers (Li et al. 2000; Shi and Day 1995). Na_2SiO_3 has also been used by others (Fan et al. 1999; Shi, Jiménez and Palomo 2011). The selected activators (Na_2SO_4 and Na_2SiO_3) react with $Ca(OH)_2$ to produce NaOH when water is added. However, in a dry form, the mixture does not behave as a hazardous powder. Also when the activator quantity is small, only a small amount of NaOH will be formed and it is also not in an isolated form, but within the mixture. Nevertheless, in that alkaline environment, glass phases of fly ash particles are expected to be broken, and made to react with $Ca(OH)_2$, thus producing Calcium Silicate Hydrate (C-S-H). Therefore, in the present work, two 'activated APC mixtures' were prepared by adding 5% Na_2SO_4 (Mixture A1) and 5% Na_2SiO_3 (Mixture A2), while the third mixture was prepared by combining 2.5% Na_2SO_4 with 2.5% Na_2SiO_3 (Mixture A3).

The final set of mixtures was designed to resolve the problem of slow strength development in the basic and activated APC mixtures. It was thought that OPC, being relatively quick reacting, could serve as a 'scaffolding' material that would assist with void filling in the APC mixtures. In concept, this would be analogous to the permanent scaffolding of the Pompidou Centre in Paris, and the mechanism of permanent shuttering in profiled-steel concrete slabs. The percentage of OPC to be added was decided as 30%. This percentage of OPC, though chosen somewhat arbitrarily, can be considered as small enough to constitute a significant replacement of OPC with other materials and large enough to make a reasonable contribution to early strength. It is also the same percentage used in the 'comparable' Mixture C1, described before, which is a high volume fly ash (HVFA) mixture that combines 30% OPC with 70% Fly Ash. The scaffolded 'basic' APC mixture is called Mixture SB1 (containing 70% APC70 and 30% OPC). The scaffolded 'activated' mixtures are called SA1, SA2 and SA3 depending respectively on whether the activator is Na_2SO_4, Na_2SiO_3 or a combination of Na_2SO_4 and Na_2SiO_3. Each of these mixtures have 30% OPC combined with 70% of the APC plus activator (i.e. 95% APC70 and 5% activator).

3.3.4 Experimental Procedures

The cement pastes were prepared by mixing dry cementitious powder with water, keeping the water to cementitious mixture ratio (w/c ratio) as 0.3 by weight. Note that, these experiments, which belonged to the stage 1 of the research, were conducted in winter, and hence the temperature of tap water was about 0 - 4°C. Hence, the temperature of water was brought to 25°C by mixing with warm water before use. Three sets of specimens of size 50mm x 50mm x 50mm were made from each mixture and cured under 3 different conditions. These were: Condition A – ambient curing till testing; Condition S - 15 hours steam curing at 60°C (i.e. a sealed condition) followed by ambient curing till testing; and Condition H - 15 hours heat curing at 60°C (i.e. an unsealed condition) followed by ambient curing till testing. The experiments were done in winter where the local temperature varied between 0°C – 30°C, and relative humidity varied between 45-55%; accordingly the ambient conditions were characterized by the above.

Mixing of the cementitious mixtures was done using a 20L capacity Hobart Mixture shown in **Fig. 3.2**. Moulds were made of non-absorbent, non-reactive plastic material. A set of moulds, casting of samples and hardened samples are shown in **Fig. 3.3, Fig. 3.4** and **Fig. 3.5** respectively.

Fig. 3.2 Hobart Mixer

Fig. 3.3 A Set of Moulds

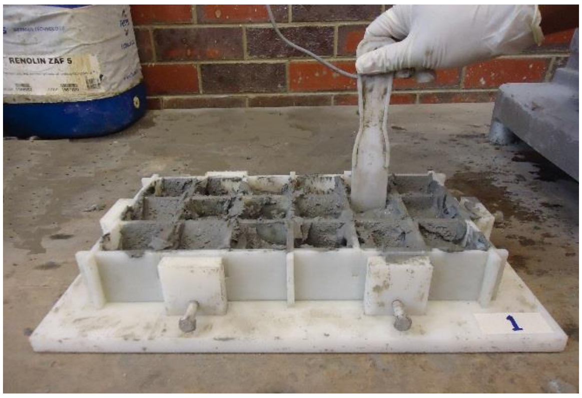


Fig. 3.4 Casting of Samples

Fig. 3.5 Hardened Samples

Compressive strength was measured at 3, 7 and 28 days, with three specimens per condition being tested as per ASTM C109. X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) techniques were used on the specimens that had been strength tested at various ages, in order to establish the presence of the constituent materials and to observe the microstructure of the resulting paste. The samples placed in XRD and SEM/EDS machines are shown in **Fig. 3.6** and **Fig. 3.7** respectively.

Fig. 3.6 A Sample Placed in XRD Testing Machine

Fig. 3.7 Samples placed in SEM Testing machine

3.4 Results and Discussion

3.4.1 Compressive Strength

The compositions of the basic, activated and scaffolded APC mixtures as well as the comparable and references mixtures and their compressive strength development are given in **Table 3.1**, together with the mean strengths (i.e. averages of 3 samples). In general, if the strength of a particular sample differed by more than 15% from the mean, it was rejected and only the average of the other two samples taken.

Table 3.1 Strength Development of All Mixtures

Mix	DESCRIPTION		COMPRESSIVE STRENGTH (MPa)								
	Composition	w/c	Condition A			Condition S			Condition H		
			3d	*7d*	*28d*	*3d*	*7d*	*28d*	*3d*	*7d*	*28d*
	Basic APC Mixture										
B1	100% APC70	**0.3**	1	1	2	3	3	5	2	3	3
	Activated APC Mixtures										
A1	95% APC70 + 5% Na2SO4	**0.3**	1	4	13	7	9	13	12	14	18
A2	95% APC70 + 5% Na2SiO3	**0.3**	2	4	12	13	12	16	14	14	16
A3	95% APC70 + 2.5% Na2SO4 + 2.5% Na2SiO3	**0.3**	2	8	20	14	19	19	18	18	20
	Scaffolding of Basic APC Mixture										
SB1	70% APC70 + 30% OPC	**0.3**	10	17	19	17	19	22	17	17	24
	Scaffolding of Activated APC Mixtures										
SA1	70% (95% APC70 + 5% Na2SO4) + 30% OPC	**0.3**	14	22	40	24	26	35	26	27	30
SA2	70% (95% APC70 + 5% Na2SiO3) + 30% OPC	**0.3**	10	12	20	14	15	20	15	14	19
SA3	70% (95% APC70 +2.5% Na2SO4 + 2.5%Na2SiO3) + 30% OPC	**0.3**	11	13	32	20	21	23	22	25	29
	Comparable Mixture										
C1	70% fly ash + 30% OPC	**0.3**	7	12	18	15	15	19	13	12	16
	Reference Mixture										
R1	100% OPC	**0.3**	31	41	54	33	37	53	44	36	44

KEY:
Condition A - (Air) - Ambient during winter where the local temperature can vary 0°C – 25°C and relative humidity : 45-55%.
Condition S - (Steam) - 15 hrs steam curing at 60°C in a sealed polythene bag in steam chamber followed by ambient curing
Condition H - (Heat) - 15 hrs heat curing at 60°C (unsealed) in oven followed by ambient curing

NOTE:
The Conditions A, H and S mentioned in the experiments of stage 2 presented in Chapter 4 are different from the conditions A, S, H mentioned above, as they were cured not under ambient conditions, but cured under controlled conditions which indicates curing in a controlled room where temperature is 20-25 °C and relative humidity is 70 % - 75%.

The results in **Table 3.1** indicate that compressive strength development of the basic APC mixture (B1) is very low. Although the activated mixtures (A1, A2 and A3) show an increase in the ambient cured 28 day-strengths, the early compressive strengths are still very low; however, the temperature treatments result in moderate strength increases at early ages too. When casting the specimens it was noticed that the hardening of both basic and activated mixtures was very slow; this suggested the need for a scaffolding (provided here by OPC) to give early strength and provide a 'skeleton' for the basic and activated APC mixtures till they get hardened. The early compressive strengths of the scaffolded mixtures (SB1, SA1, SA2 and SA3) have been improved significantly due to such scaffolding. The 28 day strength of the ambient cured SA1 mixture is in fact reasonably close to that of the reference OPC mixture. The inference from this outcome is that a scaffolded activated APC mixture can give strengths similar to OPC mixtures.

Among the activated mixtures (series A) the Na_2SO_4 activator does not perform very well, and in some cases gives the lowest strengths. However, in the scaffolded activated mixtures (series SA) it gives the best performance. Shi and Day (1995) used Na_2SO_4 or $CaCl_2$ to activate a mixture of 20% hydrated lime and 80% fly ash; and found that in the case of low calcium fly ash $CaCl_2$ was more effective; whereas in the case of high calcium fly ash Na_2SO_4 was more effective. It may be that the $Ca(OH)_2$ released by high calcium fly ash is favourable for Na_2SO_4 to perform better as an activator. In series SA too, the added OPC causes $Ca(OH)_2$ to be released during hydration.

The comparable HVFA mixture (C1) that contained 30% OPC yielded very low strengths that were even lower than the strengths of the scaffolded APC mixture SB1. This outcome indicates that if the OPC in a mixture were to be limited to around 30% (as a sustainability measure), it would perform better when used in combination with activated APC, rather than with pure APC, or with fly ash alone. It is also clear however that 70% of fly ash performs better with 30% of OPC (mixture C1) than only with 30% lime (mixture B1).

Where temperature treatments are concerned, there is not much difference in the strength results between (sealed) steam curing and (unsealed) heat curing for 15 hours. Also, such temperature treatments improve mostly the early strengths, but in some cases the ambient-cured 28 day strengths are better than those with temperature treatments. The ambient-cured mixture SA1 had an average 3 day to 28 day strength ratio of 0.35 while the 60^{o}C cured mixtures had an average strength ratio of 0.76. For the OPC mixture the corresponding ratios were 0.58 and 0.80. Therefore the increase in strength from 3 day to 28 days in the mixture SA1 is 186% under ambient conditions and 32% under elevated temperature curing conditions. For the OPC mixture the corresponding percentages are 72% and 25%, indicating that curing at 60^{o}C causes samples to attain 28 day strength at early ages. Because of this, there is not much difference between 3 and 7 day strengths under curing conditions S and H. Hence in **Table 3.1**, the 7 day strengths may even be smaller than the 3 day strengths in some cases; but this would have to be attributed to inherent specimen variability, rather than to any strength decrease with age.

3.4.1.1 Factorial Analysis

A full factorial analysis can be performed on the results for the APC mixtures, considering the effect of age, activation, scaffolding (with Na_2SO_4) and temperature on the strength, with each of those factors at two levels as follows: age (3 and 28 days); activation (none and 5% Na_2SO_4); scaffolding (none and 30% OPC); and temperature (ambient and steam). The means and standard deviations for strength variations caused by each of the four effects above are given in **Table 3.2** (in each case the second level giving the higher strength). This table shows that the greatest strength variation is caused by scaffolding (mean variation =16.79 MPa), and after that by curing age (mean variation = 9.13 MPa) and activation (mean variation = 8.21 MPa). Temperature has the least effect, with a mean variation (3.21 MPa) less than the standard deviation (5.48 MPa).

Table 3.2 Mean strength variation and standard deviation due to the 4 factors for APC mixtures

Factor	Age	Activator	Scaffolding	Temperature
Mean Variation (MPa)	9.13	8.21	16.79	3.21
Std deviation (MPa)	7.98	6.49	5.61	5.48

3.4.1.2 Analysis of Variance (AVOVA)

The results of the formal Analysis of Variance (ANOVA) for means are given in **Table 3.3**, carried out using Statistical Software called 'MINITAB 16' with the effects of activator, scaffolding and temperature (and their interactions) compared separately at 3 and 28 days. The p-value is the probability that the observed effect from one of the factors arose purely by chance; hence a factor having a low p-value is deemed to be significant. For the purpose of analysis, the significance levels are defined by convention according to the p-value as: 'very significant' ($p < 0.01$); 'significant' ($0.01 < p < 0.05$); 'somewhat significant' ($0.05 < p < 0.10$); and 'not significant' ($0.10 < p$). **Table 3.3** shows that the effects of activator, scaffolding and temperature are all significant for 3 day (i.e. early) strength. Since the effect of scaffolding for 3 day strength has a p-value of 0.012 (i.e. just over 0.01), it could even be said that it is very significant.

The two factor interactions for 3 day strength are also somewhat significant. If a two factor interaction is significant, it means that the influence of one factor (e.g. scaffolding) on strength depends on the level of the other factor (e.g. temperature). So, for example, **Table 3.1** shows that scaffolding is more effective for 3 day strength when APC is steam cured (i.e. 2.3 MPa increased to 16.9 MPa) rather than only at ambient temperature (i.e. 0.7 MPa increased to 9.8 MPa); but the effect of scaffolding on 28 day strength is more or less the same whether steam cured (i.e. 4.8 MPa increased to 22.3 MPa), or only ambient cured (i.e. 3.3 MPa increased to 19.4 MPa). This is also reflected in **Table 3.3**, in which the p-value shows a somewhat significant scaffolding-temperature interaction at 3 days, but no such interaction at 28 days.

For the 28 day strength, only the scaffolding effect is significant (p-value = 0.038), and the activator somewhat significant (p-value = 0.060); all other factors are not significant. All of the above reinforces the mean strength variation and standard deviation values in **Table 3.2**, which shows that scaffolding is the most important and the temperature the least. At 3 days, however, the temperature factor is also significant, as seen in **Table 3.3**.

Table 3.3 Tests of significance for 3 factors and interactions for strengths (for strengths at 3 and 28 days)

Age →	**3 days**		**28 days**	
Source ↓	**p-value**	**significant?**	**p-value**	**significant?**
Activator	0.042	yes	0.060	somewhat
Scaffolding	0.012	yes (very)	0.038	yes
Temperature	0.025	yes	0.874	no
Activator*Scaffolding	0.090	somewhat	0.205	no
Activator*Temperature	0.090	somewhat	0.272	no
Scaffolding*Temperature	0.070	somewhat	0.500	no

3.4.2 Microstructure Analysis

Theoretical exploration of microstructure of cementitious materials, X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) techniques are given in section 4.3.2, since those techniques are more fully utilized in the research covered in Chapter 4.

Semi-quantitative XRD analysis was carried out on 28 day old samples using the ‘internal standard’ corundum (Al_2O_3). Hence, peaks due to corundum were expected around 2-theta values of 35°, 45° and 53°, and they should be ignored. The data for XRD analysis was collected through copper radiation. The search/match algorithm DIFFRAC.EVA 3.0 (Bruker-AXS, Germany) and ICDD Powder Diffraction File (PDF4+ 2012 edition) were used to identify crystalline phases.

In X-Ray Diffraction, only crystalline materials that have definite lattice structures give clear peaks. Although non-crystalline or amorphous materials do not give such clear peaks, the formation of amorphous compounds is reflected by broad humps around the related 2-theta values in the XRD curves. Calcium Silicate Hydrate (C-S-H) and Calcium Aluminium Silicate Hydrate (C-A-S-H) formed in hydrated samples would be reflected by broad humps around 2-theta values of 29.5°, 32° and 50°.

Fig 3.8 shows the XRD curves of the raw materials and the key mixtures after ambient curing for 28 days, with the 2-theta values ranging from 6° to 56°, which is the region of interest. Portlandite and calcite are found in all curves apart from OPC powder and fly ash; and mullite is found in all samples containing fly ash. Alite and belite can be seen in all curves of mixtures containing OPC. Furthermore, broad humps (on which are superimposed other peaks) can be seen around 29.5° and 32° for all mixtures with OPC – i.e. R1, C1, SB1 and SA1. They can be seen to an extent in the OPC powder too, suggesting that there may have been some inadvertent hydration of the powder. Mixtures B1 and A1 show such humps at 29.5° only, indicating limited formation of C-S-H/C-A-S-H. The hump in the curve of the activated mixture A1 is somewhat broader than that of the B1 mixture; and this is reflected in the higher strength of A1 as well. The hump in mixture SB1 at around 29.5° is not very different from that for mixture B1, implying that mere scaffolding without activating chemicals would not lead to significant formation of C-S-H/C-A-S-H. The broadest hump at 29.5° for the APC mixtures is in the curve for SA1, which is both activated and scaffolded and displays the highest strength result.

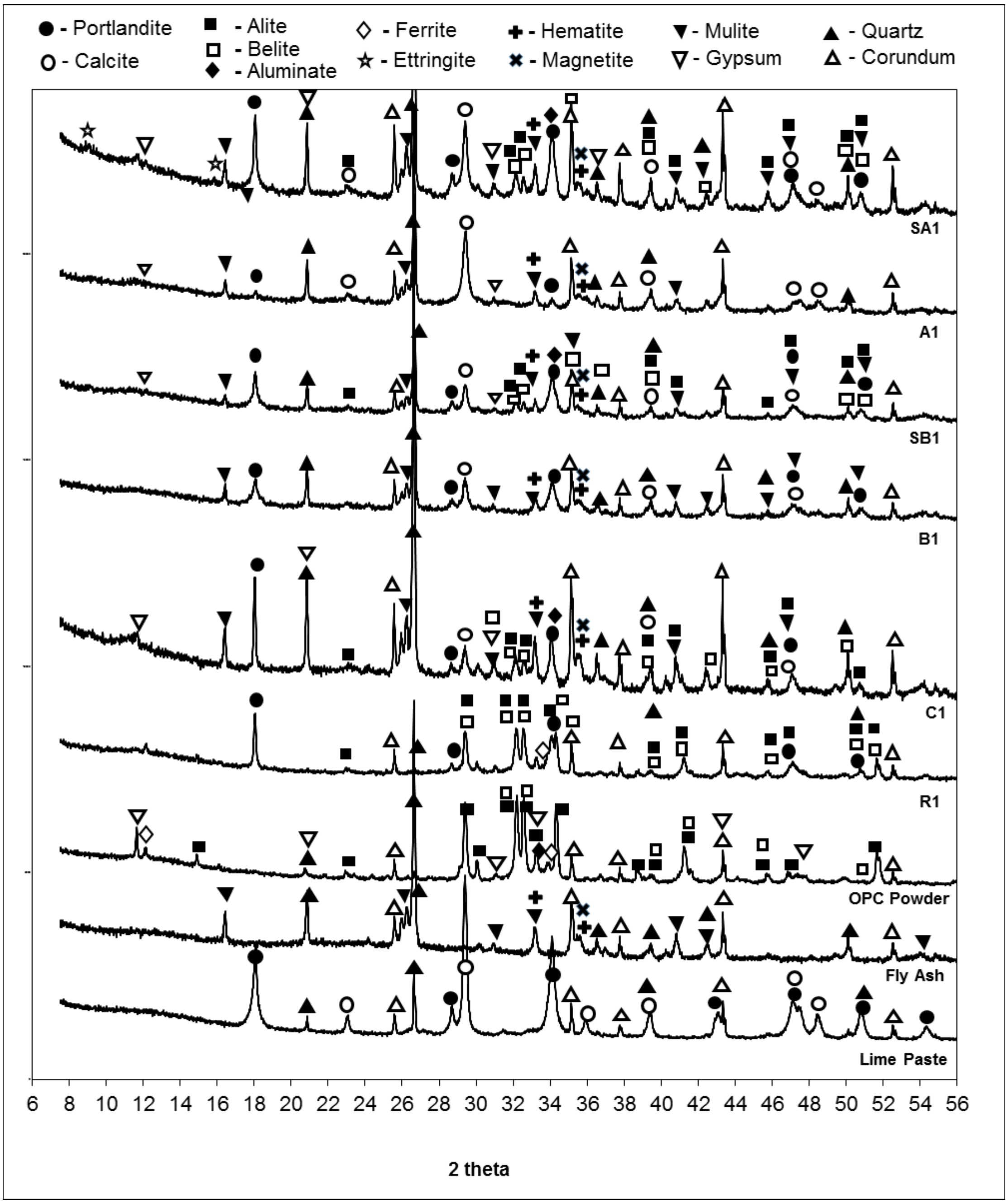
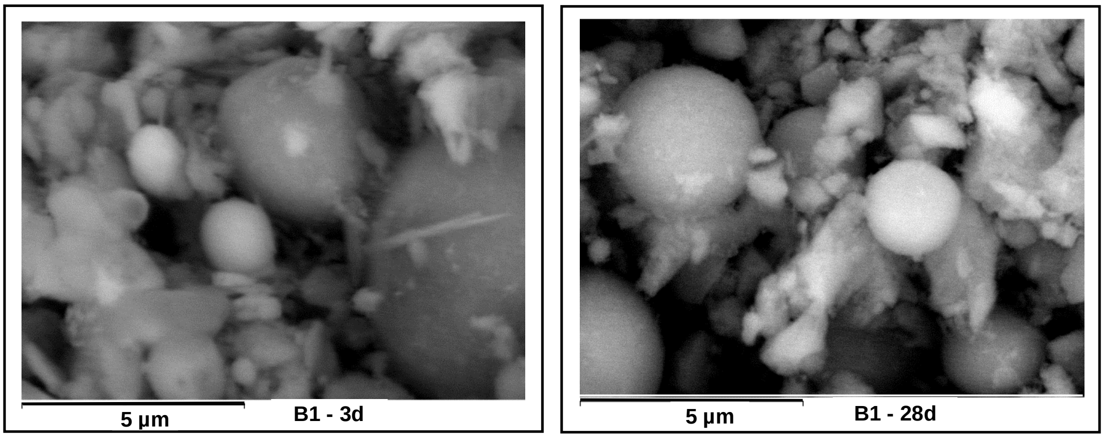


Fig. 3.8 XRD curves of raw materials and some key ambient cured mixtures

Scanning Electron Microscope (SEM) images at the ages of 3 and 28 days for the basic ambient cured APC mixture B1 are shown in **Fig. 3.9**. Here smooth, clean, spherical fly ash particles can be seen, whether at 3 or 28 days. There is no indication of any formation of C-S-H/C-A-S-H gel around fly ash particles. A proper network structure cannot be seen and both structures look very porous. Overall, the image of the 28-day sample is not very different from that of the 3-day one. This implies that fly ash particles have not reacted much with lime even after 28 days, and confirms the need for activators to initiate the pozzolanic reaction.



(a) SEM image at 3 days **(b)** SEM image at 28 days

Fig. 3.9 SEM images of ambient cured basic APC mixture B1

An SEM image of the ambient cured activated mix A1 at the age of 28 days is shown in **Fig. 3.10**, along with a relevant Energy Dispersive Spectroscopy (EDS) graph. As seen in the figure, there is a marked difference between the SEM images of Mixture B1 (**Fig. 3.9b**) and Mixture A1 (**Fig. 3.10**). While the fly ash surfaces in Mixture B1 are smooth and clean (**Fig. 3.9b**), those in Mixture A1 (**Fig. 3.10**) are not so, but covered by a grape-cluster like formation. It should be noted that Shi (1992) also observed such grape-cluster like formation in hydrated lime-natural pozzolan mixtures. Also **Fig. 3.10** displays a denser and less porous structure. The related EDS curve indicates that this formation contains Ca, Al, Si and O. Hence, based on the EDS curve, it can be deduced that the grape-cluster like formation in the SEM image of the activated APC sample is the anticipated C-S-H/C-A-S-H.

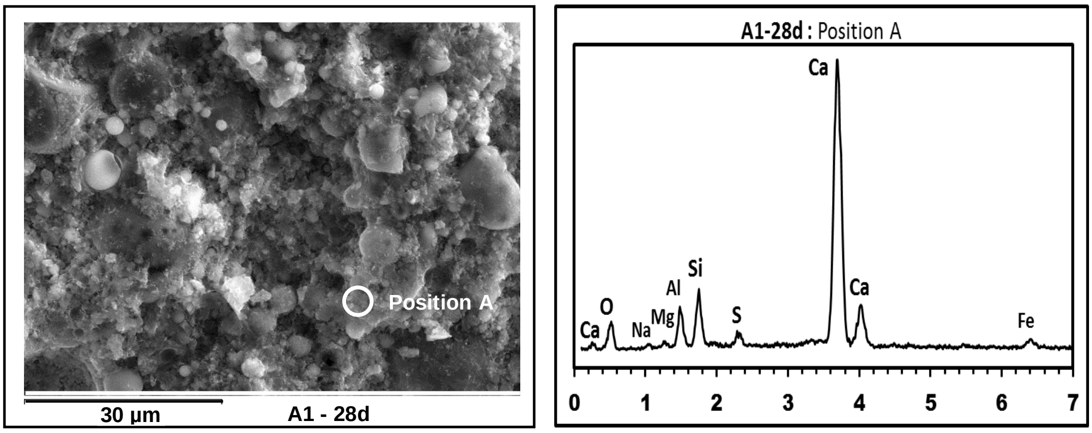


Fig. 3.10 SEM image and EDS graph of ambient cured mixture A1 at 28 days

The SEM image of the Mixture SB1, ambient cured for 28 days, is given in **Fig. 3.11**. Surfaces of the spherical fly ash particles can be seen clearly, indicating that fly ash is in an unreacted form, and confirming that scaffolding alone will not cause the fly ash to react effectively. However, as in the image of Mixture A1 (**Fig. 3.10**), a grape-cluster like formation can also be seen, at many places. This would be the C-S-H phase formed through the hydration of OPC.

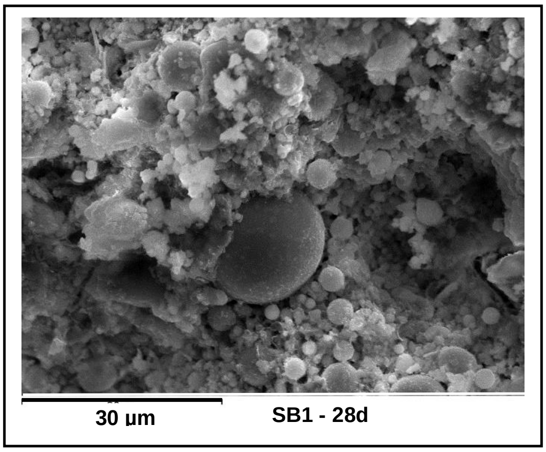


Fig. 3.11 SEM image of ambient cured mixture SB1 at 28 days

The SEM image of the ambient cured Mixture SA1 at 28 days is shown in **Fig. 3.12**, along with the EDS graph. The grape-cluster like formations can be seen in this image of the scaffolded activated APC mixture SA1 too. The EDS curve indicates that this formation consists of Ca, Al, Si and O and hence it would be C-S-H/C-A-S-H. The plate-like formations would be $Ca(OH)_2$, either originally present in the lime or liberated in the hydration of OPC. This image appears to have the densest structure when compared with the images of mixtures B1 (**Fig. 3.9b**) and A1 (**Fig. 3.10**).

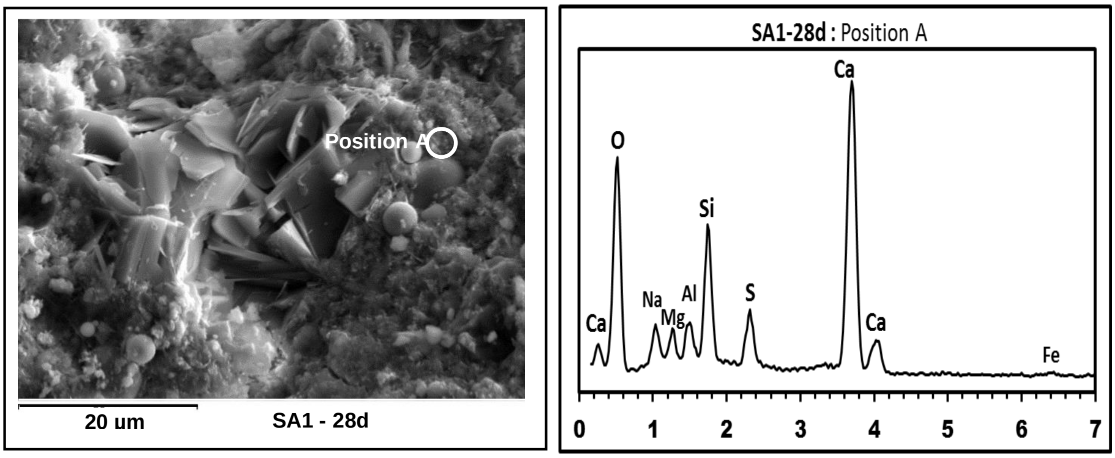


Fig. 3.12 SEM image and EDS graph of ambient cured mixture SA1 at 28 days

The microstructural investigations have helped to explain the observed strength variations. The presence and size of broad humps in the XRD curves can be related to the higher strengths of those mixtures, especially the SA1 mixture. Features of the SEM images can also be correlated with the relative strengths of mixtures in **Table 3.1**. For example, the smooth fly ash surfaces and a relatively open structure for mixture B1 is reflected in its low strength. The increased strength of mixtures A1 (due to activation), SB1 (due to scaffolding) and SA1 (due to both scaffolding and activation) can be linked to the presence of grape-cluster like formations. In particular, the high strength of mixture SA1 can be related to its displaying the densest structure among the images.

3.5 Conclusions

Alkali Pozzolan Cement (APC) is the alternative cement developed in this research, and the development was done in stages. This chapter presented the first stage of the research, which investigated the constituent materials, and their proportions to achieve a practical APC mixtures. The conclusions drawn from findings of the first stage of the research are summarized below:

1. Strength development of the basic APC mixture (containing 70% fly ash and 30% lime) was very low. Microstructural investigations revealed that this was due to the non-activation of the pozzolanic reaction.

2. Compressive strength at 28 days was considerably increased when activators were used, mainly through the improvement of pozzolanic reactivity, but early compressive strength was still low. Of the activators tried, 5% Na_2SO_4 proved to be the best when combined with scaffolding.

3. Adding 30% of OPC as a scaffolding material improved the strengths of both the basic and activated APC mixtures. However, scaffolding alone did not improve the pozzolanic reaction. When both scaffolding and activation were employed, a dense C-S-H / C-A-S-H gel structure was obtained and the APC mixture reached strengths comparable to the reference OPC mixture.

4. Microstructural investigations revealed that improvements due to scaffolding and activation were reflected in the grape-cluster-like formation in the SEM images and the presence of the elements Ca, Si, Al and O in the EDS graphs (suggesting the formation of C-S-H / C-A-S-H), and in the enhanced humps at 2-theta values of 21.5° and 32° in the XRD curves.

5. The best APC mixture was one, the composition of which can be expressed as 70% (95% APC70 + 5% Na_2SO_4) + 30% OPC, where APC70 is a mixture of 70% fly ash and 30% lime. Of the three curing conditions employed, the highest 28-day strength was achieved by the ambient curing condition.

6. Of the four factors that were varied in order to improve the strength of APC mixtures, scaffolding was found to be the most significant statistically, followed by chemical activation (with Na_2SO_4) and age (i.e. variation from 3 to 28 days). Temperature (i.e. variation from entirely ambient to 15 hours curing at 60^{o}C) was found to be significant for 3-day but not for 28-day strengths.

7. Although some further fine tuning may be required to arrive at the optimum constituent percentages, this work has demonstrated that a 'non-hazardous dry cement powder', comparable in strength to OPC and needing only ambient temperature curing, can be developed using fly ash, lime, OPC and a Na_2SO_4 activator.

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4 Structural and Microstructural Properties of APC

Overview

This chapter presents a comparison of structural and microstructural properties of different Alkali Pozzolan Cement (APC) mixtures with High Volume Fly Ash (HVFA) cement and Ordinary Portland Cement (OPC). Hence, this chapter can be considered as an extension of Chapter 3, which presented the design and development of APC. Based on the findings presented in Chapter 3, a number of practical APC mixtures were designed. Their structural and micro-structural properties were investigated and presented. The structural properties were studied through compressive testing; while microstructural properties were explored through techniques such as XRD, SEM, EDS and TA. The results indicate that compressive strength of APC is less than that of OPC, but greater than that of HVFA; this is reflected in microstructural analysis as well.

***Keywords**: compressive strength, X-ray diffraction (XRD), scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS), thermal analysis (TA)*

4.1 Introduction

In this research, an alternative cement called 'Alkali Pozzolan Cement' (APC) was developed through a number of stages. In the first stage, constituent materials and their proportions to achieve practical APC mixtures were investigated; findings were presented in Chapter 3. Those findings led to the formulation of the second stage of the research, and it is presented in this chapter.

The outcome of the first stage of the research (presented in Chapter 3) generated the following research questions:

1. If the proportions of raw materials of the dry APC mixture were slightly changed, how would it affect the properties of APC?
2. If the water to cementitious mixture ratios (w/c ratios) of the cement pastes were slightly changed, how would it affect the properties of APC?

3. If slag was used instead of fly ash to derive APC, how would it affect the properties of APC?
4. What are the similarities and differences of structural and micro-structural properties of samples made of Alkali Pozzolan Cement (APC), Ordinary Portland Cement (OPC) and High Volume Fly Ash (HVFA) cement at different ages?

The above research questions provided a framework to formulate the experimental program of the second stage of the research. That led to the design of different APC mixtures with different proportions of constituent materials, and also with different pozzolanic materials. It also steered to search for suitable criteria to investigate the properties of them.

When properties of cement products are investigated, the explorations are normally done under three headings, namely, structural properties, microstructural properties and durability properties. For the purpose of presentation, structural and microstructural properties are considered together in this chapter, and durability properties will be presented in the next chapter (Chapter 5).

Investigations of cement products are normally done using samples made of hardened cement paste (hcp), mortar and concrete. Use of hardened pastes is a common practice when properties of pure cementitious mixtures are to be investigated. For example, OPC paste (Dias, Khoury and Sullivan 1990), HVFA cement paste (Feldman, Carette and Malhotra 1990), pozzolanic cement paste (De Silva and Glasser 1992; Shi and Day 1993), geoploymer paste (De Silva and Sagoe-Crenstil 2008; Kong and Sanjayan 2010) and hybrid cement paste (Garcia-Lodeiro, Fernandez-Jimenez and Palomo 2013) have been used by researchers to investigate properties of pure cementitious mixtures. Accordingly, in the initial stage of developing a new cement, it is more logical to use hardened cement paste, as it is the basic binding material in mortar and concrete. Hence, in this research it was decided to use hardened pastes of cementitious mixtures.

Among different structural properties of cement products, compressive strength can be considered as the main property even though shear, tensile, flexural and torsional strengths are also important structural properties to be studied for completeness. However, under structural properties, it was decided to f^{oc}us on compressive strength.

When micro-structural properties are investigated, it is important to investigate the formation of microstructural elements over time. Common microstructural techniques used to investigate micro-structural properties are X-ray diffraction (XRD), scanning electron microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDS) and thermal analysis (TA). Hence it was decided to adopt these techniques in this research to investigate microstructural properties.

Based on the above information, the aim and objectives of the second stage of the research were formulated and described in the next section.

4.2 Aim, Objectives and Methodology

The main aim of the research component presented in this chapter is related to investigation of structural and microstructural properties of different Alkali Pozzolan Cement (APC) mixtures and High Volume Fly Ash (HVFA) cement with reference to Ordinary Portland Cement (OPC). The above aim was divided into the following objectives.

1. To propose a mechanism for the hydration of APC systems.

2. To compare the development of compressive strengths of different APC mixtures against the comparable HVFA mixture and reference OPC mixtures, and also to investigate the sensitivity to w/c ratio and curing conditions.

3. To investigate the microstructural properties of selected APC mixtures, against the comparable HVFA mixture and reference OPC mixture, using common techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS) and thermal analysis (TG, DTG, DTA and DSC).

Identifying microstructural properties of unknown samples involves development of ‘microstructural fingerprints’ of that sample and matching those with ‘microstructural fingerprints’ of known samples. Accordingly, in this research, in order to identify microstructural properties of APC, a need arose to prepare a data-base of fingerprints of known samples such as samples of OPC and blended cements. Hence, a focused literature review on the microstructural aspects of known cementitious systems are presented first, and thereafter the experimental procedure.

4.3 Literature Review

The purpose of conducting a literature review was not only to explore the contemporary research on microstructural investigations, but also to develop a data-base of 'microstructural fingerprints' of similar cementitious systems to be used for 'matching' when identifying microstructural properties of APC. Hence, the literature review was focused only on systems similar to APC and sub-systems existing within APC. Accordingly, the three main systems considered were 'pozzolanic cement system', 'OPC system' and 'hybrid system'. The 'geopolymer system' was not considered, as its main product is alkali-aluminosilicate, which is very different from hydrated products of APC.

For convenience, the following notation, which is commonly used in cement chemistry is used throughout this chapter.

A = Al_2O_3	C = CaO	S = SiO_2	F = Fe_2O_3
H = H_2O	$\bar{C}$ = CO_3	$\bar{S}$ = SO_3	

Using above abbreviations, complex compounds can be simply represented as below:

Dicalcium silicate	= 2Cao.SiO2		= C_2S
Tricalcium silicate	= 3Cao.SiO2		= C_3S
Tricalcium Aluminate	= 3Cao. Al_2O_3		= C_3A
Calcium Alumino Ferrite	=4Cao. Al_2O_3. Fe_2O_3		= C_4AF
Gypsum	= Ca(SO)4.2H2O	= CaO.SO_3.2H_2O	= $C\bar{S}H_2$
Calcium Hydroxide	= Ca(OH)2	= CaO.H_2O	= CH
Hydrogarnet (tricalcium aluminate hydrate)			=C_3AH_6
Ettringite (high-sulphate calcium sulphoaluminate)			= $C_3A.3CaSO_4.32H_2O$= $C_3A.3C\bar{S}.H_{32}$
Monosulphate (low-sulphate calcium sulphoaluminate)			=$C_3A.\ CaSO_4.12H_2O$ = $C_3A.C\bar{S}.H_{12}$

NOTE:

Calcium silicate hydrate does not have a fixed stoichiometry. Hence, instead of using a definite stoichiometric formula, the common symbol C-S-H is used to identify it. However, sometimes, for convenience it is written as CSH. In such a cases it should be noted that the term 'CSH' does not reflect a stoichiometric formula written according to a cement chemist's notation, hence 'CSH' does not mean $CaO.SiO_2.H_2O$.

For clarity in presentation, the literature review is divided into two main sections,

1. Hydration mechanism and formation of microstructure
2. Exploration of microstructure using different techniques

4.3.1 Hydration Mechanism and Formation of Microstructure

APC consists of lime, pozzolan, OPC and activators. Hence several systems can exist within APC. Those systems would be 'OPC system', 'pozzolanic cement system' and 'hybrid system'. Thus exploration of those systems would be useful to model the hydration mechanism of APC. Accordingly, this section focuses on literature review of hydration mechanisms of those systems.

4.3.1.1 Hydration of OPC System

When reviewing the hydration process of OPC, it is useful to consider its constituent elements. The main constituents of Portland clinker are silica (SiO_2), alumina (Al_2O_3), lime (CaO) and iron oxide (Fe_2O_3) (Neville and Brooks 1987). These four oxides exist in four major phases in Portland clinker, namely, alite (tricalcium silicate, C_3S), belite (dicalcium silicate, C_2S) aluminate (tricalcium aluminate, C_3A) and ferrite (tetracalciumalumino ferrite, C_4AF) (Newman and Choo 2003). In preparing OPC, a small quantity of gypsum is normally added to Portland clinker; hence, gypsum ($C\overline{S}H_2$) too is present in OPC, in addition to compounds mentioned above. The two calcium silicates, C_3S and C_2S, are the main contributors for strength and durability properties of OPC. Contribution of C_3A for strength is very much less, except at early ages. Despite the marginal contribution for strength, the existence of C_3A is a drawback, as it is responsible for disruption under sulphate attack by forming ettringite, which causes volume expansion (Neville and Brooks 1987).

The hydration mechanisms of two calcium silicate minerals, namely, C_3S and C_2S, are similar. They react with water and form amorphous calcium silicate hydrate (abbreviated as C-S-H), which is the main binding material in hydrated cement. The formation of C-S-H is very complex, and the composition of C-S-H depends on many factors such as age, temperature and water/solid ratio. The two major specific forms of C-S-H are designated as C-S-H (I) and C-S-H (II). C-S-H (I) has a CaO/SiO_2 molar ratio of 0.8 – 1.5, and is a poorly-crystalline material which has a foil or platelet morphology when seen in a scanning electron microscope (SEM). C-S-H (II) has a CaO/SiO_2 molar ratio of 1.5 - 2.0, and is a semi-crystalline material which has a fibrous structure (Helmuth 1987; Soroka 1980).

The hydration reactions of C_3S and C_2S are complex. Some authors have taken the CaO/SiO_2 molar ratio as 1.7 and hydration reactions are formulated as below (Newman and Choo 2003).

$$C_3S + 4.3H \rightarrow C_{1.7}SH_3 + 1.3CH$$
$$C_2S + 3.3H \rightarrow C_{1.7}SH_3 + 0.3CH$$

Other authors simplified the formula of C-S-H by assuming the CaO/SiO_2 molar ratio as 1.5 and suggested approximate hydration reactions as below (Neville and Brooks 1987).

$$2C_3S + 6H \rightarrow C_3S_2H_3 + 3CH$$
$$2C_2S + 4H \rightarrow C_3S_2H_3 + 3CH$$

The hydration mechanism of C_3A is more complex, and it depends on the concentration of gypsum in the context. In a gypsum-free context C_3A reacts rapidly with water and forms C_2AH_8 and C_4AH_{19}, which hardens rapidly and gets converted to C_3AH_6 subsequently. This process is prevented by adding gypsum to Portland clinker during the production of OPC. When adequate gypsum ($C\overline{S}.H_2$) is present, it reacts with C_3A and forms a $C_3A.3C\overline{S}.H_{32}$ (high-sulphate calcium sulphoaluminate) layer over the surface of C_3A crystals. In the literature, $C_3A.3C\overline{S}.H_{32}$ is known as 'tri-sulphate' as the molar ratio of $C\overline{S}$ to C_3A is 3, or more commonly as 'ettringite'. The reaction for the formation of ettringite is given below (Newman and Choo 2003).

$$C_3A + 3C\overline{S}H_2 + 26H \rightarrow C_3A.3C\overline{S}.H_{32}$$

The ettringite formed over the surface of C_3A crystals acts as a protective layer for C_3A; hence, the rapid reaction of C_3A with water is controlled (Newman and Choo 2003). Ettringite, which has a molar ratio of $C\overline{S}$ to C_3A as 3, is only stable when there is ample concentration of gypsum in the surrounding environment. When the gypsum concentration drops, ettringite becomes unstable and gets converted to $C_3A.C\overline{S}.H_{12}$ (low-sulphate sulphoaluminate), which is known as 'monosulphate' in the literature (Gani 1997). Further, at a lower concentration of gypsum, the remaining C_3Awould react with gypsum and form monosulphate. When there is insufficient gypsum for C_3A to react with to form ettringite or monosulphate, C_3A would react with water and produce a verity of phases such as C_4AH_{19} (Helmuth 1987), C_4AH_{13} and C_2AH_8 (Gani 1997), which will be subsequently converted into tricalcium aluminate hydrate (C_3AH_6).

The hydration process of C_4AF also depends on the concentration of gypsum in the context, as in the case of C_3A. When ample gypsum is present, C_4AF reacts with gypsum and calcium hydroxide and produces a solid solution $C_3(A,F).3C\overline{S}.H_x$. However, when the sulphate ion concentration (or gypsum concentration) drops, this solid solution is converted to $C_3(A,F).C\overline{S}.H_x$. Some sulphate ions may be replaced by hydroxide ions and result in conversion to $C_3(A,F).Ca(OH)_2.H_y$ (Soroka 1980).

Subsequently, aluminium in tri-sulphate (ettringite) and monosulphate can be partially or completely replaced by Fe; and the resultant phases are referred as **AFt** (alumino-ferrite trisulphate hydrate) and **AFm** (alumino-ferrite monosulphate hydrate) (Newman and Choo 2003).

4.3.1.2 Hydration of 'Lime-pozzolan System'

When reviewing pozolanic reactions, first, it is useful to consider the constituent elements of different pozzolanic materials. The main constituent elements in pozzolanic materials are Silica (SiO_2), Alumina (Al_2O_3), Iron Oxide (Fe_2O_3) and Lime (CaO) (Newman and Choo 2003). Silica in pozzolan exists in a crystalline phase (quartz) as well as an amorphous phase (glassy phases). The quartz phase is not involved in the hydration process, while the amorphous phase is.

The reactive silica gel reacts with calcium hydroxide and produces calcium silicate hydrate gels (C-S-H), and the reaction can be simplified as below (Helmuth 1987).

$$xCH + y\,S + zH \rightarrow C_xS_yH_{x+z}$$

The calcium silicate hydrate gels do not have a fixed stoichiometry. The CaO/SiO_2 molar ratio can range from 0 to 2 depending on concentrations of reacting materials, before reaching the equilibrium. As mentioned before, two types of C-S-H gels have been identified as C-S-H (I) and C-S-H (II). The C-S-H (I) has CaO/SiO_2molar ratio between 0.8 - 1.5, and is a poorly crystallized material characterized by crumpled foil morphology as seen in a scanning electron microscope. The C-S-H (II) has a CaO/SiO_2 molar ratio of 1.5 – 2.0 and is a semi-crystalline material characterized by fibrous morphology (Helmuth 1987).

Alumina in pozzolan produces many different hydrates such as calcium aluminate hydrates (C_4AH_{19}), gehlenite hydrate (C_2ASH_8), ettringite ($C_3A.3C\overline{S}.H_{32}$) and monosulphate ($C_3A.C\overline{S}.H_{12}$) (Helmuth 1987). When Al from alumina is introduced into C-S-H, it would form calcium aluminium silicate hydrate (C-A-S-H) (Hong and Glasser 2002). De Silva and Glasser (1993) have used lime with metakaolin as a pozzolanic material and found a variety of hydrated products including C_2ASH_8, C_4AH_{13}, C_3AH_6 and C-S-H. Further they concluded that in a $Ca(OH)_2$-rich contexts, C_3AH_6 and C-S-H exist in relatively stable phases, but C_2ASH_8 and C_4AH_{13} do not exist in relatively stable phases. However, when the calcium content decreases, C_2ASH_8 becomes stable.

In addition to silica and alumina, pozzolans may also contain crystalline minerals such as quartz (SiO_2), mullite ($3Al_2O_3.2SiO_2$), sillimanite ($Al_2O_3.SiO_2$), hematite (Fe_2O_3) and magnetite (Fe_3O_4), and they are not involved in pozzolanic reactions (Malhotra and Mehta 1996).

4.3.1.3 Hydration of 'Hybrid Akaline Cement Systems'

Hybrid alkali cementitious (HAC) systems are a wet binder comprising OPC, fly ash and alkaline solutions (typically NaOH and Na_2SiO_3 solutions). Here NaOH not only activates the pozzolan, but also reacts with it. Accordingly, the main hydrated product of ‘hybrid alkali cement’ is sodium aluminosilicate hydrate (N-A-S-H) (Garcia-Lodeiro et al. 2012). Further, in this system there is no added lime; hence, the $Ca(OH)_2$ available within the system would be the $Ca(OH)_2$ released during the hydration process of OPC. As the $Ca(OH)_2$ released is relatively small, its contribution for the pozzolanic reaction to form C-S-H is not predominant. However, OPC in the mixture would produce C-S-H. Accordingly, the HAC system is different from the APC system due to four reasons. Firstly, HAC is a wet binder which does not exist as a dry powder, whereas APC is a dry powder; secondly, activating chemicals of HAC system are NaOH and Na_2SiO_3 solutions, while that of APC system is a dry powder form of Na_2SO_4; thirdly, HAC system does not have added $Ca(OH)_2$, whereas APC does. Fourthly, the main hydration product of HAC system is N-A-S-H, whereas that of APC is C-S-H. However, there are similarities between HAC and APC systems as well. Both HAC as well as APC are pozzolanic systems, and both have OPC as one of the constituent materials among others. Accordingly, even though there are distinctive differences between APC and HAC systems, a review of HAC systems would be useful for research on APC, as there are some similarities as well.

4.3.2 Exploration of Microstructure using Different Techniques

The previous section covered the microstructural development of different cementitious systems. In this section, a literature review on identification of microstructural products is presented. The techniques used in this research are X-ray diffraction (XRD), scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS) and thermal analysis (TA). Hence, the literature review of this section is focused on the application of those techniques. Firstly, the principle behind each technique is explored, and thereafter, microstructural features of raw materials and hydrated products of systems similar to APC are presented.

4.3.2.1 X-ray diffraction (XRD)

The X-ray diffraction (XRD) technique is usually used to identify crystalline (or non-amorphous) compounds of materials, which have definite lattice structure. When a focused X-ray beam hits a lattice structure of a crystalline material, a part of the beam is absorbed, transmitted and refracted while another part is diffracted. The diffracted rays produce 'constructive inference' (amplification due to superimposition), only when Bragg's Law is satisfied (**Fig. 4.1**).

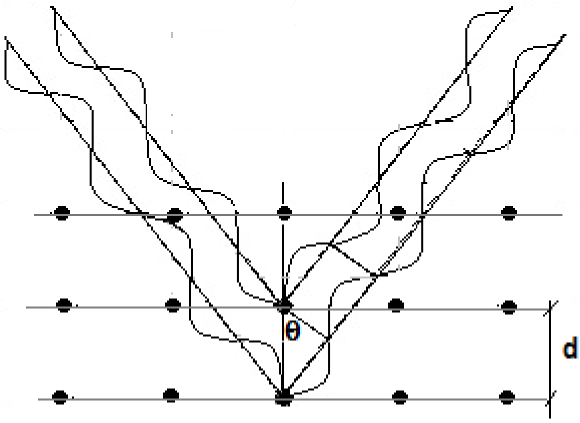


Fig. 4.1 Constructive Inference

Bragg's Law is given as ***nλ=2d sinθ ;*** where ***λ*** is the wave length of the incident X-ray beam, ***θ*** is diffraction angle, ***d*** is inter-planar spacing and the integer ***n*** is the order of the diffracted beam. In other words, a particular family of planes produce a 'diffraction peak' only at a specific diffraction angle ***θ*** in diffractogram (XRD curve).The characteristic set of ***2θ*** values (known as Bragg's angle) and diffraction peaks is a kind of a 'fingerprint' of the phases present in the sample. By comparing the 'fingerprints' with 'standard reference patterns', the crystalline compounds present in the sample can be identified. As amorphous (or non-crystalline) materials do not have definite lattice structures, they do not produce 'diffraction peaks'. However, amorphous phases can be identified by the occurrence of a specific wide halo (or broad hump) on diffraction patterns (The Hebrew University Centre for Nanoscience and Nanotechnology 2014). Accordingly, when XRD techniques are adopted for hydrated samples, the crystalline phases of compounds such as C-S-H, C-A-S-H and $Ca(OH)_2$ produce clear diffraction peaks, but poorly crystalline or amorphous phases of those compounds do not produce clear peaks. However, they may produce specific 'broad humps' or 'wide halos'.

<u>XRD Explorations of Raw Materials</u>

The use of diffractograms (XRD curves) in investigating microstructural properties involves comparison of XRD curves of raw materials and hydrated samples at different ages. The main raw materials used in this research are fly ash, slag, lime and OPC. The following paragraphs present microstructural information of those materials extracted from literature.

The pattern of XRD curves of fly ash reflects the reactivity of fly ash as described below. It is the reactive silica in pozzolans that reacts with calcium hydroxide and produces calcium silicate hydrates (Helmuth 1987). The reactivity of the glass in fly ash depends on the calcium content of the fly ash. Low-calcium fly ash contains aluminosilicate glass (or low-calcium alumina silicate glass), and high-calcium fly ash contains calcium aluminosilicate glass (or high-calcium alumina silicate glass). Hence, high calcium fly ash is more reactive than low calcium fly ash (Malhotra and Mehta 1996). The difference in the glass phases in low calcium fly ash and high calcium fly ash is reflected in their XRD curves (Diamond 1983). Diamond (1983) has performed XRD analysis with copper radiation, and noted 'broad humps' with maximum intensities at 2-theta ($\boldsymbol{2\theta}$) values of 24° and 32° for low-calcium fly ash and high-calcium fly ash, respectively. The glass present in fly ash is normally characterized by 'broad humps' rather than distinct peaks in XRD patterns.

Low-calcium fly ash typically contains quartz, mullite ($3Al_2O_3.2SiO_2$), sillimanite ($Al_2O_3.SiO_2$), hematite and magnetite; while high-calcium fly ash typically contains quartz, tricalcium aluminate ($3CaO.Al_2O_3$), calcium aluminosulphate ($4CaO.3Al_2O_3.SO_3$), anhydrite (anhydrous calcium sulfate, $CaSO_4$), free CaO, periclase (free MgO) and alkali sulphates (Malhotra and Mehta 1996).

Researchers have done XRD analysis of different fly ashes from different sources and had found similarities as well as differences. Brown, Jones and BéruBé (2011) have done XRD analysis of fly ashes from UK, Polish and Chinese sources. The first two contained only quarts and mullite, while the third one contained hematite and gypsum as well. Further, in the XRD curve of UK fly ash, there was a broad elevation in the general background, forming a 'broad hump' with low peaks, suggesting a larger amount of amorphous material. However, the XRD curve of the Chinese sample did not have such a noticeable broad hump, but rather a flatter base line with more pronounced diffraction peaks, implying re-crystallization of compounds. Chancey et al. (2010) have done XRD analysis of low calcium fly ash and found clearly defined peaks of quartz, mullite, maghemite, periclase; poorly defined peak at the location of ettringite, indicating that calcium aluminate might have hydrated when sulphates were present and formed ettringite. Farooque et al. (2010) compared XRD curves of fly ash and paste of fly ash-lime. At 90 days, they observed that 5 clear new peaks appeared, which represented C-S-H and C-H. In view of above information, it can be concluded that XRD curves of different fly ashes can be distinctly different from each other. Primarily XRD curves indicate the presence of crystalline minerals. In addition, XRD curves give an indication of presence of amorphous materials, and the degree of re-crystallization of compounds. Accordingly, the XRD curve of a given fly ash sample can be used to get an initial idea about the reactivity of fly ash.

XRD curves of blast furnace slag (BFS) too can be used to get an idea about the reactivity of slag. Malhotra and Mehta (1996) list the crystalline minerals found in blast furnace slag (BFS) as gehlenite, akermanite, diopside ($CaO.MgO.2SiO_2$) and merwinite ($3CaO.MgO.2SiO_2$). Arabi and Jauberthie (2012) analyzed BFS and found the presence of mellilite, merwinite, monticellite, quartz, calcite and iron oxide. As in the case of fly ash, the glass present in slag too is reflected by 'broad humps' rather than distinct peaks in XRD patterns; and this is clearly seen in the XRD curves of Liu et al. (2014). The XRD curve of 100% glass slag has a prominent 'broad hump' without diffraction peaks, while that of 100% crystalline slag does not have a 'broad hump' at all, but a flat base line with a number of diffraction peaks. Mostafa et al. (2001) have done XRD analysis for water-cooled and air-cooled BFS derived from the same raw material obtained from the same blast furnace, and found that water-cooled BFS had a dominant broad hump without diffraction peaks while air-cooled slag had a flatter base line with diffraction peaks for gehlenite. Therefore, it can be concluded that XRD curves of BFS too can be used to get an initial idea about the reactivity of BFS, as in the case of fly ash.

XRD curves of lime reflect the crystallinity of the material. Arabi and Jauberthie (2012) have done XRD analysis for high calcium lime which contained 70% CaO, and found diffraction peaks for crystalline portlandite [$Ca(OH)_2$], Calcite [$CaCO_3$] and brucite [$Mg(OH)_2$]. The outcome indicated that some of the $Ca(OH)_2$ had been carbonated. Further, the base line was not flat, but contains a number of 'broad humps'. Hence XRD curves of lime can be used to get an initial idea about the crystallinity of substances and also about any carbonation that has occurred.

XRD curves of OPC are useful to identify the phases present in un-hydrated powder. As described in previous paragraphs, OPC mainly contains alite, belite, aluminate, ferrite and gypsum. Elena and Lucia (2011) have done XRD analysis of OPC powder, and found crystalline phases of these materials.

XRD Explorations of Hydrated Products

When investigating microstructural properties of hydrated products through XRD curves, it would be useful to review the literature of similar cementitious systems. As mentioned before, the main systems within APC can be identified as 'pozzolanic cement system', 'OPC system' and 'hybrid system'. Following paragraphs present microstructural information of similar systems extracted from the literature.

XRD analysis of fly ash-calcium hydroxide mixtures was done by Luxan, De Rojas and Frias (1989) using different fly ashes derived from bituminous coal and lignite coal with saturated lime solutions at 40°C. XRD curves related to bituminous coal fly ash treated by calcium hydroxide indicated peaks of carboaluminate ($C_4A\overline{C}H_{11}$), monosulfoaluminate ($C_4A\overline{S}H_{12}$) and calcium aluminum hydrate (C_4AH_{13}) at 7 days, but those peaks disappeared at 28 days. Further there were no peaks indicating the presence of ettringite. Moreover, formation of C-S-H was not reflected in diffractograms. The authors concluded that the formation of C-S-H cannot be confirmed by XRD, as the peaks due to C-S-H were hidden by the peaks of calcite. Ghosh and Subbarao (2001) have done XRD analysis of a similar system, which is fly ash stabilized with lime and gypsum. The XRD curve of fly ash stabilized with 10% lime indicated a peak for C-S-H ($2\theta = 29.5°$) at 3 months; however fly ash stabilized with 10% lime and 1% gypsum indicated the appearance of such peak only after 10 months. None of the XRD curves indicated formation of ettringite. Shi, Jiménez and Palomo (2011) have done XRD analysis of blended cement mixtures of 70% fly ash and 30% clinker mixed with deionized water, but formation of any C-S-H was not reflected in XRD curves. Lee, Lee and Lee (2003) used blended cement mixtures consisting of 40% fly ash and 60% OPC with and without the activator Na_2SO_4 and performed XRD analysis. XRD curves at 3 and 7 days of both the mixtures indicated a peak of ettringite, but it had almost disappeared in the curve at 28 days. Moreover the curves indicated peaks due to $Ca(OH)_2$,but that was reduced from 3 to 28 days. XRD analysis of OPC paste was done by Elena and Lucia (2011) over a period of 28 days and they noticed a decrease of alite and belite but an emergence of C-S-H as time passes.

According to the above information, it can be concluded that the formation of hydrated products such as C-S-H may or may not be reflected by diffraction peaks, but may be reflected by broadening of peaks (or formation of broad humps). The APC mixtures consist of pozzolan, lime and OPC with activators. Therefore, it can be expected that the XRD curves of APC mixtures would indicate peaks of crystalline phases of blended cements as well as those of OPC.

4.3.2.2 Scanning Electron Microscopy and Energy Dispersive Spectroscopy

Scanning Electron Microscopic (SEM) technique is used to scan microstructural images of samples. When it is combined with Energy Dispersive X-ray Spectroscopy (EDX or EDS) techniques, chemical compositions of specific locations of the sample can be explored. When a sample is scanned by a beam of electron, the sample releases backscatter electrons, secondary electrons, auger electrons, characteristic X-rays and light. The secondary electrons and backscatter electrons contain information about the sample's surface topography; hence, by collecting and amplifying those, 'secondary images' and 'backscatter images' are produced. In X-ray microanalysis, the X-rays generated from a particular location of the samples are collected and Energy Dispersive X-ray spectroscopy (EDS graph) is developed. The different peaks of an EDS graphs indicate the different elements present at the location. With the help of SEM images and EDS graphs, the compounds present at different locations of the sample can be identified.

SEM/EDS Explorations of Raw Materials

Use of SEM/EDS techniques in investigating microstructural properties involve comparison of images of raw materials and hydrated samples of different ages. The main raw materials used in this research are fly ash, slag, lime and OPC. This section presents characteristics of the SEM images of different materials, extracted from literature, so that they can be used as a database when identifying different compounds.

Fly ash particles are spherical particles of different sizes. The size ranges from 1 to 100 µm, but the average size is about 20 µm. The surfaces of low-calcium fly ash (or Class F) look much cleaner than those of high-calcium fly ash (or Class C). The reason is that in high-calcium fly ash, there are greater amount of alkali sulfates, and they get crystallized on the surfaces of particles. Some spherical fly ash particles can be hollow and empty or filled with small spherical particles, and these characteristics can be viewed through a microscope (Malhotra and Mehta 1996). Another raw material used in this research was slag. Slag is not directly collected from the iron blast-furnace, but obtained by chilling the molten slag and thereafter grinding to a fine powder (Cook and Cao 1992). Hence microscopic images of slag show particles of irregular shape of different sizes. The main alkali material used in experiments was lime which produces calcium hydroxide. The crystallized $Ca(OH)_2$ is seen as a plate-like structure (typically hexagonal) in SEM images. The other main material used in the experiments was OPC. As OPC is a mixture of a number of components, namely, alite (C_3S), belite (C_2S), aluminate (C_3A), ferrite (C_4AF) and gypsum ($C\overline{S}H_2$) particles, of different sizes and shape are seen in SEM images. For example, alite particles are relatively large polygonal particles with straight boundaries, while belite particles are relatively small rounded particles with curved boundaries (Gani 1997; Kohlhaas and Labahn 1983).

SEM/EDS Explorations of Hydrated Products

As described before, the expected hydrated products of cementitious mixtures in this research were C-S-H, calcium hydroxide, ettringite, monosulphate, calcium aluminate hydrates, gehlenite hydrate, sulphoferrite, **AFt** and **AFm**. This section presents features of the SEM images of different hydrated products of mixtures similar to the mixtures developed in this research, so that they can be used as a data bank in identifying the products.

The focus of interest is on the main hydrated product, which is C-S-H. The morphology of C-S-H gel depends on factors such as the composition of the mixture, water content, and age. Accordingly, the C-S-H gel can exist as fibrous structures or as layers; these layers can get rolled, staked or distorted.

The other hydrated products that have drawn interest are ettringite, monosulphate and calcium aluminate hydrate. Ettringite is a needle like structure. Monosulphate has a hexagonal plate morphology, and they get arranged in rosettes during hydration. Calcium aluminate hydrate also has a hexagonal plate morphology. In addition, the hydrated samples can contain calcium hydroxide, which also has a hexagonal plate morphology (Gani 1997).

When OPC is mixed with water, the dissolved sulfate ions react with aluminate (C_3A), and form ettringite within a few minutes. After a few hours, alite (C_3S) and belite (C_2S) react with water to form C-S-H and $Ca(OH)_2$. After a few days, when the sulphate concentration drops, ettringite becomes unstable and gets decomposed to form monosulfate. The remaining C_3A would react with water and get converted to calcium aluminate hydrate, which also has a hexagonal plate morphology (Mehta and Monteiro 2006). Goñi et al. (2010) investigated the difference of hydrated products of the two main components of OPC, namely C_3S and C_2S, over a period of 28 days. The 3 day image of C_3S (alite) indicated the formation of globules of C-S-H, but these disappeared in the 28 day image, having been converted to a more compact type microstructure. The 3 day image of C_2S (belite) showed globules of C-S-H smaller in size, but even after 28 days the microstructure was less compact.

Papadakis (1999) has done SEM analysis of hardened cement paste containing 20% low-calcium fly ash and 80% OPC for a period over 6 months. He reported that $Ca(OH)_2$ released from OPC and needle-like ettringite structures could be seen at 3 days. Further, he reported that unreacted fly ash particles could be seen until 21 days. At 28 days, fly ash particles were etched but retained the spherical shape. After 6 months fly ash particles were covered by reaction products, yet there were non-reacted fly ash particles as well. Li, Roy and Kumar (1985) have done SEM analysis of hardened paste made of 70% OPC and 30% fly ash mixture which had been cured at 38 ° C till testing. They found fibrous products after 1 day, and denser hydration products after 28 days. Li et al. (2000) used 65% OPC and 35% fly ash paste, which had been cured at room temperature; and SEM images were taken over a period of 90 days. In 3 day SEM images, the surfaces of fly ash particles were smooth, indicating that they had not been reacted. At 28 days, small fly ash particles had developed into C-S-H gel, while large fly ash particles had been covered by C-S-H gel. In addition, presence of flocculent gel was reported. Even after 90 days $Ca(OH)_2$ existed. They have also done SEM analysis for mixture of fly ash and $Ca(OH)_2$ activated by gypsum and Na_2SO_4, and cured at 60 °C. It was reported that there were a lot of needle-like ettringite at 7 days; and even more ettringite at 14 days.

Some researchers used Energy Dispersive X-ray spectroscopies (EDS graphs) along with SEM images to identify the elements (other than H) present at different locations of samples and to confirm the hydrated products. It should be noted that, although H is present in specimens, peaks for H are not shown in EDS graphs as the X-ray detector does not pick H. Ribeiro, Yuan and Morelli (2012) noted peaks for Ca, Si, O, S and Al in the EDS graph of a hydrated sample containing C-S-H and ettringite. Batic et al. (2000) identified high peaks for Ca, S, Al and O in the EDS graph of a sample containing ettringite. Chakchouk, Samet and Bouaziz (2012) noted high peaks for Ca and Si and a low peak for O in the EDS graph of a sample containing C-S-H. Accordingly, EDS graphs are very useful to identify/confirm hydrated products of samples.

4.3.2.3 Thermal Analysis (TA)

Thermal analysis techniques are performed to identify hydrated products and also to obtain quantitative measurements related to different transitions that a hydrated sample undergoes when heated from atmospheric temperature to ignition. In the literature related to thermal analysis (TA), different abbreviations and conventions have been used in describing results. The following paragraphs describe different thermal analysis techniques, abbreviations used and results of similar research.

Three common thermal analysis techniques considered and the abbreviations used to identify them are

1. Thermogravimetry (TG) or Thermo Gravimetric Analysis (TGA)
2. Differential Scanning Calorimeter (DSC)
3. Differential Thermal Analysis (DTA)

In TG analysis, a small sample of material is heated at a constant rate, and the variation of weight with the increase of temperature is recorded. Then those weights are divided by the original weight and plotted against temperature; this graph is known as a Thermogram (TG curve or TGA curve). The first derivative of the Thermogram is known as the Derivative Thermogram (DTG curve or DTGA curve). In the Differential Scanning Calorimetry (DSC) technique, the heat (or energy) applied in order to increase the temperature of the sample and the reference at the same rate is recoded. The difference of heat (ΔH) is plotted against temperature (T), and this graph is known as the DSC curve. In Differential Thermal Analysis (DTA), heat is applied to the sample and to the reference at the same rate and the difference in temperature is recorded. The difference in temperature (ΔT) is plotted against the temperature (T), and this graph is known as a DTA graph. Note that when temperature is increased at constant rate, sometimes these graphs are plotted against time (t), instead of temperature (T). The above mentioned curves, TG, DTG, DSC and DTA, can be used as 'fingerprints' in identification of hydrated products.

When describing the literature related to thermal analysis, it is necessary to refer to features of thermal analysis curves. For that purpose, typical TG, DTG, DTA and DSC curves are given in **Fig. 4.2**.

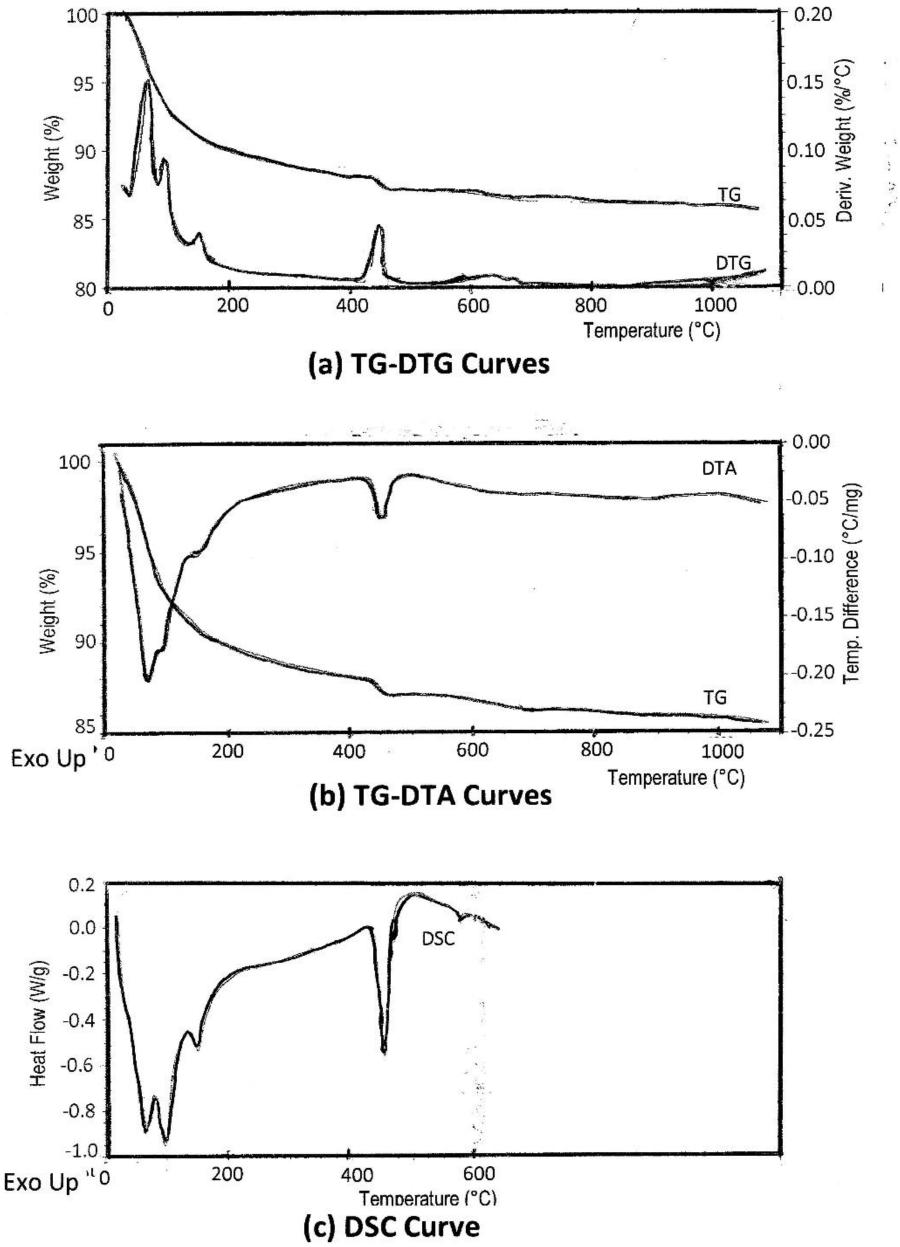


Fig. 4.2 Typical Thermal Analysis Graphs

(a) TG-DTG Curves; **(b)** TG-DTA Curves; **(c)** DSC Curve (up to 600 °C)

A typical TG-DTG graph is shown in **Fig. 4.2(a)**. The DTG curve is the first derivative of a TG curve. However the sign of the derivative has been ignored and only the absolute value considered in developing the DTG curve. The noticeable drops in the TG curve at different temperatures indicate transitions of compounds. The DTG curve gives peaks at those drops, and these peaks represent decomposed compounds during heating. The drops in the TG curve give quantitative information related to free water, hydrated products, calcium hydroxide and calcium carbonate present in the sample.

A typical TG-DTA graph of hydrated cement is shown in **Fig. 4.2(b)**. In the figure, at the lower left corner the term 'Exo Up' is mentioned; and that indicates that the exothermic direction is upwards. Accordingly, exothermic reactions (reactions that release energy) are reflected by upward peaks, while endothermic reactions (reactions that absorb energy) are reflected by downward peaks of the DTA curve. In DTA curves, transitions such as melting and decomposition are characterised by endothermic peaks, while transitions such as crystallisation and oxidisation by exothermic peaks.

A typical DSC graph of hydrated cement is shown in **Fig. 4.2(c)**. In that figure too, at the lower left corner 'Exo Up' is mentioned, indicating that the exothermic direction is upwards. The peaks, as well as sub-peaks reflect transitions of compounds as in the case of a TG-DTA graph.

Transition Stages of Hydrated Samples

When a hydrated cement sample is heated from ambient temperature up to ignition, it undergoes different transitions, namely, desorption, dehydration, dehydroxylation and decarbonation; they are described as follows:

Desorption:

During this process free water in the sample is released.

Dehydration:

During this process water bound by the hydrated products in the sample is released (The main hydrated product is C-S-H, among others such as ettringite and calcium aluminate hydrate).

Dehydroxylation:

During this process $Ca(OH)_2$ bound water in the sample is released.

$$Ca(OH)_2 \rightarrow CaO + H_2O$$

Decarbonatoion:

During this process $CaCO_3$ in the sample gets decarbonated and CO_2 is released. In addition, carbonated phases of hydrated compounds too can be decarbonated (Gabrovšek, Vuk and Kaučič 2006).

$CaCO_3$ → $CaO + CO_2$

Carbonated hydrated compounds → Decarbonated hydrated compounds

In the literature, different researchers had specified different temperature ranges related to the above transitions. Almeida and Sichieri (2006) have done TG for polymer modified mortar and specified the following rages: 123 - 345 °C for dehydration of C-S-H; 345 - 427 °C for weight loss of pyrolysis of polymer added and dehydration of parts of silicate hydrates; 427 - 475 °C for dehydroxylation of $Ca(OH)_2$; and 475 - 711°C for decarbonation of $CaCO_3$. Alarcon-Ruiz et al. (2005) have noted major weight losses in the ranges of 100 - 200 °C due to dehydration of hydrates, 450 - 500 °C due to dehydroxylation of $Ca(OH)_2$ and a range around 750 °C due to decarbonaion of $CaCO_3$. The above information implies that appropriate temperature ranges should be arrived at by examining the shape of the TG curves, and that they can be slightly different from each other. Accordingly, the temperature ranges relevant to the TG graphs of this research had to be decided based on the shapes of relevant TG curves.

DTG curves, which are the first derivatives of TG curves indicate peaks for thermogravimetric reactions. Fordham and Smalley (1985) have noted six DTG peaks. One peak for desorption of pore water at 100 °C; three peaks for dehydration of CSH at 180 °C, 350 °C and 400 °C; a peak for dehydroxylation of $Ca(OH)_2$ at 600 °C; and a peak for decarbonaion of $CaCO_3$ at 780 °C. However, the peaks at 180 °C and 400 °C were not clearly seen as they had been merged with predominant peaks at 100 °C and 350 °C. El-Jazairi and Illston (1977) have done semi-isothermal thermogravimetric analysis and noted DTG peaks for decomposition of CAH_{10} (66 °C), AH_3 (271 °C), C_3AH_6 (350 °C) and $CaCO_3$ (796 °C). Chaipanich and Nochaiya (2010) noted DTG peaks for C-S-H (between 76 - 84 °C), ettringite (between 104 - 114 °C), gehlenite hydrate (between 157-163 °C), $Ca(OH)_2$(between 458 - 464 °C) and $CaCO_3$(between 667 - 688 °C).

DTA curves give peaks when the temperature difference between sample and reference changes drastically. Depending on the position and the direction of the peak, the relevant transition and its nature (whether it is exothermic or endothermic) can be identified. Ubbrìaco and Calabrese (1998) found a shift of some endothermic peaks with the age of paste of OPC and natural pozzolan. At the age of 6 hours the DTA curve showed an endothermic peak at 100 °C due to dehydration of ettringite (which had been overlapped with the endothermic peak of C-S-H), a slight peak at 140°C due to gypsum and a clear peak at 460°C due to dehydroxylation of $Ca(OH)_2$. However, at 28 and 90 days the endothermic peak was observed at 110°C due to C-S-H (which overlapped with the endothermic peak of ettringite) and a peak at 470°C due to dehydroxylation of $Ca(OH)_2$. Hence, with the formation of C-S-H from 6 hours to 28 days, the overall endothermic effect had been shifted from 100°C to 110°C. Decarbonation of $CaCO_3$ and carbonated products of natural pozzolan was not reflected by a peak, but an endothermic phenomenon was reflected by a drastic drop around 700°C. Bradbury, Callaway and Double (1976) used high alumina cement and found peaks for CAH_{10} (at 130°C), C_2AH_8 (just below 200°C), AH_3 (at 300°C) and C_3AH_6 (at 325°C). Esteves (2011) used OPC-silica fume paste and found two major endothermic peaks; one at 110 °C for dehydration of weakly bound water in C-S-H and the other around 410°C for dehydroxylation of $Ca(OH)_2$. However, his results are important because in addition to endothermic peaks, there was an exothermic peak around 900°C, which reflects CaO-SiO crystallisation of OPC-silica fume paste.

DSC curves give peaks when there is a rapid change in heat flow between sample and reference. Those peaks reflect the transitions that the sample undergoes when heated, as in the case of DTA curves. Although most transitions are reflected in both the DSC and DTA curves, some peaks can be clearly seen only in one curve. Sha, O'Neill and Guo (1999) studied the differences of DSC curves of OPC powder and those of hydrated OPC at different ages, and noted the appearances of new peaks, disappearances of existing peaks, and shifting of some peaks with age. Up to 15 days, two sub-peaks were seen around 100-150 °C, indicating water loss of two types of molecular water; after that the first sub-peak disappeared and one dominant peak emerged. Also there were another set of sub-peaks around 165-205°C reflecting dehydration of ‘iron-substituted ettringite’ (**AFt**) and ettringite. The other dominant endothermic peak was around 450-500°C, and that reflects dehydroxylation of

$Ca(OH)_2$. A small peak was noted between 650-700 °C reflecting decarbonation. In another study by Sha and Pereira (2001a) using hydrated blast furnace slag, in addition to above endothermic peaks, exothermic peaks were noted; a prominent peak around 550°C, and a small peak around 940°C indicating formation of crystalline phases.

4.4 Materials, Methods and Experimental Program

This experimental program is a logical extension of the one given in Chapter 3, which searched for a practical cementitious mixture by mixing lime, pozzolanic materials, sodium compounds and OPC. In that experimental program the broad name 'Alkali Pozzolan Cement' (APC) was used to identify the mixtures developed. The same name is used to identify the different practical cementitious mixtures developed in this experimental program with different proportions of alkali and pozzolanic materials.

4.4.1 Raw Materials

The main pozzolanic material used in the mixtures was Class F fly ash, which had 51.6% SiO_2, 27.6% Al_2O_3 and 1.6% CaO. The remaining 19.2% contained mainly Fe compounds. The other pozzolanic material used was slag, and it constituted 34.7% SiO_2, 3.7% Al_2O_3, 32.6% CaO and 24.9% other compounds. Lime, OPC and Na_2SO_4 used were the same materials used in experiments described in Chapter 3.

4.4.2 Practical, Comparable and Reference Mixtures

The 'Practical APC' mixture that emerged from previous experimental program can be expressed as APC* = 70%(95%APC70 + 5% $Na_2S\ O_4$)+ 30%OPC. Hence, keeping this mixture in the 'central position', the other mixtures for this experimental program were designed. Accordingly, a number of 'practical APC' mixtures were designed from APC60, APC70 and APC80 [as described before, APCr = r% Pozzolan + (100-r)%Lime]. Also different pozzolanic materials, namely, fly ash and slag, were used. The comparable mixture contained 70% fly ash and 30% OPC (Mixture C). This combination was used for the 'comparable mixture', because the percentage of OPC used to design all the 'practical APC' mixtures was 30%. Moreover, it is probably the largest percentage of low calcium fly ash (Class F fly ash) that can be envisaged for 'high volume fly ash' (HVFA) mixtures, containing significantly more fly ash than the typical 25% (Kumar, Kumar and Mehrotra 2007). The mixture containing 100% OPC was used as the 'reference mixture' (Mixture R). Accordingly, the compositions of dry cement powders were decided as below:

APC Mixtures derived from fly ash
L = 70% (95% APC60 + 5% Na_2SO_4) + 30% OPC
M = 70% (95% APC70 + 5% Na_2SO_4) + 30% OPC
N =70% (95% APC80 + 5% Na_2SO_4) + 30% OPC

APC Mixtures derived from slag
P = 70% (95% APC70 + 5% Na_2SO_4) + 30% OPC

HVFA Mixtures
C = 70% fly ash + 30% OPC

OPC Mixtures
R = 100%OPC

NOTES:
1. APCr = r% Pozzolan + (100-r)%Lime

2. The above dry cement powders were mixed with water, according to w/c of 0.3 and 0.4, and two pastes from each cement were obtained. To identify those pastes, suffixes 3 and 4 were added to the letter indicating the dry mix. For example, the pastes prepared from cement M with w/c=0.3 and 0.4 were identified as M3 and M4 respectively.

For comparison purposes the mixtures were grouped into 3 different groups.

1. **M-C-R grouping**
–to compare the APC mixture M, with Comparable mix C with Reference Mixture R

2. **M-L-N grouping**
– to compare the APC mixture M, with its neighboring APC mixtures L and N

3. **M-P grouping**
- to compare the APC mixtures derived from fly ash and slag.

4.4.3 Experimental Procedures

The cement pastes were prepared by mixing dry cementitious powder with water, keeping the water to cementitious mixture ratio as either 0.3 or 0.4 by weight. The experiments were conducted in summer, and hence the temperature of tap water was about 25- 40°C. A number of sets of specimens of size 50mm x 50mm x 50mm were made from each mixture, and each set was cured under different conditions described below:

Condition A (Air)
Air cured under controlled condition, which is 20– 25 ˚C and relative humidity is 70 - 75%.

Condition W (Water)
15 hrs air curing under controlled condition followed by water curing under controlled condition till testing

Condition H (Heat)
15 hrs heat curing at 60°C in a sealed polythene bag in oven followed by air curing under controlled condition.

Condition S (Steam)
15 hrs steam curing at 60°C in a sealed polythene bag in steam chamber followed by air curing under controlled condition.

NOTE:

1. Here the term 'controlled condition' indicates curing in the controlled room, where temperature is 20 – 25 ˚C and relative humidity is 70 - 75%.

2. The conditions A, H and S mentioned in the experiments of stage 1 presented in Chapter 3 are different from the conditions mentioned above, as they were not cured under controlled conditions, but cured under ambient conditions during winter where the temperature varies between 0°C – 30°C, and relative humidity varies between 45-55%.

Testing of Samples

Compressive testing was conducted in order to investigate the development of structural properties. Development of microstructure was investigated using different techniques such as X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM) with Energy Dispersive Spectroscopy (EDS) and Thermal Analysis (TG-DTG, DTA and DSC) for selected mixtures.

The testing machines used for XRD, SEM/EDS and TG/DSC analysis are shown in **Fig. 4.3**, **Fig. 4.4** and **Fig. 4.5** respectively.

Fig. 4.3 Testing Machine used for XRD Analysis

Fig. 4.4 Testing Machine used for SEM/EDS Analysis

Fig. 4.5 Testing Machines used for TG/DSC Analysis

The details about XRD and SEM/EDS analysis are given under results and discussion.

4.5 Results and Discussion

In this section, first, a mechanism for the hydration of APC is proposed, and after that the results and interpretations of the experiments done on structural and microstructural properties of cementitious materials are presented.

4.5.1 Hydration Mechanism of APC Systems

Based on the literature review on hydration of 'OPC system' and 'pozzolanic system' given in Section 4.3.1, the hydration of 'APC system' is conceptualized as below.

APC mixtures consist of lime, pozzolan, OPC and small quantity of Na_2SO_4 powder. Hence, when mixed with water, a series of complex reactions occur. Lime powder gets converted to $Ca(OH)_2$ paste. Na_2SO_4 reacts with $Ca(OH)_2$ and produces small quantity of NaOH and $CaSO_4$ within the mixture. The NaOH produced in the mixture would increase the alkalinity of the context, and hence activates the reaction between lime and pozzolan. $Ca(OH)_2$ reacts with activated silica in pozzolan and produce calcium silicate hydrate (C-S-H). During this process, if aluminium atoms penetrate into C-S-H, a small quantity of calcium aluminium silicate hydrate (C-A-S-H) too can be formed. In addition $Ca(OH)_2$ also reacts with alumina in pozzolan and produces a variety of hydrates such as calcium aluminate hydrates, gehlenite hydrate, ettringite and monosulphate. At the same time C_3S and C_2S of the added OPC react with water and produce C-S-H independently, while C_3A and C_4AF in OPC would produce ettringite and monosulphate. Finally, iron atoms would substitute some aluminium atoms in ettringite and monosulphate; this produces 'iron-substituted ettringite' (alumino-ferrite trisulfate hydrate), which is commonly known as **AFt**, and 'iron-substituted monosulphate' (alumino-ferrite monosulfate hydrate) which is commonly known as **AFm**. Moreover, the NaOH produced within the mixture might react with pozzolan and produce a small quantity of sodium aluminosilicate hydrate (N-A-S-H) as well. However, as the NaOH produced within the mixture is relatively small, formation of N-A-S-H may be nil or marginal.

Apart from the above hydration process, crystalline minerals of pozzolan, such as quartz (SiO_2), mullite ($3Al_2O_3.2SiO_2$), sillimanite ($Al_2O_3.SiO_2$), hematite and magnetite would remain the same without getting involved in the hydration process.

4.5.2 Normal Consistency and Setting Time

The normal consistency and setting time were determined using the Vicat apparatus. Normal consistency of a mixture was taken as the w/c ratio that allows the 10mm diameter Vicat plunger to penetrate 10 mm depth in 30 seconds. The pastes prepared with w/c ratio of normal consistency were used to determine initial and final setting times. Initial setting time was taken as the time when the 1 mm diameter Vicat needle penetrates 25 mm depth in 30 seconds, and final setting time was taken as the time when no mark is left on the surface when it is dropped. **Table 4.1** gives the results of the APC mixture M, the HVFA mixture C and the OPC mixture R.

Table 4.1 Normal Consistency and Setting Times

Mix	w/c needed for Normal Consistency	Initial Setting Time (mins)	Final Setting Time (mins)
M	0.33	135	225
C	0.25	225	315
R	0.27	120	210

The results of OPC mixture R and HVFA mixture C are comparable with the results of some other researchers as well. For example, Wei, Tian and Xiao (2010) used Portland cements of grade 32.5 and 52.5; they reported the w/c ratio needed for normal consistency as 0.25 and 0.29 respectively, and their 28 day strengths as 40.5 and 61.7 MPa. The respective initial setting times were 164 min and 155 min, while final setting times were 307 min and 295 min. Naceri, Hamina and Grosseau (2009) obtained a w/c ratio for normal consistency of 0.274 with initial and final setting times of 162 min and 274 min. Singh and Garg (1999) blended 75% fly ash and 25% OPC to specific surface areas of 300, 400 and 500 m^2/kg and found w/c ratios for the normal consistencies as 0.363, 0.303 and 0.314 respectively. Fu et al. (2002) used different mixtures of HVFA blended cements along with slag, gypsum and compound activators; they got w/c ratios for normal consistencies between 0.310 and 0.330; they also got relatively high initial setting times between 280 – 380 min and final setting times between 710 – 950 min.

According to **Table 4.1**, the w/c ratio for normal consistency of the APC mixture is greater than that of the reference mixture R, and less than that of the comparable mixture C. The reason is, due to the addition of lime, the APC mixture M becomes sticky and more resistive for the 10 mm Vicat plunger to penetrate. In the case of the HVFA mixture, as there is high volume of spherical fly ash particles, it has become less resistive for 10 mm Vicat plunger to penetrate. The setting times of the OPC mixture are primarily controlled by the formation of ettringite and monosulphate due to the hydration reaction of C_3A. In the case of HVFA mixture C, there was only 30% OPC; hence, the quantity of C_3A was quite low. As a result, the formation of ettringite and monosulphate becomes very low. The APC mixture M3 too has the same percentage of OPC, and hence low contribution to formation of ettringite and monosulphate. In addition, within the APC mixture, Na_2SO_4 reacts with the lime added and produces a small quantity of $CaSO_4$ and NaOH, which would break the glass phases of fly ash. Then $Ca(OH)_2$ mainly reacts with silica in fly ash to produce C-S-H; at the same time, it also reacts with alumina in fly ash to produce a variety of hydrates including ettringite and monosulphate. Accordingly, in the APC mixture M, the pozzolanic reaction as well as the OPC reaction contribute towards the formation of ettringite and monosulphate; and as a result, setting times have been reduced. Nevertheless, when looking at the actual values in **Table 4.1**, it can be concluded that the APC mixture M and OPC mixture R are comparable with regard to normal consistency and setting times.

4.5.3 Compressive Strength

Dry cementitious powders of APC mixtures (L, M, N and P), HVFA mixture (C) and OPC mixture (R) given in Section 4.4.2 were used to prepare different pastes. From each dry mixture, two pastes were obtained by mixing with water according to w/c of 0.3 and 0.4. Samples were cured under different conditions; three samples of each mixture were tested at 3, 7 and 28 days, and mean strengths were computed. In general, if the strength of a particular sample differed by more than 15% from the mean, it was rejected and only the average of the other two samples taken. The strength developments of different mixtures are given in **Table 4.2**. Some of the mixtures given in the table were used in Stage 1 of the experimental program as well, and reported on in Chapter 3. However, slightly higher strengths are noted here, as the samples were cured under a higher relative humidity than in Stage 1. The results of Gebler and Klieger (1986) indicated that the ratio of 28 day strengths of the samples cured at 50% relative humidity to those of samples cured at 100% relative humidity, falls between 55-85%, which indicates the increase of strength with the increase of relative humidly.

Table 4.2 Compressive Strengths of Cementitious Mixtures

Mix	DESCRIPTION		COMPRESSIVE STRENGTH (MPa)											
	Composition	**w/c**	**Condition A**			**Condition W**			**Condition H**			**Condition S**		
			3d	*7d*	*28d*	*3d*	*7d*	*28d*	*3d*	*7d*	*28d*	*3d*	*7d*	*28d*
	Practical APC Mixtures- from fly ash													
L3	70% (95% APC60 + 5% Na2SO4) + 30% OPC	**0.3**	20	37	50	18	25	34	33	33	42			
L4	70% (95% APC60 + 5% Na2SO4) + 30% OPC	**0.4**	13	20	26	11	17	31	21	21	21			
M3	70% (95% APC70 + 5% Na2SO4) + 30% OPC	**0.3**	22	31	46	22	27	40	28	38	47	39	33	42
M4	70% (95% APC70 + 5% Na2SO4) + 30% OPC	**0.4**	12	20	32	12	15	27	20	20	23			
N3	70% (95% APC80 + 5% Na2SO4) + 30% OPC	**0.3**	25	25	42	23	33	41	33	36	41			
N4	70% (95% APC80 + 5% Na2SO4) + 30% OPC	**0.4**	13	21	28	12	21	30	18	21	23			
	Practical APC Mixtures - from slag													
P3	70% (95% APC70 + 5% Na2SO4) + 30% OPC	**0.3**	35	43	50	39	39	44	39	41	42			
	Comparable HVFA Mixtures -from fly ash													
C3	70% fly ash + 30% OPC	**0.3**	17	18	24	18	24	27	26	34	34	32	37	41
C4	70% fly ash + 30% OPC	**0.4**	5	10	13	6	8	11	12	16	19			
	Reference OPC Mixtures													
R3	100%OPC	**0.3**	42	49	57	34	48	59	35	52	60	46	63	71
R4	100%OPC	**0.4**	34	35	40	35	40	54	32	34	38			

KEY:
Condition A - (Air) - Air cured under controlled condition till testing
Condition W - (Water) -15 hrs air curing in controlled condition followed by water curing in controlled condition till testing
Condition H - (Heat) -15 hrs heat curing at 60°C in a sealed polythene bag in oven followed by air curing under controlled condition
Condition S - (Steam) - 15 hrs steam curing at 60°C in a sealed polythene bag in steam chamber followed by air curing under controlled condition

NOTE:
1. Here the term 'controlled condition' indicates curing in a controlled room where temperature is 20-25 ˚ C and relative humidity is 70 % - 75%.
2. The Conditions A, H and S mentioned in the experiments of stage 1 presented in Chapter 3 are different from the conditions mentioned above, as they were not cured under controlled conditions, but cured under ambient conditions during winter where the local temperature can vary 0°C – 30°C , and relative humidity can vary between 45-55%.

4.5.3.1 Comparison of Compressive Strength Results

Comparisons of compressive strengths are based on the results shown in **Table 4.2**. As indicated before, the mixtures L, M, N and P are different APC mixtures, while the mixture C is a HVF mixture. The reference mixture R is an OPC mixture. Suffixes 3 and 4 reflect the w/c ratios of 0.3 and 0.4. It should be noted that, proportion of fly ash increases (or proportion of lime decreases) in the order of L, M and N. Also the mixtures M and P contained the same proportions, but had different pozzolans, namely fly ash and slag. All the APC mixtures and comparable HVFA mixtures have same proportion of OPC (i.e. 30%).

In APC mixtures (L, M, N and P), generally 3 day strengths are higher in samples cured at elevated temperature, while 28 day strengths are higher in air cured samples. The reason is that elevated temperature curing accelerates pozzolanic reactions, hence samples gain early strength. Nevertheless, elevated temperatures also increase evaporation of free water from specimens, and as a result water available for the subsequent hydration process is reduced. In the case of water curing, even though there is enough water, the high thermal mass of the water does not allow the pozzolanic reactions to benefit from the heat generated within the specimens. On the other hand, air cured samples are not subjected to any unfavourable conditions. Hence, the hydration process continues steadily, and by the age of 28 days, the strengths of air cured samples have become higher than those of other samples. This implies that APC does not require elevated-temperature curing even though it contains a significantly high volume of pozzolan. Further, APC does not require water curing either, in order to gain strength. Hence it can be concluded that APC performs well under air curing, even though it contains a higher pozzolanic content. Furthermore, it is seen that even though there is an increase in strength from N to L, there is not much difference in strengths of L and M. Also, generally M secures a median position. Hence, it is reasonable to consider the mixture M as the central mixture.

When P3 and M3 are compared, it is seen that generally P3 has higher strength than M3. Chemical analysis indicates that slag contains 32.6% CaO while fly ash contains only 1.6% CaO as described in Section 4.4.1. XRD analysis indicates that slag contains higher content of amorphous materials than fly ash, and that is reflected in XRD curves given in **Fig. 4.9**, and described in Section 4.5.4. Higher content of amorphous materials and higher content of CaO increase the pozzolanic reaction, and hence APC derived from slag has given higher strength than APC derived from fly ash. This implies the possibility of improving strength of APC by using high-CaO pozzolans.

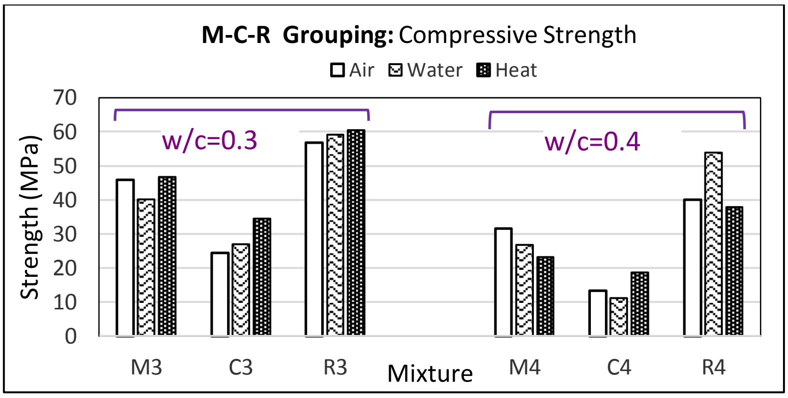
Accordingly, high calcium fly ash (Class C fly ash) would give higher strength than low calcium fly ash (Class F fly ash).

When APC mixtures are compared with HVFA mixtures having the same w/c ratio, it is very clearly seen that the APC mixtures perform much better than HVFA mixtures at all ages under all curing conditions. The reason could be due to inadequate $Ca(OH)_2$ to react with fly ash, and also non availability of any activating chemicals in HVFA mixtures. Generally under air curing conditions, the 28 day strengths of APC mixtures are over 85% higher than those of HVFA mixtures. This confirms the suitability of APC over HVFA where compressive strength is considered.

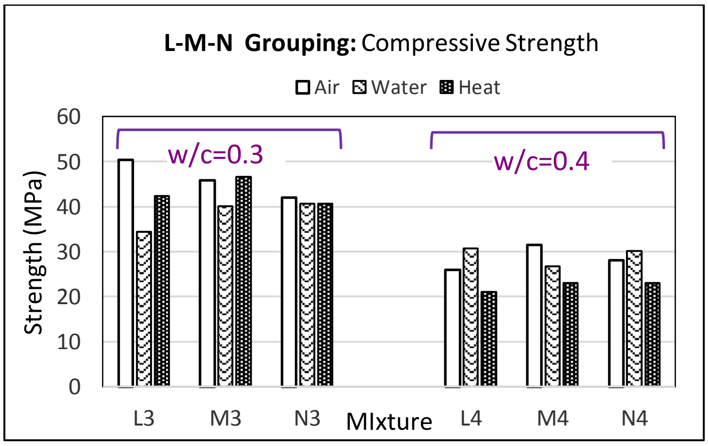
When APC mixtures are compared with the reference mixtures (OPC), it is seen that, 28 day strength of air cured APC samples are about 75% of the strength of the corresponding OPC samples, which can be considered as a reasonable achievement.

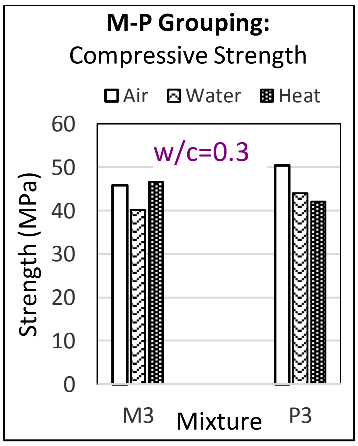
Some other researchers too have done similar investigations, and their findings are consistent with the above results. Wei, Tian and Xiao (2010) used Portland cements of grade 32.5 and 52.5 and prepared cement pastes according to their normal consistencies (0.25 and 0.29), and found their 28 day strengths as 40.5 and 61.7 MPa. Kumar, Kumar and Mehrotra (2007) mixed Portland cement clinker with fly ash in different proportions and tested at 28 days. Pure OPC gave a strength of 60 MPa; when the fly ash percentage was between 15% - 25%, the strengths were around 52 – 48 MPa; but when the fly ash percentage was increased to 35%, the strengths fell below 35 MPa. Singh and Garg (1999) prepared three blended cement mixtures of different fineness, consisting of 75% fly ash and 25% OPC, and found that the 28 day strengths were 16, 21 and 22 MPa. Qian, Shi and Wang (2001) investigated the effect of percentage of fly ash on strength, and found that 28 day strength of 100% OPC was about 54 MPa, while those of Low Volume Fly Ash (LVFA) cement (70%OPC + 30% fly ash) and High Volume Fly Ash (HVFA) cement (30%OPC + 70%fly ash) were about 24 MPa and 12 MPa respectively. However, when the mixtures were activated by Na_2SO_4,strengths increased significantly.

The following section presents the comparison of compressive strengths based on the three groupings M-C-R, L-M-N and M-P described in Section 4.4.2. **Fig. 4.6** presents the 28 day compressive strength results through those groupings.



(a)





(b) **(c)**

Fig. 4.6 Compressive Strengths at 28 days of Different Mixtures
(a) M-C-R Grouping; **(b)** L-M-N Grouping; **(c)** M-P Grouping

Fig. 4.6 (a) indicates that for both w/c ratios 0.3 and 0.4, strengths of APC mixture M are much higher than those of HVFA mixture C (M3>C3 and M4>C4), but relatively less than those of OPC mixture R (M3<R3 and M4<R4). **Fig. 4.6 (b)** shows that for a particular w/c ratio (0.3 or 0.4), strengths of APC mixtures L, M and N are similar (L3≈M3≈N3 and L4≈M4≈N4). **Fig. 4.6 (c)** gives the strengths of APC derived from fly ash (M3) and slag (P3). The strengths are generally comparable, but air cured samples of mixture P3 has given the highest strength.

4.5.3.2 Sensitivity to w/c ratio and curing condition on strength

Sensitivity to w/c and curing condition on strength was investigated using the concept of ‘sensitivity index’ with respect to a datum, which is defined as below.

$$Sensitivity\ Index\ (SI) = \frac{f_{test} - f_{ref}}{f_{ref}} = \frac{f_{test}}{f_{ref}} - 1$$

where, f_{test} - strength of the test mix

f_{ref} - strength of corresponding mix with reference w/c or curing

The ‘sensitivity index’ can be defined as the difference of strength between the test mix and reference mix as a ratio of the reference mix. The ‘central mixture’ of the experimental program was the air cured APC mixture M prepared with w/c=0.3, hence the w/c ratio of 0.3 and air curing condition were considered as the datum or reference. Accordingly, to determine sensitivity to w/c ratio on strength, the mixture with w/c = 0.3 was taken as reference, and mixture with modified w/c (say w/c = 0.4) was taken as test mixture. Similarly, to determine sensitivity to curing on strength, the mixture with air curing condition was taken as reference, and mixture with modified curing condition (say water or heat curing) was taken as the test mixture. If the sensitivity index is ‘0’, it indicates that there is ‘no sensitivity’, while the deviation from ‘0’ indicates the degree of sensitivity. Positive values of sensitivity index indicate that the strength has been increased, while the negative values indicate the strength has been decreased, as the result of change of conditions from the datum conditions. **Fig. 4.7** and **Fig. 4.8** present sensitivity to w/c and sensitivity to curing condition respectively.

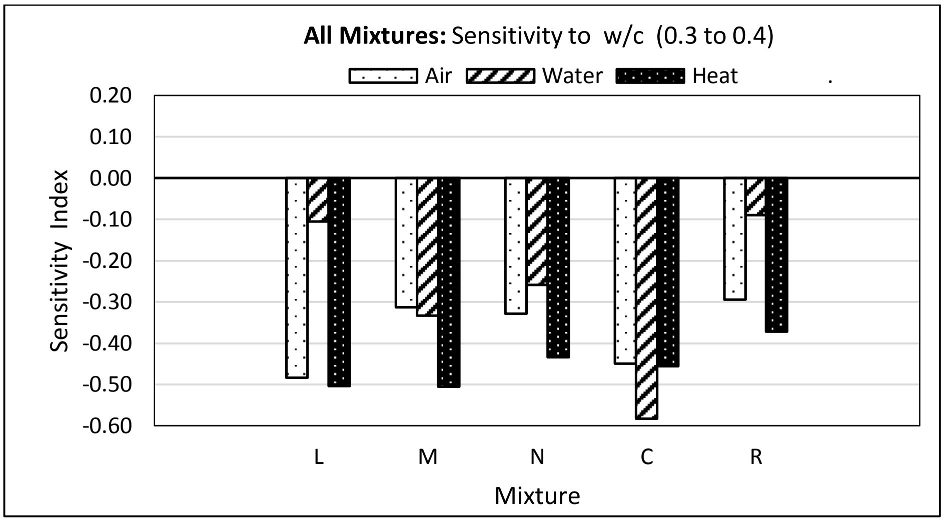
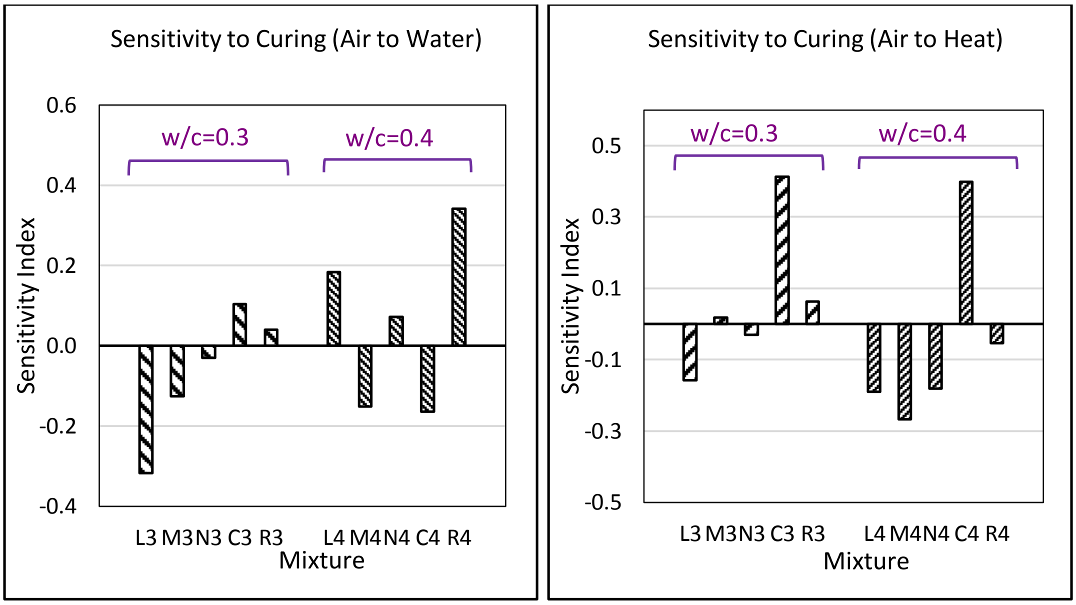


Fig. 4.7 Sensitivity to w/c ratio on Strength

In **Fig 4.7**, all the values are negative; it indicates that all the mixtures are sensitive to w/c, and also strengths are decreased with the increase of w/c from datum. **Fig. 4.7** indicates that the sensitivity to w/c on strength of water cured specimens is generally low (i.e. sensitivity indices are closer to zero) (except mixture C), when compared with other specimens. Immersion of samples in water might have reduced the differences in w/c in the process of hydration. On the other hand, sensitivity of heat cured specimens is generally high (i.e. sensitivity indices are not closer to zero). This may be because heat curing, while accelerating the hydration process, also partially removes the water required for hydration from the specimens. The effect is more on w/c=0.4 samples, as those samples naturally have less strength due to high porosity. Sensitivity of mixture C is high for all three curing conditions, because the hydration process of mixture C is very slow and it might have further slowed down when the w/c is increased to 0.4. Wei, Tian and Xiao (2010) have done a similar investigation, using OPC paste prepared by different grades of Portland cements with different w/c ratios in their experiments. For w/c of 0.40, Grade 32.5 cement and Grade 52.5 cement yielded 40 MPa and 60 MPa respectively. Accordingly, sensitivity indices to w/c ratio (for an increase of w/c by 0.05) were -0.28 and -0.08. Rattanadecho et al. (2008) tested 15 min microwave cured OPC paste samples of w/c of 0.3 and noted 28 day strength of 540 kg/cm^2 (about 50 MPa), but when w/c was increased to 0.4, the strength decreased to 425 kg/cm^2 (about 38 MPa) indicating a sensitivity index of -0.21 [=(425-540)/540].



(a) **(b)**

Fig. 4.8 Sensitivity to Curing on Strength
(a) Air to Water Curing; **(b)** Air to Heat Curing

In **Fig. 4.8(a)** and **(b)**, the first five bars represent the mixtures with w/c=0.3, and the next five the mixtures with w/c=0.4. **Fig. 4.8(a)** indicates that, sensitivity to water curing of APC mixtures L, M and N prepared with w/c of 0.3 decreases in that order, and sensitivity indices are negative. However, such a pattern cannot be seen in APC mixtures with w/c of 0.4. The reason could be described as below. APC system consists of both an alkali-pozzolan system and an OPC system. High w/c ratio and water curing are not favorable for pozzolanic reactions. When OPC system is concerned, even though high w/c is not favourable, water curing is favourable. In the case of APC mixtures with w/c = 0.3, unfavorable effects on pozzolanic reaction due to water curing could not be overridden by the favorable effect on OPC hydration. Hence overall effect is negative. However in the case of APC mixtures with w/c=0.4, in a situation where pozzolanic reaction had been reduced by high w/c, water curing helped for OPC hydration. Accordingly, overall effect can vary from mixture to mixture, and sensitivity index too can be positive or negative. According to **Fig. 4.8(b)**, heat curing tends to adversely affect samples with w/c=0.4 more than samples of w/c=0.3, because the water required for hydration is removed from the specimens. However in the case of HVFA mixture C, heat curing helps through increasing the rate of reaction. Rattanadecho et al. (2008) too studied the effect of different curing conditions, namely, air curing, water curing and 15 min microwave curing of cement paste samples made of w/c ratios of 0.4. Air cured as well as microwave cured samples had given 28 day strengths around 425 kg/cm^2 (about 38 MPa), while water cured samples had given strength around 440 kg/cm^2 (about 40 MPa). This indicates that the sensitivity index for water curing with respect to air curing is 0.04 [= (440-425)/425].

4.5.3.3 Strength Activity Index

Strength activity Index is another important indicator, and can be defined as below:

$$\boldsymbol{S}trength\ Activity\ Index\ (SAI) = \frac{Strength\ of\ the\ Test\ Mix}{Strength\ of\ corresponding\ Reference\ Mix\ at\ same\ age}$$

For example, strength activity index (SAI) of air cured mixture M3 at 28 days is obtained by dividing the 28 day air cured strength of mixture M3, by 28 day air cured strength of reference mixture R3; the SAI of air cured mixture M4 at 28 days is obtained by dividing the 28 day air cured strength of mixture M4, by 28 day air cured strength of reference mixture R4. When computing SAIs of water cured and heat cured samples, water and heat cured strengths of relevant reference mixtures were considered. **Table 4.3 (a)** and **Table 4.3(b)** present the strength activity indices based on reference mixtures with w/c=0.3 and 0.4 respectively.

Table 4.3 Strength Activity Index (SAI):
(a) Based on Reference Mixture with w/c=0.3;
(b) Based on Reference Mixture with w/c=0.4

(a)

Mix	Strength Activity Index based on Reference Mixture with w/c=0.3								
	Condition A			Condition W			Condition H		
	3d	*7d*	*28d*	*3d*	*7d*	*28d*	*3d*	*7d*	*28d*
L3	0.47	0.75	0.89	0.52	0.51	0.58	0.94	0.65	0.70
M3	0.53	0.64	0.81	0.65	0.55	0.68	0.80	0.73	0.77
N3	0.61	0.52	0.74	0.68	0.69	0.69	0.93	0.71	0.67
P3	0.84	0.87	0.89	1.16	0.82	0.75	1.11	0.80	0.70
C3	0.40	0.38	0.43	0.53	0.50	0.45	0.73	0.65	0.57
R3	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

(b)

Mix	Strength Activity Index based on Reference Mixture with w/c=0.4								
	Condition A			Condition W			Condition H		
	3d	*7d*	*28d*	*3d*	*7d*	*28d*	*3d*	*7d*	*28d*
L4	0.37	0.56	0.65	0.31	0.44	0.57	0.64	0.61	0.55
M4	0.34	0.57	0.79	0.33	0.38	0.50	0.63	0.59	0.61
N4	0.37	**0.60**	0.70	0.34	0.53	0.56	0.54	0.61	0.61
C4	0.16	0.28	0.33	0.17	0.20	0.21	0.37	0.46	0.49
R4	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

Table 4.3 (a) and **Table 4.3 (b)** show that generally SAIs of samples having w/c=0.3 is greater than those of 0.4. It is also seen that SAIs of all the APC mixtures derived from fly ash (L, M and N) are greater than those of HVFA mixtures (C), but lower than OPC mixtures (R). Further for those mixtures, an increase of SAIs can be seen from 3 days to 28 days for air cured and water cured samples. But in heat cured samples relatively high SAIs can be seen at 3 days, as heat curing accelerates the hydration process.

4.5.3.4 Early Strength Index

Early strength index (ESI) of a particular mixture for a given curing condition is obtained by dividing 3 day strength by its 28 day strength under the same curing condition. ESIs of all the mixtures are given in **Table 4.4**.

$$\boldsymbol{Early\ Strength\ Index\ (ESI)} = \frac{\mathbf{3}\ \boldsymbol{day\ Strength}}{\mathbf{28\ day}\ \boldsymbol{Strength\ of\ the\ same\ mixture}}$$

Table 4.4 Early Strength Index (ESI)

Mix	Early Strength Index = 3d strength/28d strength		
	Condition A	Condition W	Condition H
L3	0.39	0.51	0.77
L4	0.49	0.36	0.98
M3	0.48	0.55	0.60
M4	0.37	0.43	0.88
N3	0.60	0.57	0.80
N4	0.45	0.39	0.76
P3	0.69	0.89	0.93
C3	0.68	0.67	0.74
C4	0.40	0.52	0.63
R3	0.73	0.57	0.58
R4	0.85	0.65	0.85

Table 4.4 shows that early strength indices (ESIs) of heat cured samples are generally higher than those of air cured and water cured mixtures, except for OPC mixtures R3. The reason is that, other than OPC mixtures, all other mixtures contain pozzolanic materials, and hence heat curing activates pozzolanic reactions leading to a higher early strength. However in the case of the APC mixture derived from slag (P), ESIs are relatively high. The reason may be that slag contains 32.6% CaO while fly ash contains only 1.6% of CaO; hence pozzolanic reaction in slag based APC may be higher than that of fly ash based APC.

4.5.4 XRD Analysis

XRD analyses were done on selected raw materials and selected hydrated samples at the ages of 3, 28 and 112 days. The raw materials selected were fly ash, lime and OPC powder; the hydrated samples selected were APC mixture M3, comparable HVFA mixture C3 and reference OPC mixture R3. When collecting data of raw materials, the 'internal standard' corundum (Al_2O_3) was added to raw materials (lime, fly ash and OPC powder) to conduct semi-quantitative analysis. Hence, peaks due to corundum shown in XRD curves of raw materials should be ignored.

The data for XRD analysis were collected through copper radiation (λ_{Cu} = 1.54056 Å). The search/match algorithm DIFFRAC.EVA 3.0 developed by Bruker-AXS, Germany and International Centre for Diffraction Data (ICDD) Powder Diffraction File (PDF4+ 2012 edition) were used to identify crystalline phases. In addition to ICDD-PDF data, the related information such as Bragg's angle (2θ values) of crystalline compounds given in the literature too were used as a guide. When Bragg's angle (2θ values) of hydrated products given in the literature were related to cobalt radiation, they were converted to copper radiation, as the method used in this research is based on copper radiation. The conversion was done using Bragg's Law described below.

Bragg's Law:

Wave length, $\boldsymbol{\lambda = 2d\,\mathrm{Sin}\theta}$ where d - distance between planes
θ- diffraction angle

For copper → $\lambda_{Cu} = 2d\,\mathrm{Sin}(\theta_{Cu})$
For cobalt → $\lambda_{Co} = 2d\,\mathrm{Sin}(\theta_{Co})$

Hence, $(\theta_{Cu}) = \mathrm{Sin}^{-1}\,[(\lambda_{Cu}/\lambda_{Co}).\ \mathrm{Sin}(\theta_{Co})]$

Substituting λ_{Cu} = 1.54056 Å and λ_{Co} = 1.78897 Å

$$(\theta_{Cu}) = \mathrm{Sin}^{-1}\,[0.86114 \times \mathrm{Sin}(\theta_{Co})]$$
$$2(\theta_{Cu}) = 2\,\mathrm{Sin}^{-1}\,[0.86114 \times \mathrm{Sin}(\theta_{Co})]$$

Using the above equation, '2θ values' (Bragg's angle) given with respect to cobalt radiation can be converted to 2θ values with respect to copper radiation. For example if the 2θ value with respect to cobalt radiation of a C-S-H is given as 34.5°, then the relevant 2θ value with respect to copper radiation can be obtained as 29.5 ° using the above equation.

For each mineral, the 2θ values (related to copper radiation) of major diffraction peaks that have the highest intensities as given in ICDD Powder Diffraction Files (PDF4+ 2012 edition) are given below. The intensities are indicated within parenthesis.

Portlandite	$Ca(OH)_2$	- 18.0 (635), 28.69 (162), 34.11 (999), 47.12 (427), 50.83 (281)
Calcite	$CaCO_3$	- 23.05 (99), 29.40 (999), 39.4 (197), 47.50 (187), 48.50 (205)
Alite	C_3S	- 29.39(40), 29.50(75), 30.14(25), 32.25(85), 34.41 (100), 41.36(60), 51.78(55)
Belite	C_2S	- 32.13(100), 32.05 (97), 32.59 (83)
Aluminate	C_3A	- 33.19 (100), 47.66 (30)
Ferrite	C_4AF	- 33.31 (452), 33.74(999), 46.89(401)
Ettringite	$CA_3.3C\overline{S}.H_{32}$	- 9.09 (100), 15.78 (76), 22.94(31)
Monosulphate	$CA_3.C\overline{S}.H_{12}$	- 9.85 (100), 19.81 (70)
Hematite	Fe_2O_3	- 33.15 (100), 35.61 (70), 54.09 (45), 49.48 (40)
Magnetite	Fe_3O_4	- 30.09 (30), 35.42 (100), 62.51 (40)
Mullite	$Al_6Si_2O_{13}$	- 16.4 (677), 25.97 (859), 26.21 (999), 35.24 (508), 40.84 (568),
Gypsum	$C\overline{S}H_2$	- 31.12 (100), 20.73 (90), 33.35 (50), 11/61 (45)
Quarts	SiO2	- 20.86 (204), 26.64 (999), 36.53 (61), 42.4 (51), 45.78 (29), 50.13 (120)
Corundum	Al_2O_3	- 25.57 (45), 35.15(100), 43.35(66), 57.49(89)
CSH	$C_3S_2H_x$	- 29.35 (100), 32.05 (60), 50.07 (60)

NOTE:

When indicating diffraction peaks in XRD curves, the common practice is to use mineral names instead of chemical names. Hence here too mineral names are used, except in the cases of C_3A and C_4AF. The reason is,the mineral name 'celite' is used for C_4AF in some literature (Brandt 2009; Soroka 1980) and, the same name 'celite' is used for C_3A in other literature (Bezerra et al. 2011). Hence to avoid that confusion, in this chapter, the mineral name 'celite' is not used, instead C_3A and C_4AF are identified as 'aluminate' and 'ferrite'.

In X-Ray Diffraction, only the crystalline materials that have definite lattice structures give clear peaks. Hence, hydrated products such as calcium silicate hydrate (C-S-H) and calcium aluminium silicate hydrate (C-A-S-H) would not give clear peaks until they become crystalline. Shi, Jiménez and Palomo (2011) used fly ash-clinker blended cement pastes, but XRD curves did not indicate clear peaks of C-S-H. Although non-crystalline or amorphous materials have not given such clear peaks, the formation of amorphous compounds is reflected by broad humps around the relevant 2θ values in the XRD curves. Thus C-S-H and C-A-S-H formed in hydrated samples would be reflected by broad humps around 2θ values of 29.5°, 32° and 50°. Aimin and Sarkar (1991) have done XRD analysis of hydrated paste at 2 hours, 28 days and 90 days, and noted that the height of the diffraction peaks of cement components (C_3S, C_2S, C_3A and C_4AF) decreased with time, but the width of the peaks increased with time, forming broad humps indicating gradual conversion of crystalline cement components (C_3S, C_2S, C_3A and C_4AF) into amorphous C-S-H. Similar broad humps were noted by Mather (1972) , in the XRD curves of hydrated OPC pastes, and he too concluded that those humps were due to formation of C-S-H.

XRD curves of raw materials

Diffractograms of fly ash and slag are shown in the **Fig. 4.9.** When the profiles of XRD curves of fly ash and slag are compared, it is seen that the baseline of the XRD curve of fly ash is flatter than that of slag; also it does not have a 'broad hump' between 2θ values of 28 - 36° as in the XRD curve of slag. Furthermore the XRD curve of fly ash has more diffraction peaks than that of slag. That indicates the degree of crystallization of fly ash is greater than that of slag; in other words slag is more amorphous than fly ash. Liu et al. (2014) studied XRD curves of slag with different glass content and found 'broad humps' approximately between 25°C and 35°C, when the glass content is high. Diamond (1983) used different fly ashes and found that when the percentage of CaO is between 0% and 20% the position of the maximum intensity of the broad hump changes according to the equation, $2\theta = 22.7° + 0.248°*CaO\%$; but when the percentage of CaO exceeds 20%, the equation becomes $2\theta = 34°$ which implies no further movement of the position of the maximum intensity of the broad hump. Accordingly, by examining the location of broad hump, it is possible to get an idea about the reactivity of fly ash.

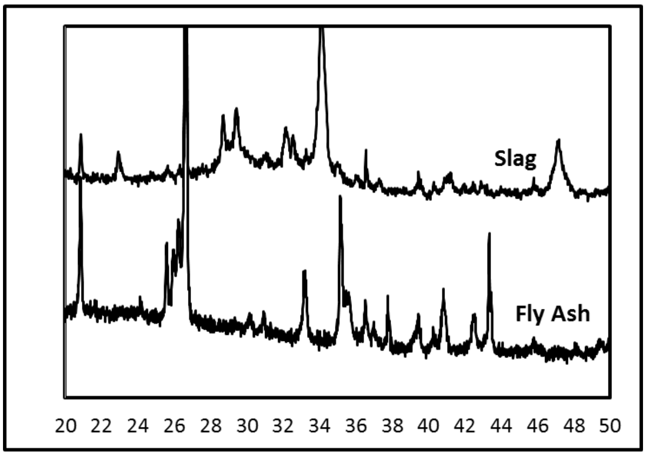


Fig. 4.9 Diffractograms of Fly Ash and Slag

Results of the chemical analysis indicates that the CaO percentages of fly ash and slag are 1.6% and 32.6% respectively. Accordingly slag is not only more amorphous, but also it contains more CaO content. Hence, it can be expected that APC derived from slag would give higher strength than APC derived from fly ash, and the compressive strength results confirm this.

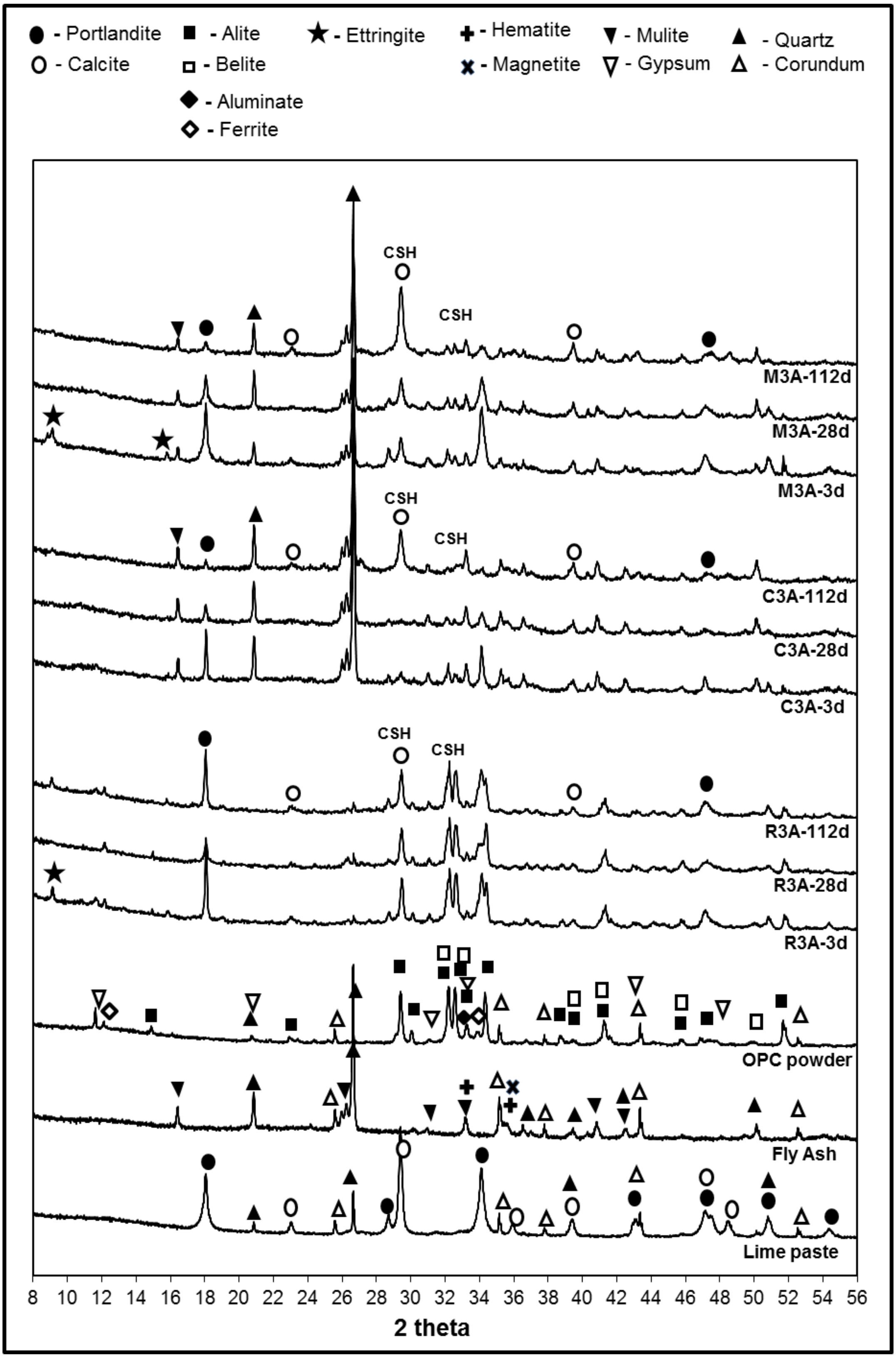


Fig. 4.10 Diffractograms of raw materials and Mixtures M3, C3 and R3

Fig. 4.10 shows the XRD curves of the raw materials and 3, 28 and 112 day old air cured samples of key mixtures (M3, C3 and R3). Only the range between 8° to 56° is shown as it is the region of interest. In the XRD curves of raw materials, all the prominent diffraction peaks are labelled. However, in XRD curves of hydrated samples, all the peaks are not labelled, but only the emerging peaks or new peaks are labelled for the sake of clarity. The other peaks of hydrated samples can be easily noted by referring to the XRD curves of the relevant raw materials.

The XRD curves of all the raw materials (fly ash, lime and OPC) have diffraction peaks due to the added corundum, around the 2θ values of 26°, 35°, 43° and 57°; hence they should be ignored. The XRD curve of lime indicates that it contains the crystalline phases of portlandite [$Ca(OH)_2$], calcite [$CaCO_3$] and quartz. The XRD curve of fly ash has a flatter base line. A flatter base line indicates that the degree of re-crystallisation of fly ash is relatively high (Brown, Jones and BéruBé 2011) . Also the XRD semi-quantitative analysis indicated that fly ash contains 58% amorphous constituents, and it confirms that over 40% had been re-crystallized. Diffraction peaks show that it contains crystalline phases of hematite (Fe_2O_3), magnetite (Fe_3O_4), mullite ($3Al_2O_3.2SiO_2$) and quartz (crystalline SiO_2); XRD semi-quantitative analysis gives their proportions as 2.0%, 2.1%, 24.5% and 13.4% respectively. These crystalline minerals are not involved in pozzolanic reactions (Malhotra and Mehta 1996). Hence, they exist in XRD curves of all the hydrated samples that contain fly ash. The XRD curve of OPC indicates that it contains quartz, in addition to the main cement components alite (C_3S), belite (C_2S), aluminate (C_3A), ferrite (C_4AF), gypsum and portlandite [$Ca(OH)_2$].

The XRD curves of hydrated samples display the diffraction peaks of their respective raw materials. The intensities of certain peaks are similar to those of raw materials, while the intensities of some other peaks have increased or decreased over the time from 3 days to 112 days. In addition, the emergence of new peaks or formation of broad humps can be noticed in certain samples.

When describing XRD curves of APC, it would be appropriate to start from OPC and move to HVFA and finally to APC, because APC can be considered an extension of HVFA and OPC. Hence that order is followed here.

The OPC mixture R3 was obtained purely from OPC, hence the XRD curves of R3 contains all the peaks of OPC powder. In addition, emergence of a peak of portlandite can be noted. That is due to the $Ca(OH)_2$ released during the process of hydration of OPC. Moreover emergence of peaks for calcite [$CaCO_3$] can be noticed and they get intensified over the time. It is due to formation of $CaCO_3$ as a result of carbonation of $Ca(OH)_2$. Clear peaks of gypsum can be seen in OPC powder, but they cannot be seen in R3, which is the hydrated OPC. A new peak of ettringite can be noted in the XRD curve of 3 day sample (curve named R3A-3d), but it cannot be seen in the XRD curve of 28 day sample (curve named R3A-28d). Gypsum in OPC powder rapidly reacts with aluminate (C_3A) to produce ettringite, but when the gypsum concentration drops, ettringite becomes unstable and reacts with remaining C_3A and turns into monosulfate (Gani 1997) . This is the reason for the fading of the peak for gypsum and emergence of the peak for ettringite but its disappearance later. Another important feature that can be noted is the decrease of the diffraction peaks of cement components such as alite (C_3S) and belite (C_2S) with time, but the broadening of the base of those peaks with time, forming broad humps around 29.5^o and 32^o. That reflects the formation of C-S-H as a result of hydration processes of C_3S and C_2S. This is consistent with the observations of Aimin and Sarkar (1991). Elena and Lucia (2011) too have done XRD analysis of hydrated OPC paste over a period of 28 days and noticed a diminution of alite and belite but emergence of C-S-H as time passes.

The HVFA mixture C3 was obtained from OPC and fly ash; hence peaks of fly ash and OPC powder, as well as peaks of the hydrated OPC mixture R3, can be seen in the XRD curve of C3. The clear peaks due to quartz and mullite are from fly ash, and they remain the same over the period. Emergence of ettringite peaks cannot be seen, as in the case of the XRD curves of R3. Non-emergence of peaks of ettringite is consistent with the observations of Luxan, De Rojas and Frias (1989), who did XRD analysis on fly ash-calcium hydroxide systems. The reason is that the mixture C3 consists of only 30% of OPC, hence gypsum from OPC spreads over the mixture C3, thus reducing the concentration of sulphate ions. When the gypsum concentration is less, the reaction between C_3A and gypsum forms monosulphate instead of ettringite (Gani 1997). Another significant feature is the emergence of peaks due to portlandite in the 3 day curve (curve C3A-3d), and diminution of intensities over the time from 3 day to 112 days. The emergence of the peak is due to the release of $Ca(OH)_2$ during the hydration process of C_3S and C_2S, and the diminution of the intensity is because of the consumption of $Ca(OH)_2$ by fly ash and also due to carbonation of $Ca(OH)_2$. Carbonation is confirmed by the emergence of peaks of calcite [$CaCO_3$] over time. At the same time broadening of the peak around 29.5° and diffusion of the peaks of the alite and belite of OPC can be noted. This reflects formation of C-S-H due to pozzolanic reaction between fly ash and $Ca(OH)_2$, and due to hydration processes of C_3S and C_2S.

The APC mixture M3 was obtained by mixing fly ash, lime and OPC and adding a small quantity of Na_2SO_4. Hence diffraction peaks of those raw materials can be noted in the XRD curves of M3. In addition, emergence of ettringite peaks can be noted in the 3 day curve (curve named M3A-3d) but they disappeared thereafter. Both the mixtures C3 and M3 have only 30% of OPC; hence contribution of gypsum from OPC is not adequate to react with C_3A to produce ettringite. This is the reason for not having ettringite in C3 as described previously. However, in the case of the APC mixture M3, the activator Na_2SO_4 had been added to the mixture. Therefore, when APC mixture M3 is mixed with water, Na_2SO_4 in the mixture reacts with $Ca(OH)_2$ and produces NaOH and gypsum; hence the concentration of gypsum in the mixture increases. When the concentration of gypsum is increased, C_3A contributed from OPC reacts with gypsum to produce ettringite (Gani 1997). Moreover when the gypsum concentration is high, reactive silica and alumina in fly ash too react with gypsum and produce ettringite (Helmuth 1987). Accordingly, ettringite is produced by both the processes mentioned above in mixture M3, and it is reflected in 3 day XRD curve of M3 (curve named M3A-3d). However, when gypsum concentration drops, ettringite becomes unstable and turns into monosulfate (Gani 1997). This is the reason for not seeing ettringite in the XRD curves for 28 days and 112 days. Another significant feature that can be seen is the decrease of peaks due to portlandite [$Ca(OH)_2$] with time from 3 days to 112 days. The decrease of $Ca(OH)_2$ is due to consumption by fly ash to form C-S-H, and also due to carbonation of $Ca(OH)_2$. Carbonation is reflected by the emergence of peaks of calcite [$CaCO_3$] and its increase over time. Also the peaks of alite and belite have diffused forming a broad hump at a 2θ value around 32° indicating the formation of amorphous C-S-H. In addition, emergence of a broad hump at a 2θ value around 29° too can be noticed, indicating formation of C-S-H/C-A-S-H.

4.5.5 SEM/EDS Analysis

SEM and EDS analyses were done on fly ash, APC mixture M3, comparable HVFA mixture C3 and reference OPC mixture R3, at the ages of 3, 7 and 112 days. The main purpose of conducting SEM and EDS analysis is to examine the formation of C-S-H over fly ash particles, and also to get an idea about the nature of the microstructure. Therefore, for each image, magnifications were adjusted to see the fly ash particles clearly; hence, the images are of different magnifications. The SEM images and EDS graphs of fly ash, as well as mixtures M3, C3 and R3 are given in **Fig. 4.11 – Fig. 4.14** respectively. EDS analyses were done on the selected locations of the samples, and these selected locations are indicated by small circles in the images. The elements present at a given location give peaks in the EDS graphs (other than for hydrogen). Hence, EDS graphs can be used to confirm the compounds identified by visual inspection of SEM images. However, EDS analysis may pick up the surrounding elements as well; hence those have to be identified and ignored.

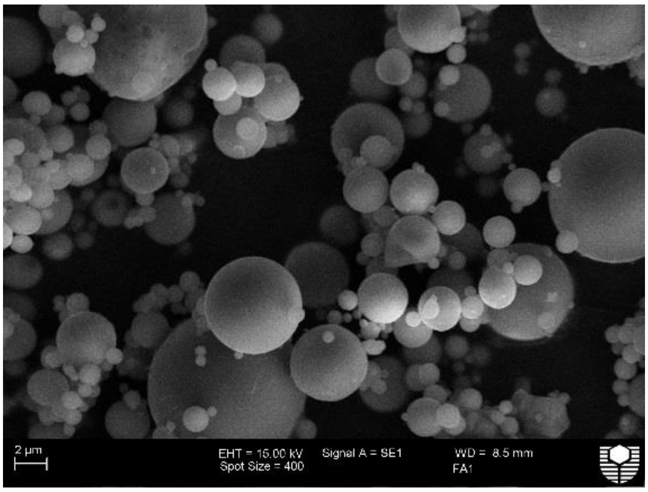
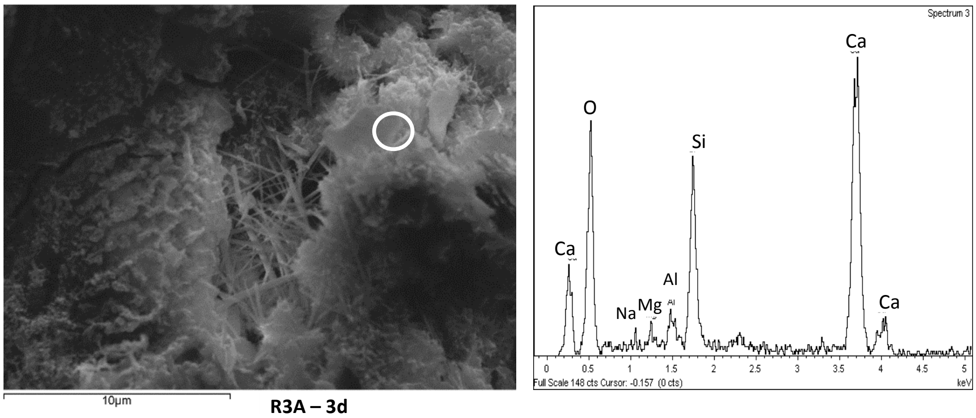


Fig. 4.11 SEM image of Fly Ash Particles

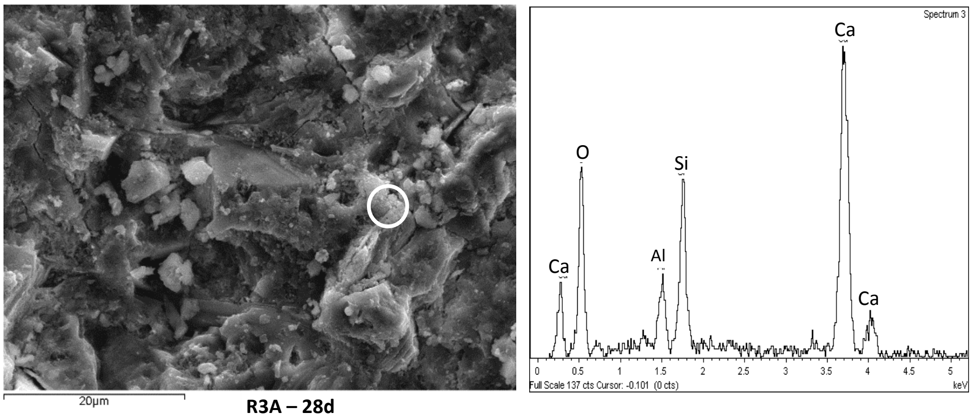
Fig. 4.11 gives an SEM image of fly ash particles. As seen in the SEM image, the size of the fly ash particles can vary within a wide range. The shapes of particles are spherical. The surfaces look very clean, and sulphates deposited on the surfaces of fly ash cannot be seen. Those features are consistent with the characteristics of low-calcium fly ash (or Class F) given by Malhotra and Mehta (1996).

When describing SEM and EDS analysis of APC, as in the case of XRD analysis, it would be appropriate to start from OPC, move to HVFA and finally to APC, because APC can be considered as an extension of OPC and HVFA. Hence that order is followed here.

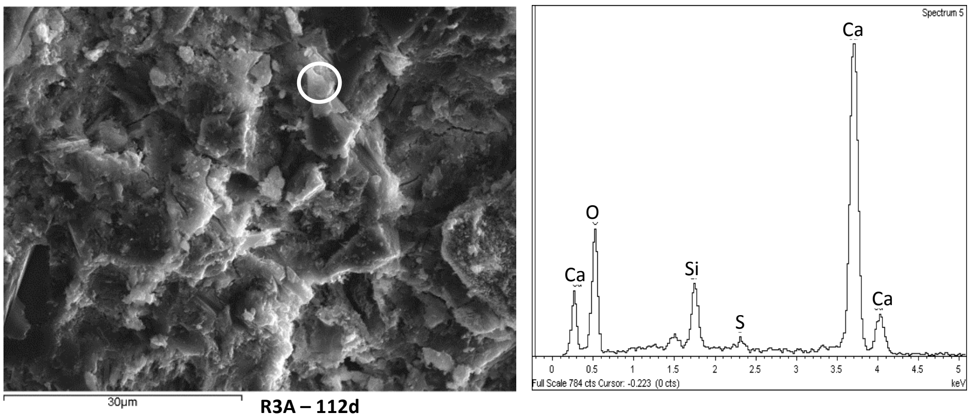
Fig. 4.12, 4.13 and **4.14** give the SEM images and EDS graphs of mixtures R3, C3 and M3, respectively, at the ages of 3, 7 and 112 days.



(a) R3A- 3 day SEM image & EDS graph

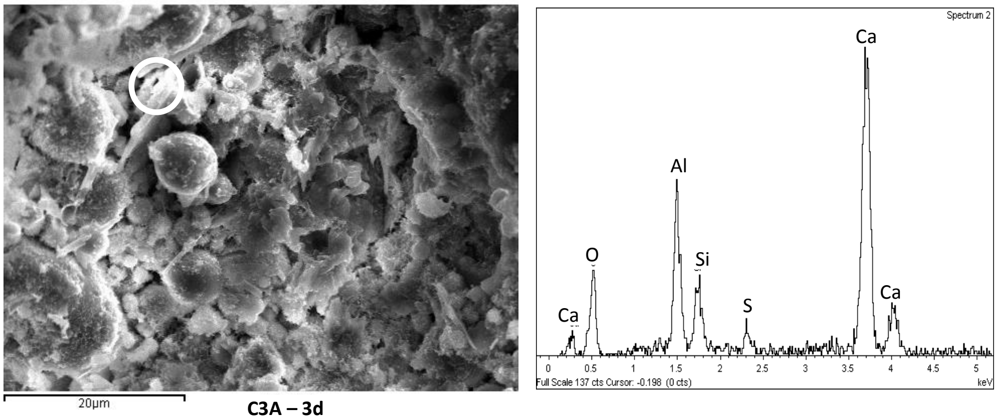


(b) R3A- 28 day SEM image & EDS graph

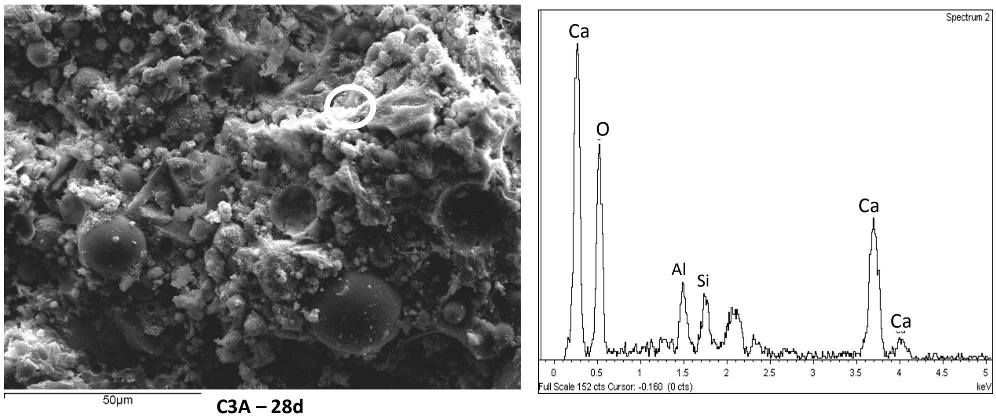


(c) R3A- 112 day SEM image & EDS graph

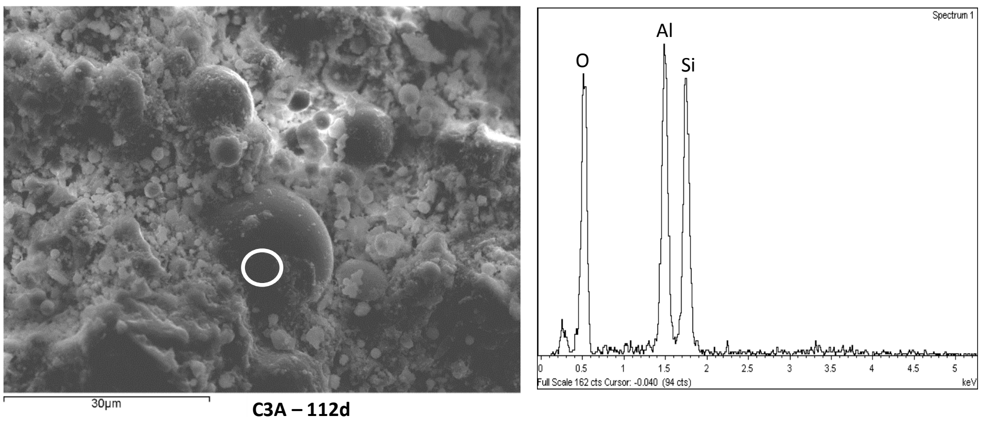
Fig. 4.12 SEM images and EDS graphs of OPC sample R3 cured at condition A



(a) C3A- 3 day SEM image & EDS graph

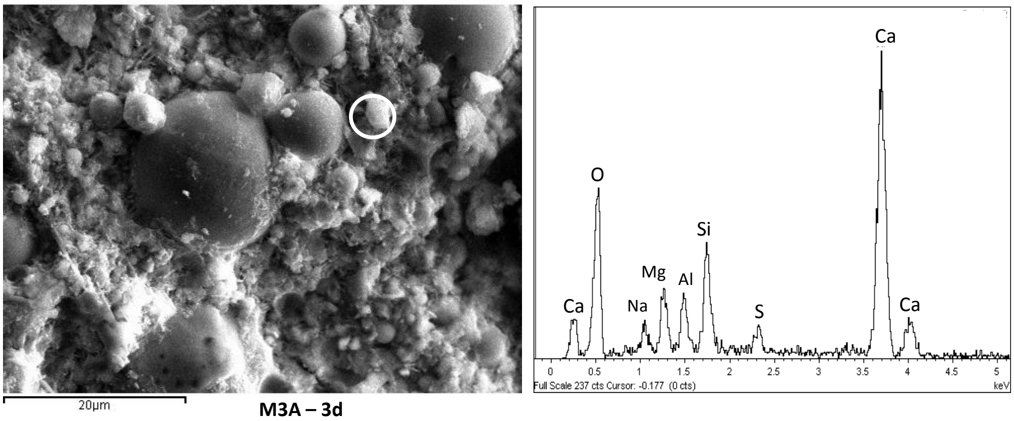


(b) C3A- 28 day SEM image & EDS graph

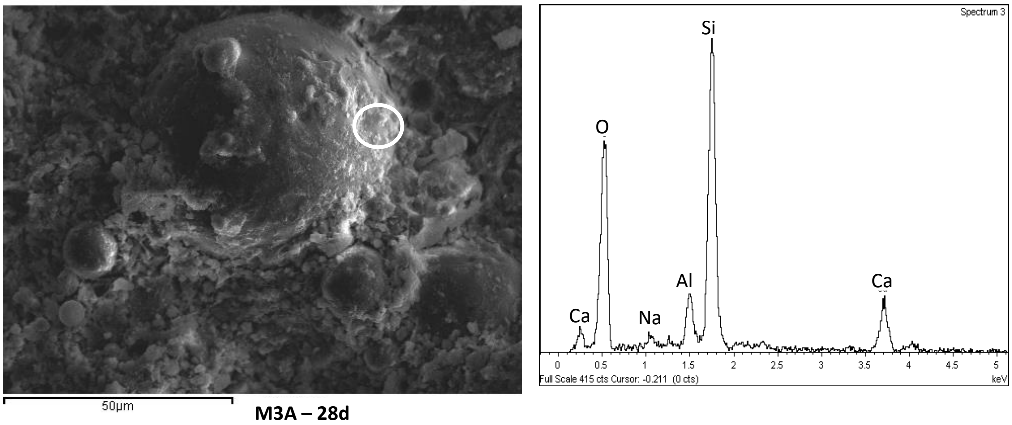


(b) C3A- 112 day SEM image & EDS graph

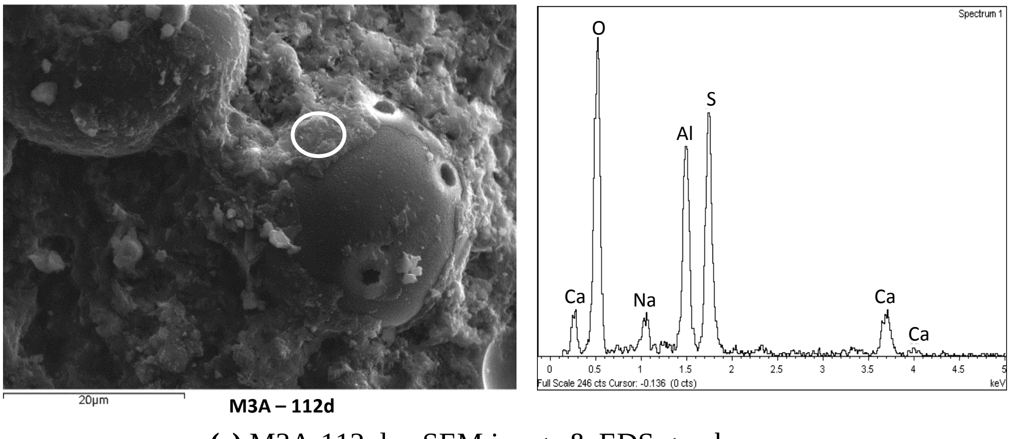
Fig. 4.13 SEM images and EDS graphs of HVFA sample C3 cured at condition A



(a) M3A-3 day SEM image & EDS graph



(b) M3A-28 day SEM image & EDS graph



(c) M3A-112 day SEM image & EDS graph

Fig. 4.14 SEM image and EDS graph of APC sample M3 cured at condition A

Fig. 4.12 shows the SEM images and EDS graphs of OPC mixture R3 at the ages of 3, 28 and 112 days. In the 3 day image needle-like structures and a cloud-like formation can be seen. According to the hydration mechanism of OPC, most probably the needle-like structure is ettringite. The cloud-like formation could be calcium hydroxide released during the hydration process and the C-S-H formed. The EDS graph confirms the formation of C-S-H through the prominent peaks for Ca, Si and O. In 28 day image C-S-H as well as $Ca(OH)_2$ released during the hydration process can be seen. It is a relatively denser and less porous structure. The 28-day image is not much different from 112-day image; it indicates that that most of the hydration has already been completed by 28 days. The EDS graph confirms that the formation was C-S-H.

The SEM images and EDS graphs of HVFA mixture C3 at the ages of 3, 28 and 112 days are shown in **Fig. 4.13**. In the 3-day image, unreacted fly ash as well as irregular shaped particles can be seen. The mixture C3 consists only of fly ash and OPC. As fly ash particles are spherical, the irregular shaped particles seen in the images may be alite and belite contributed from OPC. In the 28-day image, unreacted fly ash particles can be seen. In addition, a cloud-like formation can be seen; the EDS graph indicates that it could be calcium hydroxide, through the very prominent Ca and O peaks. Unreacted fly ash particles can be seen not only in 3-day and 28-images, but also in the 112-day image. This implies the need of an activator for pozzolanic reactions. The EDS graphs for 3 and 112 days indicate prominent peaks for Al, which were not present for the R3 mixture. This is because of the presence of fly ash in HVFA.

The SEM images and EDS graphs of APC mixture M3 cured at condition A, at the ages of 3, 28 and 112 days are shown in **Fig. 4.14**. The 3-day SEM image indicates that the reaction between fly ash and alkali had started - a web-like network had formed over the surface of the fly ash particles, and it reflects the formation of C-S-H gel over the surface of fly ash particles. Also the formation of a grape-cluster-like structure can be seen. The EDS graph indicates that they could be C-S-H. The image at 28 days is significantly different from the 3-day image. The surfaces of fly ash particles are not smooth, and are partly covered by web-like network structures indicating that the reaction between fly ash and alkali has progressed. The EDS graph also indicates that the network structure could be C-S-H. The 112-day SEM image indicates following significant features. It can be clearly seen that there are holes on the surface of fly ash particles. These holes indicate that the fly ash particles were 'eaten up' by alkali, and the pozzolanic reaction has progressed significantly. According to the EDS graph, the cloud-like formation over the fly ash particle may be both C-S-H and C-A-S-H, because of the significant peak for Al, in addition to those for Ca, Si and O.

When SEM images across the mixtures are compared the following can be noticed. When 3-day images are considered, it is seen that C-S-H/C-A-S-H formation over fly ash particles in APC mixture M3 is more than that of HVFA mixture C3. The reason is that pozzolanic reaction in M3 had been activated by Na_2SO_4, but not in mixture C3. However, C-S-H formation in OPC mixture R3 is greater than both APC and HVFA samples. In addition, needle-like ettringite can be seen only in OPC mixture R3, but it cannot be seen in APC and HVFA mixtures. When 28 day and 112 day images are considered, C-S-H/ C-A-S-H formation is greater in APC mixture M3 than in HVFA mixture C3. However the densest structure (only C-S-H) is seen in OPC mixture R3.

4.5.6 Thermal Analysis

Thermo Gravimetric Analysis (TGA), Differential Scanning Calorimeter (DSC), and Differential Thermal Analysis (DTA) were done for selected air cured samples. The samples of APC mixture M3, comparable HVFA mixture C3; and reference OPC mixture R3 were analysed at 3, 28 and 112 days, while samples of L3 and N3 were analysed at 28 days only. For the thermal analysis, the heating rate used was 10°C per minute, and nitrogen flow rate used was 40 ml per minute. During the heating process, the samples undergo different transitions. These transitions can be viewed through different perspectives, namely as chemical changes, physical changes and structural changes; these changes are inter-related. The main chemical changes are desorption of free water, dehydration of hydrated products, dehydroxylation of $Ca(OH)_2$ and decarbonation of $CaCO_3$. These transitions lead to weight losses; hence they can be easily identified by TG-DTG Analysis. Whenever a chemical change happens it leads to a structural change, but the reverse is not always true. Structural changes can happen even without chemical changes due to phase changes as a result of melting and crystallisation. Such structural changes are not reflected as weight changes; hence, those changes cannot be detected by weight loss curves (TG-DTG curves). However, they can be detected by heat/temperature flow curves (DTA and DSC curves). Because of that, in addition to TG-DTG analysis, DTA as well as DSC analyses were performed. Following sections present interpretations of the TG-DTG, DTA and DSC analyses.

4.5.6.1 TG-DTG Analysis

As mentioned in Section 4.3.2.3, TG curves give the weight changes of samples due to heating, while DTG curves give the rate of change of weight (or the first derivative of the TG curve); hence using these curves, weight losses due to transitions can be computed. Different researchers have used different methods to calculate weight losses due to desorption, dehydration, dehydroxylation and decarbonation. Marsh and Day (1988) presented a graphical method to compute the weight loss due to dehydroxylation. The method involves drawing tangents and extensions to the edges of the relevant slopes of TG curves and measuring the vertical differences. Chang and Chen (2006) graphically projected the base points of DTG peaks on to TG curves, and the vertical difference was taken as the relevant weight loss. However, when the TG-DTG curves of this research were examined, it was seen that some of slopes in the TG curves did not have clear starting points and end points or edges. Hence the above mentioned graphical methods could not be adopted. So it was decided to divide the TG curve into separate segments to reflect the above four transitions, and calculate the weight losses. Different researchers have suggested slightly different temperature ranges for transitions, considering the shapes of their TG curves. The ranges defined by El-Jazairi and Illston (1977) for dehydration, dehydroxylation and decarbonation were 105 - 440 °C, 440 - 580 °C and 580 – 1007 °C respectively. Vedalakshmi et al. (2003) identified different zones; they have taken ranges from 100 - 300 °C for dehydration of C-S-H and ettringite, 300 - 350 °C for decomposition of calcium aluminate silicate hydrate, calcium aluminate hydrate and calcium chloroaluminate and 450 - 510 °C for dehydration of $Ca(OH)_2$. Ukrainczyk et al. (2006) suggested ranges from 25 – 100 °C for desorption, 100 - 300 °C for dehydration and 430 - 460 °C for dehydroxylation. The above information from the literature implies that it is a common practice to select ranges based on the nature of the curves obtained. Accordingly, by considering all the TG-DTG curves of this research, the following temperature ranges were decided on to compute weight losses.

30 - 105 °C : Desorption

105 - 420 °C : Dehydration

420 - 550 °C : Dehydroxylation

550 – 1007 °C : Decarbonation

The above temperature ranges are as same as the ranges considered by El-Jazairi and Illston (1977) , except for the boundary between dehydration and dehydroxylation. El-Jazairi and Illston (1977) considered it as 440°C, whereas the value taken in this research was 420 °C. The reason for deviating from 440 °C is that this temperature occurs in the middle of the TG slopes in this research (See the TGA graph shown in **Fig. 4.15**). It is assumed that ignition occurs at 1007 °C. Hence weight losses after ignition point not considered. Computation of weight losses based on TG-DTG curves is demonstrated in **Fig. 4.15**. All the TG curves of the samples considered are given in **Appendix A1.2**.

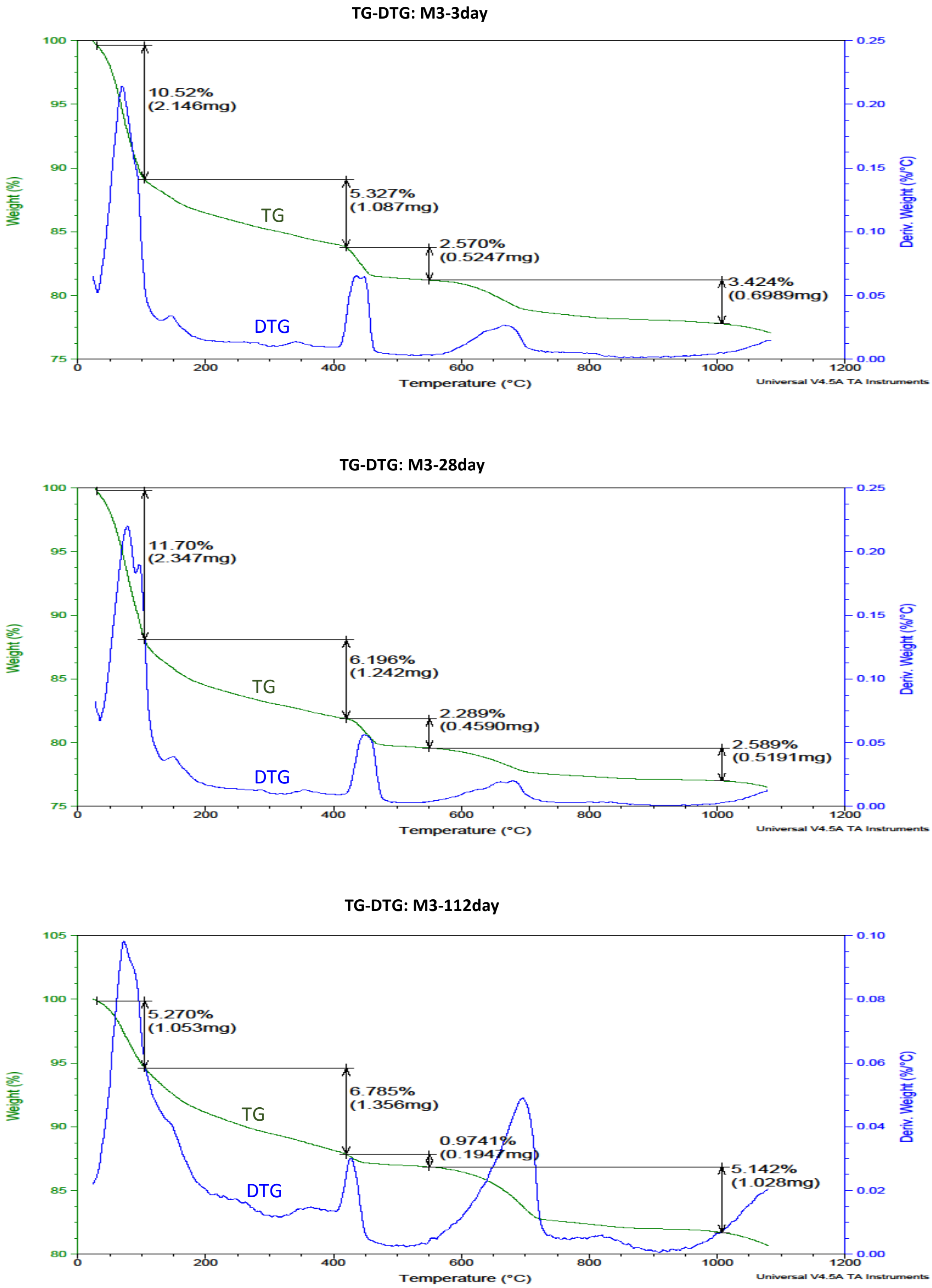


Fig. 4.15 TG-DTG graphs for APC Mixture M3 at 3, 28 and 112 days.

As described previously the range decided for desorption was 30 - 105 °C. Hence, it was assumed that the free water in the sample gets completely removed from the sample by 105 °C. Therefore, weight of the sample at 105 °C can be considered as the weight of a 'dry sample'. Weight losses due to dehydration, dehydroxylation, decarbonation as well as desorption were presented as a percentages based on the weight of dry samples (specimen calculations are given in **Appendix A1**). The results are given in **Table 4.5**. Using these values strength versus hydrate-bound water relationship (covering specimens of all types and ages) was plotted as given in **Fig. 4.16**.

Table 4.5 Loss of Weight at Different Temperature Ranges

Mix	Age	Loss of Weight at different Temp Ranges (%)				Max
	days	30 - 105 Desorption dm_V	105-420 Dehydration dm_{CSH}	420-550 Dehydroxylation dm_{CH}	550-1007 Decarbonation dm_{CC}	Strength
M3	3	11.757	5.953	2.872	3.827	23.8
	28	13.250	7.017	2.592	2.932	47.1
	112	5.563	7.162	1.028	5.428	64.0
C3	3	8.077	4.117	1.163	2.254	16.7
	28	7.733	4.892	1.104	1.226	27.8
	112	2.278	3.726	0.790	5.256	28.0
R3	3	4.050	7.884	2.394	4.405	51.8
	28	3.132	7.876	2.047	4.470	72.8
	112	5.490	8.629	2.891	2.683	65.7
M4	28	14.837	8.172	2.573	2.302	32.0
L3	28	14.837	8.429	3.819	2.390	52.6
N3	28	12.638	6.135	1.245	2.238	48.5

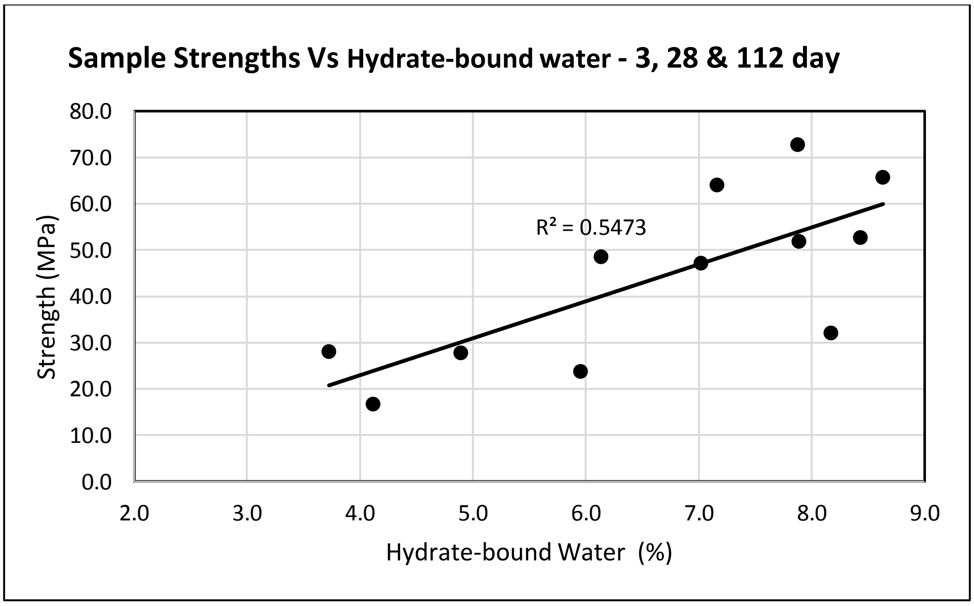
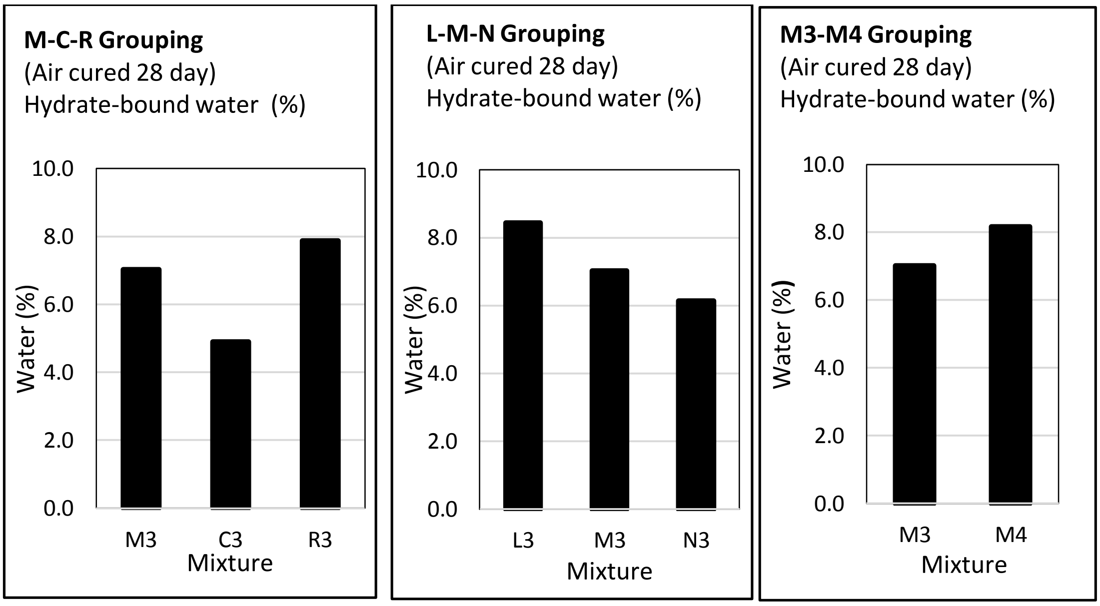


Fig. 4.16 Hydrate-bound Water Vs Strengths

In **Fig 4.16**, a 'trend line' was generated, and the 'coefficient of determination', which is normally denoted as $\mathbf{R^2}$, was computed to get an idea how well data points fit into the trend line. For above values, $\mathbf{R^2}$ is 0.5473, and indicates a reasonably clear correlation between hydrate-bound water and strength. Accordingly, it can be concluded that higher hydrate-bound water reflects a higher strength. This tallies with 'cement chemistry' as the weight loss in the region 105 – 420 °C is due to dehydration of hydrated products, mainly due dehydration of C-S-H, which is considered to be the main contributor to the strength of cementitious systems.



(a) **(b)** **(c)**

Fig. 4.17 Hydrate-bound Water (%) of Air Cured Samples at 28 days

Fig. 4.17 illustrates variations in hydrate-bound water for 28 day old air cured samples. The hydrate-bound water is a rough estimate of the C-S-H present in samples; C-S-H present in a samples is a rough measure of strength. When the mixtures M3, C3 and R3 are considered, it is seen that APC mixture M3 had a higher quantity of C-S-H than that of HVFA mixture C3, but a lesser quantity than OPC mixture R3. These results tally well with strength results, where APC had higher strength than HVFA, but lower strength than OPC. When APC mixtures are compared, the order of increasing C-S-H quantity is L3, M3 and N3 which again confirms the order of strengths. The mixtures in the M-C-R grouping as well as in the L-M-N grouping had w/c=0.3. However, in the third grouping, proportions of the constituent materials are same in mixtures M3 and

M4, except that the w/c ratio of M3 is 0.3, while that of M4 is 0.4. In **Fig. 4.17 (c)**, the C-S-H in M4 is greater than that of M3. However, the strength of M4 is significantly less than that of M3. It seems that the higher water cement ratio might have facilitate the reaction between lime and fly ash and improved the formation of C-S-H, but with an increase of porosity as well. Because of that even though M4 has a greater quantity of C-S-H than M3, its strength is less than M3.

Hydrate-bound Water

Fig. 4.18, shows 'hydrate-bound water' for 3, 28 day and 112 day old samples of M3, C3 and R3. As described before 'hydrate-bound water' is a rough measure of C-S-H present in sample.

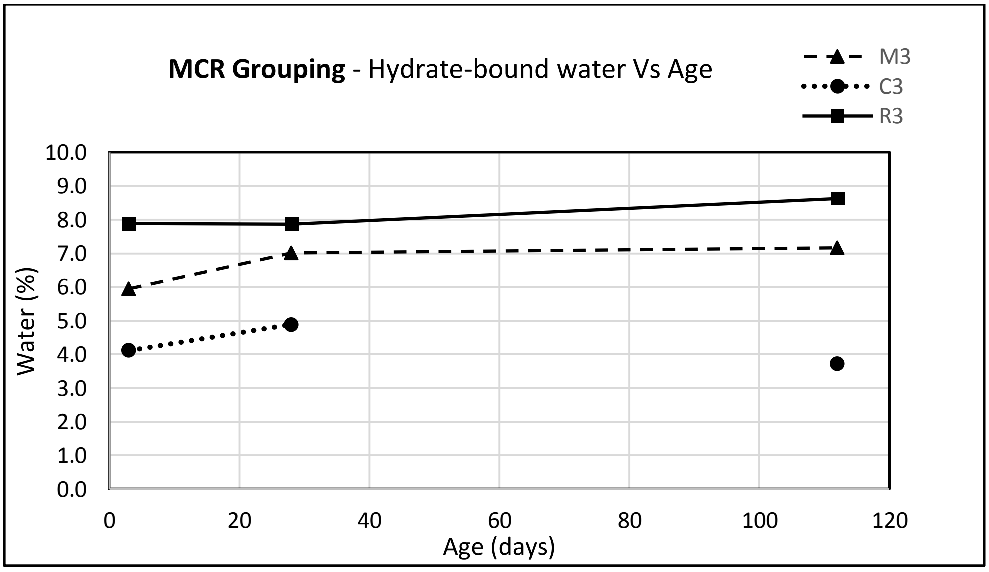


Fig. 4.18 Hydrate-bound water of M3, C3 and R3 at different ages

As expected, the quantity of 'hydrate-bound water' increased with age from 3 to 112 days in the mixtures of M3 and R3, indicating increase of formation of C-S-H over time. In the mixture C3, the quantity of 'hydrate-bound water' increased from 3 to 28 days, but the value at 112 days was less than that of 28 days. This may be due to reasons given by Pane and Hansen (2005). They mentioned that even though free water starts to boils at 100 °C, it would completely turn to gas only at 140 °C. However, the weight loss from 105 – 420 °C was taken as 'hydrate-bound water' in developing the graph shown in **Fig. 4.18**. Hence, part of it may be 'free water' that has been turned in to gas after 105 °C. Therefore, the quantities shown as 'hydrate-bound water' may be greater than the actual quantities of ‘hydrate-bound water’. This inaccuracy is applicable to all three mixtures M3, C3 and R3. However, in the cases of R3, which is the OPC mixture and in M3, which is the APC mixture, the added water would quickly get involved in chemical process; hence, the quantities of ‘free water’ that remain after 105 °C would be less. In the case of C3, which is a HVFA mixture, the pozzolanic reaction takes a fairly a long time; hence, ‘free water’ would be available in the sample over a long period of time. Hence the quantities of free-water that remain after 105 °C would be more. Therefore, the inaccuracy will be greater in C3, especially during early ages, than in the cases of R3 and M3. This may be the reason for showing higher values as ‘hydrate-bound water’ at 3 and 28 days. Actually part of it is free-water that has not been turned to gas by 105 °C. However, by the age of 112 days, major part of free-water were either involved in chemical process or evaporated, hence the inaccuracy becomes less. As a result of the above reasons, the ultimate picture of C3 shows as a drop from 28 days to 112 days. A similar drop from 28 days to 100 days had been experienced in an OPC-fly ash blended sample (20 MPa grade) by Vedalakshmi et al. (2003) as well. It should also be noted that ettringite can exist in 3 and 28 day samples; in such cases ‘hydrate-bound water’ not only includes ‘C-S-H bound water’ but also ettringite-bound water. This is confirmed by DTG and DTA analysis which is given below. In conclusion, it can be said that the APC mixture M3 which is the focus of interest in this research, and the OPC mixture R3, which is the reference mixture, indicate increase in ‘hydrate-bound water’ denoting an increase of C-S-H over time.

$Ca(OH)_2$ - bound Water Vs Age

Fig. 4.19, shows weight losses due to release of $Ca(OH)_2$ bound water for 3, 28 day and 112 day old samples of M3, C3 and R3. In the case of M3, weight loss due to dehydroxylation decreased significantly from 3 days to 112 days. This indicates the consumption of $Ca(OH)_2$ in the process of forming C-S-H through lime-fly ash reactions. In mixture C3, there is no added lime, and hence the $Ca(OH)_2$ present in the mixture is less, being only the $Ca(OH)_2$ released from OPC during the hydration process. However $Ca(OH)_2$ released from OPC reacts with fly ash; hence, the quantity of $Ca(OH)_2$ decreases, and this is reflected in **Fig. 4.19**. In R3, which is 100% OPC, during the hydration process $Ca(OH)_2$ is released, but there is no fly ash to react with, and hence the quantity of $Ca(OH)_2$ increases with time as seen in the graph.

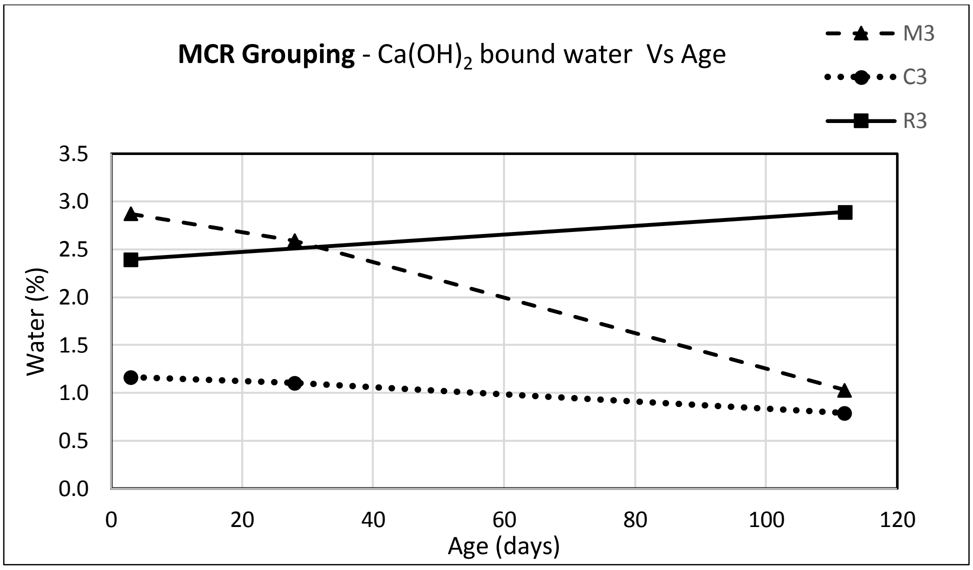


Fig. 4.19 $Ca(OH)_2$ bound water of M3, C3 and R3 at different ages

<u>$CaCO_3$ - bound CO_2 Vs Age</u>

Generally, it is considered that after dehydroxylation of $Ca(OH)_2$, decarbonation of $CaCO_3$ occurs during thermal analysis. However, in addition to $CaCO_3$, there can be other carbonated phases as well, and they too get decarbonated. Further 'structural OH^- groups' from C-S-H gel too contribute for weight loss in the same temperature range. Hence CO_2 released from $CaCO_3$ cannot be calculated accurately (Gabrovšek, Vuk and Kaučič 2006) . Because of this $CaCO_3$ bound CO_2 was not considered here.

<u>DTG curves</u>

DTG curves are the first derivatives of the TG curves. They are shown with TG curves and are given in **Appendix A1.2**. In all the DTG graphs there are prominent peaks around 100 °C, 450 °C and 700 °C, which reflect the weight losses due to desorption, dehydroxylation and decarbonation. Dehydration of hydrated products is not reflected by a prominent peak, as it does not occur at a particular temperature but throughout the range of 105 - 420 °C. However, the literature indicates that the peak due to desorption of free water overlaps with the small peak due to dehydration of ettringite, which also occurs around 100°C. Moreover, iron-substitute ettringite (AFt phase) and iron-substituted monosulphate (AFm phase) give peaks around 165 °C (Knapen et al. 2009; Sha, O'Neill and Guo 1999) . The 3-day and 28-day curves of C3 show that there is peak around 165 °C, but it disappears in the 112-day curve (**Fig. 4.20**). This indicates the presence of ettringite in 3 and 28 day samples of C3. Another feature that can be observed is a small peak around 325-350 °C, which can be seen in DTG curves of all APC curves (M3, M4, L3 and N3) and in the OPC curve R3 [**Appendix A1.2**]. According to the literature these peaks could reflect the C-S-H phase or C_3AH_6 (Bradbury, Callaway and Double 1976; Fordham and Smalley 1985) .

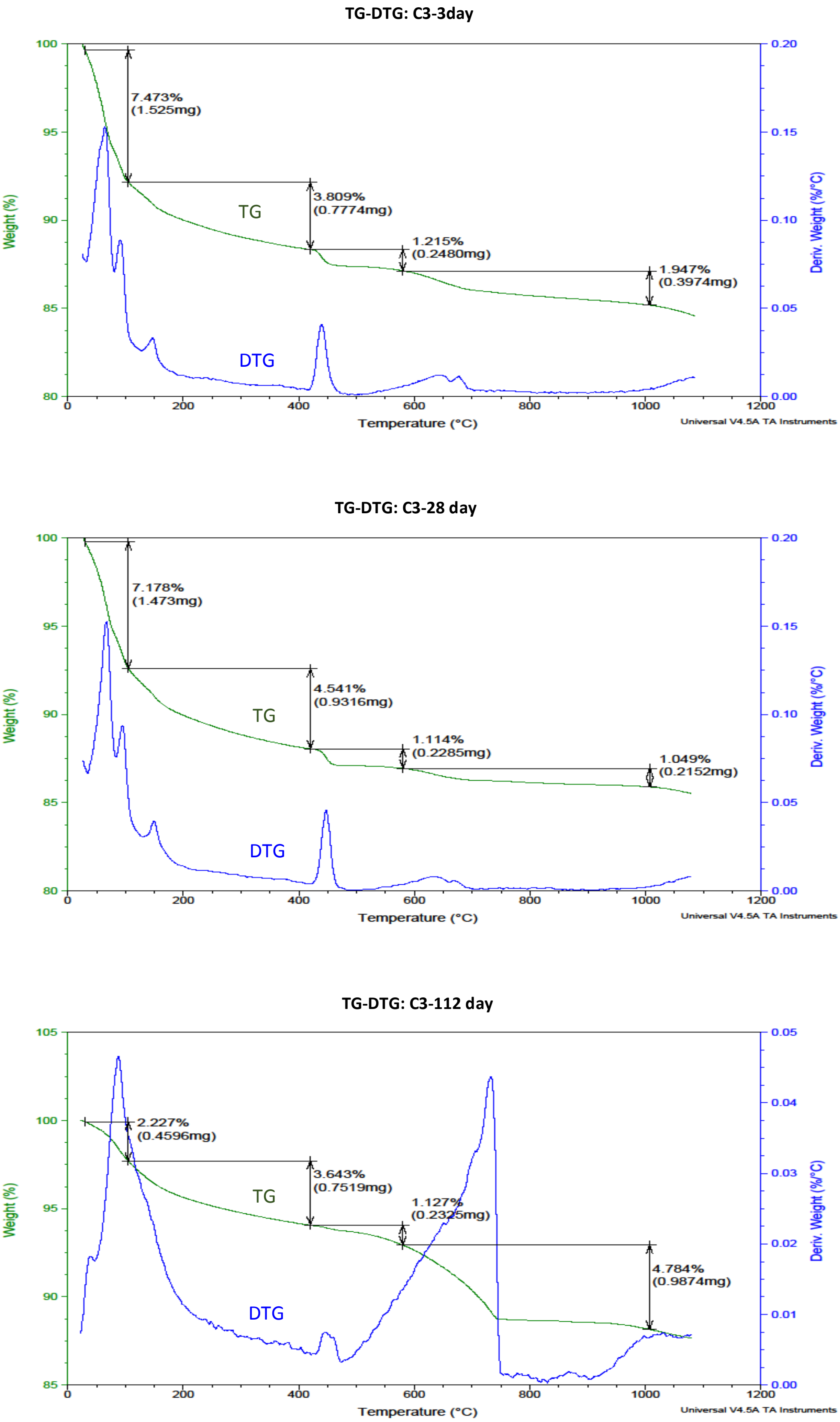


Fig. 4.20 TG-DTG curves of HVFA mixture C3

4.5.6.2 DTA Analysis

DTA curves indicate the temperature difference between sample and reference during the process. The curves of the samples considered are given in **Appendix A1.3**. In all the DTA graphs endothermic peaks around 100 °C and 450 °C (which reflect desorption and dehydroxylation) can be noted. As shown in **Fig. 4.21**, in 3 day and 28 DTA graphs of C3 a small peak around 165°C can be noticed, and based on the literature it can be confirmed as 'iron-substitute ettringite' (that is AFt phase) (Sha and Pereira 2001b) . No exothermal peaks are noticed in any of the DTA curves, which indicates the absence of crystalline phases of hydrated products. This confirms the reason for not having crystalline peaks for hydrated products in the XRD curves in Fig. 4.10.

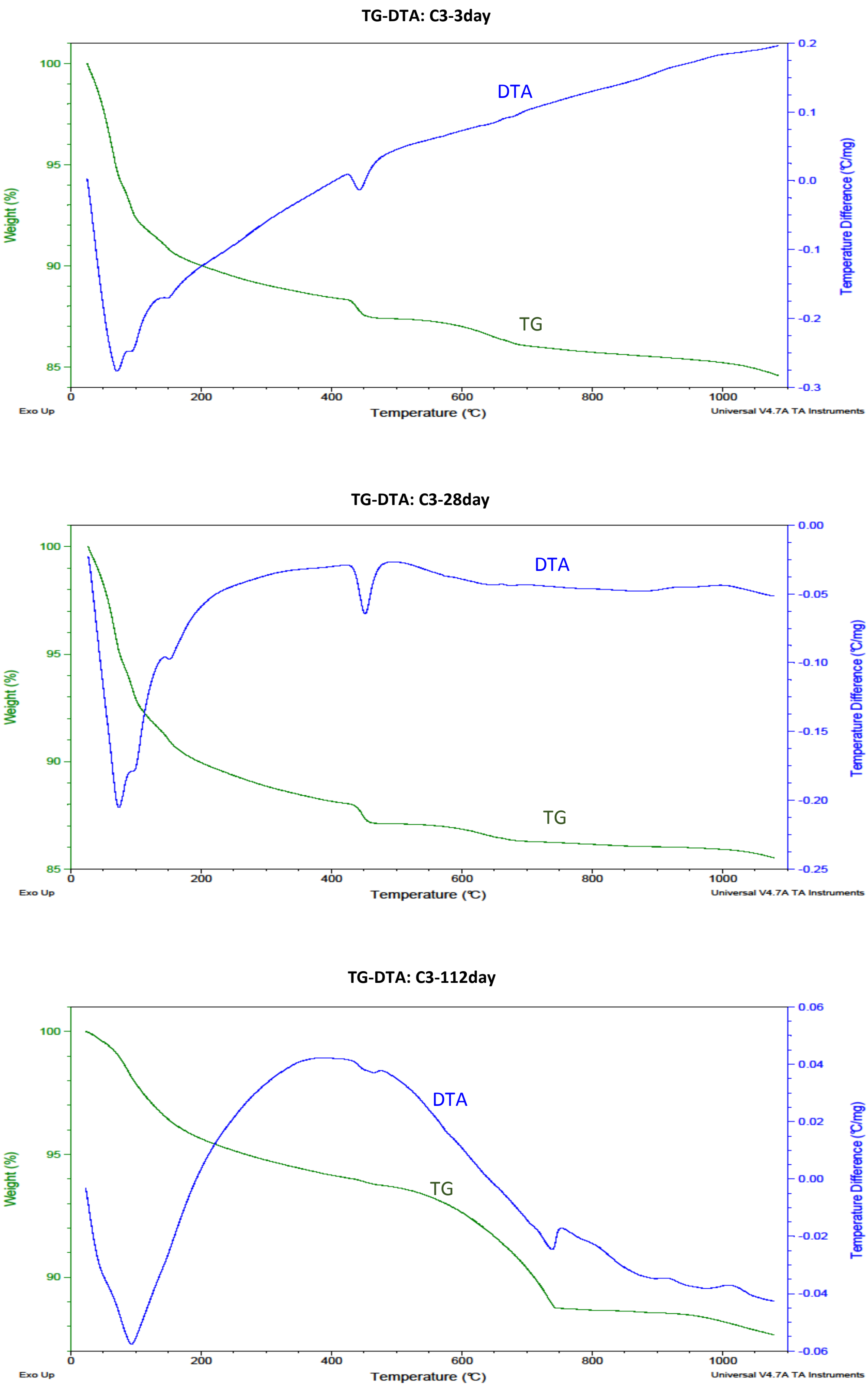


Fig. 4.21 TG-DTA curves of HVFA mixture C3

4.5.6.3 DSC Analysis

DSC curves indicate the heat flow between sample and reference during the process. The curves of the samples considered are given in **Appendix A1.4**. In all the DSC graphs, endothermic peaks around 100 °C and 450 °C (which reflect desorption and dehydroxylation) can be noted. As most of the DSC graphs were plotted only up to 600 °C, the peak for carbonation lies outside the range. A significant feature is the double sub peaks around 100 °C for desorption in 3 and 28 day DSC curves. In 112 day curves, the first sub peak disappears. As an example, the DSC curves for M3 are given in **Fig. 4.22**. A similar pattern was observed by other researchers as well, indicating that the early age samples contain two types of molecular water (Sha, O'Neill and Guo 1999). Accordingly, the first sub-peak reflects free-water, and the second sub-peak reflects C-S-H and ettringite bound water.

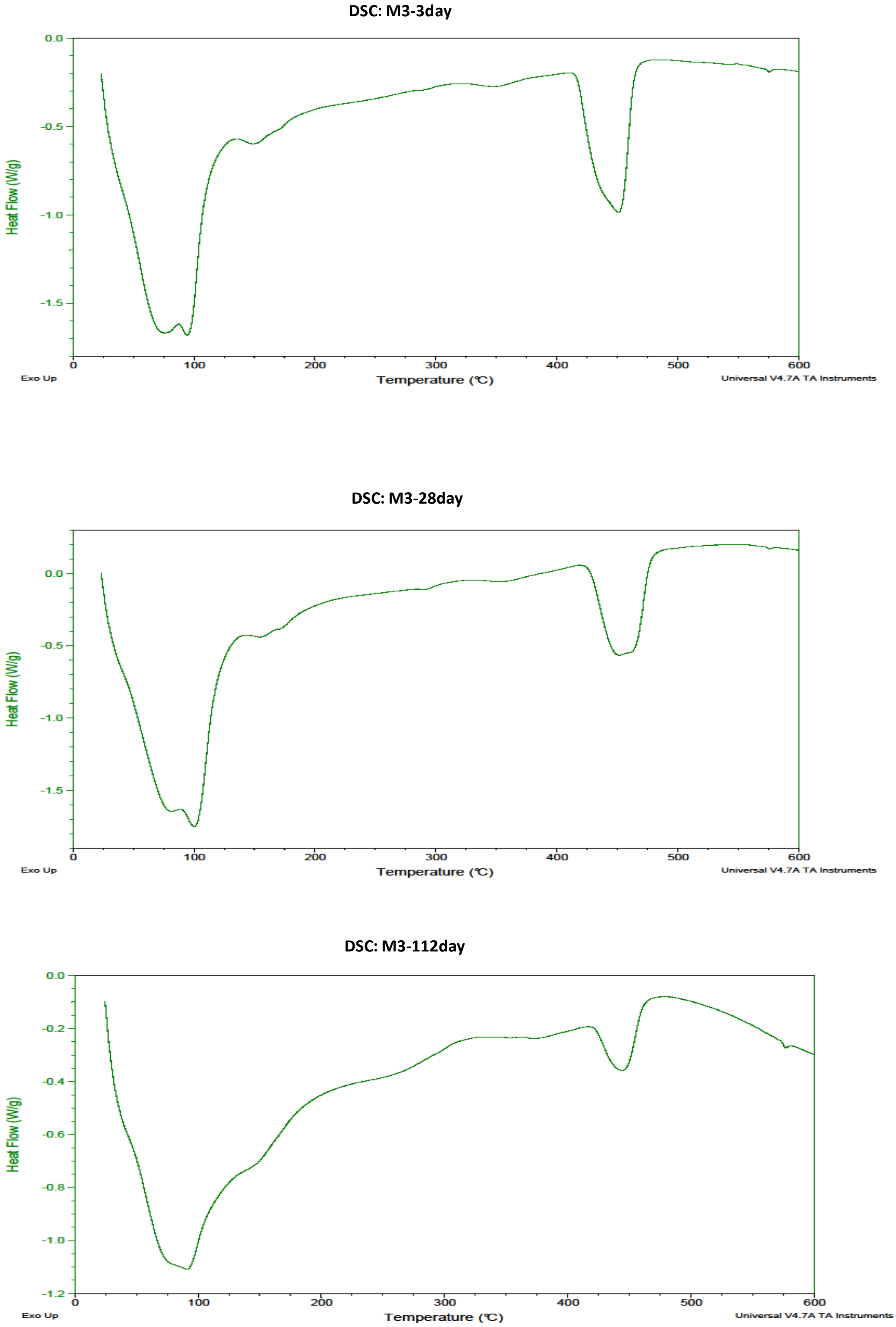


Fig. 4.22 DSC curves of APC mixture M3

4.6 Conclusions

As mentioned in the introduction, this chapter presented the second stage of the research, which was formulated based on the findings of first stage. Accordingly, APC mixtures derived from different pozzolanic materials, namely, fly ash and slag, in different proportions, were mixed with different w/c ratios of 0.3 and 0.4, and their structural and microstructural properties were experimentally investigated. The main focus of interest is APC mixture M, the composition of which can be expressed as 70% (95% APC70 + 5% Na_2SO_4) + 30% OPC; where APC70 is a mixture having 70% fly ash and 30% lime. Based on the experimental results and analyses presented in this chapter the following conclusions can be drawn:

1. The initial setting time and final setting time of the APC mixture M is close to those of the reference OPC mixture, the difference being only about 10%.

2. APC does not require elevated-temperature curing even though it contains a significantly high volume of pozzolan; it does not require water curing to gain strength. In fact, APC performs better under air curing, which is its main advantage.

3. In general, under air-curing conditions, the 28-day strength of APC mixtures are over 85% higher than that of HVFA mixtures. This confirms the suitability of APC over HVFA when compressive strength is considered. The APC mixtures also achieve around 75% of the strength of corresponding OPC mixtures.

4. APC mixtures derived from slag gave higher strengths than those derived from fly ash. One reason for this is that slag contains 32.6% CaO, while fly ash contains only 1.6% of CaO. This implies the possibility of improving strength of APC by using high-CaO pozzolans such as slag or high calcium fly ash (Class C fly ash). The other reason for the greater strength is that slag contains more amorphous silica than fly ash, as reflected in XRD curves.

5. Strength increased somewhat from APC60 to APC80 through APC70, and this was reflected in the hydrate-bound water quantities obtained from thermal analysis too.

6. The HVFA mixes showed the greatest sensitivity to changes in w/c ratio, while APC and OPC mixes were less sensitive. The w/c = 0.4 mixes were more sensitive to changes in curing, while the HVFA mixes were improved by heat curing.

7. XRD curves of hydrated samples showed the formation of C-S-H by 'broad humps' at the relevant 2θ values (around 29° and 32°). XRD curves of APC samples very clearly indicated that these broad humps become more pronounced with time (with a reduction of the alite and belite peaks and an increase in the portlandite peak), implying that the formation of C-S-H (and C-A-S-H) continues over a long duration up to 112 days, both through the direct hydration of OPC constituents C_3S and C_2S, and through the reaction of $Ca(OH)_2$ with the fly ash.

8. SEM images of APC samples indicate that fly ash particles were smooth and clear at early ages, but were 'eaten up' by $Ca(OH)_2$ to form C-S-H over time. This too confirms that the hydration process of APC continues over a long period of time. The presence of the element Al in the EDS graphs, in addition to the elements Ca, Si and O, indicate that the hydration of APC samples produces C-A-S-H in addition to C-S-H.

9. Thermal Analysis confirmed the findings of XRD and SEM analysis on the continuation of hydration processes in APC over a long period of time. DTA and DSC curves do not reflect crystallization of hydrated products.

10. It was possible to find a reasonably good general correlation between hydrate bound water and compressive strength, whatever the mix type or age.

11. Overall, it can be concluded that APC is a reasonably good alternative to OPC that does not need water curing, and that its compressive strength is much higher than that of the HVFA tested (incorporating a similar percentage of OPC).

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5 Durability Properties of Alkali Pozzolan Cement (APC)

Overview

This chapter compares the comparison of durability properties of different Alkali Pozzolan Cement (APC) mixtures with High Volume Fly Ash (HVFA) cement and Ordinary Portland Cement (OPC) ones. Hence, this chapter can be considered as an extension of Chapter 4, which presented the structural and microstructural properties of those mixtures. First, the 'susceptibility to durability issues' was investigated through the water absorption test using relatively young samples; later, 'durability issues due to chemical attacks' were investigated through sulphuric acid attack, chloride ion penetration and carbonation using mature samples. The results indicate that APC has greater resistance than HVFA for water absorption, carbonation and chloride ion penetration, but not for sulphuric acid attack. However, sulphuric acid resistance of APC is better than that of OPC.

***Keywords**: durability properties, water absorption, acid attack, chloride ion penetration, carbonation*

5.1 Introduction

As mentioned previously, in this research, an alternative cement called 'Alkali Pozzolan Cement' (APC) was developed through a number of stages. In the first stage, constituent materials and their proportions to achieve practical APC mixtures were investigated, and they were presented in Chapter 3. In the second stage, structural and microstructural properties of different practical APC mixtures were explored, and they were presented in Chapter 4. In the third stage, the durability properties of different practical APC mixtures were examined and they are presented in this chapter.

The main cause for durability problems of hydrated cement is due to interaction with chemicals. Three such chemical interactions are carbonation, acid attack and chloride ion penetration. When hydrated cement components such as concrete and mortar are exposed to the natural environment, the atmospheric CO_2 gets into contact with concrete/mortar, leading to carbonation of hydrated products. Acid attack occurs when concrete/mortar gets exposed to acidic environments. For example, sewerage systems are constantly exposed to acidic environments, as digestion in sewers creates hydrogen sulfide, which eventually produces sulphuric acid after reacting with water. In addition, concrete/mortar can also get exposed to rain, fog, snow, water or soil which can be acidic. Such environments become acidic through the influence of sulphuric and nitric acid produced by emissions of sulpher dioxide and nitrogen oxide as result of fossil fuel combustion, wildfires, volcanoes and electric discharges of lightning processes. Chloride ion penetration can occur when concrete/mortar gets into contact with saline water, soil or air. Carbonation and chloride ion penetration increase the potential for corrosion of steel embedded in concrete – most concrete applications in practice (e.g. reinforced and prestressed concrete) involve embedded steel; and corrosion is the biggest durability problem for concrete structures. Acid attack affects the concrete itself. Hence, when exploring durability properties of a cement, it would be useful to investigate resistance to carbonation, acid attack and chloride ion penetration. In addition to these three chemical tests, water absorption is another important property that gives an indication about porosity, which reflects the penetrability of chemical gases and liquids into cementitious products. This chapter presents experimental procedures and results of water absorption, carbonation, acid attack and chloride ion penetration for samples made of APC mixtures along with those made of HVFA and OPC ones.

5.2 Aim and Objectives

The main aim of this chapter is to present the results of investigations on durability properties of different APC mixtures, comparable HVFA mixtures and reference OPC mixtures. This main aim was divided in to two sub aims. The first sub-aim is to investigate the ‘susceptibility to durability issues’ and the second sub-aim is to investigate the ‘durability issues due to chemical attacks’. It was decided to investigate the ‘susceptibility to durability issues’ through water absorption testing using relatively young samples because young samples would accentuate the differences between mixes and ‘durability issues due to chemical attacks’ using mature samples because year old samples may be more representative of service conditions. Accordingly, after the literature review that gives background information on durability properties of hydrated cements, the following objectives were formulated:

1. To determine water absorption of relatively young (28 day old) specimens.
2. To investigate the effect of sulphuric acid attack on the weight of mature (1 year old) specimens.
3. To investigate sodium chloride ion penetration depth of mature (1 year old) specimens.
4. To investigate carbonation depth of mature (1 year old) specimens.

Experimental methods were adopted to achieve the above objectives.

5.3 Literature Review on Durability Tests

It is seen that, the terms such as sorption, absorption and adsorption are commonly used inter-changeably. However, these terms are used with specific meanings in the literature related to durability properties of hydrated cement. Hence, in this thesis, these terms are used with the specific meanings which are describe below (General Chemistry Online Glossary).

The term 'adsorption' refers to the adhesion of atoms, molecules or ions by the external surface or capillaries/crevices of the external surface, and is a surface phenomenon; the term 'absorption' refers to penetration of atoms, molecules or ions into the interior of the sample, and is a physical or chemical phenomenon. The term 'ion exchange' is used to describe an exchange of ions between two electrolytes or between an electrolyte solution and a complex. The term 'sorption' is a general term that covers adsorption, absorption and ion exchange. Diffusion is the movement of atom, molecules or irons from a region of high concentration to a region of low concentration. Thus diffusion of ions is different from ion exchange.

The following sections present the literature review on the durability tests related to this research.

5.3.1 Water Absorption

Water absorption test results of hydrated cement samples give an indication about the porosity of the samples. Different researchers have conducted water absorption tests for concrete, mortar and cement pastes in slightly different ways. Heritage (2001) has described a water absorption testing method for hardened concrete that was also used for aggregates. The samples were oven dried at 105 °C for 24 hours, then kept in a vacuum chamber for 0.5 hours; after that the chamber was filled with water, allowed to soak for 24 hours, and finally water absorption per unit dry weight was computed. He tested samples at various ages and his results showed that water absorption was fairly constant for samples older than 28 days. Gingos and Mohamed Sutan (2011) conducted the water absorption test in slightly different way. Samples made of mortar were oven dried at 100 ± 5 °C, covered by wax except for the bottom surface, immersed in trays containing 30-35mm of water for 7 days, and water absorption per unit dry weight computed. They compared the water absorption of mortar samples made of OPC-fly ash blended cements with OPC samples prepared with different w/c ratios. Surprisingly, when w/c ratio increased from 0.3 to 0.5, water absorption of 28 day old samples had decreased significantly. Further, for w/c of 0.5, water absorption of OPC samples was much higher (about 13%) than that of OPC-fly ash blended samples (which was below 6%). Shah and Pitroda (2013) used a slightly different method. Pozzocrete mortar samples were dried at 85 °C for 24 hours, and immersed in hot water at 85 °C for 24 hours. Water absorptions obtained for different mixtures were between 2.5% and 5.5%. Thokchom, Ghosh and Ghosh (2009b) also used a similar method, but not with hot water as in the previous method, to investigate water absorption of geopolymer mortar samples, and found that water absorption was between 5% and 12%. In the method adopted by Olivia and Nikraz (2011b), geopolymer concrete samples were oven dried at 100 ± 5 °C for over 24 hours and later immersed in water for a period over 48 hours and water absorptions computed. They found the water absorptions of the samples to be less than 5%. Kannan and Ganesan (2012) adopted the same method for blended cement mortar of rice husk ash and metakaolin, and found that water absorption continuously decreased when OPC was replaced by rice husk ash-metakaoline mixture from 0 to 40%, in steps of 10%. Cheah and Ramli (2012) studied water absorption of mortar mixtures with high calcium wood ash (HCWA) and found that water absorption had significantly increased when HCWA was added. Dias (2000) used another method for determining water permeable porosity. He submerged the specimens in water for 7 days and oven dried at 105 °C for 3 days, and permeable porosity was calculated based on saturated weights, submerged weight, and oven dried weight.

Based on the above information, it can be seen that different researchers have used different methods to investigate water absorption. Clearly, absorption would depend on the degree of saturation of specimens prior to the test; also, the drying of specimens may cause structural changes. For these reasons, standardizing of absorption testing has been very difficult. Nevertheless, according to most of the above literature, when w/c ratio increases water absorption also increases. Further, according to some of the literature, water absorption reduces with the addition of pozzolanic materials such as rice husk ash and metakaolin. However, according to some other literature, water absorption increases when high calcium wood ash is added. Accordingly, it can be concluded that the effect of w/c ratio and pozzolanic materials on water absorption can vary from case to case.

5.3.2 Sulphuric Acid Attack

Sulfuric acid attack on hydrated cement occurs in two stages - formation of gypsum and formation of ettringite (O'Connell, McNally and Richardson 2010). In the first stage H_2SO_4 reacts with $Ca(OH)_2$ and C-S-H to form gypsum ($CaSO_4.2H_2O$). In the second stage, the gypsum formed reacts with hydrated tricalcium aluminates ($C_3A.H_{12}$) to form ettringite ($C_3A.3C\overline{S}.H_{32}$) (Mondal, Uddin and Amin 2011). The reaction mechanisms given by De Ceukelaire (1989) in a non-English source has been translated by Monteny et al. (2000) as below.

<u>Stage I</u>

$$Ca(OH)2 + H_2SO_4 \rightarrow CaSO_4.2H_2O$$

$$CaO.SiO_2.2H_2O + H_2SO_4 \rightarrow CaSO_4 + SiO(OH)_4 + H_2O$$

(C-S-H)

(Note that in C-S-H the molar ratio CaO/SiO_2 can be 0.8 – 1.5, depending on the conditions. In the above equation molar ratio has been taken as 1)

Stage II

$$3CaO.Al_2O_3.12H_2O + 3(CaSO_4.2H_2O) + 14\ H_2O \rightarrow 3CaO.Al_2O_3.3CaSO_4.32H_2O$$

(ettringite)

The volume of the product (ettringite) is much greater than the total volume of initial compounds, hence significant volume expansion occurs as a result of these processes (Monteny et al. 2000). The increase in volume can lead to cracking and/or peeling of samples. Also formation of $CaSO_4$ would make the samples soft (Attogbe and Rizkalla 1988).

When conducting sulphuric acid attack tests for concrete, mortar and cement pastes, different researchers have used different concentrations of acid and different durations of immersion. The literature indicates that OPC suffers heavily from sulphuric acid attack. Tsuburaya et al. (2011) immersed OPC samples in relatively strong sulphuric acid solution (pH = 1) and noted a weight loss of about 10% in just 4 weeks. The results of Ghrici, Kenai and Said-Mansour (2007) too confirm that; OPC mortar samples placed in 3% sulphuric acid experienced about 75% weight loss in 180 days. Shaikh and Daimi (2011) also used OPC mortar with sulphuric acid of the same concentration (3%), but noted comparatively low weight loss (only 14.2%) in 90 days. However, surprisingly, Bakharev (2005) noted a 40% weight gain, instead of weight loss, when he kept OPC paste samples in relatively strong (5%) sulphuric acid solution for 5 months. The literature also indicates that sulphuric resistance of OPC can be improved by adding supplementary cementitious materials. Rajamane et al. (2012) used Portland pozzolan cement with 28% fly ash, and immersed in sulfuric acid solutions. Weight losses of the samples immersed in 2% acid at 90 days was 8.7%, whereas weight losses of those immersed in 10% acid was 22.6%. Comparable results were noted by Pacheco-Torgal and Jalali (2009); mortar samples with 20% fly ash placed in sulfuric acid solution having a pH value of 0.7 (that is about 2 mol/l solution) experienced a weight reduction about 6.5% in 28 days. Chatveera and Lertwattanaruk (2011) investigated the effect of adding black rice husk ash (BRHA) to OPC. Concrete samples made of 0%, 20% and 40% BRHA replacement were immersed in 1% sulphuric acid, and the weight losses found to be 7%, 5% and 10%, suggesting that although 20% replacement was favourable, 40% replacement was unfavourable. The literature also explores the superior performance of geopolymer concrete with respect to sulphuric acid attack resistance. Wallah and Rangan (2006) immersed low-calcium fly ash based geopolymer mortar cubes in 0.25%, 0.5% and 1% sulfuric acid for 52 weeks, and found that samples immersed in 1% solution experienced a weight loss about 1.75% in 52 weeks. Kumaravel and Girija (2013) used geopolymer concrete, but with slightly higher concentrations, namely, 0.5%, 1% and 2% sulfuric acid solutions, and found that the weight losses at 90 days were 0.91%, 1.21% and 1.36%. Thokchom, Ghosh and Ghosh (2009a) used geopolymer cubes with a significantly high concentration of sulphuric acid (that is 10%) but weight losses at 25 weeks were not very high (i.e. less than 1.75%). Accordingly, it seems that geopolymer has a relatively higher resistance for sulphuric attack. According to the literature, apart from pozzolanic materials, there are other admixtures that improve resistance to acid attack. Attogbe and Rizkalla (1988) investigated the effect of admixtures on sulfuric acid attack. They found greater weight losses when water-reducing agents were introduced, but lower weight losses when air-entraining agents were introduced. The literature says that sulphuric acid attack not only damages the samples but also reduces the strength. Mondal, Uddin and Amin (2011) immersed fresh OPC-rice husk ash mortar samples in sulphuric solutions of pH of 3 and found that compressive strength had been reduced by 50% from 3 to 90 days.

Based on the above information, it seen that different researchers have used sulphuric acid of different concentrations ranging from 0.25% to 10%. The samples used were in the form of paste, mortar or concrete. Different researchers have immersed samples for different durations; the durations may have been decided based on the damage observed. It seems that when the concentration of acid is increased the attack or the weight losses of samples is increased. Also the damage to the samples (weight loss) increases with the immersed duration. Samples made of OPC experience the heaviest weight losses, and hence resistance to sulphuric acid attack of OPC seems to be very poor. However, it is noted in most of the cases, that the resistance to sulphuric acid attack can be improved by adding pozzolanic materials. Geopolymer binders, which are derived from pozzolan, seem to have high resistance for sulphuric attack. When all the information is considered together, it can be concluded that samples would experience weight gains as well as weight losses when immersed in sulphuric acid, depending on the composition of the mixture, concentration of acid and period of immersion.

5.3.3 Sodium Chloride Penetration

When hydrated cement samples are submerged in NaCl solution, chloride ions penetrate to samples through different mechanisms. They are: capillary absorption of chloride containing liquids, permeation of NaCl solution, diffusion of free chloride ions and ion exchange (Hilsdorf and Kropp 1995). Capillary absorption is the movement of solution as a result of surface tension acting in capillaries; permeation is the movement of a permeate (such as a liquid, gas or vapour) through a porous or permeable material; diffusion is the movement of atom, molecules or irons in the pore solution from a region of high concentration to a region of low concentration; ion exchange can be described as an exchange of ions between two electrolytes or between an electrolyte solution and a 'complex' (a 'complex' is defined as a reversible association of ions, atoms or molecules through weak chemical bonds). Chloride attack increases the risk of corrosion of reinforcing steel, as free chloride ions promote corrosion in the presence of oxygen (Collepardi, Marcialis and Turriziani 1972). When unhydrated C_3A and C_4AF are present, they bind chloride ions by forming $C_3A.CaCl_2.H_{10}$ (commonly known as Friedel's salt) and $C_3F.CaCl_2.H_{10}$ (Csizmadia, Balázs and Tamás 2000), thus reducing free chloride ions. The reduction of free chloride ions decreases the risk of corrosion. Moreover, aluminates in pozzolanic materials such as fly ash and slag are capable of binding chloride ions (Jensen and Pratt 1989). However, when hydrated cement with bound chloride ions gets carbonated, chloride ions are released, thus increasing the risk of corrosion (Neville 1995). This implies that in order to get the benefit of chloride binding, it is necessary to improve resistance to carbonation as well.

Different researchers have used different methods to investigate chloride ion penetration. Otsuki, Nagataki and Nakashita (1993) adopted a simple method to determine the depth of chloride ion penetration and it is outlined below. Samples were immersed in NaCl solution for a specific period. At the end of the period samples had been taken out, split in to two, and $AgNO_3$ was sprayed on to the split surface. When $AgNO_3$ was sprayed on split surfaces, AgCl was formed in the region of chloride ion intrusion. As the formation of AgCl was characterised by white colour, the depth of penetration of Cl^- could be determined. In order to find the most suitable solution, different concentrations of $AgNO_3$, namely 0.05, 0.1, 0.2, 0.3 and 0.4 N were used, and found that the change of colour was most apparent with 0.1 N solution. He et al. (2012)

have done a comprehensive study on three $AgNO_3$–based colorimetric methods, namely, $AgNO_3$+fluoresceine, $AgNO_3+K_2CrO_4$ and $AgNO_3$ method; they concluded that $AgNO_3$ method was the most rapid, simplest and easiest method. However, they indicated that the chloride concentration at the colour change boundary was 0.28-1.69% by mass of cement or 0.072-0.714 mol/L for the $AgNO_3$. Moreover, it was seen that there was a high variability in results, because there were many influencing factors such as concrete alkalinity, sprayed volume and concentration of $AgNO_3$ solution, pore solution volume of concrete, sampling method and method used for measuring free chloride in concrete. Somna et al. (2012) used the above method to find the chloride penetration depths of concrete specimens prepared using recycled coarse aggregates and an OPC-ground bagasse ash (GBA) mixture, immersed in 3% NaCl solution. The penetration depths of the three mixtures having 20%, 35% and 50% GBA replacement were about 6 mm in 3 months; however, the depths were increased to 18, 14 and 11 mm at 18 months. Depth of chloride penetration of pure OPC was 18 mm in 3 months and it increased up to 45 mm at 18 months. Zhu et al. (2014) used a different method to study chloride ion penetration of Alkali-Activated Fly Ash (AAFA) concrete. Chloride penetrated samples were oven dried, powdered, dissolved in nitric acid solution, boiled and filtered. After that all the Cl^- in the solution were precipitated using $AgNO_3$ solution. The quantity of Cl^- was determined using the ammonium thiocyanate (NH_4SCN) titration method. They concluded that the two factors most affecting Cl^- penetration were porosity and tortuosity, which are influenced by liquid/solid ratio and slag substitution respectively. Reduction of liquid/solid ratio from 0.8 to 0.6 caused a reduction of porosity from 42.2% to 37% and reduced the Cl^- concentration by about 40% - 60%. When the fly ash component of AAFA was substituted with slag by 20% - 40%, the size of the pores got reduced and tortuosity got increased, and consequently the Cl^- penetration rate decreased. Olivia and Nikraz (2011a) used the Nordtest method of Accelerated Chloride Penetration (NT Build 443) using 3.5% NaCl solution to determine chloride contents at different depths of OPC and geopolymer concrete specimens. They found that chloride contents (% by concrete weight) of OPC at 0-15 mm, 15-30 mm and 30-45 mm were about 0.47%, 0.29% and 0.10% respectively, while those of geopolymer concrete mixtures were between 0.35-0.46%, 0.28-0.35% and 0.22-0.27% respectively, thus indicating higher penetration than in OPC concrete. Midgley and Illston (1984) adopted chemical analysis, X-Ray Diffraction and thermal analysis to investigate the penetration of chloride ions into hardened OPC paste. They found that the depth of penetration increased with the w/c ratio. Moreover, it was found that chloride ions had reacted with the anhydrous tricalcium aluminate (C_3A) in un-hydrated cement present in hardened cement paste to form $C_3A.CaCl_2.H_{10}$; this implies that when C_3A content in cement is high, then the free chloride ions in samples become less. Gjørv and Vennesland (1979) investigated chloride ion diffusion into concrete made of OPC and blended cements of slag and volcanic tuff. They found that chloride penetration of OPC concrete was 2 to 5 times higher than that of blended cement concrete. Experiments also showed that w/c ratio has an effect only on the chloride content of the concrete surface layer and also when the duration of chloride exposure is short. Moreover investigations of OPC containing 0% and 8.6% C_3A indicated that even 8.6% of C_3A is not adequate to reduce chloride penetration compared with 0% C_3A.

Based on the above literature review, it can be concluded that, chloride penetration depends on many factors such as composition of the mixture, C_3A content in OPC, quantity of aluminate rich pozzolanic material and w/c ratio. When investigating chloride ion penetration, different researchers have used NaCl solutions of different concentrations too.

5.3.4 Carbonation

Investigating the resistance to carbonation is important as carbonation leads durability problems, specifically of steel-embedded concrete, of which reinforced concrete is the most common. In the case of reinforced concrete, alkalinity with a pH value slightly above 11.5 is required to passivate the steel reinforcement. When the pH drops below this critical value, the protective oxide film (passive coating) of the steel surface constituting γ-Fe_2O_3 starts to get decomposed (Pacheco-Torgal et al. 2013). As a result, steel reinforcement becomes prone to corrosion. In addition, reduction of alkalinity can also lead to destabilization of the cementitious products of hydration. Because of this, any environment where the pH value is less than 12.5 may be categorised as 'aggressive' (Mehta and Monteiro 2006). In OPC concrete, the pH value is maintained at around 13, by the $Ca(OH)_2$ released during hydration (Gambhir 2013) . Hence, such an environment can be considered as 'favourable' for passivation of steel reinforcement. However, when hydrated cement gets carbonated, alkalinity of the environment drops to a pH value below 8 (Broomfield 2007). This process is more critical in OPC-pozzolanic blended cements. In blended cements, the $Ca(OH)_2$ released during hydration of OPC reacts with pozzolan and produces C-S-H, hence $Ca(OH)_2$ concentration drops, leading to a decrease the alkalinity. Zhang, Sun and Yan (2000) reported that, in HVFA cement pastes, the pH value decreases continuously with the age. Hence, when pozolanic cements are exposed to CO_2, the $Ca(OH)_2$ released during hydration of OPC gets carbonated quickly, the alkalinity drops fast, and ultimately creates an unfavourable environment for reinforced concrete.

According to the general understanding, it is assumed that the hydrated product C-S-H does not get decomposed and it does not get carbonated. However, C-S-H too may get carbonated (Gajda 2001); it was found that there were some $Ca(OH)_2$ in the carbonated area, which led to the conclusion that C-S-H gets decomposed into $Ca(OH)_2$, which will eventually be carbonated. According to another view, in addition to $Ca(OH)_2$, both C-S-H as well as unhydrated calcium silicates (C_3S and C_2S) too gets carbonated in the presence of moisture, and the possible equations of carbonation reactions are as follows (Papadakis, Vayenas and Fardis 1989).

<u>Carbonation of $Ca(OH)_2$</u>

$$Ca(OH)_2 + CO2 \rightarrow CaCO_3 + H_2O$$

<u>Carbonation of C-S-H</u>

$$3CaO.2SiO_2.3H2O + 3CO_2 \rightarrow 3CaCO_3.2SiO_2.3H2O$$

<u>Carbonation of unhydrated calcium silicates</u>

$$3CaO.SiO_2 + 3CO_2 + nH2O \rightarrow SiO_2.nH_2O + CaCO_3$$

$$2CaO.SiO_2 + 2CO_2 + nH2O \rightarrow SiO_2.nH_2O + CaCO_3$$

Based on numerical simulations, Peter et al. (2008), concluded that the influence on carbonation of unhydrated calcium silicates (C_3S and C_2S) is small; but the influence of C-S-H can be higher when the C-S-H content is high.

When exposed to constant relative humidity and temperature, the depth of carbonation is related to the exposure duration, in accordance with the Fick's second law of diffusion, and it can be expressed as follows, giving rise to the 'square root rule' (Bijen 2003; Grantham, Majorana and Salomoni 2009)

$$D = k.(t)^{1/2}$$

Where 'D' is carbonation depth, 't' is time of exposure and 'k' is the carbonation coefficient.

Obviously the carbonation depends on the CO_2 concentration in the context. The CO_2 concentration in atmosphere is only about 0.03% (Shipman, Wilson and Todd 2009; Warneck 1999). As the concentration of CO_2 is low, the carbonation process under natural conditions is relatively slow. Because of that, it is common practice to use accelerated carbonation tests with higher concentration of CO_2 for the investigations of carbonation depths of hydrated cement samples.

Sisomphon and Franke (2007) suggested a formula, based on Fick's law of diffusion, to relate carbonation processes in natural environment to those in an accelerated carbonation chamber as below.

$$\frac{k_{acc}}{k_{env}} = \frac{\sqrt{\frac{2D.C_{acc}}{C_0}}}{\sqrt{\frac{2D.C_{env}}{C_0}}}$$

Here, 'D' is the carbonation depth considered, 'C_{acc}' and 'C_{env}' are the CO_2 concentrations in the accelerated carbonation chamber and the natural environment; 'k_{acc}' and 'k_{env}' are carbonation constants for the accelerated carbonation chamber and the natural environment, and C_0 is the sample property constant. Environmental CO_2 concentration is 0.03%. Hence if concentration in the test chamber is taken as 100 times that of natural environment, i.e. 3% CO_2, then the above formula can be reduced to the one below (since $C_{acc}/C_{env} = 100$).

$$\frac{k_{acc}}{k_{env}} = 10$$

Accordingly, the carbonation rate under natural environmental conditions is approximately 10 times slower than the rate under an accelerated carbonation chamber having 3% CO_2.

Khunthongkeaw, Tangtermsirikul and Leelawat (2006), based on his analytical studies, proposed an equation to determine carbonation depth in the natural environment using the results of accelerated carbonation test as below.

$$D_{env} = A.D_{acc}\,(t)^{1/2}$$

Here 'D_{env}' is the carbonation depth in natural environment, 'D_{acc}' is the carbonation depth of the sample tested in the accelerated carbonation chamber and 'A' is a constant which depend on CO_2 concentration and relative humidity.

To determine the depth of carbonation of hydrated cement samples, the phenolphthalein colour-staining test can be adopted. Phenolphthalein is a pH indicator; if pH value is above 10 it becomes pink-fuchsia in colour, while the colour does not get changed if the pH value is less than 8.3 (Morandeau, Thiéry and Dangla 2014). As mentioned above pH values of un-carbonated hydrated cement is about 13, and that of carbonated hydrated cement is about 8. Hence, when phenolphthalein is sprayed on to a freshly split surface of a sample, the region that has not been carbonated turn into pink/purple colour, while the colour does not get changed in the areas that have been carbonated (Gajda 2001).

The literature indicates that carbonation of hydrated cement samples depends on many factors. Gonen and Yazicioglu (2007) investigated carbonation of concrete under different relative humidity values (35%, 55% and 80%), CO_2 concentrations (0.03% and 40%), and different durations of exposures (0.25, 1 and 3 days) using samples prepared under different levels of compaction porosity (poor, medium and high). They found that carbonation was highest when relative humidity was 55%. It was also noted that when porosity increased, the depth of carbonation too increased. Obviously carbonation increased with the increase of CO_2 concentration. Lee, Do Gyeum Kim and Cho (2012) performed accelerated carbonation tests at 20°C, 60% relative humidity and

CO_2 concentration of 5% for samples of cement paste, mortar and concrete made of blended cements with 20% fly ash prepared with the different w/c ratios of 0.40, 0.45 and 0.50. The carbonation depths of cement paste were 8.5, 10.5 and 10.8 mm, while depths of mortar were 8.47, 16.61 and 16.61 mm, and depths of concrete were 14.88, 15.00 and 29.56 mm. The results indicated that the carbonation depths were minimum in samples made of paste, while it is maximum in samples made of concrete. Further the results showed that when w/c increased carbonation depth too increased. Matsuzawa, Kitsutaka and Tsukagoshi (2010) investigated carbonation depths of concrete exposed to 5% CO_2, 60% relative humidity and temperatures of 20° C and 60° C. The 13 week carbonation depths of samples having w/c ratios 0.4, 0.5 and 0.6 tested at 20° C were about 2, 9 and 11mm, while those tested at 60 $^\circ$ C were 13, 19 and 22 mm. According to their results carbonation depths increased with w/c, and also with temperature. Jiang, Lin and Cai (2000) investigated the effect of the curing period (or age) on carbonation depth, tested in an accelerated carbonation chamber (20% CO_2 and 70% relative humidity), using concrete samples made of OPC and high volume fly ash (HVFA) cements (two mixtures having 55% and 70% fly ash replacements), and concluded that with the increase of curing period, carbonation depth got reduced (or resistance to carbonation got increased). Atiş (2003) investigated the effect of fly ash percentage using concrete samples of OPC and HVFA cements (two mixtures of 50% and 70 % of fly ash) placed in an accelerated carbonation chamber with 5% CO_2 and found that HVFA mixtures having higher percentage of fly ash had the higher carbonation depths. Rozière, Loukili and Cussigh (2009) used concrete samples made of OPC and low volume fly ash (LVFA) cement (with 30% fly ash), kept in a carbonation chamber at 65% relative humidity with 50% CO_2, and noted that resistance to carbonation of LVFA was not as good as that of OPC (carbonation depth of LVFA was greater than that of OPC). The results of the research on HVFA and LVFA mentioned above indicated that addition of fly ash reduced the resistance to carbonation. Research shows that not only fly ash, but also other pozzolanic materials reduce resistance to carbonation. Cheah and Ramli (2012) studied carbonation of mortar mixtures with high calcium wood ash (HCWA), and confirmed that the depth of carbonation increased when OPC was replaced by 5%-10% HCWA. Rukzon and Chindaprasirt (2010) conducted carbonation tests with 5% CO_2 and 50% relative humidity for mortar samples made of OPC and rise husk ash (RHA) and observed that carbonation depths get increased with the increase of RHA percentage. Pipilikaki and

Katsioti (2009) investigated carbonation of concrete samples made of OPC and quaternary blended cements (QBC) derived by mixing OPC, fly ash, pozzolan and limestone, kept at 1% CO_2 and 70% relative humidity, and found that the carbonation coefficient (k) for OPC concrete was 15.7, but that of two samples made of QBC concrete were 17.9 and 21.8, which indicate higher carbonation rates than for OPC. Accordingly, not only fly ash but also HCWA, RHA and QBC lead to increased carbonation depths.

Based on the above literature review on carbonation, it can be concluded that carbonation depth depends on many factors such as composition of the sample, w/c ratio, porosity, CO_2 concentration, relative humidity, temperature, curing period and duration of exposure. When supplementary materials such as pozzolan or limestone are added to OPC, resistance to carbonation gets reduced. When curing period is increased, resistance to carbonation increases. Researchers have used different CO_2 concentrations, relative humidity, types of samples (paste, mortar and concrete) and compositions.

5.4 Materials, Methods and Experiments

The experimental program presented here can be considered an extension of the experimental program presented in Chapter 4, which was about structural and microstructural properties of different APC mixtures. Hence, samples made of the same cementitious mixtures were used to conduct the durability tests. Thus the same notations were used to identify different mixtures and curing conditions. Further, mixtures were also categorized and analyzed according to the same groupings given in Section 4.4.2.

The main aim in this part of the research was to investigate the susceptibility to durability problems using young (28 day old) samples through water absorption because young samples would accentuate the differences between mixes, and the resistance for chemical attacks of mature (1 year old) samples because year old samples may be more representative of service conditions. Hence 28 day old samples were used for water absorption tests and 1 year old specimens for chemical tests. For each test three samples were used, and average values computed for analysis.

5.4.1 Water Absorption Test

The objective of doing water absorption testing in this research is to get an initial idea about the porosity and absorption of chemicals. Hence, a test method where all six surfaces are exposed to the water was considered as more suitable than methods that cover some surfaces with wax. Thus, in designing the test, related literature given in Section 5.3.1 on water absorption of concrete, mortar, masonry units including ASTM C140 were used as a guide, even though the samples used in this research were of cement paste. Since the aim was to test the water absorption of relatively young samples, 28 day old air cured and water cured specimens were used for test. Samples were immersed in water at 20 – 25 ° C, such that top surface of the sample was at least 150 mm below the surface of water. To ensure all the 6 faces of specimens were in contact with water, specimens were placed on a special type of plastic specimen holders, the platforms of which were made of a square net, so that the surface area of the specimen in contact with the net is negligible, and water was in contact with specimens without any obstruction. The samples were immersed in water for 24 hours and saturated surface dried weights (W_s) were recorded. After that they were dried in an oven at 105 °C for not less than 24 hours till the weight did not drop over 0.2% in 2 hours, and dried weights (W_d) were recorded. The water absorption was determined as follows:

$$Water\ Absorption\ (\%) = \frac{(Ws - Wd)}{Wd} * 100\%$$

From each mixture, three specimens were used for the water absorption test. The water absorption of each specimen was determined and the mean water absorption was computed.

5.4.2 Sulphuric Acid Attack Test

In designing the sulphuric acid attack test, related literature given in Section 5.3.2 on acid attack of concrete, mortar and masonry units including ASTM C267 were used as a guide, even though the samples used in this research were of cement paste. The parameters such as concentration of acid and durations to be immersed were decided according to the objectives of the research. To investigate the sulphuric attack on cementitious mixtures, air cured specimens were immersed in 3% H_2SO_4 acid for 16 weeks. Since the acid gets contaminated with cementitious material and its acidity reduces over time, the acid in the containers was replenished with fresh acid every 4 weeks. To ensure all the 6 faces of specimens were in contact with the acid, specimens were placed on special type of plastic sample holders. In these sample holders the platform was made of a square net, so that the surface area of the specimen in contact with the net is negligible, and acid can easily be in contact with specimens (**Fig. 5.1**).

(a) **(b)**

Fig. 5.1 Sulphuric Acid Test

(a) Sample placed on Plastic Sample holder; **(b)** Sample with an Acid container

Different researchers have used different ratios between volume of specimen to volume of acid. Wallah and Rangan (2006) used the ratio of 1:4 to test sulphuric acid attack on geopolymer concrete samples. However, in this experiment, a ratio of 1:5 was used in order to fully immerse the specimen with an adequate cover, considering the size of the container. Before immersing the samples, the 'dry weights' (W_d) were measured. After immersion, the weights (W_i) were measured at 2 hrs, 1 day, 3 days, 7 days, and after that every 7 days up to 112 days. The acid attack for each specimen was determined as percentage weight change as follows:

$$Weight\ Change\ (\%) = \frac{(Wi - Wd)}{Wd} * 100\%$$

The use of above indicator as a measure of acid attack is consistent with the other researchers as well (Ghrici, Kenai and Said-Mansour 2007) From each mixture, three specimens were used for sulphuric test, weight loss of each specimen was calculated, and the average taken.

In addition, visual observations were recorded throughout the period. These observations were focused on visible damage to the sample, colour change of samples, colour change of acid solution and deposits in the containers.

5.4.3 Sodium Chloride Penetration Test

It appears that researchers have used different methods to investigate chloride penetration of hydrated samples, such as rapid chloride permeability test, ponding test and submersion test. It is said that the permeability test and chloride ponding test are controversial due to various issues. One is the effect on results when there are pozzolanic materials such as fly ash, slag or silica fume in the mixture (Ryan 1999). In this research the simple submersion test, where test specimens are submerged in NaCl solution was adopted. A 5% NaCl solution was used, and the duration of immersion was 12 weeks (around 3 months). Since the NaCl solution gets contaminated with cementitious material and becomes alkaline over time, the NaCl solution in the containers was replenished with fresh solution every 4 weeks. The ratio between volumes of specimen to NaCl solution was taken as 1:4 in order to fully immerse the specimen with an adequate cover, considering the size of the container. To ensure all the 6 faces of specimens were in contact with the NaCl solution, specimens were placed on the same type of sample holders used in sulphuric acid test (**Fig. 5.2**).

Fig. 5.2 NaCl Test: Sample with the container with NaCl solution

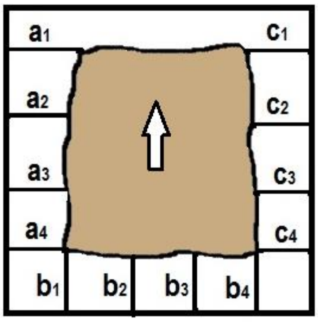
Water cured samples of all the mixtures were used for testing. In addition, air cured samples too were used for testing from the mixtures M3, C3 and R3. After 12 weeks (around 3 months) of immersion, samples were taken out of the NaCl solution, and split into two pieces over the trowelled face, so that the resulting cross section is bound by the specime's bottom face, two side faces and top (or trowelled) face. To determine the depth of penetration the $AgNO_3$ method was used. In this method 0.1 N $AgNO_3$ solution is applied on the split surfaces. In the region of chloride penetration, $AgNO_3$ reacts with chloride ions and AgCl (silver chloride) is formed. $AgNO_3$ not only reacts with chloride ions to form AgCl, but also reacts with hydroxyl ions to form Ag_2O (silver oxide) as shown in following equations (Ismail et al. 2013).

$$Ag^+ + Cl^- \rightarrow AgCl \text{ (silver-white colour)}$$

$$Ag^+ + OH^- \rightarrow AgOH \rightarrow Ag_2O \text{ (brown colour)}$$

The colour of AgCl is silver-white, but changes colour when exposed to UV light. The colour of Ag_2O is brown. Hence when brown coloured Ag_2O is formed, silver-white coloured AgCl is seen on the brown background.

In measuring the chloride penetration depth, the trowelled surface was ignored in order to avoid the influence of trowelling. Mean depth of penetration of each sample was determined taking 4 measurements from each face other than from the trowelled face, as shown in **Fig. 5.3**. Thus the mean depth of each sample was computed by taking 12 measurements from each sample. Considering the mean depth of each sample of a particular mixture, the average chloride penetration depth for that mixture was computed. In **Fig. 5.3** the top face or trowelled face is indicated by the direction of the arrow.



$$d = \frac{[a_1 + a_2 + a_3 + a_4 + b_1 + b_2 + b_3 + b_4 + c_1 + c_2 + c_3 + c_4]}{12}$$

Fig. 5.3 Determination of Chloride Penetrated Depth

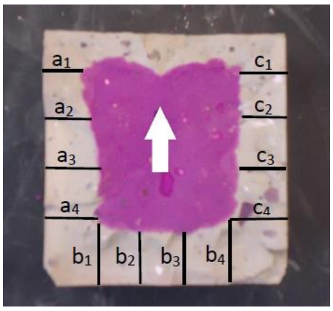
5.4.4 Carbonation Test

Investigation of resistance to carbonation was done through the accelerated carbonation test with the aid of a carbonation chamber shown in **Fig. 5.4**. Inside the chamber the temperature was around 20 - 25 °C, and relative humidity around 65%. To control the relative humidly, multiple trays of saturated $NaNO_2$ solution were used. The concentration in the test chamber was set to 3% CO_2, which is 100 times of natural environment. Samples were kept on 'cake trays' as shown in **Fig. 5.4**, so that all the faces were in contact with CO_2 without any obstacle.

(a) **(b)**

Fig. 5.4 Carbonation Test
(a) Carbonation Chamber; **(b)** Samples kept on a 'cake tray' inside the chamber

Two sets of specimens from each mixture were kept in the carbonation chamber. One set was taken out after 4 weeks and the other after 12 weeks. It should be noted that, when describing results, the durations of 4 weeks and 12 weeks are described as 1 month and 3 months for convenience. The specimens were split into two pieces over the trowelled face, so that the cross section is bound by the bottom, two sides and top (or trowelled) faces. A 1% phenolphthalein solution was applied on freshly split sections. When phenolphthalein is applied, the non-carbonated region (the region where the pH is greater than 7) turns purple, while carbonated areas remain colorless. In measuring carbonation depth, the trowelled surface was ignored, to avoid the influence of trowelling. The mean depth of penetration of each sample was determined taking 4 measurements from each face other than from the trowelled face, and shown in **Fig. 5.5**. Accordingly, mean depth of each sample was computed taking 12 measurements from each sample. Considering the mean depth of each sample of a particular mixture, average carbonation depth for that mixture was computed. In the **Fig. 5.5** the top face or trowelled face is indicated by the direction of the arrow.



$$d = \frac{[a_1 + a_2 + a_3 + a_4 + b_1 + b_2 + b_3 + b_4 + c_1 + c_2 + c_3 + c_4]}{12}$$

Fig. 5.5 Determination of Carbonation Depth

5.5 Results and Discussion

Durability tests were conducted according to methods described in Section 5.4. Using the raw measurements, different indicators, such as percentage water absorption, percentage weight change due to sulphuric attack, chloride ion penetration depth, and carbonation depth were computed as described previously. Further, in order to investigate how the results vary when parameters are changed, sensitivity analyses were performed using the concept of ‘sensitivity index’, with respect to a datum. As described in Section 4.5.3.2 of Chapter 4, the ‘central mixture’ of the experimental program was the APC mixture M prepared with w/c = 0.3, hence the conditions of that mixture were considered as the datum.

The results of the durability tests were analysed and compared with the aid of the same comparison groupings given in Chapter 4, namely the M-C-R grouping, M-L-N grouping and M-P grouping.

5.5.1 Water Absorption

5.5.1.1 Water Absorption per unit weight

Water absorption per unit weight of sample expressed as a percentage (percentage water absorption) is graphically presented in **Fig. 5.6**.

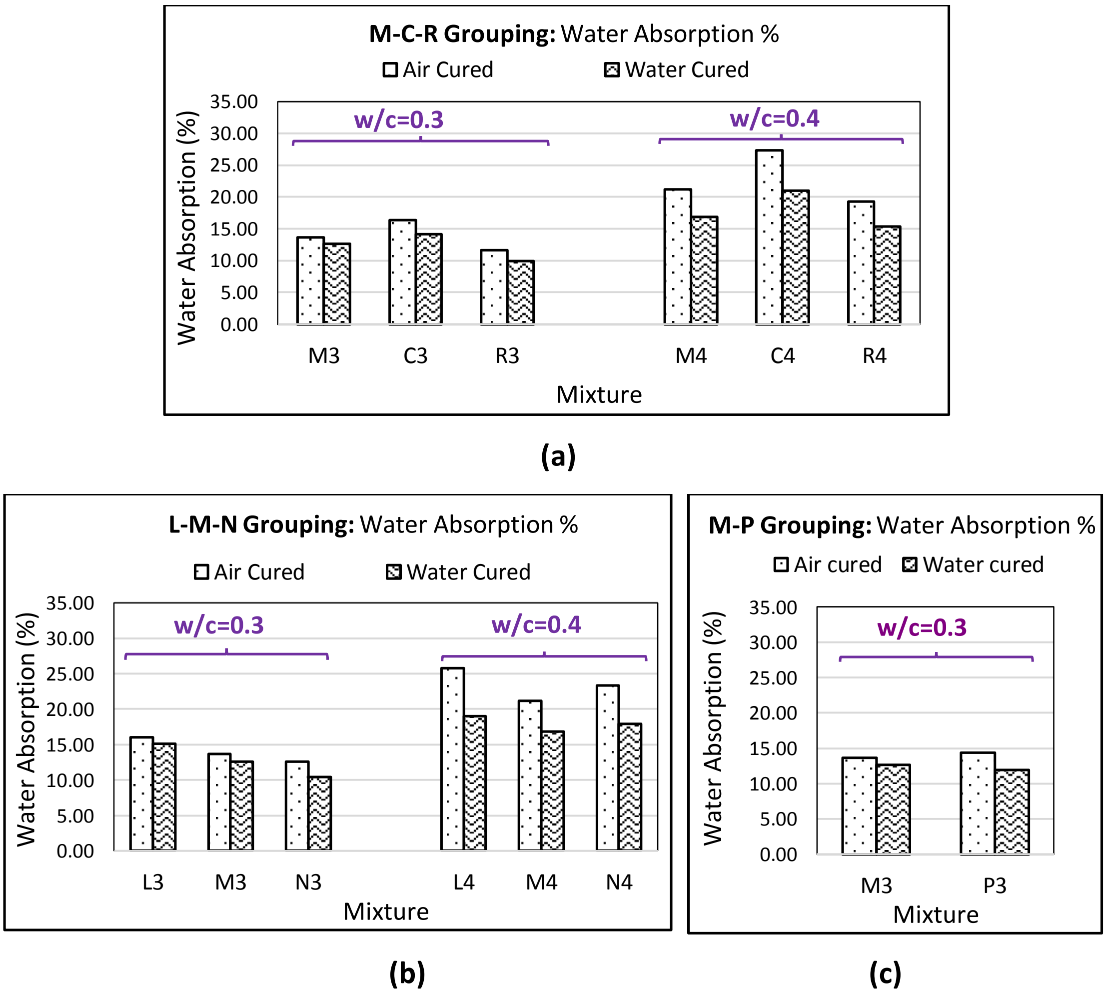


Fig. 5.6 Percentage Water Absorptions:
(a) M-C-R Grouping; **(b)** L-M-N Grouping; **(c)** M-P Grouping

According to **Fig. 5.6 (a)**, **Fig. 5.6 (b)** and **Fig. 5.6 (c)**, it is very clearly seen that for a given mixture, air cured samples have higher water absorption than water cured samples. The other obvious observation is that for a particular mixture, water absorption is higher in specimens of w/c=0.4 than those of 0.3 (L4>L3; M4>M3; N4>N3; C4>C3; R4>R3). **Fig. 5.6 (a)** indicates that, for a given w/c ratio, both for water and air cured samples, water absorption of APC mixture M is greater than that of OPC mixture R but less than HVFA mixture C (for w/c of 0.3: R3<M3<C3; for w/c of 0.4: R4<M4<C4). According to **Fig. 5.6 (b)** for a given w/c ratio, both for water and air cured samples, the water absorption of APC mixtures L, M and N shows a decreasing trend in that order (ignoring the slight deviation of M4). These observations lead to following discussion.

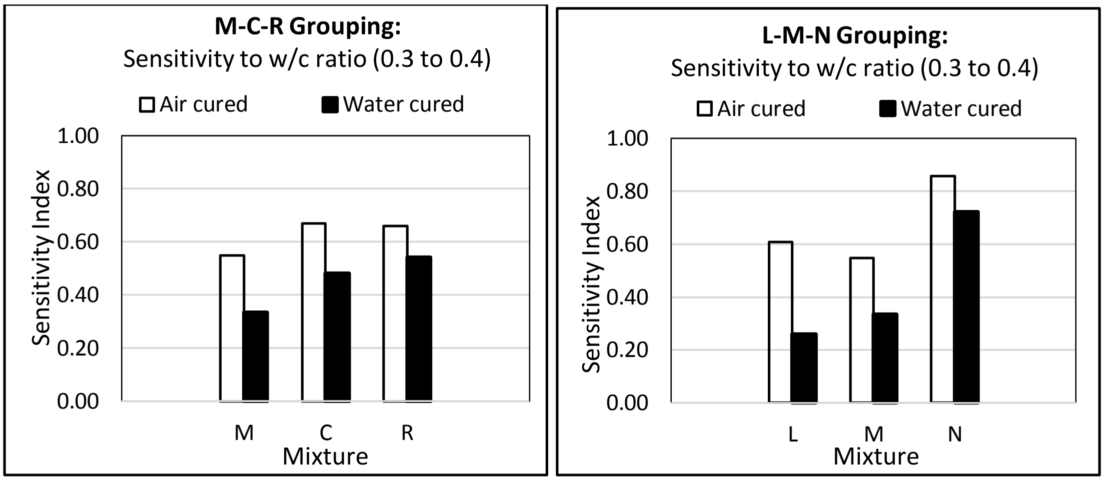
5.5.1.2 Sensitivity to w/c ratio on water absorption

Sensitivity to w/c on water absorption was investigated using the concept of 'sensitivity index', which is defined as below.

$$Sensitivity\ Index\ (SI) = \frac{W_{test} - W_{ref}}{W_{ref}} = \frac{W_{test}}{W_{ref}} - 1$$

where, W_{test} - water absorption of the test samples (samples with w/c =0.4)
W_{ref} - water absorption of the reference samples (samples with w/c =0.3)

Accordingly, sensitivity to w/c ratio on water absorption of a particular mixture was computed by dividing the water absorption of samples prepared with w/c = 0.4 by the water absorption of samples prepared with w/c=0.3 and deducting unity from this ratio. If the sensitivity index is '0', it indicates that there is 'no sensitivity'; and the deviation from '0' (whether positive or negative) indicates the degree of sensitivity. The results are graphically presented in **Fig. 5.7**.



(a) **(b)**

Fig. 5.7 Sensitivity to w/c on Water Absorption
(a) M-P-R Grouping; **(b)** L-M-N Grouping

Fig. 5.7 (a) and **Fig. 5.7 (b)** indicate that both air and water cured samples are sensitive to w/c ratio. Positive sensitivity indices indicate that water absorption related to w/c of 0.4 are greater than that of w/c of 0.3. The deviation of sensitivity index from 0 indicates the degree of sensitivity. According to **Fig. 5.7 (a)**, sensitivity to w/c of APC mixture M is slightly less than that of HVFA mixture C and OPC mixture R, and according to **Fig. 5.7 (b)** sensitivity to w/c of APC mixture N is slightly higher than that of APC mixtures L and M, under both curing conditions.

5.5.1.3 Sensitivity to curing condition on water absorption

Sensitivity to curing on water absorption too was investigated using the concept of 'sensitivity index', which is defined as below.

$$Sensitivity\ Index\ (SI) = \frac{W_{test} - W_{ref}}{W_{ref}} = \frac{W_{test}}{W_{ref}} - 1$$

where, W_{test} - water absorption of the test samples (water cured samples)
W_{ref} - water absorption of the reference samples (air cured samples)

Accordingly, sensitivity to curing on water absorption of a particular mixture was determined by dividing the value of water absorption of water cured samples by the value of water absorption of air cured samples and deducting unity from this ratio. If the sensitivity index is '0', it indicates that there is 'no sensitivity'; and the deviation from '0' (whether positive or negative) indicates the degree of sensitivity. The results are graphically presented in **Fig. 5.8**.

Negative sensitivity indices in **Fig. 5.8 (a)** and **Fig. 5.8 (b)** indicate that water absorption related to water curing is less than that of air curing. The general observation is that for a given w/c ratio, there is not much difference in the sensitivity index among mixtures M,C,R or among APC mixtures L, M, N.

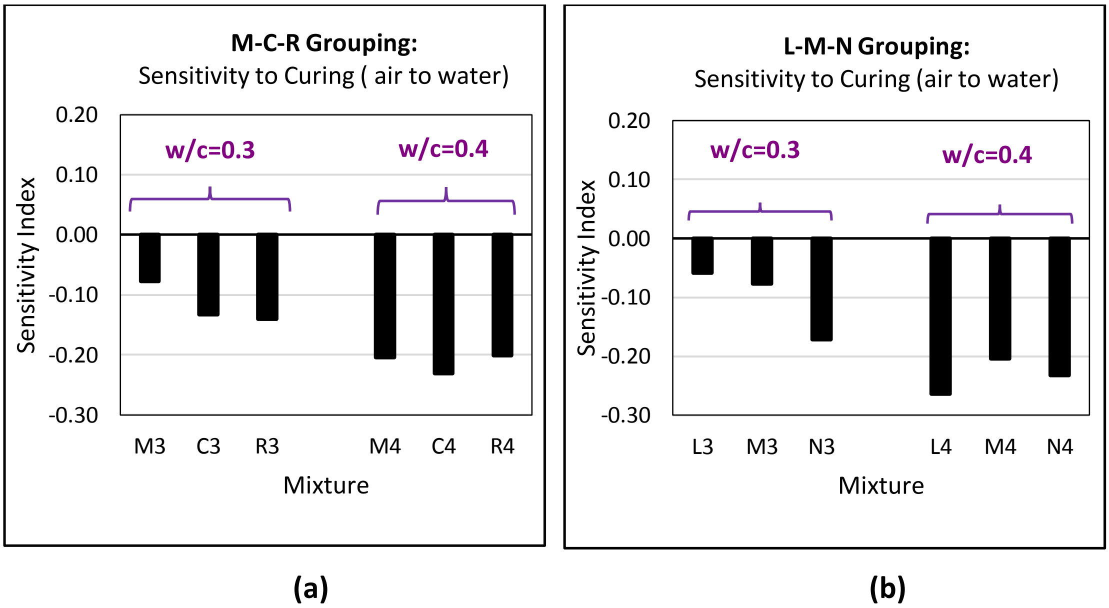


Fig. 5.8 Sensitivity to Curing on Water Absorption:
(a) M-P-R Grouping; **(b)** L-M-N Grouping

5.5.1.4 Discussion on Water Absorption

The samples used for water absorption tests were 28 day old samples. Hence, it is mainly the porosity of the samples at 28 days that would govern the water absorption. When the hydration processes of different mixtures are compared, the hydration process of OPC is the fastest, followed by APC and HVFA. Hence by the age of 28 days, the degree of pore structure filling by C-S-H gel and other hydrated products would decreases in the order of OPC, APC and HVFA, and as a result water absorption increases in the same order. Among APC mixtures derived from fly ash, namely L, M and N, the mixture L has the highest proportion of lime, and probably there might be unreacted excess lime by the age of 28 days. When immersed in water, unreacted lime can get washed away making it porous. As a result among APC mixtures, water absorption of the mixture L is greater than that of the others. APC mixtures M and P, are derived according to the same formula but using different pozzolanic materials, namely fly ash and slag. Compressive strength results of M and P indicate that their strengths are similar. Hence probably their hydration processes, formation of C-S-H and filling of pore structure by C-S-H are similar. As a result water absorption of APC mixtures M and P are similar. When the w/c ratio of mixtures are concerned, obviously for a given mixture, samples having w/c ratio of 0.4 will be more porous than those having w/c of 0.3, and hence water absorption would be greater in samples having w/c of 0.4, than those of 0.3. Where curing conditions are concerned, water curing help to produce more hydrated products, and hence for a given mixture, a greater part of the pore structure would be filled by hydrated products in water cured specimens. As a result water cured samples become less porous than air cured samples, hence water absorption is less in water cured specimens.

5.5.2 Sulphuric Acid Attack

5.5.2.1 Percentage weight changes

For the purpose of comparison, percentage weight changes were computed according to the formula given in Section 5.4.2, and organised using the three groupings M-C-R, L-M-N, and M-P described above, and graphically presented in **Fig. 5.9**, **Fig. 5.10** and **Fig. 5.11**. In those figures solid lines were used to represent mixtures having w/c=0.3, while dashed lines were used to represent mixtures having w/c=0.4.

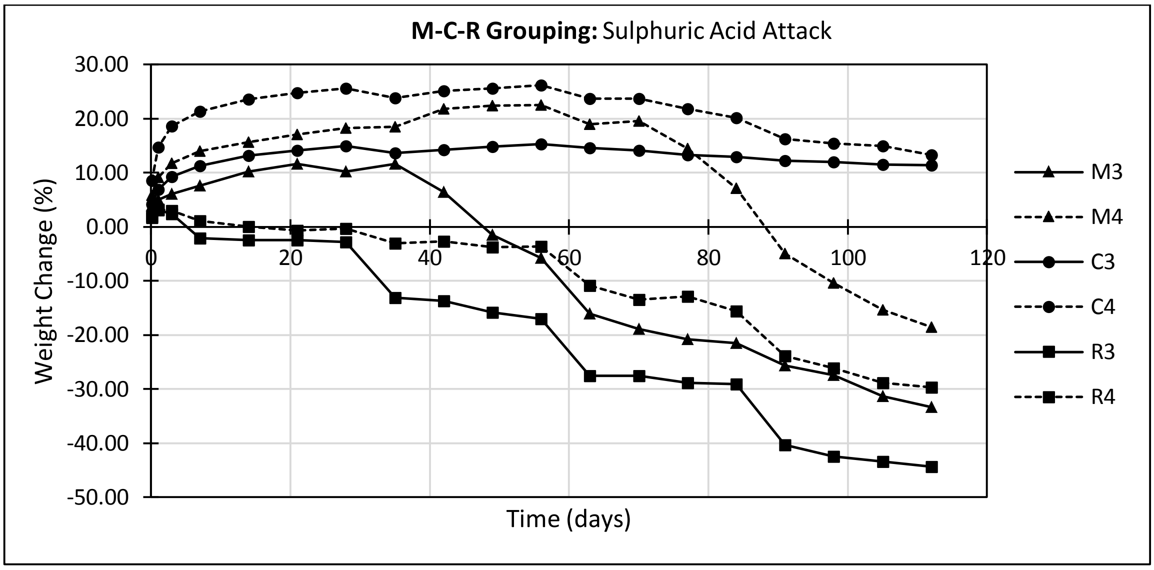


Fig. 5.9 Percentage Weight Changes of Mixtures M, C and R

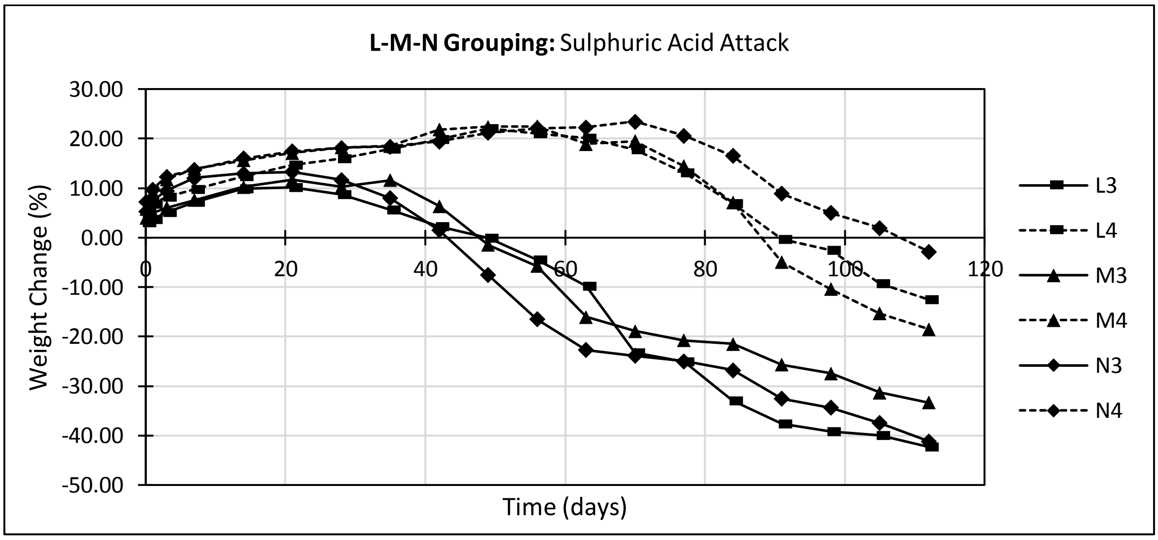


Fig. 5.10 Percentage Weight Changes of Mixtures L, M and N

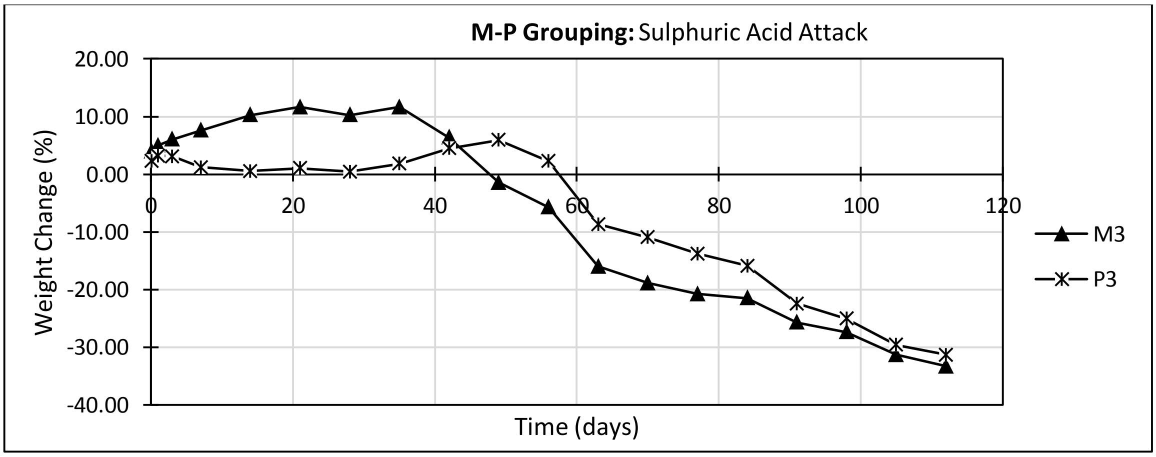


Fig. 5.11 Percentage Weight Changes of Mixtures M and P

Fig. 5.9 indicates percentage weight changes of the APC mixtures (M3 and M4), comparable HVFA mixtures (C3 and C4) and reference OPC mixtures (R3 and R4). These mixtures can be grouped as high weight loss (R3 and R4), medium weight loss (M3 and M4) and 'no weight' loss (C3 and C4), considering the positions of the curves at the end of the period. In each of the above groups the w/c=0.4 curves (C4, M4 and R4), fall above the w/c=0.3 curves (C3, M3 and R3). The results indicate that for a given mixture, when w/c ratio increases the weight loss reduces. This is consistent with the results of Fattuhi and Hughes (1988) who investigated sulphuric acid attack on samples made of cement pastes having different w/c ratios. Another significant feature that can be noticed is the marked weight losses during the periods from 28-35, 56-63 and 84-91 days in OPC mixtures R3 and R4, which occurred just after the replenishment of acid at 28, 48 and 84 days. **Fig. 5.10** presents the weight loss curves of different APC mixtures L, M and N. In that figure, it is very clearly seen that there are two distinct clusters which represent mixtures of w/c=0.3 (L3, M3 and N3) and w/c=0.4 (L4, M4 and N4). This implies that the effect of w/c overrides any differences in variability among APC mixtures. **Fig. 5.11** presents weight loss curves of APC mixtures derived according to same formula, but using different pozzolanic materials, namely fly ash (M3) and slag (P3). There is hardly any difference between these two curves at the end of the period.

5.5.2.2 Visual Observations on Sulphuric Attack

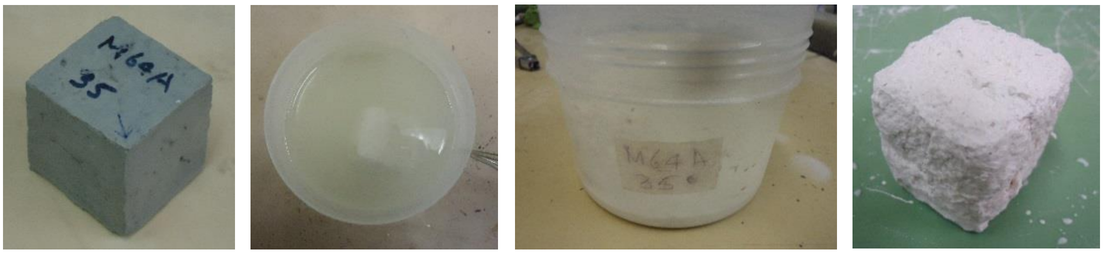
Based on the visual observations, acid attack on samples can be categorised as below.

1. Samples made of APC derived from fly ash (mixtures L3, L4, M3, M4, N3, N4)
2. Samples made of APC derived from slag (mixture P3)
3. Samples made of HVFA (mixtures C3, C4)
4. Samples made of OPC (mixtures R3, R4)

Typical samples from each category are shown in **Fig. 5.12** to **Fig. 5.15**. In those figures, the first one is a photograph of the sample taken after immersing 1 hour and the last one is a photograph of the sample after immersing 112 days. The other photograph shows the container with acid at 112 days.

(a) (b) (c)

Fig. 5.12 Sulphuric attack on a sample of APC mixture M3
(a) Sample after immersing 1 hr; **(b)** The container with the sample at 112 days;
(c) sample after immersing 112 days

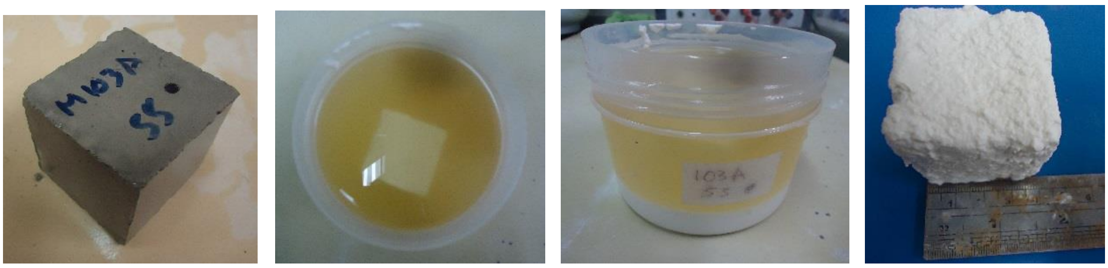


(a) (b) (c) (d)

Fig. 5.13 Sulphuric attack on a sample of APC mixture P3
(a) Sample after immersing 1 hr; **(b)** The container with the sample at 112 days;
(c) Whitish deposits in the container after 112 days **(d)** sample after immersing 112 days

(a) (b) (c)

Fig. 5.14 Sulphuric attack on a sample of HVFA mixture C3
(a) Sample after immersing 1 hr; **(b)** The container with the sample at 112 days;
(c) sample after immersing 112 days



(a) (b) (c) (d)

Fig. 5.15 Sulphuric attack on a sample of OPC mixture R3
(a) Sample after immersing 1 hr; **(b)** The container with the sample at 112 days;
(c) Whitish deposits in the container after 112 days **(d)** sample after immersing 112 days

Typical pictures of samples made of APC derived from fly ash are shown in **Fig. 5.12**. The following observations can be noted. Sulphuric acid, which was a clear colourless solution, got foggy (transparent whitish-grey) over the time due to reaction with samples and contamination with hydrated products. Samples got soft due to acid attack and small pieces got separated from the samples. However, there were distinct differences in observations of acid attack on the samples made of APC derived from slag and those made of fly ash. Typical pictures of samples made of APC derived from slag are given in **Fig. 5.13**. As seen in the pictures, the sulphuric acid got foggy; however, the colour was not greyish, but whitish. The samples which were grey in colour before immersion, had become totally white as the result of acid attack. Samples became soft due to acid attack and small pieces separated from the samples. In addition a very fine white powder/cream was formed and deposited in the container. Observations of acid attack on HVFA samples were quite different. Typical pictures of HVFA samples are shown in **Fig. 5.14**. Unlike in the cases of APC, the acid solution did not get very foggy. Although it was greyish, it was quite transparent, and hence can be considered as clear. It seems that the damage to the samples was minimum (almost no damage). No pieces were separated from the samples. Only lightly bonded hydrated products and fly ash particles of the surface of the samples had been separated. Other than that no deposits can be seen in the container. The observations of acid attack on OPC samples were quite different from all others. Typical pictures of OPC samples are shown in **Fig. 5.15**. The acid solution got very foggy, and the colour of acid got yellowish-white. The colour of the samples which were grey before immersion, had become totally white over the period of time. Acid attack did not separate pieces from the sample, but the material had been taken away layer by layer (peeled) from the sample. Hence the shape of the sample remained same, but the size of the cube was reduced significantly. As result of peeling of layers, in 16-week time 50x50x50 mm cube reduced to a smaller cube, the size of which was less than 40x40x40 mm. That indicates over 50% volume reduction. Further it was seen that a very fine white powder/cream had been formed and deposited in the container.

When sulphuric acid attack was compared across the mixtures, following can be stated. Sulphuric acid got foggy over the time. However, it was least foggy (or not foggy) in the case of HVFA, somewhat foggy in APC, and extremely foggy in the case of OPC. When damage to the samples are concerned, again there was least damage (or no damage) to HVFA, moderate damage to APC, but relatively high damage to OPC samples. Accordingly, it can be concluded that, when resistance to sulphuric acid attack is concerned HVFA performs best, then APC and OPC is the last.

5.5.2.3 Discussion on Sulphuric Acid Attack

In order to analyse the results of sulphuric acid attack, it is essential to understand the underlying mechanisms. Hence, first, those mechanisms are briefly described and thereafter discussion is presented.

The samples immersed in sulphuric acid solution were mature samples, which were one-year old. Hence, it can be assumed that hydration process had been completed to a greater extent. Hydrated cement contains C-S-H (hydrated products of C_3S, C_2S, and also products of pozzolanic reaction), $C_3A.H_{12}$ (hydrated product of C_3A) and $Ca(OH)_2$ (released from hydration process of OPC or from added lime). Sulphuric acid reacts with these products in two main stages as described in Section 5.3.2.

Formation of gypsum in stage I causes volumetric expansion, and also make the samples soft. In stage II, formation of ettringite is characterized by significant volumetric expansion. Hence, when there is no space to accommodate the ettringite formed, expansive stresses are exerted on the internal structure that leads to cracking and/or peeling. Accordingly, for a given sample, the damage due to sulphuric acid attack mainly depends on 3 factors.

1. Quantity of $C_3A.H_{12}$
2. Quantity of $Ca(OH)_2$
3. Volume of pore structure available to accommodate the expansive products formed.

Initial weight increase and subsequent weight loss

In the first stage, H_2SO_4 reacts with available $Ca(OH)_2$ and forms gypsum ($CaSO_4.2H_2O$), which causes weight and volume increase. Molecular weights of $Ca(OH)_2$ and $CaSO_4.2H_2O$ are 74 and 172 respectively; hence the reaction causes a 232% weight increase. Only part of the gypsum may be leached out, hence there is a net weight gain. In the second stage, the gypsum formed reacts with $C_3A.H_{12}$ and forms ettringite, which also causes volume expansion. Hence formation of ettringite causes expansive stresses on the internal structure that leads to cracking and/or peeling. As a result substances separate from the sample and hence the weight of samples decrease. As this process continues, weight loss too would continue.

Effect of w/c ratio

The results indicate that for a given mixture, when w/c ratio increases the weight loss reduces. For a given mixture, when w/c increases, the OPC content per volume decreases, hence contents of C_3S, C_2S and C_3A per volume too decrease. As a result, hydrated products such as $C_3A.H_{12}$, CSH and $Ca(OH)_2$ released during hydration process also decrease. Therefore, subsequent formation of gypsum and ettringite too decreases, hence damage to samples decreases. Abdelmseeh, Jofriet and Hayward (2008) too had given similar interpretation for decrease of damage due to sulphuric attack with the increase of w/c. Moreover, when w/c ratio increases, samples become more porous, hence there will be more voids for expansive ettringite to expand into, rather than causing expansive stresses on the internal structure that leads to damage of samples. In conclusion, for a given mixture, when w/c ratio increases the quantity of gypsum and ettringite formed decreases, and the volume of pore structure increases; hence, damage caused to the sample decreases. These could be the reasons for lower weight loss (less damage) for the samples of w/c=0.4 than that of w/=0.3 for a given mixture in **Fig. 5.9** and **Fig. 5.10**.

Comparison of APC, HVFA and OPC

The results indicate that OPC samples (R3 and R4) experience heavy weight losses and APC samples (M3 and M4) experience moderate weight losses, while HVFA samples (C3 and C4) do not experience any weight loss. HVFA constitutes only 30% OPC, hence samples would have less quantity of $C_3A.H_{12}$. Also the $Ca(OH)_2$ released from OPC during hydration process would be less; and that would have been consumed by fly ash, by the time of immersion of samples. Hence subsequent formation of ettringite would be less and formation of gypsum would be null or minimum. Further, HVFA samples are more porous (based on water absorption results), hence there could be voids for ettringite to expand into. Hence no expansive stresses would be exerted on the internal structure, and no damage caused to HVFA samples with no weight losses experienced. APC too constitutes only 30% OPC and hence samples have less $C_3A.H_{12}$

quantity. Hence subsequent formation of ettringite would be less. Even though APC has added lime, a greater part of it might have been consumed by fly ash; yet there could be unreacted free $Ca(OH)_2$, and that could have reacted with H_2SO_4 and formed gypsum. Also APC samples are not as porous as HVFA samples (based on strength results and water absorption results), but more porous than OPC samples. Hence APC samples experienced moderate damage and weight loss. OPC samples have a comparatively large quantity of $C_3A.H_{12}$. Further quantity of $Ca(OH)_2$ released during the hydration process could be substantial. Hence subsequent formation of gypsum and ettringite would be high. Further, OPC samples were less porous, hence expansive reactive products exert expansive stresses on the internal structure and damage the samples, leading to severe weight losses. Accordingly, 'damage to the samples' will increase in the order of HVFA, APC and OPC.

Comparison of different APC mixtures L, M and N

In APC mixtures L, M and N, have 30% OPC, but different lime contents. Hence APC samples L, M and N too would have the same quantity of $C_3A.H_{12}$. So, subsequent formation of ettringite would be approximately the same. As a result, for a given w/c the damage caused by expansive ettringite was approximately the same and resulting weight losses were similar. However, when w/c ratio increases, samples become more porous hence the damage (weight loss) of each APC mixture is reduced.

Comparison of APC mixtures derived from fly ash and slag

APC mixtures M3 and P3 were derived according to a same formula, by mixing the same percentages of pozzolanic materials, lime, OPC and activators. However, pozzolanic material of M is fly ash, while that of P is slag. Hence APC samples M3 and P3 have same quantity of $C_3A.H_{12}$. So subsequent formation of ettringite would be approximately the same. Hence the damage caused by expansive ettringite was approximately the same and resulting weight losses were similar.

5.5.3 Sodium Chloride Penetration

5.5.3.1 Chloride ion penetration depths

Fig. 5.16 depicts the chloride ion penetration depths of air cured and water cured samples of APC mixture M3, HVFA mixture C3 and OPC mixture R3. **Fig. 5.17** shows the penetration depths of water cured samples of all mixtures.

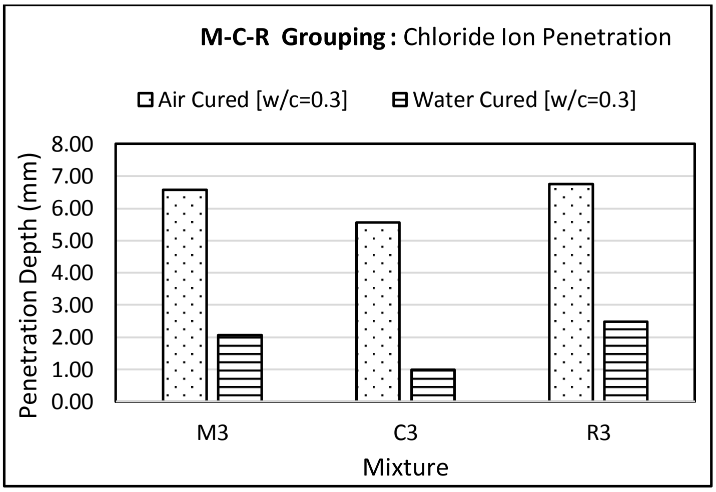


Fig. 5.16 Chloride Penetration Depths of Air and Water Cured Samples

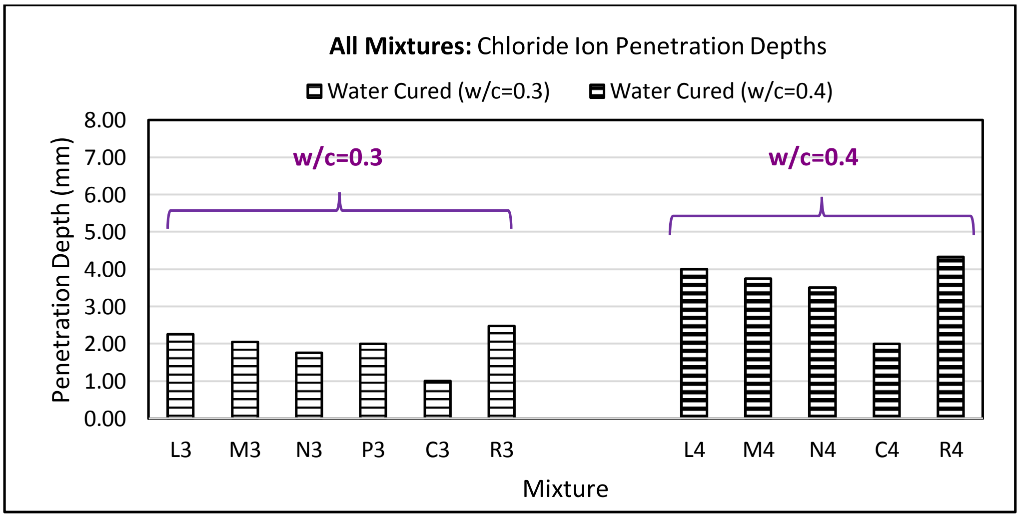


Fig. 5.17 Chloride Penetration Depths of Water Cured Samples

Fig. 5.16 indicates that air cured samples of M3, C3 and R3 have greater penetration than those of water cured samples. In other words, water curing has enhanced chloride ion resistance. Under both curing conditions, specimens made of comparable mixture

C3, which is an HVFA mixture, have the least penetration depths. For both air curing and water curing, samples of APC mixture M3 and OPC mixture R3 have similar penetration depths. In **Fig. 5.17**, which is about water cured samples, L3, M3 and N3 are three different APC mixtures derived from fly ash with w/c=0.3, and their respective mixtures with w/c=0.4 are L4, M4 and N4. APC mixtures M3 and P3 were derived according to same formula and w/c of 0.3, but using different pozzolanic materials, namely fly ash and slag. HVFA mixtures of w/c=0.3 and 0.4 are C3 and C4; respective OPC mixtures are R3 and R4. According to **Fig. 5.17**, it is very clear that the samples with w/c=0.4 have higher penetration depths than samples with w/c=0.3. Further, under each w/c ratio, specimens made of HVFA have the least penetration depths. Also under each w/c, APC samples and OPC samples have similar penetration depths. So, it can be concluded that when w/c ratio increases the penetration depth also increases. Further, HVFA samples have the least penetration compared to OPC and APC. These results are consistent with the investigations done by some other researchers as well. Collepardi, Marcialis and Turriziani (1972) reported that pozzolanic cement paste has higher chloride resistance than OPC paste, and depth of chloride ion penetration of OPC can be 3 times larger than that of pozzolanic cements. Meck and Sirivivatnanon (2003) used concrete samples made of OPC and OPC-fly ash blended cements, and the results indicated that chloride penetration depths of OPC were greater than those of blended cements. Somna et al. (2012) obtained similar results from samples made of OPC and OPC - ground bagasse ash. Chindaprasirt, Rukzon and Sirivivatnanon (2008a) used mortar samples made of OPC and OPC-fly ash blended cements and the results indicated that penetration depths could be reduced by adding fly ash. However, when samples exposed to high CO_2 environment were tested, it was seen that chloride penetration depths of blended cement had increased.

5.5.3.2 Sensitivity to w/c ratio on chloride ion penetration

The concept of ‘sensitivity index’ was used to investigate the sensitivity to w/c ratio on chloride ion penetration, and it is defined as below.

$$Sensitivity\ Index\ (SI) = \frac{d_{test} - d_{ref}}{d_{ref}} = \frac{d_{test}}{d_{ref}} - 1$$

where, d_{test} - chloride ion penetration depth of the test samples (with w/c =0.4)
d_{ref} - chloride ion penetration depth of the reference samples (with w/c=0.3)

Accordingly, sensitivity to w/c ratio on chloride ion penetration of a particular mixture was computed by dividing the chloride ion penetration depth of samples prepared with w/c = 0.4 by the chloride ion penetration depth of samples prepared with w/c=0.3, and deducting unity from this ratio. If the sensitivity index is ‘0’, it indicates that there is ‘no sensitivity’; the deviation from ‘0’ (whether positive or negative) indicates the degree of sensitivity. The results are graphically presented in **Fig. 5.18**.

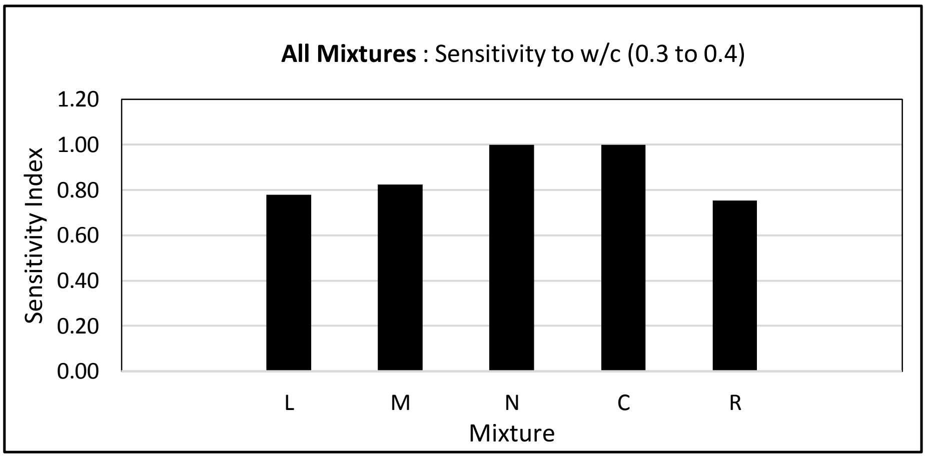


Fig. 5.18 Sensitivity to w/c ratio on Chloride Ion Penetration

According to **Fig. 5.18** the mixture N, which was the APC mixture with largest proportion of fly ash, and HVFA mixture C, which also has the highest overall percentage of fly ash, were more sensitive to w/c ratio than other mixtures. The targeted APC mixture M was less sensitive than HVFA mixture C with respect to chloride ion penetration.

5.5.3.3 Discussion on Sodium Chloride Ion penetration

The depth of penetration of chloride ions into specimens is governed by many factors, such as porosity, tortuosity, permeability, diffusion capacity and ion exchange capacity. When the specimens are porous and have voids, chloride ions intrude into samples easily, and ‘absorption’ would be a major criterion governing the penetration. However, if the voids have been filled with water, then there will be a resistance for the sodium chloride solution to intrude. In such a case, chloride ions travel from the region of high concentration to that of low concentration through the solution, and the criterion would be ‘diffusion’. Furthermore, the specimens would have unreacted $Ca(OH)_2$; hence, when these samples are immersed in water, the OH^- ions will be released to water. Especially in water cured samples, the pore structure has been filled with water for a long time, and hence, the pore water will be very rich with negatively charged OH^- ions. When the water cured samples were immersed in a NaCl solution, which is rich with negatively charged Cl^- ions, ‘ion exchange’ can happen. That is, OH^- ions in pore water inside the specimen and Cl^- ions in the surrounding solution exchange their positions; as a result Cl^- ions in the surrounding NaCl solution get into the specimen. When pozzolanic materials are added to mixtures, chloride ion penetration reduces, and the reasons have been explained by numerous researchers as follows. Zhu et al. (2014) state that rate of penetration of Cl^- ions depends on the porosity and tortuosity of the sample. In their research on alkali-activated fly ash (AAFA), when 20%-40% fly ash was substituted by slag, the size of pores had been reduced and tortuosity had been increased. The reason may be the differences in size and shape of two materials. Hence it can be assumed that mixing of OPC with fly ash too would reduce pore size and increase tortuosity, as finer and smaller fly ash particles can segment pores created by larger OPC particles. Chindaprasirt, Rukzon and Sirivivatnanon (2008b, 2008a) state that introduction of fly ash exerts a dispersing effect on cement particles and creates larger number of nucleation sites increasing hydration products and reducing $Ca(OH)_2$; as a result the resistance to Cl^- ion penetration improves. In the light of the above mentioned information, the results can be interpreted as below:

- Air cured samples of APC, HVFA and OPC have greater penetration than those of water cured samples. Chloride ion penetration of air cured samples are governed initially by absorption, and thereafter by ion exchange; while penetration of water cured samples are governed initially by diffusion, and thereafter ion exchange. The combined effect of absorption and ion exchange seems to be more effective than that of diffusion and ion exchange.

- When APC, HVFA and OPC samples were compared, HVFA has the least penetration, both in air cured and water cured samples. The reason could be that HVFA comprises only OPC and fly ash, but no added lime. The $Ca(OH)_2$ released during hydration reacts with fly ash and forms C-S-H; hence the free-$Ca(OH)_2$ was either very much less or non-existent. Hence, OH^- concentration in pore water becomes less, and resulting ion exchange becomes less. Also, addition of fly ash makes samples more tortuous, obstructing the penetration.

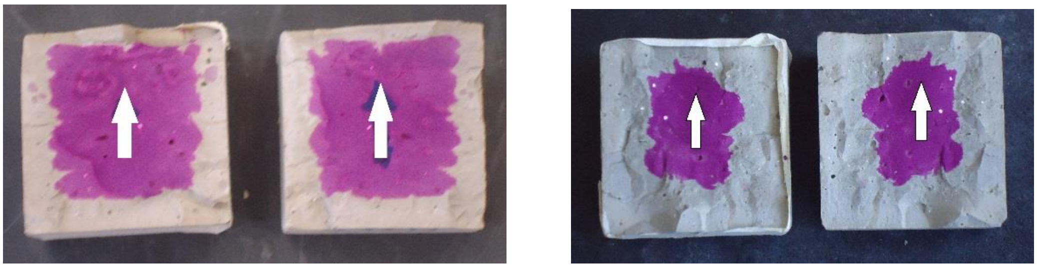
- When water cured APC samples having different proportions of fly ash were considered, it is seen that when proportion of fly ash increases the depth of penetration decreases. In APC mixtures L, M and N, the proportion of fly ash increases in that order; hence, complementary portion of lime decreases; as a result the quantity of unreacted $Ca(OH)_2$ decreases; hence, ion-exchange decreases. This pattern can be seen for samples with w/c ratios of 0.3 as well as 0.4.

- The penetration depth pattern in OPC, APC and HVFA mentioned above can be seen for water cured samples with w/c ratios of 0.3 as well as 0.4. However, relevant depths were greater when w/c ratio is 0.4 than those of 0.3. When w/c ratio increases porosity increases. Hence porosity of samples having w/c ratio of 0.4 is greater than the porosity of samples having w/c ratio of 0.3. When those samples were water cured, water retained by samples with w/c ratio of 0.4 will be greater than samples of w/c of 0.3. Hence, diffusion and ion exchange is higher in the samples prepared with higher w/c ratio.

5.5.4 Carbonation

5.5.4.1 Carbonation depths

Typical split sections of specimens at 1 and 3 months after applying phenolphthalein are shown in **Fig. 5.19**. The top or troweled faces are indicated by the direction of arrows.



(a) **(b)**

Fig. 5.19 Split sections of samples of APC mixture N3
(a) at 1 month; (b) at 3 months

As the samples used were 50mm cubes, when carbonation depths of two opposite sides reach 25 mm, the whole specimen gets fully carbonated. Hence using 50mm cubes, carbonation depths of only up to 25 mm could be determined. Samples of some mixtures got fully carbonated in 3 months as shown in **Fig. 5.20**, hence they were not considered in further analysis.

Fig. 5.20 Split sections of fully carbonated sample of HVFA mixture C3

The **Fig. 5.21** presents carbonation depths related to different mixtures at 1 and 3 months. In this figure, carbonation depths of samples made with w/c of 0.3 and 0.4 from a particular mixture are presented as couples. The fully carbonated depth is indicated by the dashed line.

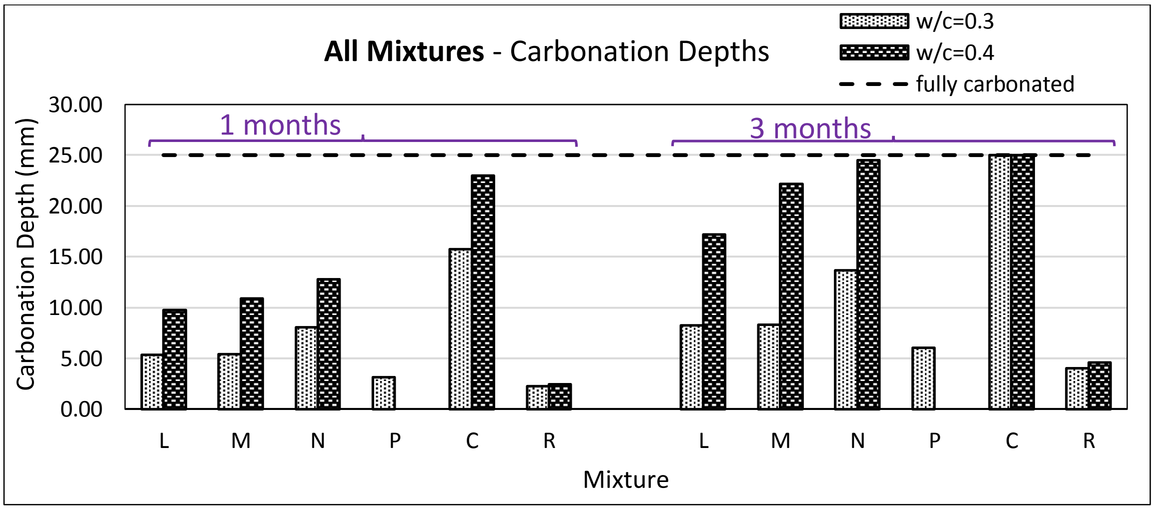


Fig. 5.21 Carbonation depths of all mixtures at 1 and 3 months

According to **Fig. 5.21**, both at 1 and 3 months, the most carbonated samples were those made of HVFA mixture C, and the least carbonated sample were those made of OPC mixture R, while samples of APC mixtures L, M, N and P lie in between. None of the samples were fully carbonated in 1 month. However, by 3 months' time, samples of

HVFA mixture C prepared with w/c of 0.3 as well as 0.4 had got fully carbonated. APC mixture N too almost got fully carbonated. It is very clear that, carbonation depths of w/c = 0.4 were greater than those of w/c = 0.3 in all mixtures. When APC mixtures L, M and N are compared, the proportion of fly ash increases in that order, and **Fig. 5.21** shows that depths of carbonation too increase in the same order. This pattern can be seen at both 1 month and 3 months. When APC mixtures derived from fly ash (mixture M) and that derived from slag (mixture P) are considered, it is seen that carbonation depth of P was less than that of M, both at 1 and 3 months.

The **Fig. 5.22** gives the 'depth increase ratio', which is the ratio between carbonation depths at 3 months to 1 month.

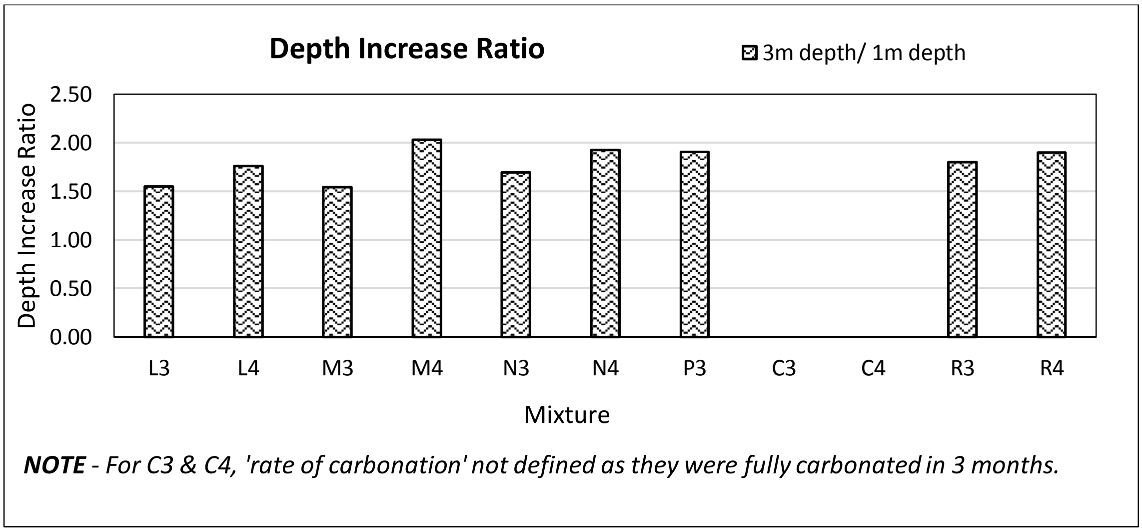


Fig. 5.22 Rate of Carbonation for all mixtures

According to **Fig. 5.22**, it is seen that, for all the mixtures, the 'depth increase ratio' falls between 1.50 and 2.00, and generally close to 1.7.

According to the 'square root of time theory' given in Section 5.3.4, when samples are exposed to a constant relative humidity and temperature, the depth of carbonation is given by following equation.

$$D = k.(t)^{1/2}$$

Where 'D' is carbonation depth,'t' is time of exposure and 'k' is the carbonation coefficient.

By employing the above equation at 1 and 3 months, following relationship can be derived

$$D_3/D_1 = (t_3/t_1)^{1/2} = (3/1)^{1/2} = 1.732 \approx 1.7$$

Hence, the 'depth increase ratio' being around 1.7 endorses the 'square root of time theory'.

5.5.4.2 Sensitivity to w/c ratio on carbonation

Sensitivity to w/c on carbonation was investigated using the concept of 'sensitivity index', which is defined as below.

$$Sensitivity\ Index\ (SI) = \frac{d_{test} - d_{ref}}{d_{ref}} = \frac{d_{test}}{d_{ref}} - 1$$

where, d_{test} - Carbonation depth of the test samples (with w/c =0.4)
d_{ref} - Carbonation depth of the reference samples (with w/c =0.3)

Accordingly, sensitivity to w/c ratio on carbonation depth of a particular mixture was computed by dividing the carbonation depth of samples prepared with w/c = 0.4 by the carbonation depth of samples prepared with w/c=0.3 and deducting unity from this ratio. If the sensitivity index is '0', it indicates that there is 'no sensitivity'; the deviation from '0' (whether positive or negative) indicates the degree of sensitivity. The results are graphically presented in **Fig. 5.23**.

As HVFA mixtures were fully carbonated in 3 months, sensitivity to w/c ratio of HVFA at 3 months could not be calculated, and hence it is not indicated.

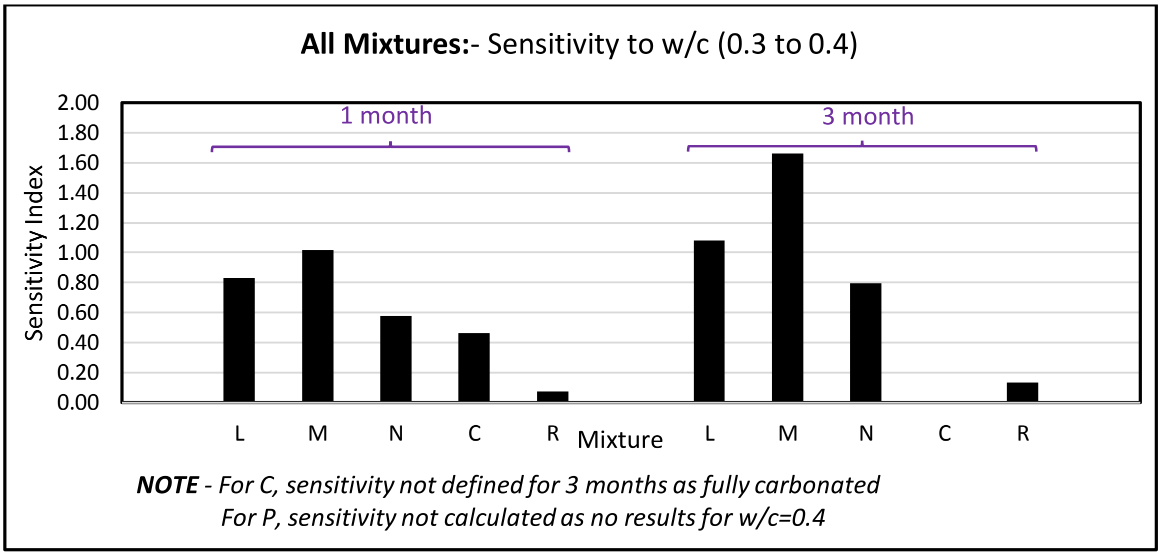


Fig. 5.23 Sensitivity to w/c for Carbonation

It is seen that sensitivity to w/c is greater at 3 months than at 1 month in all mixtures. It is also seen that APC mixtures, L, M and N as well as HVFA mixture C are more sensitive than OPC.

5.5.4.3 Discussion on Carbonation

HVFA constitutes only OPC and fly ash, but no added lime. The $Ca(OH)_2$ released during the hydration process reacts with fly ash and produces C-S-H. Hence in HVFA samples, the free $Ca(OH)_2$ is very much less. Also HVFA samples are more porous than OPC and APC samples (based on water absorption results). Hence, CO_2 can penetrate the HVFA samples more easily. Thus, the limited $Ca(OH)_2$ in HVFA samples get carbonated quickly. In the case of OPC, the free $Ca(OH)_2$ available within the samples is greater. Further OPC samples are less porous than APC and HVFA samples; hence CO_2 cannot penetrate OPC samples so easily. Thus it takes a longer time for $Ca(OH)_2$ in OPC samples to get fully carbonated. Conditions in APC fall in between HVFA and OPC; hence the carbonation results too reflect a median position. Thus resistance to carbonation decreases in the order of OPC, APC and HVFA. This is consistent with the results of other researchers who noted the decrease in resistance to carbonation with addition of fly ash (Atiş 2003; Rozière, Loukili and Cussigh 2009)

Among APC mixtures L, M and N, the fly ash content increases, and lime content decreases, in that order. Lime available would react with fly ash and produce C-S-H during the hydration process; hence, free $Ca(OH)_2$ content also decreases in the same order. When the free $Ca(OH)_2$ in a sample is less, it gets carbonated quickly. Thus resistance to carbonation decreases in the same order (L>M>N).

For a given mixture, when w/c ratio increased, it is seen that carbonation depth has increased, and this is consistent with other researchers as well (Matsuzawa, Kitsutaka and Tsukagoshi 2010). There are two reasons for this. Firstly, when w/c ratio increases, content of cementitious components (C_3S, C_2S, and also added lime and fly ash) per unit volume decreases. Hence, the quantity of free $Ca(OH)_2$ contributed by lime and $Ca(OH)_2$ released during hydration of C_3S and C_2S, would be less. Further, when the w/c ratio increases, the porosity increases (based on water absorption results). The lower quantity of $Ca(OH)_2$ and more porous structure make the samples get carbonated easily.

5.6 Conclusions

This chapter presented the third stage of the research, which focused on durability of different practical APC mixtures. Here durability properties were investigated through selected tests, namely, water absorption of relatively young (28 day old) specimens, sulphuric acid attack on mature (1 year old) specimens, sodium chloride ion penetration of mature (1 year old) specimens and carbonation of mature (1 year old) specimens. Based on the experimental results presented in this chapter, the following conclusions can be drawn:

1. Resistance to water absorption of APC mixture M was greater than that of HVFA Mixture C, but slightly less than that of OPC mixture R. The reason is that the hydration process of APC is faster than that of HVFA, but slower than OPC. Therefore, the degree of pore structure filling by C-S-H would decrease in the order of OPC, APC and HVFA, and porosity decreases in the same order. Among fly ash-based APC samples, water absorption of the mixture L was the greatest. The reason could be that it has the greatest proportion of lime, and unreacted lime would get leached away, thus making samples more porous. Water absorption of APC

mixtures derived from fly ash and slag are similar. The reason would be that their porosities are similar due to similar hydration processes.

2. The Sensitivity to w/c ratio for water absorption of APC mixture M is slightly less than that of HVFA mixture C and OPC mixture R. The reason could be that the lime in APC could contain CaO in addition to $Ca(OH)_2$. Then some of the excess water would react with CaO to form $Ca(OH)_2$, which would also be involved in pozzolanic reactions, rather than increasing the porosity. Hence, a slight increase of w/c would not increase water absorption of APC to a greater extent as in the cases of HVFA and OPC. Sensitivity to w/c of APC mixture N is clearly higher than that of APC mixtures L and M, under both curing conditions. Of the APC mixtures, mixture N has the least quantity of lime; hence, it needs less water than the others for the hydration process. Excess water would increase porosity, and sensitivity to w/c for water absorption would be higher in N than in others.

3. Resistance to sulphuric acid attack of APC samples was greater than that of OPC samples, but less than that of HVFA samples. APC and HVFA samples have only 30% of OPC, and therefore have less C_3AH_{12} than OPC samples. Therefore, the subsequent formation of expansive ettringite would be less than that in OPC. Even though APC and HVFA have the same quantity of C_3AH_{12}, the ettringite formed would expand into the relatively larger pore structure of HVFA without exerting expansive stresses on the internal structure and damaging the sample. As a result, even though damage caused to APC samples is less than that of OPC, it is greater than that of HVFA. Resistance to sulphuric acid attack of fly ash-based APC mixtures L, M and N and slag-based APC mixture P as are similar, because both groups have the same quantity of C_3AH_{12}.

4. When sensitivity to the w/c ratio for sulphuric acid attack was considered, it was seen that in all mixtures, the damage due to sulphuric attack was higher in the samples made with w/c=0.3 than with w/c=0.4. The reason is that when w/c ratio increases, samples become more porous, thus providing more room for ettringite to expand into; hence, the damage cause by expansive stresses becomes less.

5. Resistance to the sodium chloride ion penetration depth of APC samples was greater than that of OPC samples, but less than that of HVFA samples. Both APC and HVFA samples have OPC and fly ash, and differences in the size and shape of the two materials make the paste structure more tortuous, obstructing the penetration of chloride ions. Also, OPC samples have free OH^- ions due to $Ca(OH)_2$ released during the hydration process while APC samples have free OH^- ions due to the added lime; hence, chloride ion penetration occurs through ion exchange in those samples. However, in HVFA, the greater part of $Ca(OH)_2$ released during hydration gets involved in pozzolanic reactions, and hence the free-$Ca(OH)_2$ is either very much less or non-existent. Hence, chloride ion penetration through ion exchange becomes less. As a result, the depth of chloride ion penetration decreases in the order of OPC, APC and HVFA. In APC mixtures L, M and N, the proportion of lime decreases in that order; and as a result, free OH^- ions decrease. Hence, chloride penetration through ion-exchange decreases in the same order.

6. When sensitivity to w/c ratio for sodium chloride ion penetration is considered, it is seen that sensitivities are greatest in HVFA sample C and APC sample N. In HVFA mixture C and APC mixture N, the quantity of $Ca(OH)_2$ is less, and hence water consumed in pozzolanic reactions is also less. Therefore, a greater part of excess water would increase porosity, rather than being involved in hydration reactions. As a result, sensitivity to w/c of those samples becomes significantly high.

7. Resistance to carbonation of APC samples is greater than that of HVFA samples, but less than that of OPC samples. HVFA samples are more porous than OPC and APC samples, and have less free $Ca(OH)_2$ than OPC and APC samples. Hence, CO_2 penetrates easily and the limited $Ca(OH)_2$ gets carbonated sooner which means that the carbonated region deepens quickly. On the other hand, OPC samples are less porous, and have more free $Ca(OH)_2$; hence, the carbonated region deepens slowly. Conditions in APC fall in between HVFA and OPC; hence, the carbonation results also reflect a median position. Thus, resistance to carbonation decreases in the order of OPC, APC and HVFA. In fly ash-based APC samples L, M and N, the free $Ca(OH)_2$ decreases in that order, and depth of carbonation increases in the same order. Slag based-APC samples are less porous than fly ash-based APC samples. Further, they have more free $Ca(OH)_2$ (since slag has more CaO than fly ash). As a

result, resistance to carbonation is greater in the slag based-APC sample P, than in fly ash-based ones.

8. When sensitivity to w/c ratio on carbonation is considered, it is seen that for all mixtures, sensitivity is greater at 3 months than at 1 month. It is also seen that APC and HVFA samples are more sensitive than OPC ones. Initially, all samples have a relatively high quantity of free $Ca(OH)_2$. However, with time, free $Ca(OH)_2$ decreases due to the carbonation process and also due to pozzolanic reactions (in APC and HVFA samples). Therefore, with the passage of time, the remaining limited $Ca(OH)_2$ is carbonated faster in more porous samples than in less porous ones. Hence, in all samples sensitivity to w/c is higher at 3 months than at 1 month. APC and HVFA samples are more porous than OPC ones, and when w/c increases, their porosity increases further. Hence, sensitivity to w/c of APC and HVFA is greater than that of OPC.

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6 Ecological and Financial Costs of APC

Overview

This chapter presents a comparison of the ecological and financial costs of different Alkali Pozzolan Cement (APC) mixtures with High Volume Fly Ash (HVFA) cement and Ordinary Portland Cement (OPC). In this study, only two of the main aspects of ecological cost were considered, namely, the energy required to produce cementitious mixtures, and carbon dioxide emitted during the production of mixtures. The energy consumption and carbon dioxide emission were calculated per unit weight of dry cement powder, and also per unit volume per unit strength of hydrated hardened cement. Then the mixtures were grouped according to their compositions, namely, fly ash-based APC, slag-based APC, HVFA and OPC. The statistical means and variability values of the energy and carbon dioxide emission were computed. The results indicate that the ecological and financial costs of APC are much less than those of OPC, when considered either as the cost per weight or cost per unit volume per unit strength of hydrated paste.

***Keywords**: ecological cost, financial cost, embodied energy, carbon dioxide emission*

6.1 Introduction

'Alkali Pozzolan Cement' (APC) is an alternative cement developed in this research. In Chapter 3, the design and development of APC were presented. Chapter 4 presented the structural and microstructural properties of APC mixtures, while the durability properties of APC mixtures were examined in Chapter 5. This chapter focuses on the ecological and financial costs of APC, and compares these with the costs of High Volume Fly Ash (HVFA) cement and Ordinary Portland Cement (OPC) mixtures.

The popular meaning of the term 'cost' is limited to the 'monetary value' or 'financial cost'. Hence, generally, the cost of a product means the financial cost of that product. However, when it comes to the discourse of sustainability, the 'ecological cost' is more important, as the 'financial cost' does not represent a correct picture of the ecological damage done by the product. Furthermore, ‘financial cost’ is a context-dependent and time-dependent entity; hence, it fluctuates continuously. For example, financial costs of a product can go upside down overnight through the introduction of a new tax, even though its quality has not been changed. Moreover, the ‘financial cost’ depends on the cost of raw materials, machinery and labor; hence, it can vary from context to context and time to time. On the other hand, the ‘ecological cost’ of a product gets changed only if the ecological damage associated with that product is changed; it also does not depend on the cost of resources, labor or tax; hence, it is not time- or context-dependent. Therefore, ecological cost can be considered as a universal measure related to a product and process. However, financial cost should not be underestimated, as it is a major consideration when it comes to marketing a product. Even though the ecological cost of a product is low, it may become unmarketable if its financial cost is too high.

According to the ‘integral sustainability’ philosophy, lower financial cost alone would not make a product ‘integrally sustainable’; its eco-friendliness is a major aspect to be satisfied. This implies the importance of investigating both the financial as well as ecological cost of a new product, in order to make it ‘integrally sustainable’. The aim and objectives presented in this chapter are formulated accordingly.

6.2 Aim & Objectives

The main aim of this chapter is to investigate both the ‘ecological cost’ and ‘financial cost’ of the cementitious mixtures developed in this research. Generally, ecological cost is a very broad term and includes many components. However, in this study, only two of the major components were considered. The first is the energy requirement to produce cementitious mixtures, and the second is the carbon dioxide (CO_2) emission during production of mixtures. Accordingly, after a brief literature review which gives background information on ecological and financial cost, the following objectives are pursued:

1. To investigate the ecological cost with respect to embodied energy of different APC mixtures along with HVFA and OPC mixtures.

2. To investigate the ecological cost with respect to CO_2 emissions of different APC mixtures along with HVFA and OPC mixtures.
3. To investigate the financial cost of different APC mixtures along with HVFA and OPC mixtures.

Further, the above investigations were conducted using the following bases:

(a). Cost per unit weight of dry cement powder

(b). Cost per unit volume of hydrated cement per unit strength

Moreover, the ultimate aim is to compute,

i. Mean values

and

ii. Variability values

of embodied energy, CO_2 emissions and financial cost of different cementitious mixtures on the above bases. The simplest measure of variability is the 'range'. Most common measures of variability are 'variance' and 'standard deviation'. However, it is not uncommon to define different variability measures according to the need; one such measure is 'relative range of variation' which is defined as 'range to mean ratio' (Vincent 2006). In this research, variability was defined as the difference between the upper bound and the lower bound of data, expressed as a percentage of the mean.

To achieve the above aim and objectives, different methods were adopted, namely, literature surveys, market surveys, experimental methods, analytical methods and numerical methods. Embodied energy and CO_2 emission values of constituent materials were determined from available literature surveys, while current prices of constituent materials were determined through market surveys. Strengths and volumes of unit weights of hydrated pastes were determined by experimental methods; finally, all the data were combined and analyzed.

6.3 Literature Review on Ecological and Financial Cost

In order to make a product integrally sustainable, two of the major aspects to be taken into account are the financial and ecological costs. The concept of 'financial cost' is not a complex one, but the concept of 'ecological cost' is a very complex concept that reflects the damage to the ecological sustainability of the planet. When it comes to building construction materials, various yardsticks have been developed to assess the ecological sustainability of materials; there are also guidelines to ensure the ecological sustainability of materials by various institutes and by individuals. The report titled 'Building for Sustainable Future: construction without depletion' published by The Institution of Structural Engineers (1999) emphasizes the importance of taking into account the 'five global consequences' in sustainable decisions, including the selection of construction materials. Accordingly, damage to the ecological sustainability of construction materials can be assessed based on the damage done to these five spheres:

1. Resource depletion
2. Energy depletion
3. Climate change
4. Biodiversity
5. Human health

In order to assess the total environmental impact of a product, it is necessary to perform Life Cycle Assessments (LCA), which can be described as an approach to identify/compare environmental impacts of the production, marketing, transport, distribution, operation and disposal of the product through the whole life cycle or cradle-to-grave lifetime of the product (Environmental Justice Organizations 2014). The main LCA parameters for building materials can be listed as follows (Canadian Architect 2014):

1. Material usage
2. Embodied energy
3. CO_2 emissions
4. Air pollution
5. Solid waste generation
6. Water pollution
7. Other parameters applicable for particular conditions

Certain parameters may be more critical than others for assessing ecological sustainability of products. When it comes to cementitious materials, out of the above parameters, embodied energy and CO_2 emissions, are two common parameters used to compare environmental impact, when comprehensive LCA is not performed. The significance of embodied energy is due to its influence on resource depletion, greenhouse gases (global warming), environmental degradation and reduction of biodiversity. Hence, the measure of embodied energy is considered as a reasonable indicator of the overall ecological impact of building materials, assemblies or systems (Canadian Architect 2014). While embodied energy is an indicator for overall ecological impact, CO_2 emission is an indicator of the contribution towards the global warming. Perhaps because of these reasons, embodied energy and CO_2 emissions are widely considered as parameters in investigations of ecological impact of building materials. Reddy (2009) has taken into account embodied energy and CO_2 emission to investigate sustainability of building materials. Higgins (2006) identified energy consumption and CO_2 emission along with mineral extraction as the three major environmental burdens of cement production. Cole and Rousseau (1992) concluded that energy use for material production and air pollution indices can be used in selecting building materials. Xing, Xu and Jun (2008) used energy consumption and environmental emissions (gases, where CO_2 is the main contributor) as indices in developing a life-cycle inventory model for use of concrete in buildings. Fitch and Cooper (2004) proposed life cycle energy analysis as a method of building material selection. Kumar Mandal and Madheswaran (2010) considered CO_2 emission as the basis for interstate analysis of environmental efficiency of the Indian cement industry. Research studies on development of database management systems for embodied energy and CO_2 emissions of building materials, for example research conducted by Dias and Pooliyadda (2004), also imply the importance of embodied energy and CO_2 emissions in sustainability assessments of building materials. The above information confirms that embodied energy and CO_2 emissions are two of the common sustainable indices used by the researchers.

The term 'embodied energy' has been defined in many ways. The 'Building Energy Data Book' of the US Department of Energy defines embodied energy as "the energy used during the entire life cycle of a product, including the energy used for manufacturing, transporting, and disposing of the product" (US Department of Energy 2012) . Even though cement is a product, it is also a raw material for mortar and concrete. Therefore, 'disposing' is not very applicable for cement. A more relevant and common definition for the embodied energy of building materials is the 'energy embodied in the product' (Emmanuel 2004) or 'cumulative energy demand' (Lawson 1995). However, in another definition, the type of energy considered is specified and embodied energy is defined as 'non-renewable energy embodied in the product' (Canadian Architect 2014). However, such a definition is more useful for comparing the differences of embodied energy of the same product manufactured using different energy sources (such as hydropower electricity, coal power electricity and solar power electricity), rather than comparing the embodied energy of alternatives of a same product (for example, alternatives of cement). Accordingly, for the purpose of comparing alternative cements, the embodied energy of cement can be described as the total energy required to manufacture cement, starting from the acquisition of raw materials to the manufacture the cement, and it can be expressed as energy per unit weight.

When it comes to estimation of 'CO_2 emission' of a product, it too can be estimated up to the manufacturing stage or disposal stage. However, as mentioned previously, in the case of cement, 'disposing' is not very applicable, as cement is a product as well as a raw material for mortar and concrete. Hence, for the purpose of comparison of different alternative cements, it is more appropriate to consider the total CO_2 emission up to the manufacturing stage.

Data bases and inventories of embodied energy and CO_2 emissions of primary building materials have been developed by various institutions such as Building Research Association of New Zealand (Alcorn 1998), Sustainable Energy Research Team of University of Bath, UK (Hammond and Jones 2011) and Sustainable Product Information Network for the Environment (SPLINE) of Chalmers University of Technology, Sweden (CPM LCA Database 2014). Using the values of embodied energy and CO_2 emission of primary materials, those of compound materials can be computed. A cumulative methods approach had been adopted by many researchers in computing embodied energy and/or CO_2 emission for simple systems such as blended cement mixtures (Jones, McCarthy and Newlands 2011) and geopolymer mixtures (Mathew, Sudhakar and Natarajan 2013); as well as for complex systems such as mortar (Venkatarama Reddy and Jagadish 2003), bricks (Kumar, Buddhi and Chauhan 2012), blocks (Ostwal and Chitawadagi), structural members (Jayasinghe 2011) and also for whole buildings (Pooliyadda and Dias 2005). In those calculations, miscellaneous minor energy inputs during combining of the constituents have been ignored. This literature provides guidance to compute embodied energy and CO_2 emissions of cementitious mixtures obtained by mixing different materials in different proportions.

Damineli et al. (2010) proposed a complex index called 'CO_2 intensity indicator' for concrete, incorporating performance with environmental damage. The 'CO_2 intensity indicator' is defined as the amount of CO_2 emitted to deliver one unit performance, which is expressed as below:

$$CO_2 \text{ intensity indicator } (CO_{2_i}) = \frac{CO_2 \text{ emitted per unit volume of concrete } (\text{kg}/m^3)}{\text{compressive strength of concrete (MPa)}}$$

Using the 'CO_2 intensity indicator' as a guide, it is possible to define similar indicators for embodied energy and cost as below.

$$Embodied\ energy \text{ indicator } (EE_i) = \frac{\text{Embodied energy per unit volume of concrete } (\text{MJ}/m^3)}{\text{compressive strength of concrete (MPa)}}$$

$$Cost \text{ indicator } (C_i) = \frac{\text{Cost per unit volume of concrete } (\$/m^3)}{\text{compressive strength of concrete (MPa)}}$$

The above indicators can be used to assess ecological impact of materials.

6.4 Methodology

The research objectives stated in Section 6.2 can be briefly described so as to determine the embodied energy, CO_2 emissions and financial costs of each cementitious mixture, first per unit weight of dry powder, and second per unit volume per unit strength of hardened cement. When searching for embodied energy and CO_2 emission values of raw materials, data were extracted from a number of reliable sources. Using those values, the statistical mean and variability values of embodied energy and CO_2 emission of different cementitious mixtures were computed. The mean and variability values were used to assess the 'uncertainty' of measures. The strengths of hardened cement pastes were obtained using experimental results. Costs of producing APC mixtures were computed based on market prices of constituent materials. Market surveys were conducted to find market prices of these materials. Using these prices, the mean costs of producing different APC mixtures were computed with cost ranges and variability values.

The cementitious mixtures used in this research were already described in Chapter 4. The constituent materials of cementitious mixtures are fly ash, slag, lime, OPC and Na_2SO_4. Hence, firstly, the embodied energy, CO_2 emissions and costs of these constituent materials were determined. Then using those values, embodied energy, CO_2 emissions and costs of the actual cementitious mixtures were estimated. Finally, they were assessed with respect to unit weight of dry cement as well as with respect to the unit volume per unit strength of hardened hydrated cement.

Embodied energy, CO_2 emissions and financial costs of constituent materials

Embodied energy and CO_2 emissions of the constituent materials were extracted from the available literature including inventories/reports/data sheets published by institutions and also from the published papers of individual researchers. Financial costs of those raw materials were found from market surveys. It is noted that, embodied energy, CO_2 emission and financial costs of constituent materials differ significantly, depending on many factors such as the nature of raw materials, production process and efficiency of production plant. Accordingly, instead of extracting data from one source, data were extracted from multiple sources. In some literature, the required data were readily available, hence they were directly used. However, in other literature, the required data were not given; instead, only related data were given. In such cases, the required data were computed by making appropriate assumptions and conversions. Using these data, for each parameter, an average value, range and variability were computed.

Volume of hydrated pastes

Volumes of hydrated pastes were determined by mixing different mixtures according to given w/c ratios and measuring their volumes, as given in **Appendix A2**. It was noted that for each mixture, volume per unit weight of cement was more or less the same; hence, a range cannot be determined. Therefore, they are expressed as single-point measures, without a range.

Strengths of hydrated pastes

Chapter 4 presented the experimental procedure of determining the strengths of hardened hydrated cement pastes. Upper bounds, lower bounds, mean values and variability values related to strengths of different mixtures were determined using the experimental results.

Using the mean values and ranges of embodied energy, CO_2 emissions and costs of constituent materials, embodied energy and CO_2 emissions of different cementitious, mixtures were calculated. The lower and upper bounds of the constituent materials were used to compute the lower and upper bounds of the dry cement powders, while mean values of constituent materials were used to compute the mean values of dry cement powders. Variabilities of cementitious mixtures were computed by dividing the range between the lower and upper bounds by the mean.

6.5 Results and Discussion

Results related to constituent materials and cementitious materials are presented separately in the following sections.

6.5.1 Ecological and Financial Costs of Constituent Materials

The constituent materials of the cementitious mixtures used in this research were lime, fly ash, slag, OPC and Na_2SO_4.

6.5.1.1 Embodied Energy

The embodied energy values of different raw materials derived from the literature are given in **Table 6.1**. When the embodied energy of OPC is considered, it is seen that the values given in the literature are spread over a wide range. This is because different production methods are used such as the wet method and the dry method. In the case of lime, the production method is not as complicated as the production process of OPC, and the embodied energy is also not spread over a wide range. The two pozzolanic materials used in developing APC are fly ash and ground granulated blast furnace slag, both industrial by-products. However, taking into account the miscellaneous processes related to the removal of these by-products, nominal values have been assigned for the embodied energy for these by-products in the literature. In addition to abovementioned materials, small quantities of Na_2SO_4 were used to activate the pozzolans. Half of the world's Na_2SO_4 production is obtained from by-products of chemical industries, and the other half from mirabilite, which is a natural mineral form of decahydrate (Epina eBook Team 2011). If the by-product is used, the embodied energy can be taken as zero or nominal. However, if it is produced, then energy is required in the production process, and it is taken as 4.593 MJ/kg (CPM LCA Database 2014).

Table 6.1 Embodied Energy of Materials

Material	Embodied Energy Values given in Literature (MJ/kg)	Range (MJ/kg)	Mean (MJ/kg)
OPC	[1]5.5, [2]4.298, [3]4.593, [4]4.8, [5]4.282, [6]4.53, [7]5.85, [8]4.5	4.282 – 5.850	4.794
Lime	[1]5.30, [7]5.63	5.300 – 5.630	5.645
Fly Ash	[1]0.10, [2]0.033	0.033 - 0.100	0.067
Slag	[1]1.60, [2]0.857	0.857 – 1.600	1.228
Na_2SO_4	[3]4.593	4.593- 4.593	4.593

NOTE:
The superscripts before the values indicate the references, which are given below:
1. Inventory of Carbon & Energy (ICE) - Version 2.0 (Hammond and Jones 2011)
2. The Concrete Industry Sustainability Performance Report (Mineral Products Association 2009)
3. Life Cycle Inventory Data : SPLINE (CPM LCA Database 2014)
4. Life Cycle Inventory of Portland Cement Manufacture, PCA R&D Serial No. 2095b (Marceau, Nisbet and Van Geem 2006)
5. Dias and Pooliyadda (2004)
6. Mathew, Sudhakar and Natarajan (2013)
7. Venkatarama Reddy and Jagadish (2003)
8. Kumar, Buddhi and Chauhan (2012)
9. British Cement Association – Fact Sheet 18 (Part 1) (BCA 2009)
10. IPCC Guidelines for National Greenhouse Gas Inventories: Vol.2 Workbook (Houghton 1997)

6.5.1.2 CO_2 Emissions

The CO_2 emissions related to different raw materials extracted from the literature are given in **Table 6.2**. When CO_2 emissions related to OPC are considered it is seen that the values given in the literature are not spread over a wide range. Even though fly ash and ground granulated blast furnace slag are industrial by-products, nominal values have been assigned for CO_2 emissions, as in the case of embodied energy, taking into account the miscellaneous work related to their removal.

Table 6.2 CO_2 Emissions of Materials

Material	CO_2 Emission Values given in Literature (kg CO_2/kg)	Range (kg CO_2/kg)	Mean (kg CO_2/kg)
OPC	[1]0.93, [2]0.819, [3]0.805, [4]0.928, [8]0.95, [9]0.93	0.805 – 0.950	0.894
Lime	[1]0.76, [10]0.79	0.760 - 0.790	0.775
Fly Ash	[1]0.004, [2]0.008	0.004 – 0.008	0.006
Slag	[1]0.0.083, [2]0.052	0.052 – 0.083	0.068
Na_2SO_4	[3]0.00	0.000 – 0.000	0.000

NOTE:
The superscripts before the values indicate the references, which are given below:
1. Inventory of Carbon & Energy (ICE) - Version 2.0, 2011 (Hammond and Jones 2011)
2. The Concrete Industry Sustainability Performance Report, 2009 (Mineral Products Association 2009)
3. Life Cycle Inventory Data : SPLINE -CPM LCA Database (CPM LCA Database 2014)
4. Life Cycle Inventory of Portland Cement Manufacture, PCA R&D Serial No. 2095b (Marceau, Nisbet and Van Geem 2006)
5. Dias and Pooliyadda (2004)
6. Mathew, Sudhakar and Natarajan (2013)
7. Venkatarama Reddy and Jagadish (2003)
8. Kumar, Buddhi and Chauhan (2012)
9. British Cement Association – Fact Sheet 18 (Part 1), 2009 (BCA 2009)
10. IPCC Guidelines for National Greenhouse Gas Inventories: Vol.2 Workbook, 1997 (Houghton 1997)

6.5.1.3 Financial Cost of Constituent Materials

For cost analysis, market prices of raw materials, as at August 2014, were taken into account. In the case of lime and OPC, which are common building materials, the selling prices of the three main brands in Western Australia were obtained. It was noted that there was not much difference in market prices of 20 kg OPC bags of the three brands. Two brands sold OPC at $8.00 per bag, while the third brand sold it for $7.40. The price range of 20 kg lime bags too was very narrow, with two brands having a price of $9.50 while the other a price of $8.80. Accordingly, mean market prices for 1 kg of OPC and lime were taken as 0.390 $/kg and 0.463 $/kg respectively.

Fly ash is a by-product of coal power plants, while slag is a by-product of the iron industry; hence, both are considered as industrial wastes, usually sent to dumping sites. As industries pay for the removal of the waste materials, the prices of those materials could be considered as zero or negative. Yet, in this analysis, they were not taken as zero in order to appreciate the cost involved in maintaining controls in collecting these waste materials to be used in developing cements. The relevant costs were obtained from market information providers, and the cost of fly ash was taken as 80 – 85 $/ton with an average cost of 82.5 $/ton, while the cost of slag was taken as 90 – 95 $/ton with an average cost of 92.5 $/ton. It may be relevant to mention that these values are within a very high price range, and on-line trading web sites (such as www.alibaba.com) indicated that fly ash and slag can be found for 40 US$/ton and 45 US$/ton, respectively, which is 50% less than the prices considered in the analysis.

As mentioned in Section 6.3, Na_2SO_4 can be derived from industrial by-products, as well as from the natural mineral mirabilite (Epina eBook Team 2011). Hence, Na_2SO_4 can be obtained for a relatively low price. However, when Na_2SO_4 is sold in bags of 25 kg, the selling price of a ton of Na_2SO_4 with guaranteed purity of 99% was 330 $/ton (that is 0.330 $/kg) in August 2014, at a leading industrial chemical supplier in Australia. It may be relevant to mention that this price is relatively very high, and chemical business websites such as ICIS Chemical Business, USITC, which is a global market information provider in the regions including Australia, indicated that the market price of Na_2SO_4 in August 2014 was 100 – 105 US$/ton (105-110 Australian $/ton), which is about 65% less than the prices considered in the analysis. The market prices of the raw materials considered for the cost analysis are summarised in **Table 6.3**.

Table 6.3 Market Prices of constituent materials - Summary

Material	Market Price ($ / kg)	
	Range	Mean
OPC	0.370 - 0.400	0.390
Lime	0.440 - 0.475	0.463
Fly Ash	0.080 - 0.085	0.083
Slag	0.090 - 0.095	0.093
Na_2SO4	0.330 - 0.330	0.330

6.5.2 Ecological and Financial Indicators of Cementitious Mixtures

The embodied energy and CO_2 emissions of building materials are normally expressed per unit weight, and those parameters would be useful to obtain an idea about the environmental damage caused by those materials. However, those parameters do not reflect the useful work done (or performance) by those materials in return. In particular, when comparing alternatives of the same product (for example, alternative cements), it would be logical to consider their performances along with the ecological damage caused by those alternative products. This argument is also applicable when comparing the cost of alternative products. Accordingly, for the three parameters considered, embodied energy, CO_2 emissions and costs, the following indicators were developed.

Embodied Energy Indicators

(a) Embodied energy per unit weight of dry cement powder *(MJ/kg)*

(b) Energy per unit volume of hardened paste per unit strength *(MJ/m^3/MPa)*

CO_2 emission Indicators

(a) CO_2 emission per unit weight of dry cement powder *(kg of CO_2 /kg)*

(b) CO_2 emission per unit volume of hardened paste per unit strength *(kg of CO_2 /m^3/MPa)*

Financial Cost Indicators

(a) Financial cost per unit weight of dry cement powder *($/kg)*

(b) Financial cost per unit volume of hardened paste per unit strength *($/$m^3$/MPa)*

As described in the literature review, several other researchers (Damineli et al. 2010) have used similar indicators to assess the environmental impact of building materials.

To compute the above indicators, some additional information was required, namely, volumes per unit weight of hydrated cements and their strengths, in addition to embodied energy and CO_2 emissions. Volumes of hydrated pastes were experimentally determined by preparing different mixtures according to given w/c ratios and measuring their volumes; these are given in **Appendix A2**. The strengths of different mixtures were experimentally determined as explained in Chapter 4. For each mixture, upper bound, lower bound, mean and variability of strength were determined. Using all this information, the embodied energy indicators, CO_2 emission indicators and financial cost indicators, are computed and presented in the following sections.

6.5.2.1 Embodied Energy Indicators

The embodied energy indicators of different cementitious mixtures with mean and variability values are presented in **Table 6.4**.

Table 6.4 Embodied Energy of Different Cements

Mix No	Description			Embodied Energy per unit weight of dry cement powder		Embodied Energy per unit volume of cement paste per unit strength	
	Composition of Dry Mixture	Type of Pozzolan	w/c	Mean (MJ/kg)	Var	Mean (MJ/m³/MPa)	Var
L3	70%[95%APC60+5%Na_2SO_4]+30%OPC	fly ash	0.3	3.079	19%	97.9	34%
L4	70%[95%APC60+5%Na_2SO_4]+30%OPC	fly ash	0.4	3.079	19%	169.2	43%
M3	70%[95%APC70+5%Na_2SO_4]+30%OPC	fly ash	0.3	2.720	21%	98.8	29%
M4	70%[95%APC70+5%Na_2SO_4]+30%OPC	fly ash	0.4	2.720	21%	127.9	24%
N3	70%[95%APC80+5%Na_2SO_4]+30%OPC	fly ash	0.3	2.361	23%	93.8	48%
N4	70%[95%APC80+5%Na_2SO_4]+30%OPC	fly ash	0.4	2.361	23%	124.3	30%
P3	70%[95%APC70+5%Na_2SO_4]+30%OPC	slag	0.3	3.261	27%	103.4	33%
C3	70%[100%APC100]+30%OPC	fly ash	0.3	1.485	35%	106.1	64%
C4	70%[100%APC100]+30%OPC	fly ash	0.4	1.485	35%	170.8	59%
R3	100%OPC	none	0.3	4.794	33%	146.6	101%
R4	100%OPC	none	0.4	4.794	33%	183.9	38%
KEY : APCr = r% Pozzolan + (100-r)%Lime							

Table 6.4 indicates that the values of embodied energy per unit weight for APC derived from fly ash fall approximately between 2.3- 3.0 MJ/kg, while that of OPC is about 4.8 MJ/kg. That is, the embodied energy per unit weight of APC mixtures is only about 48%-60% that of OPC. When it comes to embodied energy per unit volume per unit strength, w/c ratio plays a major role, as strength decreases with the increase of w/c. For w/c of 0.3, embodied energy per unit volume of paste per strength of OPC is about 145 $MJ/m^3/MPa$, while that of the APC mixtures of fly ash is around 97 $MJ/m^3/MPa$, which is about 67% of OPC. This implies that whether the basis of calculation of the embodied energy is per unit weight or per unit volume per unit strength, the 'performance with respect to environmental damage' of APC is much better than that of OPC. Fly ash-based APC is somewhat better than slag-based APC in both indicators, when comparing corresponding mixtures.

The cementitious mixtures given in **Table 6.4** were grouped and their 'group-means' and average variabilities computed and given in **Table 6.5**. There, all the APC mixtures were grouped together even though their w/c ratios are different, as the aim is to obtain a general value.

Table 6.5 Embodied Energy of Different Groups of Cements

Type of Mixture	Embodied Energy per unit weight of dry cement powder		Embodied Energy per unit volume of cement paste per unit strength	
	Group Mean (MJ/kg)	Average Var	Group Mean ($MJ/m^3/MPa$)	Average Var
APC made of Fly Ash	2.72	21%	118.65	35%
HVFA	1.49	35%	138.45	62%
OPC	4.79	33%	165.25	70%

According to **Table 6.5**, even if the 'group figures' are taken, it is confirmed that the 'performance with respect to environmental damage' of APC is better than that of OPC regarding embodied energy. Embodied energy per unit weight and embodied energy per unit volume per unit strength of APC derived from fly ash are only about 57% and 72% of those of OPC respectively. HVFA has a better performance than APC for embodied energy per unit weight, but APC does better (in fact the best) with respect to embodied energy per unit volume per strength.

6.5.2.2 Carbon Dioxide Emission Indicators

The CO_2 emission indicators of different cementitious mixtures, with mean and variability values are presented in **Table 6.6.**

Table 6.6 CO_2 Emissions of Different Cementitious mixtures

Mix No	Description: Composition of Dry Mixture	Type of Pozzolan	w/c	CO_2 emission unit weight of dry cement powder: Mean (kg/kg)	Var	CO_2 emission per unit volume of cement paste per unit strength: Mean kg/m³/MPa)	Var
L3	70%[95%APC60+5%Na_2SO_4]+30%OPC	fly ash	0.3	0.477	11%	15.154	25%
L4	70%[95%APC60+5%Na_2SO_4]+30%OPC	fly ash	0.4	0.477	11%	26.192	34%
M3	70%[95%APC70+5%Na_2SO_4]+30%OPC	fly ash	0.3	0.426	12%	15.457	19%
M4	70%[95%APC70+5%Na_2SO_4]+30%OPC	fly ash	0.4	0.426	12%	20.010	15%
N3	70%[95%APC80+5%Na_2SO_4]+30%OPC	fly ash	0.3	0.374	13%	14.877	37%
N4	70%[95%APC80+5%Na_2SO_4]+30%OPC	fly ash	0.4	0.374	13%	19.709	20%
P3	70%[95%APC70+5%Na_2SO_4]+30%OPC	slag	0.3	0.454	14%	14.407	19%
C3	70%[100%APC100]+30%OPC	fly ash	0.3	0.272	17%	19.464	44%
C4	70%[100%APC100]+30%OPC	fly ash	0.4	0.272	17%	31.325	39%
R3	100%OPC	none	0.3	0.894	16%	27.344	78%
R4	100%OPC	none	0.4	0.894	16%	34.289	22%
KEY : APCr = r% Pozzolan + (100-r)%Lime							

Table 6.6 indicates that values of CO_2 emission per unit weight for APC derived from fly ash falls approximately between 0.35 - 0.45 kg /kg, while that of OPC is about 0.9 kg/kg. That is, CO_2 emissions per unit weight of APC mixtures are only about 40%-55% that of OPC. When it comes to CO_2 emission per unit volume per unit strength, the w/c ratio has a greater effect, as strength decreases with the increase of w/c. CO_2 emission per unit volume of paste per strength of OPC is about 27 kg/m^3/MPa, while that of APC mixtures of fly ash is around 15 kg/m^3/MPa, which is only about 55% of OPC. This implies that whether the basis of calculation of the CO_2 emission is per unit weight or per unit volume per unit strength, APC is much better than OPC. The performance of slag-based APC is similar to the corresponding fly ash-based APC, with one indicator being slightly better and the others slightly worse.

The cementitious mixtures given in **Table 6.6** were grouped, and their group-means and average variabilities computed and given in **Table 6.7**. All the mixtures were grouped together even though their w/c ratios are different, as the aim is to obtain a general value.

Table 6.7 CO_2 emissions of Different Groups of Cements

Type of Mixture	CO_2 emission unit weight of dry cement powder		CO_2 emission per unit volume of cement paste per unit strength	
	Group Mean (kg/kg)	Average Var	Group Mean (kg/m^3/MPa)	Average Var
APC made of Fly Ash	0.43	12%	18.57	25%
HVFA	0.27	17%	25.39	42%
OPC	0.89	16%	30.82	50%

Table 6.7 indicates that even though 'group figures' are taken, CO_2 emission per unit weight and CO_2 emission per unit volume per unit strength of APC derived from fly ash is only about 50% and 60% of those of OPC. Here, too, HVFA has a better performance than APC for CO_2 emissions per unit weight, but APC does better (in fact the best) with respect to CO_2 emissions per unit volume per unit strength.

6.5.2.3 Financial Cost Indicators

The finical cost indicators of different cementitious mixtures, with mean and variability values are presented in **Table 6.8.**

Table 6.8 Costs of Different Cementitious Mixtures

Mix No	Description			Cost per unit weight of cement powder		Cost per unit volume of cement paste per unit strength	
	Composition of Dry Mixture	Type of Pozzolan	w/c	Mean $/kg	Var	Mean $/m^3/MPa	Var
L3	70%[95%APC60+5%Na_2SO_4]+30%OPC	fly ash	0.3	0.285	7%	9.050	21%
L4	70%[95%APC60+5%Na_2SO_4]+30%OPC	fly ash	0.4	0.285	7%	15.642	30%
M3	70%[95%APC70+5%Na_2SO_4]+30%OPC	fly ash	0.3	0.259	7%	9.421	14%
M4	70%[95%APC70+5%Na_2SO_4]+30%OPC	fly ash	0.4	0.259	7%	12.195	10%
N3	70%[95%APC80+5%Na_2SO_4]+30%OPC	fly ash	0.3	0.234	7%	9.299	31%
N4	70%[95%APC80+5%Na_2SO_4]+30%OPC	fly ash	0.4	0.234	7%	12.319	14%
P3	70%[95%APC70+5%Na_2SO_4]+30%OPC	slag	0.3	0.264	7%	8.370	12%
C3	70%[100%APC100]+30%OPC	fly ash	0.3	0.175	7%	12.486	35%
C4	70%[100%APC100]+30%OPC	fly ash	0.4	0.175	7%	20.095	29%
R3	100%OPC	none	0.3	0.390	8%	11.928	69%
R4	100%OPC	none	0.4	0.390	8%	14.958	13%
KEY : APCr = r% Pozzolan + (100-r)%Lime							

Table 6.8 indicates that the cost of APC derived from fly ash falls approximately between 0.24 – 0.29 $/kg, while that of OPC is about 0.39 $/kg. That is, the cost of APC mixtures is only about 60% - 73% of the cost of OPC. When cost per unit volume per unit strength is considered, w/c ratio plays a major role, as strength decreases with the increase of w/c. For w/c is 0.3, cost per unit volume of paste per strength of OPC is about 12 $/m^3/MPa, while the cost of APC mixtures of fly ash is around 9.25 $/m^3/MPa, which is about 78% of that of OPC. This implies that whether the basis of calculation of the cost is per unit weight or per unit volume per unit strength, APC is financially more economical than OPC. The cost performance of slag-based APC is similar to the corresponding fly ash-based APC one, with one indicator slightly better and others slightly worse.

The cementitious mixtures given in **Table 6.8** were grouped and their group means and average variabilities computed and given in **Table 6.9**. There, all the mixtures were grouped together even though their w/c ratios are different, as the aim is to obtain a general value.

Table 6.9 Costs of Different Groups of Cements

Type of Mixture	Cost per unit weight of cement powder		Cost per unit volume of cement paste per unit strength	
	Mean $/kg	Var	Mean $/m^3/MPa	Var
APC made of Fly Ash	0.259	7%	11.321	20%
HVFA	0.175	7%	16.291	32%
OPC	0.390	8%	13.443	41%

Table 6.9 indicates that even the group values reflect that APC is more financially economical than OPC. Cost per unit weight and cost per unit volume per unit strength of APC derived from fly ash is about 67% and 84% of OPC. As before, HVFA has a better performance than APC for cost per unit weight, but APC does better (in fact the best) with respect to cost per unit volume per unit strength.

6.6 Conclusions

The main aim of this chapter is to present both the ecological and financial costs of producing the cementitious mixtures developed in this research. Accordingly, in this study, energy requirements to produce cementitious mixtures, the CO_2 emissions during production of mixtures, and the financial costs of producing these mixtures, were computed and compared. These investigations were conducted according to two criteria: the first one based on unit weight of dry cement powder, and the second one based on unit volume per unit strength of hydrated cement. The results of the investigations led to the following conclusions:

1. When the embodied energy of dry cementitious powders are considered, the embodied energy per unit weight of the fly ash-based APC group is 2.7 MJ/kg, while that of the OPC group is about 4.8 MJ/kg. That is, the embodied energy per unit weight of APC mixtures is only about 57% of the OPC ones. When hydrated pastes are considered, the embodied energy per unit volume per unit strength of the fly ash-based APC group is around 119 MJ/m^3/MPa, while that of the OPC group is about

165 MJ/m^3/MPa; this means that APC's percentage is only about 72% of OPC. This implies that, regardless of whether the basis of calculation of the embodied energy is per unit weight or per unit volume per unit strength, APC is a very much less energy intensive material than OPC.

2. When CO_2 emission of dry cementitious powders are considered, the CO_2 emission per unit weight for fly ash-based APC group is 0.4 kg of CO_2/kg of cement, while that of OPC group is about 0.9 kg of CO_2/kg of cement. That implies that CO_2 emissions per unit weight of APC mixtures are only about 48% of that of OPC ones. When hydrated pastes are considered, CO_2 per unit volume per unit strength of fly-ash-based APC is around 19 kg/m^3/MPa, while that of the OPC group is about 31 kg/m^3/MPa, indicating that APC's amount is only about 60% of OPC's amount.

3. When the financial cost of dry cementitious powders is considered, the fly ash-based APC group is approximately about 0.26 $/kg, while the OPC group is about 0.39 $/kg. That is, the financial cost of APC powder is only about 66% of the cost of OPC. When financial cost per unit volume per unit strength of hydrated pastes are considered, fly ash-based APC is around 11.32 $/m^3/MPa, while OPC is about 13.44 $/m^3/MPa. In other words, APC's financial cost is only about 84% of OPC's financial cost.

4. The HVFA mixtures show better performance than the APC ones for embodied energy, CO_2 emissions and cost, when considering a 'per unit weight' basis, but APC ones perform better in all three when considering a 'per unit volume per unit strength' basis.

5. There is little to choose between indices of the slag based APC and the corresponding fly ash-based one.

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7 Cross-comparison: APC and HVFA with OPC

Overview

This chapter presents a comparison of the technological and economical aspects of Alkali Pozzolan Cement (APC) mixtures developed in this research. In terms of technological aspects, compressive strength and durability properties such as resistance to water absorption, carbonation, sulphuric acid attack and chloride ion penetration were considered. When performance is considered, generally APC performs better than High Volume Fly Ash (HVFA) cement with respect to three of the most important aspects, namely, strength, resistance to water absorption and carbonation. APC also performs better than Ordinary Portland Cement (OPC) with respect to sulphuric acid resistance as well as chloride ion penetration. Further, when economic aspects are considered, the ecological and financial costs of APC are less than those of OPC and HVFA.

Keywords*: Comparison of technological and economical aspects, compressive strength, durability properties, economic aspects*

7.1 Introduction

In this research, an alternative cement, called 'Alkali Pozzolan Cement' (APC) was developed and its properties investigated. Chapter 3 presented the design and development of APC, while structural and microstructural properties of different APC mixtures were presented in Chapters 4. The durability properties of APC mixtures were presented in Chapter 5. Chapter 6 focused on the ecological and financial costs of APC. In all the above investigations, the properties and costs of APC mixtures were compared with those of High Volume Fly Ash (HVFA) mixtures and Ordinary Portland Cement (OPC) mixtures. Each of the investigations mentioned above were done separately; hence the comparisons too were done separately. This chapter brings all these results onto one platform to have a holistic view and to make a holistic comparison.

7.2 Aim and Objectives

The main aim of this chapter is to bring together all the aspects of different cementitious mixtures and to make a holistic comparison. This main aim can be expanded into two objectives:

1. to compare the technological aspects with respect to structural and durability properties;
2. to compare the economic aspects with respect to ecological economy and financial economy.

7.3 Methodology

To achieve the objectives, first the cementitious mixtures were categorized, and thereafter groupings were developed for comparison. Subsequently, comparisons were made and ranking was done based on performance. The process is described below:

The cementitious mixtures used in this research were already described in Chapter 4. However, for the purpose of this summarizing chapter, they are reproduced below.

APC Mixtures

L = 70% (95% APC60 + 5% Na_2SO_4) + 30% OPC
M = 70% (95% APC70 + 5% Na_2SO_4) + 30% OPC
N = 70% (95% APC80 + 5% Na_2SO_4) + 30% OPC

HVFA Mixtures

C = 70% FA + 30% OPC

OPC Mixtures

R = 100%OPC

NOTE:

1. APCr = r % Pozzolan + (100-r)%Lime

2. The above dry cement powders were mixed with water, according to w/c of 0.3 and 0.4, and two wet mixtures from each cement were obtained. To identify those wet mixtures, suffixes 3 and 4 were added to the letter indicating the dry mix. For example, wet mixture prepaid from cement M with w/c=0.3 and 0.4 were identified as M3 and M4 respectively.

Here, the main interest is obviously on the targeted fly ash-based APC mixture M with w/c ratio of 3 (that is APC mixture M3). The comparable mixtures are those containing the same percentage of OPC as the targeted APC mixtures (that is, 30% OPC), where the rest is fly ash. Hence, for this research, comparable mixtures are termed as High Volume Fly Ash (HVFA) mixtures for convenience. The mixture consisting of 100% OPC was taken as the reference.

The three groupings used for comparison are given below.

1. **M-C-R Grouping**
   - to compare the APC mixture M, with Comparable mixture C with Reference Mixture R

2. **M-L-N Grouping**
   - to compare the APC mixture M, with its neighboring APC mixtures L and N

3. **APC-HVFA-OPC Grouping**
   - to compare the 'APC group' with the 'HVFA group' and 'OPC group'

The above three groupings were employed to compare technological and economical aspects of cementitious mixtures as described in the following sections.

7.4 Results and Discussion

7.4.1 Comparison of Technological Aspects of Mixtures

The technological aspects considered are listed below.

1. 28 day compressive strength
2. Water absorption
3. Accelerated carbonation
4. Weight change due to sulphuric attack
5. Chloride ion penetration

The above aspects were investigated under 3 criteria:

1. Performance
2. Robustness with respect to w/c
3. Robustness with respect to curing

Mixtures prepared with w/c=0.3 were considered to access performances, because APC mixtures are generally prepared with such low w/c values. For comparison of strengths, for a given mixture, maximum strength obtained under all curing conditions was taken for assessments.

Here 'robustness' means "the ability of a system to maintain desired characteristics (or resistance to change of desired characteristics) in spite of fluctuations of its components or its environment" (Carlson and Doyle 2002; Huber 2004), and it reflects the opposite of 'sensitivity'. Accordingly, robustness of a given aspect (say, strength) with respect to w/c implies the 'resistance to change' of that aspect (strength) when the w/c ratio is changed. Similarly, robustness with respect to curing means 'resistance to change' of the aspect under different curing conditions. In order to compare robustness with respect to the w/c ratio, the two w/c ratios considered were 0.3 and 0.4, while to compare robustness with respect to curing, the two conditions considered were air curing and water curing. In order to quantify robustness, one parameter of the mixture (say w/c) is changed and strengths are determined, and ratio between strengths is computed. If the ratio is unity, this means that the change of that parameter does not have any effect on strength. In other words, the mixture is fully robust with respect to that parameter. On the other hand, if the ratio is not equal to unity, it means that the mixture is not completely robust; the deviation from unity reflects the 'degree of deviation from robustness'. As the interest here is only the 'degree of robustness', rather than the direction of change, the smaller value was always divided by the larger, and deviation from unity considered for interpretations.

To determine compressive strengths and water absorptions, samples made of different w/c ratios and cured under different conditions were used. Hence, robustness with respect to w/c as well as curing conditions could be found. However, in this research, carbonation, sulphuric acid attack and chloride ion penetration were found using samples made of different w/c but not using samples cured under different conditions. Hence, robustness with respect to curing conditions could not be determined.

Table 7.1, **Table 7.3** and **Table 7.5** depict the comparison of technological aspects based on previously mentioned groupings, namely, M-C-R, L-M-N, and APC-HVFA-OPC. The first two (M-C-R and L-M-N) were developed to compare individual mixtures; hence, results of individual mixtures were used. The third grouping (APC-HVFA-OPC) was developed for overall comparison; therefore, the group averages were used. The data required for these tables were extracted from the results presented in Chapters 4 and 5. The 28-day strength results were extracted from the results given in Section 4.5.3; durability results of water absorption, sulphuric acid attack, chloride penetration, and accelerated carbonation, were extracted from the results given in Sections 5.5.1, 5.5.2, 5.5.3, and 5.5.4. By examining the **Table 7.1, Table 7.3** and **Table 7.5**, the mixtures were ranked and summarised in **Table 7.2, Table 7.4** and **Table 7.6**.

Table 7.1 Performance and Robustness of Mixtures M, C and R

M – C – R Grouping			
CRITERIA / ASPECT	**Performance of Specimens made with w/c = 0.3**	**Robustness to w/c (based on w/c = 0.3 & 0.4)**	**Robustness to Curing (air cured & water cured)**
28d Strength	For any curing condition (M3)max =47 MPa (R3)max =57 MPa (C3) max =27 MPa **Performance : R > M > C**	For Air Cured Specimens M4/M3 = 32/46 =0.70 C4/C3 =13/24 =0.54 R4/R3 = 40/57 =0.70 **Robustness : R ≈ M > C**	For Specimens of w/c=0.3 M3W/M3A=40/46 =0.87 C3A/C3W=24/27= 0.89 R3W/R3A=56/57 =0.98 **Robustness : M ≈ C ≈ R**
Water Absorption	For Air Cured Specimens M3=13.6% C3=16.3% R3=11.6% **Performance : R > M > C**	For Air Cured Specimens M3/M4 = 13.6/21.1=0.64 C3/C4= 16.3/27.3 =0.60 R3/R4= 11.6/19.2 =0.60 **Robustness : M ≈ R ≈ C**	For Specimens of w/c=0.3 M3W/M3A = 12.61/13.67 =0.92 C3W/C3A = 14.17/16.34 =0.88 R3W/R3A = 9.97/11.6 =0.86 **Robustness: M ≈ C ≈ R**
Accelerated Carbonation	For Air Cured Specimens M3=8.3 mm C3>25 mm R3=4.0 mm **Performance : R > M > C**	For Air Cured Specimens M3/M4= 8.3/22.2=0.37 C4> 25mm; C3>25mm; C3/C4=? R3/R4= 4.04/4.58=0.88 **Robustness : R > M > C**	---
Sulphuric Attack (based on weight loss at 112 days)	For Air Cured Specimens M3= 33.3% C3= 11.4% R3= 44.3% **Performance : C > M > R**	For Air Cured Specimens M4/M3 = 18.5/33.3 = 0.55 C3/C4 =11.4/13.2 = 0.86 R4/R3 = 29.6/44.3= 0.67 **Robustness : C > R > M**	-----
Chloride ion Penetration	For Water Cured Specimens M3 =2.0 mm C3 =1.0 mm R3 =2.5 mm **Performance: C > M > R**	For Water Cured Specimens M3/M4 =2.06/3.75 = 0.55 C3/C4 = 1.0/2.0 = 0.50 R3/R4 = 2.47/4.33 = 0.57 **Robustness : R ≈ M > C**	----

NOTE

1. In determining 'robustness', the smaller value is always divided by larger. Closeness to 'unity' indicates greater robustness.

2. Following symbols were used with the meanings indicated:
> : better than ≈ : approximately equal

Table 7.2 Ranks of Mixtures M, C and R for Technological Aspects

M					C					R			
	Pfmnc	Rbst wrt w/c	Rbst wrt curing			Pfmnc	Rbst wrt w/c	Rbst Wrt curing			Pfmnc	Rbst wrt w/c	Rbst Wrt curing
Strength	2	1	1		Strength	3	3	1		Strength	1	1	1
Wtr Ab	2	1	1		Wtr Ab	3	1	1		Wtr Ab	1	1	1
Carbn	2	2			Carbn	3	3			Carbn	1	1	
Acid Attc	2	3			Acid Attc	1	1			Acid Attc	3	2	
Cl Pntrn	2	1			Cl Pntrn	1	3			Cl Pntrn	3	1	

KEY: Pfmnc – Performance Rbst – Robustness
Wtr Ab – Water Absorption Carbn –Carbonation Acid Attc – Acid Attack Cl Pntrn – Chloride Ion Penetration

Table 7.3 Performance and Robustness of Mixtures L, M and N

L - M - N Grouping			
CRITERIA / ASPECT	**Performance of Specimens made with w/c = 0.3**	**Robustness to w/c (w/c = 0.3 & 0.4)**	**Robustness to Curing (air cured & water cured)**
28d Strength	<u>For any curing condition</u> (L3)max=50 (M3)max=47 (N3)max=42 **Performance: L > M > N**	<u>For Air Cured Specimens</u> L4/L3 = 26/50 = 0.52 M4/M3 = 32/46 = 0.70 N4/N3 = 28/42 = 0.67 **Robustness: M ≈ N > L**	<u>For Specimens of w/c=0.3</u> L3W/ L3A = 34/50 = 0.68 M3W/ M3A = 40/46 = 0.87 N3W/ N3A = 41/42 = 0.98 **Robustness: N ≈ M > L**
Water Absorption	<u>For Air Cured Specimens</u> L3=16.02% M3=13.67% N3=12.56% **Performance: N ≈ M > L**	<u>For Air Cured Specimens</u> L3/L4 = 16.0/25.7 = 0.62 M3/M4 = 13.6/21.1 = 0.64 N3/N4 = 12.5/23.3 = 0.54 **Robustness: M ≈ L > N**	<u>For Specimens of w/c=0.3</u> L3W/ L3A = 15.0/16.0 = 0.94 M3W/ M3A = 12.6/13.6 = 0.93 N3W/ N3A = 10.4/12.5 = 0.83 **Robustness: L ≈ M > N**
Accelerated Carbonation	<u>For Air Cured Specimens</u> L3=8.25 M3=8.3 N3=13.6 **Performance: L ≈ M > N**	<u>For Air Cured Specimens</u> L3/L4 = 8.3/17.2 = 0.48 M3/M4 = 8.3/22.2 = 0.37 N3/N4 = 13.7/24.5 =0.56 **Robustness: N > L > M**	---
Sulphuric Attack (based on weight loss at 112 days)	<u>For Air Cured Specimens</u> L3= 42.2% M3= 33.3% N3= 41.1% **Performance: M > L ≈ N**	<u>For Air Cured Specimens</u> L4/L3 = 12.4/42.2 = 0.29 M4/M3 = 18.5/33.3 = 0.56 N4/N3 = 2.8/41.1 = 0.07 **Robustness: M > L > N**	------
Chloride ion Penetration	<u>For water Cured Specimens</u> L3W = 2.25 M3W = 2.06 N3W = 1.75 **Performance: N ≈ M ≈ L**	<u>For water Cured Specimens</u> L3/L4 =2.25/4.00 = 0.56 M3/M4 = 2.06/3.75 = 0.55 N3/N4 = 1.75/3.50 = 0.50 **Robustness: L ≈ M > N**	

<u>NOTE</u>
1. In determining 'robustness', the smaller value is always divided by larger. Closeness to 'unity' indicates greater robustness.
2. Following symbols were used with the meanings indicated:
> : better than ≈ : approximately equal

Table 7.4 Ranks of Mixtures L, M and N for Technological Aspects

			L				M				N
	Pfmnc	Rbst wrt w/c	Rbst wrt curing		Pfmnc	Rbst wrt w/c	Rbst Wrt curing		Pfmnc	Rbst wrt w/c	Rbst Wrt curing
Strength	1	3	3	Strength	2	1	1	Strength	3	1	1
Wtr Ab	3	1	1	Wtr Ab	1	1	1	Wtr Ab	1	3	3
Carbn	1	2		Carbn	1	3		Carbn	3	1	
Acid Attc	2	2		Acid Attc	1	1		Acid Attc	2	3	
Cl Pntrn	1	1		Cl Pntrn	1	1		Cl Pntrn	1	3	

<u>KEY:</u> Pfmnc – Performance Rbst – Robustness
Wtr Ab – Water Absorption Carbn –Carbonation Acid Attc – Acid Attack Cl Pntrn – Chloride Ion Penetration

Table 7.5 Performance and Robustness of Groups APC, HVFA and OPC

APC – HVFA – OPC Grouping			
CRITERIA / ASPECT	**Performance of specimens of w/c = 0.3**	**Robustness to w/c (w/c = 0.3 & 0.4)**	**Robustness to Curing (air cured & water cured)**
28d Strength	**For any curing condition** Max{APC group mean} = (50+46+42)/ 3= 46 (air cured group) Max{HVFA group mean} = 34 (heat cured group) Max{OPC group mean} = 60 (heat cured group) **Performance:** **OPC > APC > HVFA**	**For air cured specimens** APC4/APC3 group mean =(26/50+32/46+28/42)/3 = 0.63 HVFA4/HVFA3 group mean =13/24 = 0.54 OPC4/OPC3 group mean = 40/57 = 0.70 **Robustness:** **OPC > APC > HVFA**	**For Specimens of w/c=0.3** APC3W/APC3A group mean =(34/50+40/46+41/42)/3 = 0.84 HVFA3W/HVFA3A group mean = 24/27 = 0.89 OPC3W/OPC3A group mean = 56/57 = 0.98 **Robustness:** **OPC > HVFA > APC**
Water Absorption	**For air cured specs of w/c=0.3** APC group mean = (16.0+13.6+12.5)/3 = 14.0% HVFA group mean = 16.3% OPC group mean = 11.6% **Performance:** **OPC > APC > HVFA**	**For air cured specs of w/c=0.3** APC3/APC4 group mean =(16.0/25.7+13.6/21.1+12.5/23.3)/3= 0.60 HVFA3/HVFA4 group mean = 16.3/27.3 = 0.60 OPC3/OPC4 group mean = 11.6/19.3 = 0.60 **Robustness :** **OPC ≈ APC ≈ HVFA**	**For Specimens of w/c=0.3** APC3W/APC3A group mean =(15.1/16.0+12.6/13.6+10.4/12.5)/3 =0.90 HVFAW/HVFAA group mean = 14.1/16.3 = 0.87 OPCW/OPCA group mean = 9.9/11.6 = 0.85 **Robustness:** **APC ≈ HVFA ≈ OPC**
Accelerated Carbonation	**For air cured specs of w/c=0.3** APC group mean =(8.25+8.33+13.67)/3=10.0mm HVFA group mean > 25 mm OPC group mean = 4.04 mm **Performance:** **OPC > APC > HVFA**	**For air cured specs of w/c=0.3** APC3/APC4 group mean = (8.3/17.2+8.3/22.2+13.7/24.5)/3=0.47 HVFA3/HVFA4 group mean HVFA4 >25mm; HVFA3>25mm OPC3/OPC4 group mean = 4.0/4.6 = 0.87 **Robustness:** **OPC > APC > HVFA**	---
Sulphuric Attack (based on weight loss at 112 days)	**For air cured specs of w/c=0.3** APC group mean =(42.2+33.3+41.1)/3 = 38.8 HVFA group mean =11.4 OPC group mean = 44.3 **Performance:** **HVFA >APC > HVFA**	**For air cured specs of w/c=0.3** APC4/APC3 group mean =(12.4/42.2+18.5/33.3+2.8/41.1)/3=0.31 HVFA3/HVFA4 group mean = 11.4/13.2 = 0.86 OPC4/OPC3 group mean = 29.6/44.3 = 0.67 **Robustness:** **HVFA > OPC >APC**	-----
Chloride ion Penetration	**For water cured specimens** APC group mean = (2.25+2.06+1.75)/3 = 2.1 HVFA group mean =1.0 OPC group mean = 2.4 **Performance:** **HVFA > APC > OPC**	**For air cured specs of w/c=0.3** APC3/APC4 group mean =(2.25/4.00+2.06/3.75+1.75/3.50)3= 0.54 HVFA3/HVFA4 group mean =1.00/2.00/1.00=0.50 OPC3/OPC4 group mean =2.47/4.33 = 0.57 **Robustness:** **OPC ≈ APC > HVFA**	

NOTE

1. **In determining 'robustness', the smaller value is always divided by larger. Closeness to 'unity' indicates greater robustness.**

2. **Following symbols were used with the meanings indicated:**
> : better than ≈ : approximately equal

Table 7.6 Ranks of APC, HVFA and OPC for Technological Aspects

APC					HVFA					OPC			
	Pfmnc	Rbst wrt w/c	Rbst wrt curing			Pfmnc	Rbst wrt w/c	Rbst Wrt curing			Pfmnc	Rbst wrt w/c	Rbst Wrt curing
Strength	2	2	3		Strength	3	3	2		Strength	1	1	1
Wtr Ab	2	1	1		Wtr Ab	3	1	1		Wtr Ab	1	1	1
Carbn	2	2			Carbn	3	3			Carbn	1	1	
Acid Attc	2	3			Acid Attc	1	1			Acid Attc	3	2	
Cl Pntrn	2	1			Cl Pntrn	1	3			Cl Pntrn	3	1	

KEY: Pfmnc – Performance Rbst – Robustness
Wtr Ab – Water Absorption Carbn –Carbonation Acid Attc – Acid Attack Cl Pntrn – Chloride Ion Penetration

Table 7.1 shows the comparison of technological aspects for the mixtures M, C and R. The rank that each mixture achieved regarding different aspects is presented in **Table 7.2**. It is seen that APC mixture M secures 1st or 2nd rank in almost all the slots (except robustness with respect to acid attack). When performance is considered, it performs better than HVFA mixture C with respect to three of the most important aspects, namely, strength and resistance to water absorption and carbonation. It also shares the highest rank for robustness against w/c ratio and curing condition with respect to strength and resistance to water absorption. In addition, the APC mixture M performs better than the OPC mixture R with respect to sulphuric acid resistance and chloride ion penetration. Hence, it can be concluded that when performance and robustness are considered, APC mixture M is generally better than HVFA mixture C.

Table 7.3 compares the technological aspects of the APC mixtures L, M and N. The rank that each mixture secured for different aspects is given in **Table 7.4**. If a close inspection is made, it is seen that APC mixture L performs best with respect to strength. However, the APC mixture M performs best in all durability aspects, namely, resistance to water absorption, carbonation, acid attack and chloride ion penetration. Accordingly, it can be concluded that when overall performance and robustness are considered, APC mixture M is generally better than APC mixtures L and N.

Table 7.5 presents the comparison of technological aspects of the groups of mixtures, namely, APC, HVFA and OPC. The rank that each group attained for different aspects is presented in **Table 7.6.** It is seen that the APC group secures 1st or 2nd rank in almost all the slots (except robustness with respect to acid attack and strength). When performance is considered, APC performs better than HVFA with respect to three of the most important aspects, namely, strength, resistance to water absorption and carbonation. In addition, the APC performs better than OPC with respect to resistance to sulphuric acid resistance and chloride ion penetration. Hence, it can be concluded that when performance and robustness are considered, APC mixtures are generally better than HVFA mixtures.

Although the notion of robustness was considered for analysis, in general, differences in robustness within the groupings was not that significant. It could be said that, in general, robustness is greater against changes in curing than against changes in w/c ratio.

7.4.2 Comparison of Economical Aspects of Mixtures

The three groupings mentioned in Section 7.3, namely M-C-R, L-M-N and APC-HVFA-OPC, were compared in terms of economic aspects related to different cementitious mixtures. The economic aspects considered are listed below.

1. Economy with respect to embodied energy
2. Economy with respect to CO_2 emission
2. Economy with respect to financial cost

The above aspects were investigated under two bases, namely

1. Cost per unit weight
2. Cost per unit volume per unit strength

When cost per unit weight of dry cement powder is assessed, w/c ratios or curing conditions are not applicable. However, when cost per unit volume of hardened paste per strength is assessed, both w/c ratio and curing conditions come into the scene. For this analysis, air cured specimens prepared with w/c of 0.3 were considered, as those were considered as standard conditions in this research, as explained in Chapter 4. Performance and robustness regarding the given aspects were compared by employing the same three groupings used before, namely, M-C-R, L-M-N and APC-HVFA-OPC. The results are given in **Table 7.7**, **Table 7.9** and **Table 7.11**. The data in these tables were extracted from **Table 6.4**, **Table 6.6** and **Table 6.8** of Chapter 6. The first two groupings M-C-R and L-M-N were developed to compare individual mixtures; hence, mixtures having w/c=0.3 were taken into account. However, the grouping APC-HVFA-OPC was developed for overall comparison. Hence, mixtures having w/c of 0.3 and 0.4 were considered together. By examining **Tables 7.7**, **Table 7.9** and **Table 7.11**, the mixtures were ranked and summarised in **Table 7.8**, **Table 7.10** and **Table 7.12**.

Table 7.7 Economic Aspects of Mixtures M, C and R

M-C-R Grouping		
ASPECT \ CRITERIA	Based on unit weight of dry cement powder	Based on unit volume per unit strength of hydrated cement with w/c = 0.3
Embodied Energy Economy	M = 2.720 MJ / kg C = 1.485 MJ / kg R = 4.794 MJ / kg **C > M > R**	M = 98.8 MJ/m³/MPa C = 106.1 MJ/m³/MPa R = 146.6 MJ/m³/MPa **M > C > R**
CO_2 Emission Economy	M = 0.426 kg of CO_2/kg C = 0.272 kg of CO_2/kg R = 0.894 kg of CO_2/kg **C > M > R**	M = 15.46 kg of CO_2/ m³/MPa C = 19.46 kg of CO_2/ m³/MPa R = 27.34 kg of CO_2/ m³/MPa **M > C > R**
Financial Economy	M = 0.259 $ / kg C = 0.175 $ / kg R = 0.390 $ / kg **C > M > R**	M = 9.42 $/m³/MPa C = 12.49 $/m³/MPa R = 11.93 $/m³/MPa **M > R > C**

Table 7.8 Ranks of Mixtures M, C and R for Economic Aspects

M				C				R		
	Based on unit wt of dry cement powder	Based on unit vol per strength of hydrated cement			Based on unit wt of dry cement powder	Based on unit vol per strength of hydrated cement			Based on unit wt of dry cement powder	Based on unit vol per strength of hydrated cement
Embodied Energy Economy	2	1		Embodied Energy Economy	1	2		Embodied Energy Economy	3	3
CO2 Emission Economy	2	1		CO2 Emission Economy	1	2		CO2 Emission Economy	3	3
Financial Economy	2	1		Financial Economy	1	3		Financial Economy	3	2

Table 7.9 Economic Aspects of APC mixtures L, M and N

L-M-N Grouping		
CRITERIA / ASPECT	Based on unit weight of dry cement powder	Based on unit volume per unit strength of hydrated cement with w/c = 0.3
Embodied Energy Economy	L = 3.079 MJ / kg M = 2.700 MJ / kg N = 2.361 MJ / kg **N > M > L**	L = 97.9 MJ/m³/MPa M = 98.8 MJ/m³/MPa N = 93.8 MJ/m³/MPa **N ≈ L ≈ M**
CO_2 Emission Economy	L = 0.477 kg of CO_2/kg M = 0.426 kg of CO_2/kg N = 0.374 kg of CO_2/kg **N > M > L**	L = 15.1kg of CO_2/ m³/MPa M = 15.5 kg of CO_2/ m³/MPa N = 14.9kg of CO_2/ m³/MPa **N ≈ L ≈ M**
Financial Economy	L = 0.29 $ / kg M = 0.26 $ / kg N = 0.23 $ / kg **N > M > L**	L = 9.05 $ / m³/MPa M = 9.42 $ / m³/MPa N = 9.30 $ / m³/MPa **L ≈ N ≈ M**

Table 7.10 Ranks of Mixtures L, M and N for Economic Aspects

L				M				N		
	Based on unit wt of dry cement powder	Based on unit vol per strength of hydrated cement			Based on unit wt of dry cement powder	Based on unit vol per strength of hydrated cement			Based on unit wt of dry cement powder	Based on unit vol per strength of hydrated cement
Embodied Energy Economy	3	1		Embodied Energy Economy	2	1		Embodied Energy Economy	1	1
CO2 Emission Economy	3	1		CO2 Emission Economy	2	1		CO2 Emission Economy	1	1
Financial Economy	3	1		Financial Economy	2	1		Financial Economy	1	1

Table 7.11 Economic Aspects of APC group, HVFA group and OPC group

APC - HVFA – OPC Grouping		
CRITERIA / ASPECT	Based on unit weight of dry cement powder	Based on unit volume per unit strength of hydrated cement with w/c = 0.3 & 0.4
Embodied Energy Economy	APC = 2.72 MJ / kg HVFA = 1.49 MJ / kg OPC = 4.79 MJ / kg **HVFA > APC > OPC**	APC = 118.65 MJ/m³/MPa HVFA = 138.45 MJ/m³/MPa OPC = 165.25 MJ/m³/MPa **APC > HVFA > OPC**
CO2 Emission Economy	APC = 0.43 kg CO_2/kg HVFA = 0.27 kg CO_2/kg OPC = 0.89 kg CO_2/kg **HVFA > APC > OPC**	APC = 18.57 kg of CO_2/m³/MPa HVFA = 25.39 kg of CO_2/ m³/MPa OPC = 30.82 kg of CO_2/ m³/MPa **APC > HVFA > OPC**
Financial Economy	APC = 0.259 $ / kg HVFA = 0.175 $ / kg OPC = 0.390 $ / kg **HVFA > APC > OPC**	APC = 11.32$ / m³/MPa HVFA = 16.29$ / m³/MPa OPC = 13.44$ / m³/MPa **APC > OPC > HVFA**

Table 7.12 Ranks of Groups APC, HVFA and OPC for Economic Aspects

APC				**HVFA**				**OPC**		
	Based on unit wt of dry cement powder	Based on unit vol per strength of hydrated cement			Based on unit wt of dry cement powder	Based on unit vol per strength of hydrated cement			Based on unit wt of dry cement powder	Based on unit vol per strength of hydrated cement
Embodied Energy Economy	2	1		Embodied Energy Economy	1	2		Embodied Energy Economy	3	3
CO2 Emission Economy	2	1		CO2 Emission Economy	1	2		CO2 Emission Economy	3	3
Financial Economy	2	1		Financial Economy	1	3		Financial Economy	3	2

Table 7.7 presents the comparison of economic aspects of the mixtures M, C and R; and the rank each mixture achieved for different aspects is presented in **Table 7.8**. It is seen that, when economic aspects based on the unit weight of dry cement are considered, the APC mixture M is more economical than OPC mixture R, in all three economic aspects. Moreover, when the same aspects were examined on a more realistic

basis, i.e. on unit volume per strength of hardened cement, very clearly the APC mixture M gains the top rank. Hence, it can be concluded that when economic aspects are considered, APC mixture M is better than HVFA mixture C and much better than OPC mixture R.

Table 7.9 compares economic aspects of the mixtures L, M and N. The ranks each mixture achieved for different aspects are presented in **Table 7.10**. When economic aspects based on unit weight of dry cement are considered, the APC mixture N is the most economical mixture, in all three economic aspects. However, when the same aspects were examined based on unit volume per strength of hardened cement, it is seen that all three APC mixtures are equally economical in all three aspects.

Table 7.11 presents the comparison of economic aspects of the groups of mixtures, namely, APC, HVFA and OPC. The rankings of each group according to different aspects are presented in **Table 7.12**. It is seen that, when economic aspects based on unit weight of dry cement are considered, the APC is more economical than OPC, in all three economic aspects. Moreover, when the same aspects were examined on a more realistic basis, i.e. on unit volume per strength of hardened cement, the APC group very clearly ranked highest. Hence, it can be concluded that APC is better than HVFA and much better than OPC.

7.5 Conclusions

The main aim of this chapter is to compare the technological and economic aspects of different cementitious mixtures developed in this research. The technological aspects considered are 28-day compressive strength, water absorption, accelerated carbonation, weight change due to sulphuric attack and chloride ion penetration; and these aspects were investigated under three criteria, namely performance, robustness with respect to w/c and robustness with respect to curing. The economic aspects considered for comparison are: embodied energy, CO_2 emission, and financial cost. These were investigated under two criteria, namely cost per unit weight and cost per unit volume per strength. The conclusions drawn from the comparisons are:

1. When performance is considered, the APC mixture M is better than the HVFA mixture C with respect to three of the most important aspects, namely strength, resistance to water absorption and carbonation. Also the APC mixture M performs better than OPC mixture R with respect to resistance to sulphuric acid attack and chloride ion penetration.

2. Generally, the performance of the three APC mixtures L, M and N are more or less similar for all the aspects, namely strength, resistance to water absorption, carbonation, acid attack and chloride ion penetration.

3. When the performance of groups is considered, again the APC group is better than the HVFA group with respect to strength, resistance to water absorption and carbonation. Also, the APC group performs better than the OPC group with respect to resistance to sulphuric acid attack and chloride ion penetration.

4. Although the notion of robustness was considered for analysis, in general, differences in robustness within the groupings were not that significant. It could be said that, in general, robustness is greater against changes in curing than against changes in w/c ratio.

5. When economic aspects based on unit weight of dry cement were considered, the APC mixture M is more economical than the OPC mixture R, in all three economic aspects, namely embodied energy economy, CO_2 emissions economy and financial economy. Moreover, when the same aspects were examined based on unit volume per strength of hardened cement, the APC mixture M is unquestionably better than the OPC mixture R as well as the HVFA mixture C.

6. When economic aspects were examined based on unit volume per strength of hardened cement, it was seen that all three APC mixtures L, M and N are equally economical in all three aspects.

7. When economic aspects based on unit weight of dry cement are considered, the APC group is more economical than OPC in all three economic aspects. When the same aspects were examined based on unit volume per strength of hardened cement, the

APC group is very clearly more economical than the HVFA group and the OPC group.

7.6 References

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8 Development of Framework to Assess 'Integral Sustainability' of APC

Overview

This chapter presents the development of frameworks needed to investigate integral sustainability of 'Alkali Pozzolan Cement' (APC). First, an 'integral sustainability model' that integrates economical, ecological, existential and ethnological sustainability was developed. Thereafter, two modified frameworks were developed, based on the standard tetra-quadrant integral framework. In the first framework, pronouns of the standard framework were modified so as to differentiate between 'collections of individuals' and 'collectives of individuals'. The second modified framework is a three-dimensional framework, derived by adding a third dimension to the two- dimensional standard framework. The third dimension added was the 'certain-uncertain' dimension that is used to differentiate 'certain' and 'uncertain' aspects of subjective and objective information related to APC. Finally, the chapter explores the use of these frameworks to investigate the development of APC for integral sustainability.

Key words: *integral sustainability, tetra-quadrant framework, octa-octant framework, certain-uncertain axis.*

8.1 Introduction

The main aim of this research is to develop an alternative cement called 'Alkali Pozzolan Cement' (APC) for integral sustainability. The term 'integral sustainability' implies an integration of a number of sustainability aspects. The design and development of APC mixtures was presented in Chapter 3, while properties of APC mixtures were presented in Chapters 4 and 5. Chapter 6 focused on the ecological and financial costs of APC mixtures. All these results were brought onto one platform to have a holistic view in Chapter 7. Next, in order to investigate the integral sustainability of APC, suitable integral sustainability frameworks have to be developed, and this chapter presents the development of such frameworks.

Investigation of integral sustainability of APC was based on integral theory, which was described in Section 1.3. Aaccording to integral theory, any issue is linked to four irreducible realities, which are subjective, inter-subjective, objective and inter-objective realities; and these realities can be assigned to the upper left (UL), lower left (LL), upper right (UR) and lower right (LR) quadrants of the tetra-quadrant framework, respectively as indicated in **Fig. 1.2** in Chapter 1. Moreover, the four quadrants UL, LL, UR and LR of the standard tetra-quadrant framework are conventionally assigned the four pronouns I, WE, IT and ITS respectively (Esbjörn-Hargens 2009) and depicted in **Fig. 8.1**. The newly coined pronoun 'ITS' is used to represent the collective form of 'IT', and it is assigned to LR quadrant.

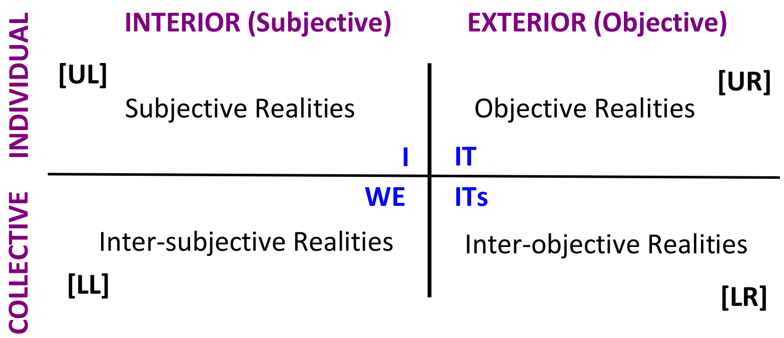

Fig. 8.1 Standard Tetra-quadrant Framework and related Pronouns

The standard tetra-quadrant framework shown **Fig. 8.1** is a general framework. When it is employed for a specific case, the four types of realities are specifically defined. For example, when formulating an integral sustainability framework for architectural design DeKay (2011) drafted a map to achieve all-quadrants sustainability as shown in **Fig. 8.2**.

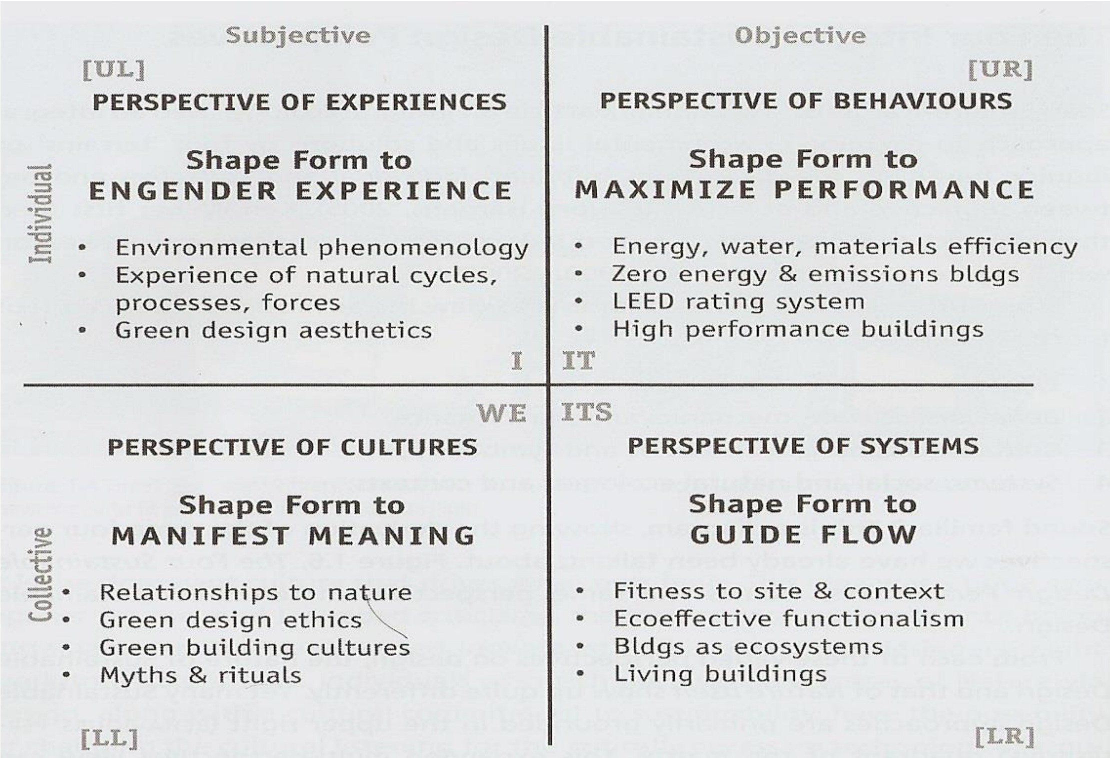

Fig. 8.2 Map for All Quadrant Sustainability (DeKay 2011)

Considering the nature of information given in the map shown in **Fig. 8.2**, DeKay (2006) named sustainably regarding UR, LR, LL and UL quadrants as technological sustainability, ecological sustainability, cultural sustainability and the individual's sustainability consciousness; and developed an 'integral sustainability model' for architectural design which is shown in **Fig. 8.3**.

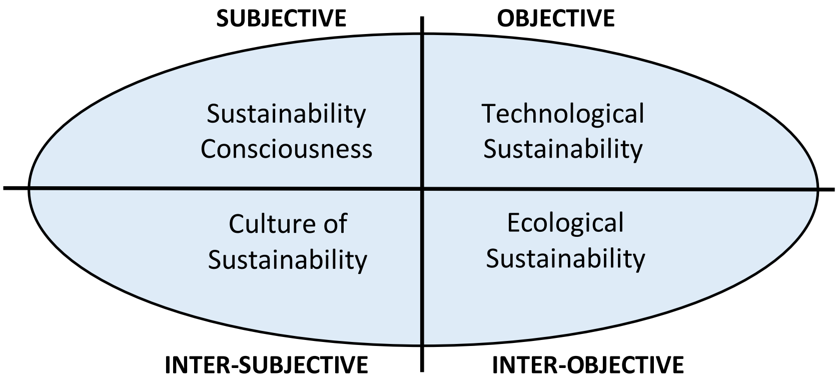

Fig. 8.3 DeKay's Integral Sustainability Model

DeKay's integral sustainability model was developed specifically for architectural design, hence no special attention was given to economic aspects. However this research on APC deals with economic aspects as well. Hence domains of the DeKay's model needed to be re-defined or modified to be used for this research. Further, in the standard tetra-quadrant framework, pronouns are assigned to reflect individual and collective forms. However, in this research it was also necessary to differentiate between 'collections' and 'collectives', in order to investigate perceptions of individuals as well as collective groups of individuals. Hence the pronouns of the standard tetra-quadrant framework needed to be modified. Moreover, it was also necessary to take in to account the certainty/uncertainty of relevant aspects, in order to investigate the stability of integral sustainability of APC. Hence a need arose to develop a new framework to take into account certainty/uncertainty of aspects. These requirements led to formulate the objectives of this chapter.

8.2 Aim and Objectives

The main aim of this chapter is to present the development of necessary frameworks to investigate the development of Alkali Pozzolan Cement (APC) for integral sustainability. The main aim was sub divided into the following objectives.

1. To formulate an 'integral sustainability' model to be used as a guideline for the entire research.
2. To modify the basic pronouns related to the four quadrants of the integral framework, in order to differentiate between 'collections of individuals' and 'collectives of individuals'.
3. To develop a new framework to take into account the certainty/uncertainty of aspects related to four quadrants of the integral sustainability framework.
4. To explore the application of the integral frameworks mentioned above, in order to investigate the integral sustainability of APC.

A theoretical approach was adopted in order to achieve the above objectives.

8.3 Formulation of Integral Sustainability Model

As described in Chapter 1, the term 'integral sustainability' implies not only ecological sustainability which falls into the LR quadrant, but also sustainability with respect to all the four quadrants. In other words, in order to achieve integral sustainability, it is necessary to achieve objective sustainability, inter-objective sustainability, subjective sustainability and inter-subjective sustainability. Hence, the drafting of a map similar to the one shown in **Fig 8.2** (prepared by DeKay for architectural design) is necessary to develop an 'integral sustainability model' to be employed in this research.

As mentioned previously, in the standard tetra-quadrant integral framework, subjective and objective entities are recognised at individual and collective forms. Accordingly, if 'individual forms' are considered as 'elements', then 'collective forms of individuals' can be considered as 'systems'. However, every system is a sub-system of a larger system, and every element is a system of sub-elements. Hence, in preparing an integral map, the 'operating level' has to be defined first, and systems and sub-systems (or elements) have to be determined, before making entries to the quadrants.

When objective entities are considered, first the objective properties have to be defined; and based on that, inter-objective properties have to be noted. For example, at a material level study, clouds, rains and ocean are considered as objective entities, while the 'water cycle', which is the system made of these, is considered as an inter-objective entity. However, at a molecular level study, H_2O molecules (water molecules) are considered as objective entities, while clouds, rain, rivers and ocean which are the systems made of H_2O molecules are considered to be inter-objective entities. Similarly, at an atomic level study, H (Hydrogen) and O (Oxygen) atoms are considered as objective entities, while H_2O molecules are considered as inter-objective systems. This process can be continued even beyond the atomic level. When it comes to measuring units, at a primary level, dimensions such as length, mass, time and temperature are considered as objective units, while their derivatives such as volume, density, strength and energy are considered as inter-objective units.

The concept of an 'operating level' is applicable not only to objective entities, but also to subjective entities. In investigating the perceptions of an issue, 'individual views' are considered under ‘subjective’, and ‘views of collectives of individuals’ or ‘social/cultural group views’ are considered under ‘inter-subjective’. However, at a higher level, a single cultural group can be considered as an individual unit (for example, a cultural group of a multi-cultural society); and the whole society can be considered as a collective form of cultural groups. So, even a cultural group can be considered as an element and the whole society made of those groups can be considered as a system. However, the common practice is to consider individual persons as elements and cultural groups as systems, in most of the practical cases.

In a study of a cement, properties such as strength of cement, cost of cement and emissions of cement are considered as objective properties, and their derivatives are considered as inter-objective. Where perceptions about the cement are concerned, concerns of ‘individuals’ are considered under ‘subjective’, and concerns of ‘collectives of individuals’ or ‘social groups’ are considered under ‘inter-subjective’. Accordingly, a map was prepared to cover the relevant entities of this research on integral sustainability of APC, and given in **Fig. 8.4**.

[UL] **SUBJECTIVE** **<u>Enlightening individuals about the product</u>** • Concerns regarding use of quality product • Concerns regarding use of eco-friendly product • Concerns regarding use of economical product **<u>Familiarising individuals about the product</u>** • Concerns regarding use of non-familiar product **<u>Making individuals feel comfortable/good</u>** • Concerns about risk • Concerns about assurance	[UR] **OBJECTIVE** **<u>Improving performance</u>** • Strength, quality • Resistance to durability problems **<u>Reducing consumptions</u>** • Material use • Energy use **<u>Reducing emissions</u>** • Greenhouse gases • Effluents **<u>Reducing cost</u>** • Market Price
INTER- SUBJECTIVE **<u>Working together with professional/social groups</u>** • Professional recommendations about quality • Social trends such as 'go green' [LL]	**INTER- OBJECTIVE** **<u>Reducing consumption per 'performance unit'</u>** • Material use per unit strength • Energy use per unit strength **<u>Reducing emissions per 'performance unit'</u>** • Greenhouse gases per unit strength • Effluents per unit strength **<u>Reducing price per 'performance unit'</u>** • Market Price per unit strength [LR]

Fig. 8.4 Map for Investigation of Integral Sustainability of APC

In order to accommodate the information shown in the map in **Fig. 8.4**, the four domains of sustainability were defined as economical sustainability, ecological sustainability, existential sustainability and ethnological sustainability; and the 'integral sustainability model' was formulated to be employed in this research. It is given in **Fig. 8.5**.

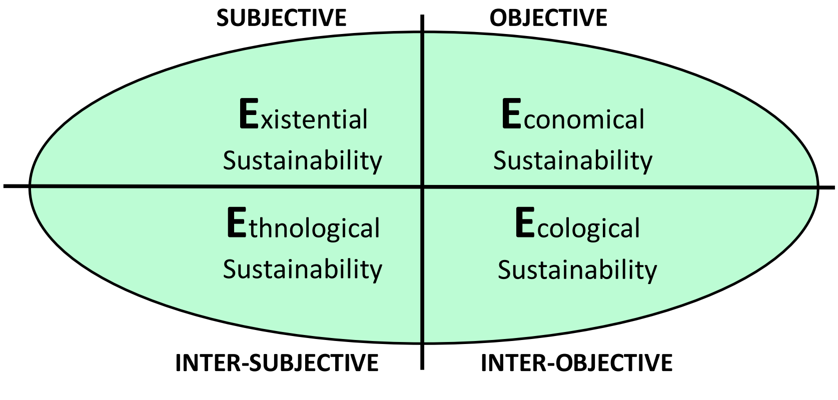

Fig. 8.5 Integral Sustainability model with **4E**s

UR Quadrant Sustainability: *Economical Sustainability*

Economy means ‘less input’, along with ‘more useful output’, and ‘less unwanted output’ (objective entities). Accordingly, to achieve economical sustainability, performance of the product has to be improved while consumption of resources, emissions, production cost and market price of the product have to be reduced. It should be noted that application of engineering/technology too comes under this domain, as they lead to improved performance and efficiency by reducing input and improving useful output.

LR Quadrant Sustainability: *Ecological Sustainability*

Ecology deals with the impact on the environment (inter-objective relationships). Accordingly, to achieve ecological sustainability, environmental impacts have to be reduced. In the case of APC, this can be redefined as reduction of environmental impact per unit performance.

UL Quadrant Sustainability: *Existential Sustainability*

The existential domain is linked with the qualities associated with an individual’s existence such as feelings, attitudes, consciousness, norms and values. Accordingly, to achieve existential sustainability, the product should be able to address the individual’s sustainability consciousness, values, ethics and feelings of being good by adopting sustainable practices.

LL Quadrant Sustainability: *Ethnological Sustainability*

Ethnology is related to ‘collectives of individuals’ or society and cultures. Accordingly, to achieve ethnological sustainability, the product should resonate with ecological concerns of the society, ‘go green’ cultures, social trends and professional recommendations.

In summary, the ‘integral sustainability model’ shown in **Fig. 8.5** indicates that in order to attain integral sustainability for APC, the 4Es of sustainability, that is, economical, ecological, existential and ethnological sustainability have to be achieved. Accordingly, in order to develop APC for integral sustainability, the above four domains have to be satisfied. Hence this integral sustainable model will be used as the platform for developing APC for integral sustainability.

8.4 Modifications to Basic Pronouns of Tetra-quadrat Framework

The standard integral framework with standard pronouns was given in **Fig. 8.1**. In the standard framework, the UL quadrant represents a 'subjective individual'; hence the first person (singular) nominative form 'I' is assigned to the UL quadrant. The LL quadrant represents 'subjective collectives'; hence the first person (collective) nominative form 'WE' is assigned to the LL quadrant. The pronoun 'WE' reflects a 'collective of individuals', but not a 'collection of individuals' (which will be explained later). The UR quadrant represents external realities; hence the third person (singular) nominative form 'IT' is assigned to UR quadrant. The LR quadrant represents 'collective realities' or 'systems', and hence the third person (collective) nominative pronoun has to be assigned. For that purpose, the pronoun 'ITS' has been used in the above mentioned standard tetra-quadrant framework. Here the term 'ITS' is different from the third person (singular) possessive form 'Its', and means 'collective IT's.

Although the pronouns of the standard framework reflect individual and collective forms, they do not differentiate between 'collections' and 'collectives'. In this research it was needed to differentiate between 'collections' and 'collectives', mainly to investigate 'perceptions of individuals' and 'perceptions of collective groups of individuals'. Hence the need arose to modify the pronouns of above framework according to a logical structure. Arranging pronouns in a logical structure would be extremely useful when it comes to analysing or interpreting information related to collections and collectives. Two alternative solutions were considered initially, and then the most appropriate was selected and developed. The two alternative solutions are shown in **Fig. 8.6**, and described below. It should be mentioned that these pronouns are not linguistic pronouns, but 'symbolic pronouns'; hence the terms 'Is' and 'ITs' have to be understood accordingly.

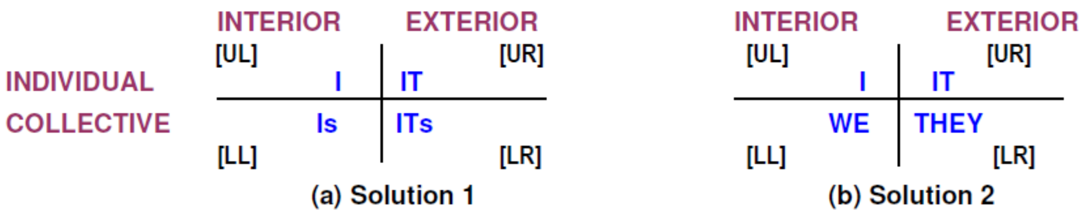

Fig. 8.6 Alternative Solutions

Alternative Solution 1

In alternative solution 1, a newly defined pronoun, 'Is', was assigned to the LL quadrant, while the pronouns of the other three quadrants were kept unchanged as indicated in **Fig. 8.6 (a)**. Here the meaning of the term 'Is' is exactly the same as the meaning of 'WE' in the standard framework, and conveys the idea of a collective. The reason for the amendment is to arrange the pronouns in both sides of the frame work in the same logical form. That is, pronouns of the lower quadrants are obtained by adding the suffix 's' to the pronouns of the upper quadrants. Note that the LR pronoun was also given a lower case 's' for the above reason.

Alternative Solution 2

In alternative solution 2, the pronoun of the LR quadrant 'ITS' in the standard framework, was replaced by the pronoun 'THEY', and other pronouns kept unchanged as indicated in **Fig. 8.6 (b)**. Then pronouns on both left and right sides take the same logical form. That is pronouns of lower quadrants of the framework are the collective forms of the pronouns of the upper quadrants.

Selection and Development of Alternative 2

As shown in **Fig. 8.6**, in both alternative solutions, the left and right hand side pronouns follow the same logical pattern. Hence for general investigations, any one of the above solutions can be used. However, solution 2 can be extended to reflect 'collections' of pronouns by adding the suffix 's'. On the other hand, in the case of solution 1, if suffix 's' is added to the subjective 'I' to reflect a 'collection of I's, it can be confused with the 'collective I', which has been already defined as 'Is' in the LL quadrant of solution 1. Therefore, since it is solution 2 that would give the opportunity to extend the framework to collections of both single and collective entities, it has been selected for this research.

The distinction between 'collections' and 'collectives' can be understood as follows. To form a 'collective' group, there should be a relationship or agreement or resonance between individuals; otherwise it will be just a ('mere') collection of individuals. In other words, there should be an 'inter-subjective agreement' between individuals to claim that they are a collective group, 'WE'. Having differentiated between collections and collectives, it was needed to consider both in this research. In other words, it was needed to consider following four cases:

1. Single individual
2. Collections of individuals
3. Single collective
4. Collections of collectives

With the above purpose, the new pronouns Is, WEs, ITs and THEYs were defined to indicate collections of I, WE, IT and THEY. Note again that these pronouns are not linguistic pronouns, but ‘symbolic pronouns’. The difference between collections and collectives can be graphically illustrated as in **Fig. 8.7**.

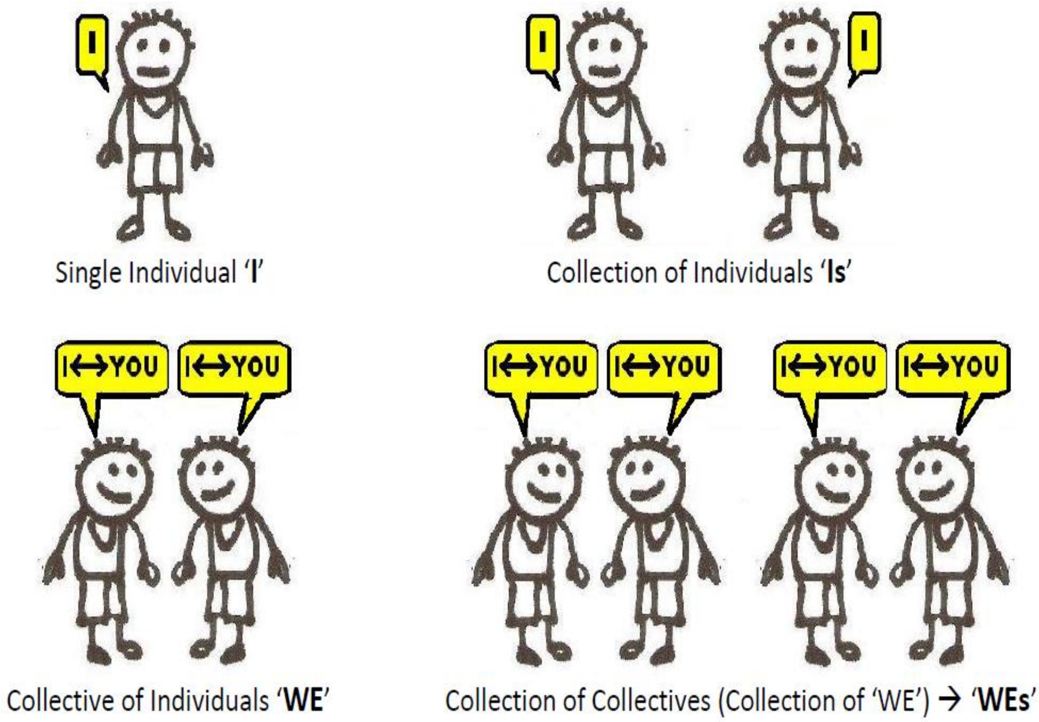

Fig. 8.7 Difference between ‘Collections’ and ‘Collectives’

These newly coined pronouns are assigned to quadrants as shown in **Fig. 8.8**.

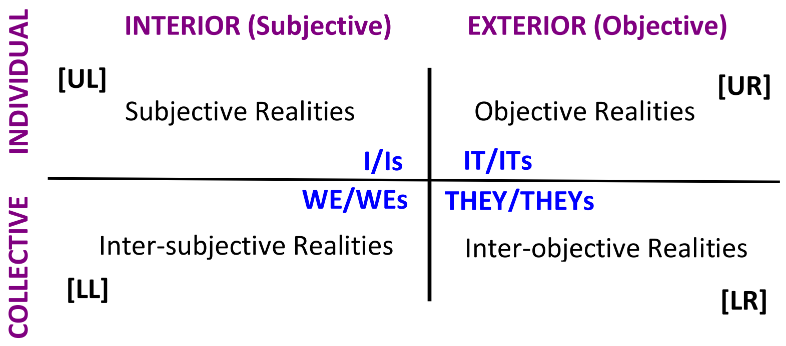

Fig. 8.8 Modified pronouns of Tetra Quadrant Framework

It must be emphasized that the modified pronoun 'ITs' assigned to the UR quadrant of **Fig. 8.8** has a different meaning than the pronoun 'ITS' in the standard tetra quadrant framework assigned to the LR quadrant of **Fig. 8.1**. In the standard framework 'ITS' means a collective of 'IT's; thus it is assigned to the LR quadrant. In the proposed modified framework, 'ITs' means a collection of individual 'IT's; and thus assigned to the UR quadrant. In the standard framework, 'ITS' is a system whereas in the modified framework 'ITs' is a collection of external realities. A system in the modified framework is indicated by 'THEY' and a collection of systems by 'THEYs'. With that understanding, the pronouns of the four quadrants may be abbreviated as I(s), WE(s), IT(s) and THEY(s), as indicated in **Fig. 8.9**.

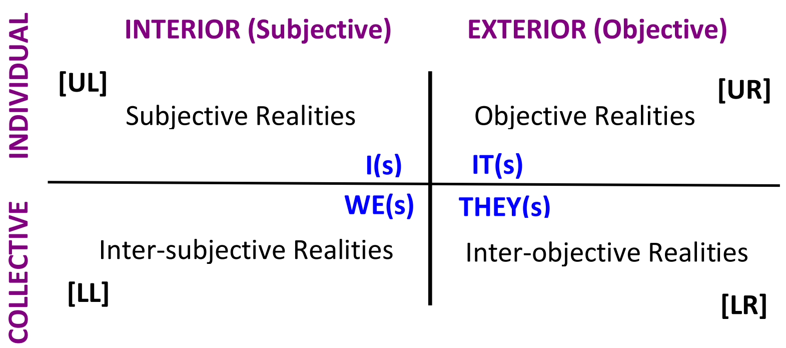

Fig. 8.9 Modified pronouns of Tetra Quadrant Framework

The above framework can be employed to gather and analyse individual and collective (subjective) perspectives about an issue. For example, this research investigates people's views about Alkali Pozzolan Cement (APC). A single individual's view will fit into the category 'I' of the UL quadrant. If a number of individuals have the same view independently, then it will fit into the category 'Is' of the same quadrant (UL quadrant), but if they have the same view collectively, then it will fit into the category 'WE' of the LL quadrant. On the other hand when there are different collective views, those will fit into the category 'WEs' of the LL quadrant. In other words, sub-cultures can be recognised by the category 'WEs' in the LL quadrant.

Similarly, a single independent property of Alkali Pozzolan Cement (APC) may be assigned to the 'IT' category of the UR quadrant, and different independent properties will fall into category 'ITs' of the same quadrant. However, a system or a complex entity developed from collective properties have a place in the category 'THEY' in the LR quadrant. When different sub-systems are to be recognised they are assigned under the category 'THEYs' in the same quadrant.

8.5 Development of Octa-octant Framework

The stability of the integral sustainability of a product depends on the stability of the four-quadrant sustainability regarding that product. The stability of the four-quadrant sustainability depends on the certainty/uncertainty of the aspects related to them. Hence, need arose to develop a new framework to take into account the certainty/uncertainty of the aspects related to the four quadrants of integral sustainability framework. Accordingly the standard two-dimensional framework was extended into a three-dimensional framework by integrating a third dimension called 'certainty - uncertainty', and a new framework was developed, as shown in **Fig. 8.10**.

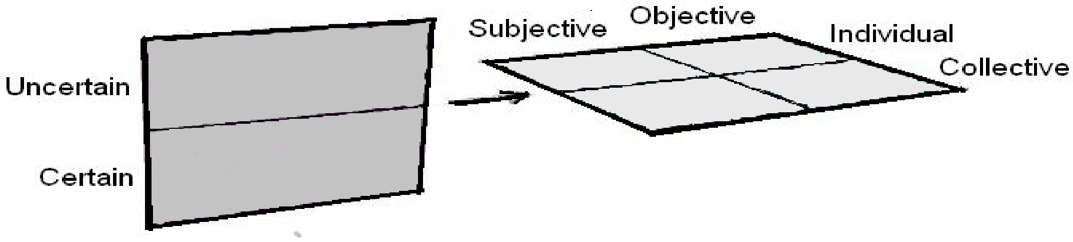

Fig. 8.10 Inclusion of certain-uncertain dichotomy into framework

The three dimensional framework derived by integrating subjective-objective, individual-collective and certain-uncertain dichotomies is shown in **Fig. 8.11**.

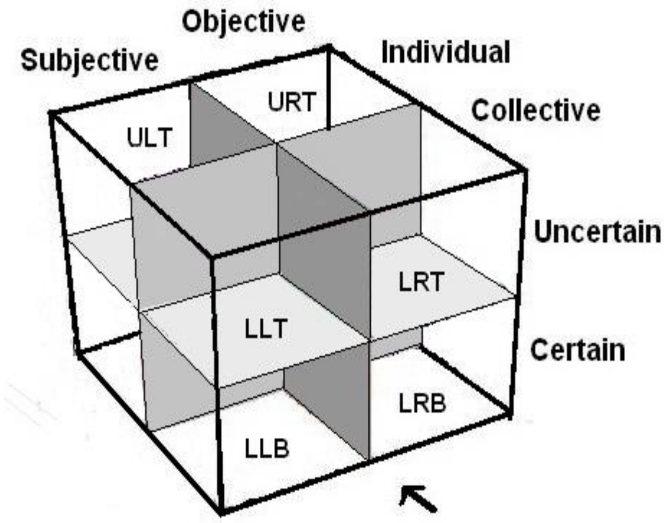

Fig. 8.11 Three-dimensional AOAL octa-octant framework

The framework in **Fig. 8.11** has eight 'octants', which are identified using the words left, right, upper, lower, top and bottom. The reference direction (or direction of view) is indicated by the arrow. For example, the 'individual-objective-certain space' is represented by the upper right bottom octant (URB) and the 'individual-objective-uncertain space' is represented by the upper right top octant (URT). In the standard two-dimensional framework, there are 4 numbers of $^1/_4$ s. Hence, the Greek prefix '*tetra*' and the Latin term '*quadran*t' had been used in the formation of the term 'tetra-quadrant framework'. The three-dimensional framework consists of 8 numbers of $^1/_8$ s. Accordingly, the Greek prefix '*octa*' and the Latin term '*octant*' are used to coin the term 'octa-octant framework'.

The three dimensional octa-octant framework implies that an issue can be viewed through 8 different lenses. In other words, it says that the four quadrants of the two-dimensional tetra-quadrant framework can be investigated through the ‘lens of certainty’ as well as the ‘lens of uncertainty’. Looking at an issue as a separate entity (UR) or as a member of a system or structure (LR) using idealized (perhaps Platonic) concepts, formula, or theory is a way of looking at the issue through ‘certain lenses’. However, when real world entities are considered, the issue will be looked through ‘uncertain’ lenses. For example, if lime used in producing Alkali Pozzolan Cement (APC) is in the form of pure calcium oxide, which has well documented chemical properties, it will enable the researcher to predict its behaviour fairly accurately – this will be considered as the ‘certain’ lens. However, if the lime used is in the form of commercially available burnt limestone, it will create uncertainties because of variations in the degree of purity and exposure to atmosphere during storage. Another very specific manifestation of the ‘certain’ vs ‘uncertain’ axis is the way that measurements are taken and reported. The acknowledgement of randomness (with the aid of a variability index) in measurements in addition to single point mean values can be described as looking through certain/uncertain lenses. Low values of variability imply less randomness, and high values of variability imply more randomness. Less randomness implies more certainty, and more randomness implies less certainty (or uncertainty). This is applicable for subjective perspectives as well. The degree of ‘certainty/uncertainty’ about perceptions can be captured through fuzzy sets, which will be described below and in Chapter 9.

8.6 Application of Integral Frameworks

As mentioned before, the investigation of integral sustainability of Alkali Pozzolan Cement (APC) was primarily based on the integral sustainability model shown in **Fig. 8.5**. However, in order to investigate specific aspects, two frameworks were derived. The tetra-quadrant framework with modified pronouns was given in Section 8.4; and the newly developed octa-octant framework was given in Section 8.5. Application of those framework are explored in following sections.

8.6.1 Tetra-quadrant Framework with Modified Pronouns

In order to investigate integral sustainability of Alkali Pozzolan Cement (APC), objective as well as subjective aspects of integral sustainability of APC have to be investigated at individual and collective levels. Moreover, it was also necessary to differentiate between 'collections' and 'collectives', in order to investigate perceptions of individuals as well as collective groups of individuals. Hence, the pronouns of the standard tetra-quadrant framework were modified. The application of that framework is described below.

8.6.1.1 Objective aspects of Integral Sustainability of APC

To investigate objective views of the integral sustainability of Alkali Pozzolan Cement (APC), relevant information can be obtained from established theories, as well as from experimental, analytical and numerical methods. The information gathered are quantitative; hence, quantitative techniques are used for analysis. However, when an entity is measured, instead of single valued measures, a spread of measures or the 'uncertainty' of the measures are taken into account (e.g. ranges, standard deviations and coefficients of variance that are common in statistics). Examples of the entities relevant to the objective quadrants are listed below.

Entries to UR quadrant

- Strength of APC {with mean and variability}
- Embodied Energy of APC of powder {with mean and variability}
- Carbon dioxide emission of APC powder {with mean and variability}
- Financial cost of APC powder {with mean and variability}

Entries to LR quadrant

- Embodied energy per unit volume per unit strength of APC {with mean and variability}
- Carbon dioxide emission per unit volume per unit strength of APC {with mean and variability}
- Financial cost per unit volume per unit strength of APC {with mean and variability}

8.6.1.2 Subjective views of Integral Sustainability of APC

To investigate subjective views of the integral sustainability of Alkali Pozzolan Cement (APC), the 'quadratic approach', described by Esbjörn-Hargens (2009) was adopted as shown in **Fig. 8.12**.

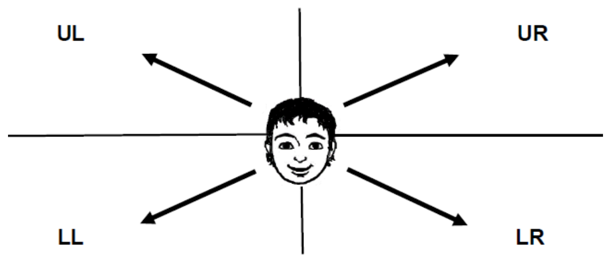

Fig. 8.12 Quadratic Approach

In a 'quadratic approach', the 'individual' is placed at the centre and his/her views about four realities are considered. When generating data, the respondent is placed at the centre of the tetra-quadrant framework and he is asked to look at APC through the 4 integral lenses of the quadrants. Examples of the themes in each quadrant are listed in **Fig. 8.13**.

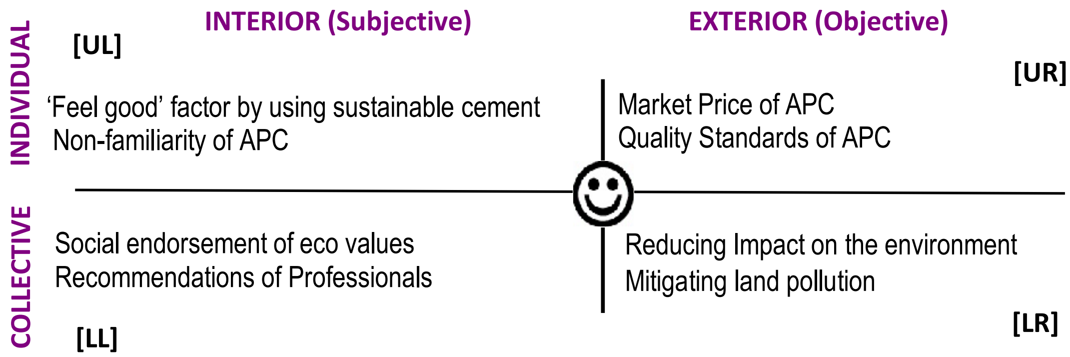

Fig. 8.13 Subjective information about APC – quadratic view

In the organisation of information, an 'individual response' is denoted by the symbolic pronoun 'I' while 'collections of individual responses' are denoted by the symbolic pronoun 'Is'; and both are assigned to the subjective UL quadrant. 'Collective responses' are denoted by the symbolic pronoun 'WE', while 'collections of collective responses' are denoted by the symbolic pronoun 'WEs'; and they are assigned to inter-subjective LL quadrant. If it is wished to glean these perspectives from questionnaire surveys, questions that ask “What do you feel about using APC?” will generate information for the categories I and Is, whereas those that ask “What in your opinion would the society you live in feel about APC?” will generate information for the categories WE and WEs. Hence, two separate summarizing figures (such as Fig. 8.13) are generated, one to represent the aggregate ‘I(s)’ responses; and the other to represent the aggregate ‘WE(s)’ responses.

Data generation is done with the aid of a questionnaire (which includes closed-ended and open-ended questions) or from structured interviews. Responses to closed-ended questions are in the form of linguistic labels (e.g. ‘very low’ to ‘very high’). Hence they are not represented on a ‘step scale’ with clear-cut boundaries, but are converted to a fuzzy scale, where the boundaries are fuzzy. To explain fuzzy scales, a simple example of ‘price categories’ is considered. Consider a particular commodity, the price of which is categorised in a ‘step-scale’ as shown below:

$ 1 – 20: very cheap
$ 21 – 40: cheap
$ 41 – 60: moderate
$ 61 – 80: expensive
$ 81 – 100: very expensive

In the step scale, a commodity of which the price (for example) is $41 as well as $60 is identified as ‘moderate’, although there is a fairly large difference of $19 between them. At the same time even though the price difference between $60 and $61 is just $1, the $60 price is identified as ‘moderate’, while the $61 one as ‘expensive’. Due to this problem, the step scale does not always reflect a realistic representation of the linguistic data. Therefore, a fuzzy scale, such as the one shown **Fig. 8.14**, is preferred.

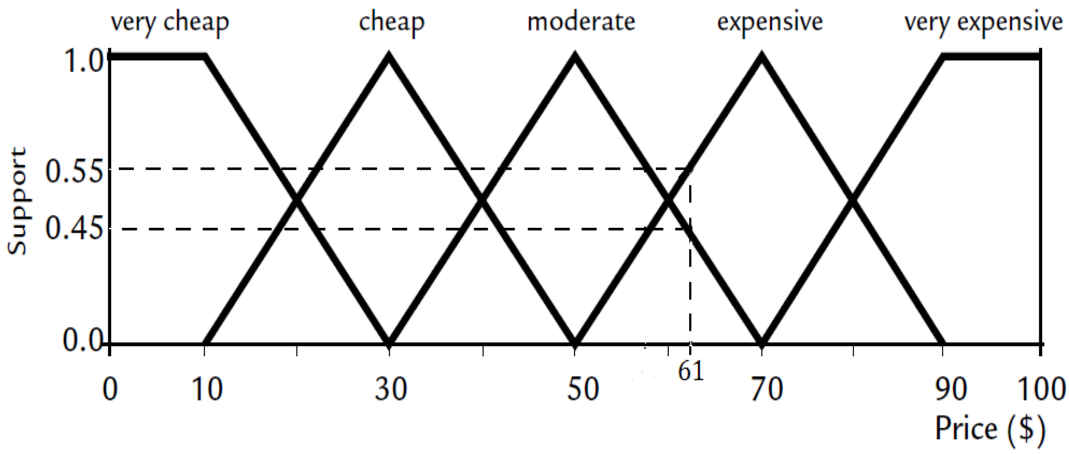

Fig. 8.14 Fuzzy Scale

In this fuzzy scale, products of different prices are identified as below:

$40 product - *fuzzy support of 0.5 for cheap and 0.5 for moderate*

$50 product - *fuzzy support of 1.0 for moderate*

$60 product - *fuzzy support of 0.5 for moderate and 0.5 for expensive*

$61 product - *fuzzy support of 0.45 for moderate and 0.55 for expensive*

Unlike in a 'step-scale', there are no abrupt changes in a 'fuzzy-scale', but gradual ones. Also in reality, human preferences generally have fuzzy rather than clear-cut boundaries, with 'overlapping areas' between them. For example, in reality a person who considers $60 as an affordable moderate price for a certain commodity would not consider it unaffordable and expensive if its price is increased by only $1 and made $61. Hence, a fuzzy scale is more appropriate to reflect subjective preferences. In view of the above, it was decided to use fuzzy scales in analysing responses to closed-ended questions. In applying fuzzy scales, the responses 'very low' to 'very high' are arranged along the x–axis and the degree of support (0 to 1) for the responses are indicated on the y-axis. Each response will in fact be a fuzzy set and techniques are available for averaging fuzzy responses and later converting them back to the linguistic labels 'very low' to 'very high' with the fuzzy support for each, as demonstrated for example by Dias (1999) . Responses for open-ended questions and interviews are qualitative and they are analysed and recorded as themes.

8.6.1.3 Integration of objective and subjective views of Integral Sustainability

As described above, subjective and objective information can be gathered using relevant techniques. In the next step, a 'quadrivial approach' is used to integrate the information (Esbjörn-Hargens 2009). In a 'quadrivial approach', Alkali Pozzolan Cement (APC) is placed at the centre and viewed from the four different lenses, as shown in **Fig. 8.15** enabling the researcher to assess the overall integral sustainability of Alkali Pozzolan Cement (APC).

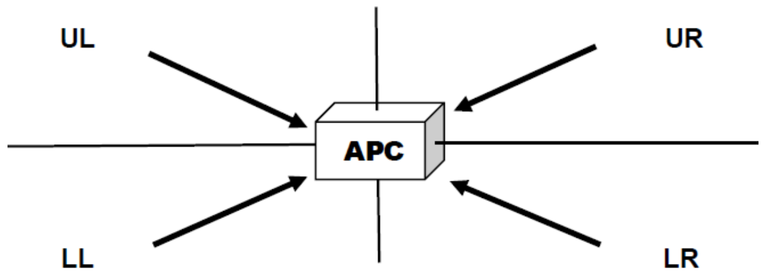

Fig. 8.15 Quadrivial Approach

Such a tetra-quadrant framework with just one entry in each quadrant (as examples) is given in **Fig. 8.16**. Note that the measures for the objective quadrants have quantitative values with means and ranges and those for subjective quadrants have linguistic labels with fuzzy support – the values are fictitious. It should be noted that all the summarized information from all 4 quadrants of the quadratic view (**Fig. 8.13**) relating to the 'I(s)' perspective is placed in the UL quadrant of the quadrivial view (**Fig. 8.16**); and that relating to the 'WE(s)' perspective in the LL quadrant of Fig**. 8.16**. The quadrivial view is therefore a more comprehensive though succinct one, where the left hand quadrants are concerned. Conversely, the two separate 'I(s)'and 'WE(s)' quadratic views can be seen as an expansion or articulation of the UL and LL quadrants respectively in the quadrivial view.

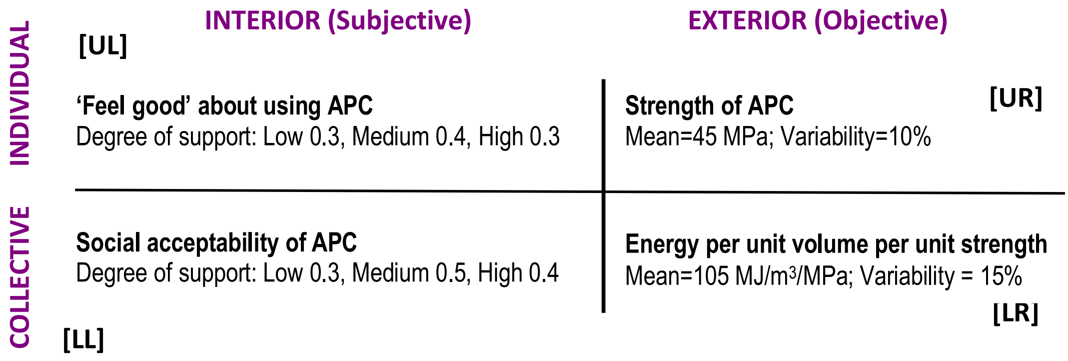

Fig. 8.16 Integration of Objective & Subjective information

8.6.2 Octa-octant framework

As described before, in order to design APC for integral sustainability, the four quadrant sustainability has to be satisfied. However, the stability of integral sustainability depends on the certainty and uncertainty of the aspects related to each quadrant. To represent the certainty/uncertainty of each aspect the modified octa-octant framework is used. This can help to minimise uncertainty as much as possible so that the integral sustainability of APC can be made stable.

Information recorded in the four quadrants of the tetra-quadrant framework are examined and classified as to whether they reflect certainty or uncertainty. They are then transferred into the eight octants of the octa-octant framework. Once again examples of perspectives in each of the 8 'octants' are given as follows:

URB – Less random objective entities of APC (e.g. strength with low variability)

URT – More random objective entities of APC (e.g. embodied energy with high variability)

LRB – Less random inter-objective relationships of APC (e.g. cost per unit volume per unit strength with low variability)

LRT – More random inter-objective relationships (e.g. embodied energy per unit volume per strength with high variability)

ULB – Less fuzzy individual perceptions (e.g. individual concerns about 'quality standards' with less fuzziness)

ULT – More fuzzy individual perceptions (e.g. individual concerns about 'feel good factor' with high fuzziness)

LLB – Less fuzzy social perceptions (e.g. social concerns about 'market price' with less fuzziness)

LLT – More fuzzy social perceptions (e.g. social concerns about 'social trends' with high fuzziness)

The primary aim of this audit is to obtain a realistic picture about the current situation about APC, and then to make improvements. The four 'uncertain' octants will lead to the degree to which information is random, imprecise or even missing. Uncertainty may be reduced as where as possible, by conducting more testing (for objective aspects) or opinion surveys (for subjective aspects). Improvements in sustainability on the other hand can only be made by changing resource and/or technology inputs (for objective aspects) or by greater awareness creation and/or image building with respect to APC (for subjective aspects). This type of integral audit will be helpful to understand where the deficiencies are (i.e., whether they are in objective or subjective aspects, which are where more efforts should be directed to) and also whether the need is to reduce uncertainty or in fact to improve sustainability.

8.7 Conclusion

The aim of this research is to investigate the development of Alkali Pozzolan Cement (APC) for integral sustainability. Accordingly, first of all, there was a need to develop an integral sustainability framework capable of integrating the four aspects of sustainability related to the four quadrants of the integral framework. Moreover, in order to differentiate 'collections' and 'collectives', a necessity arose to modify the pronouns of the standard tetra quadrant framework. Furthermore, to investigate the 'stability' of integral sustainability of APC, a totally new three-dimensional framework has been developed. Finally, the application of above modified frameworks to APC has been illustrated. The conclusions stemming out of the work presented in this chapter are:

1. An integral sustainability framework with the 4Es of sustainability, that is, economical, ecological, existential and ethnological sustainability, can be used as the basis for this research.

2. The basic pronouns related to the four quadrants of the standard tetra-quadrant framework have been modified as I(s), WE(s), IT(s) and THEY(s), in order to recognise and differentiate 'collections of individuals' from 'collectives of individuals'. With the aid of this framework, the 'collection of views related to APC' and 'collective views related to APC' can be generated and analysed.

3. In analysing subjective information, it is believed that qualitative estimates having 'step-scales' or clear-cut boundaries are not appropriate, since subjective preferences do not have clear-cut boundaries. Hence, a 'fuzzy scale' with fuzzy boundaries has been proposed for analysing subjective information.

4. In analysing objective information, the inadequacy of 'point measures' that give single values has been recognised; hence, the 'spread of measures' has been proposed to reflect uncertainty.

5. A third dimension has been added to the two-dimensional tetra-quadrant framework and the three-dimensional octa-octant framework derived. The third dimension added was the 'certain – uncertain' dichotomy. This three-dimensional octa-octant framework can be used to differentiate 'certain' and 'uncertain' aspects of subjective and objective information related to APC.

6. The 'integral sustainability' of 'Alkali Pozzolan Cement' (APC) can be effectively assessed with the aid of the modified integral frameworks.

7. The two-dimensional tetra-quadrant framework with modified pronouns and uncertainty estimates, and the newly developed three-dimensional octa-octant framework, are both general theoretical frameworks that can be used for assessing the integral sustainability not only of APC, but other products, services and entities as well.

8.8 References

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9 Individual and Social Concerns of APC

Overview
This chapter presents the investigation of individual and social concerns regarding the integral sustainability of Alkali Pozzolan Cement (APC). Social surveys were conducted in three contexts, namely, Australia, America and Sri Lanka. The data collected through closed-ended questions were analysed using fuzzy techniques, and data generated through open-ended questions were analysed using grounded theory techniques. Results indicate that the individuals and societies in all three countries are more concerned about market price, quality standards, sustainability issues and recommendations from professionals when selecting a cement. Results also indicate that, in all three contexts, there is generally a high probability that individuals and societies will accept APC as an integral sustainable cement.

Key words: *Social concerns, fuzzy techniques, grounded theory techniques*

9.1 Introduction

In order to develop 'Alkali Pozzolan Cement' (APC) for integral sustainability, in addition to the objective properties of APC, subjective concerns (individual and social) regarding APC have to be incorporated. Chapters 3 to 7 presented the objective properties of APC. Chapter 8 introduced two integral sustainability frameworks to be employed to investigate the integral sustainability of APC. This chapter presents an investigation of the individual and social concerns of APC.

It may be relevant to mention that, even though the aim here is to design APC for social acceptability, it should not be just due to an attractive feature such as lower market price or as a result of advertising. Instead, the acceptance should be based on considerations of the aspects related to the four quadrants (four-quadrant aspects) of the integral sustainability framework.

As described in Chapter 1, the process of developing APC for integral sustainability is not a linear process but a circular one. In addition to considering the properties of APC and its environmental impact, individual and social concerns about APC have to be taken into account from the beginning of the development process. Hence, even during the development stage, the properties of APC have to be presented to people, and their 'four-quadrant concerns' have to be queried and incorporated in design. This chapter presents an investigation of a social survey conducted during the development process of APC, the findings from which would be extremely useful for the further development of APC.

Literature related to individual or social concerns about 'four-quadrant aspects' of a new cement seems to be non-existent. Hence, the literature available on the acceptability of other products was used to provide some guidance when formulating the research (even though previous studies were not related to cement and did not focus on integral sustainability).

Yeniyurt and Townsend (2003) conducted an empirical investigation to study cultural differences in the acceptance of new products. They concluded that there is a significant association between cultural aspects and diffusion rates of new products. They also confirmed that the role of the culture associated with the acceptance of new products is affected by the economic, educational and urbanization structures of the context. This implies that the acceptance of a product is associated with culture, which is an aspect related to the lower left quadrant of the integral sustainability frame work. Schlegelmilch, Bohlen, and Diamantopoulos (1996) investigated the effect of environmental consciousness on green purchasing decisions, and concluded that consumers' overall environmental consciousness had a positive impact on pro-environmental purchasing behaviour. Hence, the acceptance of green products is influenced by an individual's environmental concerns, which pertains to the upper left quadrant of the integral sustainability framework. Brown and Wahlers (1998) conducted an exploratory study on environmentally concerned consumers. They found that even environmentally concerned consumers were hesitant about accepting environmentally friendly products because they did not believe the 'eco-friendly claims' attached to products. This implies that mere 'eco-friendly claims' are not enough to make a product acceptable, but that confirmation of its eco-friendliness by a reliable authority is of paramount importance. Therefore, the recommendations of professionals would help to convince a potential customer. Pickett-Baker and Ozaki (2008) investigated the effect of marketing and branding techniques when introducing green products. They found that the majority of consumers were likely to trust a well-known branded product rather than a lesser-known environmentally friendly product. This implies that the majority is concerned about the aspects in the upper left quadrant rather than in the lower right quadrant. However, they also found that consumers ‘feel good’ when purchasing the brands that cause less damage to the environment. Moreover, it was determined that consumers trust the product if it is associated with a well-known brand. This implies that even a non-familiar product, if it is introduced under a familiar brand name, can be made acceptable. In summary, it is seen that acceptance of a new green product generally depends on many factors such as market price, quality, familiarity, brand name, cultural trends, environmental concerns and confirmation of qualities, all of which are related to different quadrants of the integral sustainability framework. This background knowledge was used to decide the aspects to be focused on in terms of the individual and social concerns related to the four quadrants of the framework.

9.2 Aim and Objectives

The main aim of this chapter is to present the outcome of the investigation of a social survey conducted during the development of APC, which includes individual and social concerns (subjective and inter-subjective concerns, according to the integral theory terminology) regarding the integral sustainability of Alkali Pozzolan Cement (APC). This main aim was achieved through the following objectives.

1. To identify aspects of APC relevant to the four quadrants of the integral sustainability framework, and develop a method/strategy to determine the individual and social concerns regarding selected aspects through a social survey.

2. To present a brief assessment on the integral sustainability of APC, based on the results of the social survey.

3. To discover the individual and social concerns specific to a given social context, and to address these concerns when developing APC for integral sustainability.

9.3 Methodology

A series of strategies had to be adopted to achieve the above objectives. Firstly, the aspects of APC relevant to the four quadrants of integral sustainability framework had to be identified, then methods had to be developed to determine the individual and social concerns about those aspects. After that, the contexts in which the data would be generated had to be decided. All these methods and strategies are described in detail below.

9.3.1 Identification of Integral Sustainability Aspects of APC

As described in Section 9.1, in order to develop APC for integral sustainability, it has to be designed so as to take into account individual and social concerns; moreover, it has to be accepted by consumers, based on aspects related to the four quadrants of integral sustainability framework (four-quadrant concerns). However, the number of aspects related to each quadrant may be very large, and cannot all be considered in this study. For the purpose of demonstration, it was therefore decided to consider only two aspects for each quadrant.

In the process of identifying the aspects, a list of aspects in each quadrant was first prepared with the help of brainstorming sessions, and analysis of literature and advertisements. As mentioned in Section 9.1, the literature indicates that people consider many factors when selecting a product, including economic concerns, quality, environmental concerns, familiarity, trustworthiness and cultural trends. It was also noted that advertisements highlight price, quality, eco-friendliness and recommendations of professionals. Brainstorming sessions added more aspects to the lists for each quadrant. Two important aspects from each list related to each quadrant of the integral sustainability framework given in **Fig. 8.4** were selected to generate individual and social responses; they are given below:

UR Quadrant: (Economical sustainability)

Market price
Quality standards

LR Quadrant: (Ecological sustainability)

Impact on the sustainability of the Earth
Mitigating land pollution due to fly ash

UL Quadrant: (Existential sustainability)

'Feel good' factor
Non-familiarity

LL Quadrant: (Ethnological sustainability)

Social trends
Recommendations of professionals

Accordingly, eight specific aspects related to APC were selected in order to investigate people’s concerns. In addition, it was decided to investigate the overall view of APC.

9.3.2 Development of a Strategy to Generate Individual and Social Concerns

In this research, there was a need to determine not only individual concerns, but also social concerns about the aspects related to integral sustainability of APC. Several direct methods, such as questionnaire surveys and interviews, can be used to determine individual concerns. However, social concerns cannot be determined as directly as individual concerns. Moreover, as mentioned in Section 8.4, the difference between ‘collections’ and ‘collectives’ has been identified in this research; hence, a mere ‘collection of individuals’ cannot be considered as a ‘collective’. Therefore, a collection of ‘concerns of individuals’ cannot be considered as a ‘concern of the society’. It is the ‘collective concern’ that can be considered as the ‘concern of the society’.

Theoretically, the ‘collective view’ of a small focus group about a particular issue can be generated at a round table discussion. An issue is given to a focus group, and participants are asked to discuss the issue until a common view emerges. This method is appropriate for a small focus group, but not for a larger group or for society. Hence, an indirect method had to be developed to obtain the ‘social view’. In this indirect method, individuals were asked about ‘their individual view’ about “the society’s view about an issue”. The ‘majority’s view about the society’s view about a given issue’ was considered as the ‘society’s view about the issue’.

9.3.3 Selection of Contexts and Participants

Individual and social concerns may be contextual as well as universal. Hence, for the purpose of demonstration, participants from the three different contexts, which are directly related to the study area, were selected.

1. Participants at the Concrete 2013 Conference, Australia (Australian Technologists)
2. Participants at the Integral Theory Conference 2013, USA (American Integralists)
3. Participants at the Green Building Workshop 2013, Sri Lanka (Sri Lankan Environmentalists)

Note that, for convenience, hereafter the three groups above are termed Australian Technologists, American Integralists and Sri Lankan Environmentalists.

It was reasonable to assume that participants at the Concrete 2013 Conference were interested in cement; while participants at the Integral Theory Conference were interested in Integral Sustainability. Hence, the interests of these two groups were directly related to the two major areas of this research, namely 'cement' and 'integral sustainability'. Further, it was reasonable to assume that the participants at the Green Building Workshop were interested in environmental issues.

9.3.4 Selection of an Instrument for data generation

In order to generate data, different methods, such as questionnaire surveys and interviews, could be used. However, as the data generation had to be done in the contexts given in Section 9.3.3 within a limited time, it was not practical to conduct interviews. Hence, it was decided to use a questionnaire as an instrument for data generation. The following section gives the details of the questionnaire design.

Design of the Questionnaire for Data Generation

The purpose of the questionnaire was to determine the individual and social concerns regarding certain aspects relevant to the integral sustainability of APC, and also to generate data that was unique or specific to different contexts. Closed-ended questions allow the participants to express different degrees of concerns about given aspects. On the other hand, open-ended questions can generate new information. Hence, both closed-ended questions and an open-ended question were included in the questionnaire.

The complete questionnaire is given in **Appendix A3**. The questions on the first page are intended to collect demographic data about the participants; subsequent pages consist of three separate sections to generate subject-related data. Section 1 contains closed-ended questions to generate data related to different aspects of APC, while Section 2 contains a close-ended question to determine the overall view about APC. Section 3 is in a different format and contains an open-ended question to generate unique data arising from the contexts.

Questions in Sections 1 and 2 have the same format - an 'introductory statement' and two sub-sections, namely, part (a) and part (b). The 'introductory statement' of each question presents aspects related to 'Alkali Pozzolan Cement' (APC). In part (a), the participants are asked to indicate the degree of importance that '**they'** would assign to the given aspect when selecting the new cement over the conventional cement, if they were to build their own house. In part (b), the participants were asked to indicate the degree of importance that they think that '**the society they presently live in'** would assign to the given aspect in selecting the new cement over conventional cement, in order to build houses. In other words, in part (b), participants are asked about 'their view on the society's view'. Accordingly, from part (b) results, it is possible to discover what the majority thinks about society's view. In a given context, the majority's agreement about the society's view can be considered as the society's view of the context concerned. Both in parts (a) and (b), a spectrum of linguistic labels from Very Low (VL) to Very High (VH) are given to indicate the responses. To avoid the central tendency, the category 'medium' has been divided into 'medium low' (ML) and 'medium high' (MH). Participants are made aware that the size of the ranges ML and MH are half of the size of ranges of other linguistic labels. To ensure that the participants understand this clearly, it is also shown visually using the mini-table shown in **Fig. 9.1**, which is given under each question. Participants are asked to respond by putting a cross (X) in the relevant cell of the mini-table.

Very Low	Low	Medium		High	Very High
		Med. Low	Med. High		

Fig. 9.1 Mini-table provided to indicate responses

In Section 3 of the questionnaire, there is one open-ended question inviting participants to express any view related to the selection of cement.

The data generated through Sections 1 and 2 of the questionnaire concern different aspects related to APC, while the data generated through Section 3 have no such focus, but have emerged freely. Hence, two different methods have to be used to analyse the data; they are described in Section 9.3.5 and demonstrated in Section 9.4.

9.3.5 Methods of Data Analysis

9.3.5.1 Responses to Closed-ended Questions

Responses to these questions are given using linguistic labels (e.g. 'very low' to 'very high'). In reality, human preferences are expressed in linguistic labels (such as 'very low', 'low', 'moderate', 'high', 'very high') and do not have clear-cut boundaries; therefore, their boundaries are fuzzy, and there will be 'overlapping areas' between them. Hence, the responses to these questions are not represented on a 'step scale', but are converted to a fuzzy scale. An example of a fuzzy scale was given in Section 8.6.1.2.

9.3.5.2 Responses to Open-ended Questions

In Section 3 of the questionnaire, the open-ended question provided a platform to generate freely the data grounded in the contexts. Hence, those data are analyzed using 'grounded theory techniques'. Grounded theory is a relatively new research methodology developed in the field of social sciences, to discover a theory by analyzing the data. Even though it was developed in the field of social sciences, grounded theory techniques have been successfully applied in many other fields (Haig 1995). Further, grounded theory techniques have been combined with other analytical techniques and applied not only to develop theories, but also to identify phenomena. For example, Dias and Chandratilake (2005) used grounded theory techniques in civil engineering, not to develop a theory, but to identify the vulnerability of buildings to blast events. Accordingly, in this research too, it was decided to adopt grounded theory techniques, not to develop a theory, but to discover important design considerations of APC for integral sustainability. The application of grounded theory techniques is demonstrated in detail in Section 9.4.2.

9.3.6 Data Generation

The questionnaire surveys were conducted in the three contexts described in Section 9.3.3. In order to ensure that the participants have a reasonable understanding about the context (the society they live in), only the responses of participants residing for over five years in the given context were considered for analysis.

Context 1 – 'Australian Technologists'

Participants were selected from the Concrete 2013 Conference held in Queensland, Australia from 16- 18 October 2013. It was a biennial conference organised by the Concrete Institute of Australia. Hence, participants were identified as 'Australian Technologists'. A total of 80 participants took part in the research, but only 61 returned the completed questionnaire. The demographic details indicated that 10 of them had been residing for fewer than five years in Australia; hence, their responses were not accepted for analysis. Accordingly, the number of valid participants considered for analysis was 51.

Context 2- 'American Integralists'

Participants were selected from the Integral Theory Conference 2013 held in San Francisco, America (USA) from 18-21 July 2013. It was a biennial conference organised by the Metaintegral Foundation, USA. Hence, participants were identified as 'American Integralists'. The term 'America' is used only to identify the 'United States of America' (USA), excluding other countries in North and South America. A total of 83 participants took part in the research, but only 64 returned the completed questionnaire. The demographic details indicated that 24 of them had resided for fewer than five years in America; hence, their responses were not accepted for analysis. Accordingly, the number of valid participants considered for analysis was 40.

<u>Context 3- 'Sri Lankan Environmentalists'</u>

Participants were selected from the workshop on 'Green Buildings' held in Colombo, Sri Lanka on 26, July 2013. It was a workshop organised by the Green Building Council of Sri Lanka. Hence, participants were identified as 'Sri Lankan Environmentalists'. A total of 39 participants took part in the research, but only 38 returned the completed questionnaire. The demographic details indicated that 1 of them had resided for fewer than five years in Sri Lanka; hence, his responses were not accepted for analysis. Accordingly the number of valid participants considered for analysis was 37.

9.4 Analysis, Results & Interpretations

As described in Section 9.3.5, two different methods were adopted to analyse responses to closed-ended questions and open-ended questions. These are demonstrated below.

9.4.1 Close-ended Questions

The questions in Sections 1 and 2 of the questionnaire were closed-ended questions. First, the theoretical framework used for analyzing data is described and then its application demonstrated. Thereafter, a brief assessment of integral sustainability of APC is presented.

9.4.1.1 Theoretical Framework for Analysis of Closed-ended Questions

The theoretical framework suggested by Dias (1999) was adopted for the analysis of the responses to closed-ended questions. First, the responses to closed-ended questions, which were in the form of linguistic labels (e.g. 'very low' to 'very high'), were arranged along the x–axis, and the degree of support (0 to 1) for the responses was indicated on the y-axis as shown in **Fig. 9.2**.

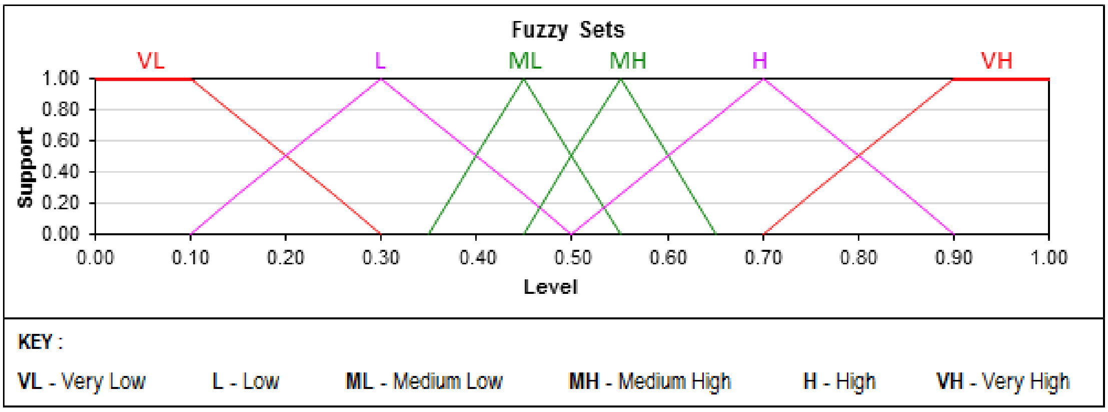

Fig. 9.2 Fuzzy Sets

The area covered by each fuzzy set in **Fig. 9.2** is 0.2, except that of ML and MH. The response 'Medium' has been divided into two responses 'Medium Low' (ML) and 'Medium High' (MH) to avoid central tendency. Hence, fuzzy sets ML and MH were established to cover an area of 0.1, so that their sum is 0.2.

Theoretical Explanation

The responses obtained from the participants of three different contexts, namely Australia, America and Sri Lanka, were grouped and analysed separately to investigate the contextual differences in views regarding the issues. Firstly, responses for a particular question were selected from a particular context. Then those responses were converted to fuzzy curves. Next, those fuzzy curves were added together to obtain a cumulative curve. The mean response to that question was found by dividing the area covered by the cumulative curve by the total number of responses to that particular question. Alternatively, by dividing the ordinates of cumulative curve by the number of responses to that particular question, the ordinates of the mean curve can be determined. The area covered by the mean curve is the mean response.

Mathematical Explanation

The above procedure is expressed mathematically below.

The complete fuzzy set F is defined by the general equation,

$$F = [x_i, \mu_F(x_i) \mid x_i = x_1 \ldots x_n]$$

Where, $\mu_F(x_i)$ is the support allocated to x_i in F, that indicates the degree to which x_i belong to F.

Six fuzzy sets have been defined to cover the linguistic range VL to VH. A particular curve can be denoted F_r. Then the 'Degree of Identity' (DoI) of the mean response with a selected fuzzy curve F_r is defined as,

$$DoI(M, F_r) = | M \cap F_r | / | F_r |$$ where M = Mean responses, F_r = Fuzzy curve considered

Here, $M \cap F_r = [x_i, \min(\mu_F(x_i), \mu_M(x_i))]$

$$| F_r | = \sum \mu_F(x_i), \quad x_i = x_1 \ldots x_n$$

$$| M \cap F_r | = \sum \min [\mu_F(x_i), \mu_M(x_i)], \quad x_i = x_1 \ldots x_n$$

Here the operator ll represents the relevant area of the fuzzy set.

In all cases we will have, $0 \leq DoI(M, F_r) \leq 1$

For the purpose of interpretation, a cut-off level (α) is introduced for DoIs, and the DoIs falling at or above this cut-off level are termed 'significant DoIs'.

The most significant DoI or the largest DoI represents the 'mode' (similar to statistical mode) of responses, which can be defined as the response that is spread over a particular linguistic label most often, or the most predominant view.

Graphical Explanation

The theoretical explanations given above can be graphically depicted with the aid of the following example.

In the fuzzy sets shown in **Fig. 9.3**, x_i varies from 0 to 1 in discrete steps of 0.05. For example, the linguistic label 'High' or 'H' is defined for x_i values of 0.55, 0.60, 0.65, 0.70, 0.75, 0.80 and 0.85 with supports $\mu_F(x_i)$ of 0.25, 0.50, 0.75, 1.00, 0.75, 0.50 and 0.25 respectively. The mean responses for question 5(a) of participants of the group 'Australian Technologists' has been superimposed on the range of fuzzy sets.

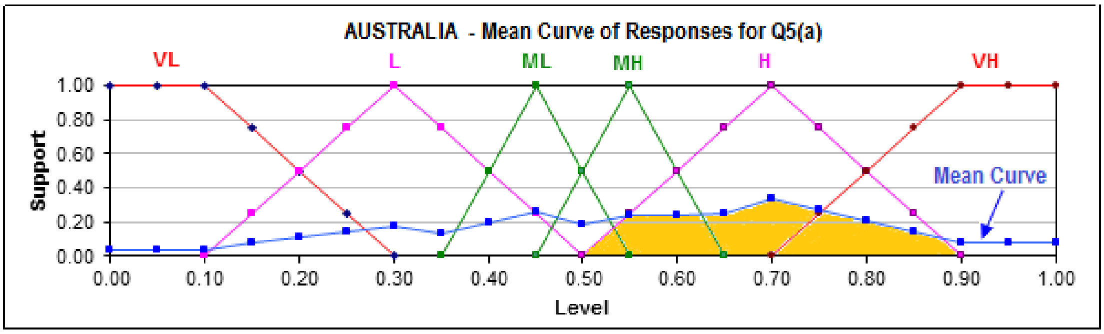

Fig. 9.3 Mean responses for question 5(a) of participants of Australia

The computation of the Degree of Identity (DoI) of mean responses with a particular fuzzy curve F_r, which is denoted by DoI (M, F_r), is described below. The mean response is represented by the area under the mean curve M. Then entity $|M \cap F_r|$ represents the area of intersection of the mean curve M and the fuzzy curve F_r. The entity $|F_r|$ represents the area under the fuzzy curve 'F_r'. The ratio of the former to the latter gives the Degree of Identity (DoI) of the mean response with the fuzzy curve F_r. In **Fig. 9.3**, the fuzzy curve considered (F_r) is the curve that represents the linguistic label 'high' or H. The intersection of the mean curve and the fuzzy curve H is highlighted. Then DoI for H can be computed by dividing this area by the area under the fuzzy curve H (specimen calculations are given in **Appendix A4**).

The entity DoI(M, F_r), which is the 'degree of identity of mean responses' (M) with a given fuzzy curve (F_r) indicates the extent to which a given linguistic label along with its neighbouring labels has been assigned as the response to a particular question. For example, in the case of the fuzzy curve H, there is one neighbouring label in the upper end, which is VH, while there are two neighbouring labels in the lower end, namely MH and ML. Accordingly, the physical meaning of degree of identity (DoI) is the extent to which the responses have been spread over a given linguistic label. Hence, if the value of DoI with respect to a particular fuzzy curve (say H) is relatively large, then it can be stated that the 'concerns are significant' to level 'H'.

9.4.1.2 Analysis of Responses of Closed-ended Questions

The purpose of the questionnaire is to obtain an idea of the subjective views of people, if APC were introduced to them. The questions in Part (a) required participants to express their individual views, whereas the questions of Part (b), asked them what they consider to be their society's view (social view). Therefore, in a given context, the majority's agreement about the society's view was considered as the social view of the context concerned.

In the following paragraphs, the local societies of Australian Technologist, Sri Lankan Environmentalists, and American Integralists are identified as 'Australian Society', 'Sri Lankan Society', and 'American Society' respectively for convenience.

The relevant graphs of the mean responses superimposed on fuzzy sets are given in **Appendix A4**. The DoIs for all the fuzzy curves corresponding to the linguistic labels were computed for the responses obtained from Australia, Sri Lanka and America, and given in **Table 9.1**, **Table 9.2** and **Table 9.3** respectively. In these tables, the second column indicates the question number. The aspects related to these questions are given below.

Q 1: Market price
Q 2: Quality standards
Q 3: Impact on the sustainability of the Earth
Q 4: Mitigating land pollution due to fly ash
Q 5: Non-familiarity
Q 6: 'Feel good' factor
Q 7: Social trends
Q 8: Recommendations of professionals
Q 9: Overall acceptability of the new cement

It should be noted that questions 1 to 8 belong to Section 1 of the questionnaire and they have the same format. Question 9 belongs to Section 2 and its format is different from that of questions 1 to 8. As mentioned previously, questions 1 to 8 are intended to ascertain the degree of importance of different aspects that are considered when selecting APC. However, question 9 queries the degree of overall acceptance of APC. Hence, the DoIs of question 9 are shown separately from the DoIs of questions 1 to 8, in **Table 9.1**, **Table 9.2**, and **Table 9.3**. In each table, there are two main parts. Part (a) represents the DoIs related to individuals, while Part (b) represents DoIs related to society. Both Part (a) and Part (b) contain the whole spectrum of linguistic labels from VL to VH.

For convenience, the interval between 0 and 1 was arbitrarily divided into three, and the boundary of the first one third (that is, 0.33) was chosen as the cut-off level. As mentioned previously, DoIs falling at or above this cut-off level were interpreted as 'significant DoIs'. Those above 0.55 are labelled 'highly significant DoIs'. In **Table 9.1**, **Table 9.2**, and **Table 9.3**, the 'significant DoIs' are indicated in normal black fonts. The maximum DoI for each question, which reflects the 'mode' (similar to statistical mode) for each question, is indicated by bold black fonts. The non-significant DoIs, or DoIs falling below the cut-off level, are not considered in the interpretations; hence, they are purposely indicated using small fonts with a light font, so that 'significant DoIs' can be easily identified.

Table 9.1 DoIs for 'Australian Technologists'

AUSTRALIA														
Sectn	Q	Part (a) - Individuals							Part (b) - Society					
		VL	L	ML	MH	H	VH		VL	L	ML	MH	H	VH
1	Q1	0.07	0.11	0.25	0.45	**0.58**	0.27		0.03	0.09	0.16	0.38	**0.67**	0.38
	Q2	0.03	0.05	0.10	0.31	**0.61**	0.51		0.06	0.16	0.26	0.42	**0.49**	0.33
	Q3	0.02	0.07	0.19	0.52	**0.56**	0.33		0.06	0.18	0.28	0.46	**0.50**	0.28
	Q4	0.01	0.08	0.25	0.48	**0.56**	0.33		0.06	0.18	0.25	0.43	**0.53**	0.31
	Q5	0.11	0.27	0.38	0.40	**0.43**	0.20		0.07	0.14	0.26	0.40	**0.55**	0.32
	Q6	0.05	0.20	0.39	**0.45**	0.43	0.25		0.06	0.17	0.35	0.48	**0.50**	0.22
	Q7	0.15	0.29	0.38	**0.39**	0.37	0.20		0.04	0.16	0.28	0.45	**0.55**	0.28
	Q8	0.02	0.06	0.16	0.43	**0.61**	0.40		0.00	0.04	0.16	0.42	**0.63**	0.40
2	Q9	0.02	0.07	0.17	0.45	**0.69**	0.31		0.04	0.12	0.24	0.53	**0.55**	0.26

KEY
Q1 - Market price
Q2 - Quality standards
Q3 - Impact on the sustainability of the Earth
Q4 - Mitigating land pollution due to fly ash
Q5 - Non-familiarity
Q6 - 'Feel good' factor
Q7 - Social trends
Q8 - Recommendations of professionals
Q9-Overall acceptability

Table 9.2 DoIs for 'American Integralists'

AMERICA														
Sectn		Part (a) - Individuals							Part (b) - Society					
	Q	VL	L	ML	MH	H	VH		VL	L	ML	MH	H	VH
1	Q1	0.03	0.12	0.26	**0.53**	0.50	0.27		0.02	0.10	0.22	0.26	0.34	**0.62**
	Q2	0.02	0.07	0.13	0.31	0.50	**0.57**		0.02	0.10	0.22	0.39	0.45	**0.46**
	Q3	0.00	0.02	0.10	0.27	0.55	**0.61**		0.06	0.21	0.43	**0.53**	0.36	0.17
	Q4	0.04	0.06	0.13	0.36	0.50	**0.52**		0.13	0.32	**0.46**	0.44	0.32	0.12
	Q5	0.17	**0.50**	0.44	0.31	0.22	0.14		0.07	0.19	0.28	**0.52**	0.48	0.23
	Q6	0.02	0.03	0.11	0.39	**0.61**	0.46		0.10	0.33	0.45	**0.46**	0.32	0.13
	Q7	0.12	0.32	0.39	**0.47**	0.33	0.16		0.03	0.14	0.32	**0.56**	0.47	0.22
	Q8	0.00	0.03	0.12	0.33	**0.57**	0.54		0.00	0.03	0.17	0.49	**0.56**	0.40
2	Q9	0.00	0.01	0.07	0.26	0.55	**0.63**		0.02	0.12	0.32	**0.52**	0.44	0.28

KEY
Q1 - Market price
Q2 - Quality standards
Q3 - Impact on the sustainability of the Earth
Q4 - Mitigating land pollution due to fly ash
Q5 - Non-familiarity
Q6 - 'Feel good' factor
Q7 - Social trends
Q8 - Recommendations of professionals
Q9-Overall acceptability

Table 9.3 DoIs for 'Sri Lankan Environmentalists'

SRI LANKA														
Sectn		Part (a) - Individuals							Part (b) - Society					
	Q	VL	L	ML	MH	H	VH		VL	L	ML	MH	H	VH
1	Q1	0.04	0.14	0.25	0.44	**0.65**	0.26		0.04	0.16	0.30	0.36	**0.57**	0.32
	Q2	0.03	0.08	0.15	0.33	**0.58**	0.48		0.08	0.25	0.33	0.36	**0.45**	0.31
	Q3	0.00	0.00	0.05	0.29	**0.62**	0.58		0.07	0.22	0.29	0.38	**0.52**	0.30
	Q4	0.01	0.06	0.15	0.33	**0.60**	0.49		0.19	0.23	0.24	0.38	**0.45**	0.25
	Q5	0.20	0.33	0.37	**0.42**	0.33	0.14		0.29	**0.50**	0.39	0.28	0.24	0.08
	Q6	0.00	0.02	0.11	0.36	**0.58**	0.53		0.10	0.23	0.30	0.42	**0.49**	0.24
	Q7	0.05	0.12	0.23	0.43	**0.57**	0.33		0.01	0.08	0.23	0.48	**0.58**	0.33
	Q8	0.00	0.02	0.08	0.33	**0.67**	0.50		0.03	0.11	0.23	0.36	**0.51**	0.44
2	Q9	0.00	0.01	0.09	0.42	**0.68**	0.43		0.04	0.12	0.32	0.47	**0.51**	0.27

KEY
Q1 - Market price
Q2 - Quality standards
Q3 - Impact on the sustainability of the Earth
Q4 - Mitigating land pollution due to fly ash
Q5 - Non-familiarity
Q6 - 'Feel good' factor
Q7 - Social trends
Q8 - Recommendations of professionals
Q9-Overall acceptability

In **Table 9.1**, **Table 9.2**, and **Table 9.3**, for a given question, the ‘width of the spread’ of the significant DoIs gives an indication about the fuzziness regarding the view. For example, if the Significant DoIs are limited to one column, this means that within that context the view is less fuzzy or very focused. On the other hand, if Significant DoIs are spread over 3 or 4 columns, this means that in that context, the view is more fuzzy. By counting the number of columns that have been occupied by ‘significant DoIs’, the width of the spread of ‘significant DoIs’ for a given aspect can be computed. The spreads of ‘significant DoIs’ of the three contexts are given in **Table 10.3**.

Table 9.4 Widths of Spread of Significant DoIs

Qn	AUSTRALIA		AMERICA		SRI LANKA	
	Part (a)	Part (b)	Part (a)	Part (b)	Part (a)	Part (b)
Q1	2	3	2	2	2	2
Q2	2	3	2	3	3	3
Q3	3	2	2	3	2	2
Q4	3	2	3	2	3	2
Q5	3	2	2	2	4	2
Q6	3	3	3	3	3	2
Q7	3	2	3	3	3	3
Q8	3	2	3	3	3	3

KEY

Q1 - Market price
Q2 - Quality standard
Q3 - Impact on the sustainability of the Earth
Q4 - Mitigating land pollution due to fly ash
Q5 -Non-familiarity
Q6 -'Feel good' factor
Q7 -Social trends
Q8 -Recommendations of professionals

In **Table 10.3**, the first column specifies the question numbers, and the aspects considered in each question are indicated under the ‘key’. In the next three double columns, Part (a) and Part (b) represent the spread of ‘Significant DoIs’ of the individuals and societies of the contexts indicated. This table is used for certainty/uncertainty analysis in Chapter 10.

9.4.1.3 Subjective Views on Integral Sustainability of APC

For a particular question, the ‘region of spread of Significant DoIs’ indicates the importance given to the aspect related to that question. If ‘significant DoIs’, of a given aspect fall on the right hand side (RHS) of a spectrum of linguistic labels, then it can be said that the aspect considered is important. Similarly, if 'significant DoIs' fall on left hand side (LHS) of the spectrum, then the aspect is considered to be less important.

For a given question, and for a selected part [Part (a) or Part (b)], the maximum DoI represents the 'mode' (similar to statistical mode) of responses for the question. Mode can be defined as the linguistic label that is supported most by the responses. Accordingly, the mode implies the predominant view on that aspect by individuals/society. For example, for a particular aspect, in Part (b), if the mode is in the column VH, then the predominant view of the society is that the importance of that aspect is very high. In other words, the society may have different views concerning degrees of importance, but among them the predominant view is VH.

Before further discussion, it should be noted that the following terminologies are used in the interpretation of the results.

Sig DoIs	= Significant DoIs	= DoIs ≥ 0.33
HiSig DoIs	= Highly Significant DoIs	= DoIs ≥ 0.55

Mode	- Maximum DoI for Part (a) or (b) of a question considered
Australian Technologists	- Respondents of 'Concrete 2013' Conference
American Integrals	- Respondents of 'Integral Theory Conference 2013'
Sri Lankan Environmentalists	- Respondents of 'Green Building 2013 Workshop'
RHS	- Right hand side region
LHS	- Left hand side region
MDL	- Middle region

In addition, the following abbreviated form is used.

Australia : Part (a)-Sig DoIs RHS, Mode H **Part (b)-** Sig DoIs MDL, Mode MH

The above may be expressed as follows:

"For Australia, in part (a), the significant DoIs spreads over the RHS and the mode is H; in part (b), the significant DoIs spreads over the middle-region and the mode is in MH".

When the results given in **Table 9.1**, **Table 9.2** and **Table 9.3** were analysed, the following specific features for each aspect emerged.

Q1: Market Price

Australia	**: Part (a)-**Sig DoIs RHS, Mode H	**Part (b)-** Sig DoIs RHS, Mode H
America	**: Part (a)-**Sig DoIs RHS, Mode MH	**Part (b)-** Sig DoIs RHS, Mode VH
Sri Lanka	**: Part (a)-**Sig DoIs RHS, Mode H	**Part (b)-** Sig DoIs RHS, Mode H

The results imply that market price is generally considered as important by individuals and societies of all three countries. However, the predominant view of American Integralists is that market price is only moderately important; yet the predominant view of their society is that that market price is very important.

Q2: Quality Standard

Australia	**: Part (a)-**Sig DoIs RHS, Mode H	**Part (b)-** Sig DoIs RHS, Mode H
America	**: Part (a)-**Sig DoIs RHS, Mode VH	**Part (b)-** Sig DoIs RHS, Mode VH
Sri Lanka	**: Part (a)-**Sig DoIs RHS, Mode H	**Part (b)-** Sig DoIs RHS, Mode H

The results indicate that quality standard is generally considered as important by individuals and societies of all three countries. In particular, the predominant view of American Integralists and their society is that quality standard is very important.

Q3: Impact on Sustainability on Earth

Australia	**: Part (a)-**Sig DoIs RHS, Mode H	**Part (b)-** Sig DoIs RHS, Mode H
America	**: Part (a)-**Sig DoIs RHS, Mode VH	**Part (b)-** Sig DoIs RHS, Mode MH
Sri Lanka	**: Part (a)-**Sig DoIs RHS, Mode H	**Part (b)-** Sig DoIs RHS, Mode H

The results denote that the 'impact on sustainability of earth' is generally considered as important by individuals and societies of all three countries. In particular, the predominant view of American Integralists is that 'impact on sustainability of earth' is very important, even though the predominant view of their society is that it is moderately important.

Q4: Mitigating Land Pollution

Australia	**: Part (a)-**Sig DoIs RHS, Mode H	**Part (b)-** Sig DoIs RHS, Mode H
America	**: Part (a)-**Sig DoIs RHS, Mode VH	**Part (b)-** Sig DoIs RHS, Mode ML
Sri Lanka	**: Part (a)-**Sig DoIs RHS, Mode H	**Part (b)-** Sig DoIs RHS, Mode H

The results suggest that 'mitigating land pollution' is generally considered as important by individuals and societies of all three countries. In particular, the predominant view of American Integralists is that 'mitigating land pollution' is very important; however, their society's predominant view is that it is only moderately important.

Q5: Non-familiarity

Australia	**: Part (a)-**Sig DoIs MDL, Mode H	**Part (b)-** Sig DoIs RHS, Mode H
America	**: Part (a)-**Sig DoIs LHS, Mode L	**Part (b)-** Sig DoIs RHS, Mode MH
Sri Lanka	**: Part (a)-**Sig DoIs MDL, Mode MH	**Part (b)-** Sig DoIs LHS, Mode L

The results indicate that the attitude regarding 'non-familiarity' differs from country to country. Australian Technologists consider it as moderately important, while their society considers it as important. Sri Lankan Environmentalists consider it as only moderately important, while Sri Lankan society considers it to be of low importance. In the case of America, the society considers it as important, but American Integralists consider it to be of low importance. The predominant view of American Integralists, Sri Lankan Environmentalists and their societies are that 'non-familiarity' is not highly important.

Q6: 'Feel-good Factor'

Australia	**: Part (a)-**Sig DoIs RHS, Mode MH	**Part (b)-** Sig DoIs RHS, Mode H
America	**: Part (a)-**Sig DoIs RHS, Mode H	**Part (b)-** Sig DoIs LHS, Mode MH
Sri Lanka	**: Part (a)-**Sig DoIs RHS, Mode H	**Part (b)-** Sig DoIs RHS, Mode H

The results imply that the 'feel-good factor' is generally considered as important by individuals and societies of all three countries, except for American society. The predominant view of individuals and societies of the three countries is that 'feel-good factor' is highly important, other than for the view of Australian Technologists and American Society.

Q7: Social Trends

Australia	**: Part (a)-**Sig DoIs RHS, Mode MH	**Part (b)-** Sig DoIs RHS, Mode H
America	**: Part (a)-**Sig DoIs RHS, Mode MH	**Part (b)-** Sig DoIs RHS, Mode MH
Sri Lanka	**: Part (a)-**Sig DoIs RHS, Mode H	**Part (b)-** Sig DoIs RHS, Mode H

The results indicate that 'social trends' are generally considered as important by individuals and societies of all three countries. The predominant view of Australian Technologists and American Integralists is that 'social trends' are only moderately important, but that of Sri Lankan Environmentalist is that they are highly important.

Q8: Recommendations of Professionals

Australia	**: Part (a)-**Sig DoIs RHS, Mode H	**Part (b)-** Sig DoIs RHS, Mode H
America	**: Part (a)-**Sig DoIs RHS, Mode H	**Part (b)-** Sig DoIs RHS, Mode H
Sri Lanka	**: Part (a)-**Sig DoIs RHS, Mode H	**Part (b)-** Sig DoIs RHS, Mode H

The results indicate that the 'recommendations of professionals' is considered as important by individuals and societies of all three countries. The predominant view of individuals and societies of all three countries is that it is highly important.

Q9: Overall Acceptability

Australia	**: Part (a)-**Sig DoIs RHS, Mode H	**Part (b)-** Sig DoIs RHS, Mode H
America	**: Part (a)-**Sig DoIs RHS, Mode VH	**Part (b)-** Sig DoIs RHS, Mode MH
Sri Lanka	**: Part (a)-**Sig DoIs RHS, Mode H	**Part (b)-** Sig DoIs RHS, Mode H

The results very clearly show that the 'overall acceptability of APC' by individuals and societies of all three countries is high. The predominant view of individuals and societies of all three countries is that the 'overall acceptability of APC' is high.

Noticeable Features of Data in Three Tables

From the above analysis, the following clear features can be noted.

General Pattern of Significant DoIs

'Significant DoIs' tend towards the RHS for Parts (a) and (b) in Australia and Sri Lanka, but are scattered over the whole range in America. This implies that Australian Technologists and Sri Lankan environmentalists and their societies generally consider as important properties of APC such as quality and price, as well as external variable factors such as social trends. However, American Intergralists consider that the properties of APC are important, but not the external variable factors such as non-familiarity and social trends. The reason may be that American Integralists might be having an integral view about APC, and hence depend less on external variable factors.

General pattern of Mode

The position of most of the modes is H in Parts (a) and (b) in Australia and Sri Lanka, but VH in Part (a) and MH in Part (b) in America. This implies that there is an agreement of predominant views between individuals and societies in the context of Australia and Sri Lanka. But in the case of America, there is no such agreement of predominant views between individuals (American Integralists) and their society (American society). In fact, the predominant views of American Integralists indicate that the aspects related to integral sustainability of APC such as quality standards as well as sustainability issues are very important. The reason may be due to the holistic views held by American Integralists (in contrast to those of their society).

Internal Validity

The position of most number of modes in Section 1 of the questionnaire (Q1 to Q8) and the position of the mode of Q9 in Section 2 are the same in all three tables, for both Parts (a) and (b). In the tables, questions in Section 1 are related to individual aspects and in Section 2 to overall acceptability. Hence, the good fit between positions of modes in Section 1 with Section 2 confirms internal validity.

Objective aspects related to APC

'Significant DoIs' of Q1 (market price) and Q2 (quality standard) are spread over RHS in Parts (a) and (b) in all three countries. This indicates that individuals and societies of all three countries consider that the objective aspects of market price and quality standards as highly important. The reason is that contemporary societies are very concerned about the primary expectation of cement, that is, its quality; at the same time, they are concerned about the money they spend. ‘Significant DoIs’ of Q3 (impact on the sustainability of earth) and Q4 (mitigating land pollution) are spread over RHS in Parts (a) and (b) in all three countries, except for Part (b) of America. This implies that individuals and societies generally consider ecological issues as important. The reason may be that the current discourse on sustainability may have made them aware about ecological issues.

Quality Standard and Quality Assurance

Q2 is about the ‘quality standards’ and Q8 about ‘recommendation of professionals’. Significant DoIs of Q1 and Q8 are spread over RHS in Parts (a) and (b) in all three countries. This implies that individuals and societies of all three countries consider ‘quality standards’ as important; further, they need some confirmation/assurance from professionals. This implies that the ‘quality’ alone may not work, but also requires confirmation. Contemporary society is very concerned about the performance of a product they select. Also, the establishment of professionalism in contemporary society has caused the society to seek and trust professional recommendations.

Reciprocal Pattern between Q5 (non-familiarity) and Q6 (feel good factor)

The spread of ‘Significant DoI’ in Q5 and Q6 shows a reciprocal pattern (i.e. spread in opposite directions) in all three countries, generally in both Parts (a) and (b). That implies that the acceptance of non-familiar products is inversely related to the ‘feel good’ by using sustainable products. The reason may be that individuals as well as societies have realistic views about the issue; that is, they accept the fact that a new product is always non-familiar. Hence, those who want to feel good by selecting eco-friendly cement are prepared to forego ‘familiarity’. On the other hand, those who want to adhere to ‘familiarity’ are happy to sacrifice the ‘feel good factor’.

Predominant Views on Overall Acceptability

In Q9 (overall acceptability), numerical values of modes of Part (a) are always greater than those of Part (b). The position of the mode is H in Parts (a) and (b) in Australia and Sri Lanka; but VH in (a) and MH in (b) of America. This implies that ‘overall acceptability of APC' is generally high for societies, and much higher for individuals in all three countries. In particular, acceptance by American Integralists is very high, which is reflected by a high mode (value = 0.63) positioned in VH. The reason may be that there is a tendency in contemporary society towards accepting eco-friendly products provided that they have the required quality and the market price is reasonable.

Contextual Differences

When country-wise comparisons are made, the noticeable difference is that in Sri Lanka, in Parts (a) and (b) of Q7, Significant DoIs tend towards the far RHS end, but not so in Australia and America. This suggests that Sri Lankan Environmentalists as well as Sri Lankan society consider that 'social trends' play an important role a cement is selected, while Australian Technologists, American Integralists and their societies do not think so. The reason may be attributed to the 'collective, dependent, eastern culture' in Sri Lanka, compared to the 'individualistic, independent, western culture' in Australia and America.

When society-wise comparisons are made, an evident difference is that in America, in Part (b) of Q6, Significant DoIs tend towards the far LHS, but not so in Australia and Sri Lanka. This indicates that American Society does not consider the 'feel good factor' resulting from the selection of eco-friendly cement as important. Another notable feature is that in Sri Lanka, in Part (b) of Q5, Significant DoIs tend towards the far LHS, but not so in Australia and America. This suggests that for Sri Lankan society, non-familiarity is not an issue. The reason may be that the 'big store' and 'branded name' concept are firmly established in Australia and America when purchasing most products, but not so in Sri Lanka.

When individual-wise comparisons are made, a marked difference is that in America and in Sri Lanka, in Part (a) of Q5, Significant DoIs are spread towards far LHS, but not so in Australia. This implies that for American Integralists and Sri Lankan Environmentalists, non-familiarity is not an issue. The reason may be that American Integralists and Sri Lankan Environmentalists might not have considered 'non-familiarity' as a problem, if the product is eco-friendly, as they are mainly interested in environmental issues. For Australian Technologists, the term 'non-familiarity' might have meant not only the non-familiarity of the product name, but also the non-familiarity of the performance of the product. Perhaps because of that, to them non-familiarity' is an issue to a certain extent.

Most Predominant Concerns Emerging from Closed-ended Questions

As described in Section 9.1, in order to develop APC for integral sustainability, it has to be designed so that it takes into account the individual and social concerns about aspects related to the four quadrants of the integral sustainability framework. Accordingly, the concept of integral sustainability is essentially a contextual concept. However, that does not mean that integral sustainability cannot be made multi-contextual. Obviously, by satisfying the important concerns of different contexts, it can be made integrally sustainable in multiple contexts. Hence, it would be useful to identify the most predominant concerns in different contexts. For that purpose, aspects having DoIs greater than 0.55 were identified; these are presented in **Table 9.5**.

Table 9.5 Most Prominent Concerns of Individuals and Societies

CONTEXT	Part (a) – Individuals	Part (b) - Society
Australia	Quality standards : **H(0.61)** Prof. recommendations : **H(0.61)** Market price : **H(0.58)** Impact on sustainability : **H(0.56)** Mitigating land pollution : **H(0.56)**	Market price : **H(0.67)** Prof. recommendations : **H(0.63)**
America	Impact on sustainability : **VH(0.61)** 'Feel good' factor : **H(0.61)** Quality standards : **VH(0.57)** Prof. recommendations : **H(0.57)**	Market price : **VH(0.62)** Social trends : **MH(0.56)*** Prof. recommendations : **H(0.56)**
Sri Lanka	Prof. recommendations : **H(0.67)** Market price : **H(0.65)** Impact on sustainability : **H(0.62)** Mitigating land pollution : **H(0.60)** Quality standards : **H(0.58)** 'Feel good' factor : **H(0.58)** Social trends : **H(0.57)**	Social trends : **H(0.58)** Market price : **H(0.57)**

NOTE:

* For America, Part (b), DoI for social trends is not under H or VH, hence social trend is not considered as important, but only moderately important by the society. Hence, it is not considered in the interpretations.

All the DoIs given in **Table 9.5** are not only greater than 0.55, but they are the maximum DoIs for each aspect; hence they are 'modes' as well. Modes reflect the 'predominant views' among individuals and society. When a mode is in H or VH, then it implies that there is a predominant view that the relevant aspect is considered as important. However, if the mode is not under H or VH, that means that the predominant view is that the aspect considered is not important. For example, for America, in Part (b) the DoI value of 0.56 under MH implies that the society has a predominant view that 'social trends' are only moderately important. Hence, that can be neglected.

General Observations

In **Table 9.5**, in all three countries, Part (a) has more entries than Part (b). This implies that among Australian Technologists, American Integralists and Sri Lankan Environmentalists, there are more predominant views compared to their societies. The reason could be that the individuals in all three countries are 'focused groups' related to disciplines. Hence, their thinking might have been guided by their common specific knowledge.

Market Price

Generally, among individuals and societies of all three countries, there is a predominant view that market price is important. This implies that in all three countries, individuals as well as societies are very concerned about economic factors.

Quality Standard and Quality Assurance

Among Australian Technologists, American Integralists and Sri Lankan Environmentalists, there are strong views that quality standards as well as professional recommendations are important. This suggests that not only is manufacturing APC according to quality standards important, but equally important is the confirmation or assurance from professionals. Among societies, even though there is no such strong view about quality standards, their predominant view on professional recommendations implies that confirmation of quality standards is important. Most probably, lay persons in a society generally do not look for specific aspects such as compressive strength, but depend on professional recommendations.

Impact on Sustainability of the Earth

Australian Technologists, American Integralists and Sri Lankan Environmentalists strongly expressed the view that consideration of ‘impact on sustainability’ is important. This is further supported by a predominant view about the consideration of ‘mitigating land pollution’, which is closely related to sustainability issues.

Other Predominant Views

The other predominant views are that social trends and the feel-good factor are important. Actually, these aspects are closely related to the three aspects mentioned above. When the product has less adverse impact on the planet’s sustainability, the consumer feels good about using it. When the market price is lower, the product might be bought by many and become familiar, which eventually may create a social trend.

9.4.2 Open-ended Questions

The data generated through Sections 3 of the questionnaire are not focused on any particular theme regarding APC, but were freely generated. The theoretical framework used for analysis and interpretations is described in the following sections.

9.4.2.1 Theoretical Framework for Analysis of Open-ended Question

Section 3 of the questionnaire contained an open-ended question; and the responses were analysed using ‘Grounded Theory’. According to Grounded theory, the theory behind a phenomenon is grounded in the data. Hence, the development of a theory involves un-earthling it from the data. It involves four stages as depicted below:

CODES → CONCEPTS → CATEGORIES → THEORY

In the first stage, the data are analysed, the key points are identified and coded. In the second stage, the codes are compared, similar codes are grouped, and concepts are allowed to emerge. In the third stage, the concepts are compared and similar concepts are grouped, and broad categories are formed. In the fourth and final stage, the categories are linked, and that would lead emergence of the theory. As the theory emerges from the live data, the need for separate ‘testing of the theory’ does not arise.

However, a separate set of data would help to improve and/or modify the theory (Allan 2003).

In this research, the purpose of employing 'Grounded Theory Techniques' is not to develop a theory, but to unearth the concepts grounded in the selected contexts, and thereafter assign them to one of the four categories of the Integral Sustainability Framework. Using those categories, instead of developing a theory, a set of strategies was developed to achieve integral sustainability of APC. Accordingly, a bottom-up approach was adopted to develop the concept and thereafter a top-down approach was applied to assign the concepts to the relevant categories of the Integral Sustainability Framework. The procedure is demonstrated in detail in the following section.

9.4.2.2 Analysis of Responses of Open-ended Questions

Concepts, categories and theories discovered by grounded theory techniques are context-dependent. Normally, grounded theory techniques are applied to a raw set of data related to a particular context, and then the concepts, categories and theories related to that context are discovered. These are used as the platform to analyse a new set of data related to another context, and to improve/amend concepts, categories and theories. Then the improved concepts, categories and theories are used as the platform to analyse the next set of data, and this process is repeated. Hence, it is always better to start the analysis with the largest set of data, so that a greater number of concepts, categories and theories can be discovered at the beginning. In this research, the largest set of data came from Sri Lankan participants (although most of the participants were from Australia and America, the majority of the responses to the open-ended questions were from Sri Lankan participants). Hence, the 'data set' generated from Sri Lanka was selected for analysis. The process of analysis is demonstrated bellow.

<u>Stage I - Coding</u>

Firstly, each of the transcripts was read, and codes (expressions arising from data) were identified and numbered. To demonstrate the coding process, the transcripts of the participants numbered SL08 and SL02 are used, as shown in **Table 9.6**.

Table 9.6 Example of the Coding Process

ORIGINAL TRANSCRIPT **(Respondent's Own Words)**	**KEY POINTS** **(Expressions)**	**CODING**
SL08 I am **not quite familiar** with cements and the technology behind that. So if I am about to select the cement for my own house to build it; the main factor I will consider will be the **familiarity** and the past experience. I am **not quite confident** to move with this new technology, since I am **not quite sure**. May be that is **lack of knowledge**, but cement in building a house act a major role. I think if it fail everything might fail and collapse. So what kind of **assurance** I will get that will not happen? On the other hand I like **sustainability**. I like **going green**. But when comes to extremely critical issues like this, I am not ready to take or buy it all of a sudden. Even though the test results, research, whatever says it is up to the standards (not only this, any cement, any material) I will not buy it, if it is to be applied for a critical application. Also sometimes I might apply this cement for **non-critical applications** other than walls, slabs, structure etc. Thank you!	• Not familiar with cement & technology. • Familiarity and past experience main factors in selecting cement. • Not confident to move with new technology, due to lack of knowledge about cement. • Cement plays a major role in house construction, hence if it goes wrong everything fails. • What kind of assurance is given about APC? • Not willing to use APC for critical work such as walls, slabs, structure. • Would use APC for non-critical applications. • Individual is concerned about sustainability, hence prefer 'go green' practices.	SL8/1- **Individua**l concerns sustainability, hence prefer green products, SL8/2 - **Individual** would opt for familiarity and past experience due to lack of knowledge about APC, SL8/3- **Individual** not confident to move with new technology due to lack of knowledge. SL8/4- **Individual** would not choose APC even quality standards are confirmed, unless assurance is given SL8/5- **Individual** is hesitant to use APC for the main components of a house (walls, slabs), but may use it for minor applications (plastering).
SL02 According to my experience **people** in Sri Lanka tend to be a bit **reluctant to change** or new things that affect their lives (in this case building a home spending a lot of money). They **wouldn't want to be the first to try** it out, even though how strong the facts are. But ones few people have tried it out people in the local society would take it up very fast. At present the **people** in Sri Lanka are **not that conscious on their own environment** and the implication of their actions on the same. On a personal note I wouldn't mind looking into a new technology if it is proven. But will not take up a new thing blindly unless its performance has been proven.	• People tend to be reluctant to change. • Majority wait till others try first. Once a product is tried by others, the society will take it up quickly. • People not conscious about environment and adverse impact of people's activities. • Individual is ready to try new technology if proven, but not blindly.	SL2/1- People (**society)** tend to be a bit reluctant to change (that is reluctant to use a new cement such as APC) SL2/2- Majority of the people (**society)** wait till others try APC first. After that many would be ready to try. SL2/3 - People (**society)** are not environmentally conscious (no social consciousness about environment) SL2/4- **Individual** ready to go for technology, provided it is proven.

As demonstrated in Table 9.6 above, transcripts of all the respondents were read and codes were developed. Some of the codes extracted from the set of Sri Lankan Environmentalists, which will be used in the next stage, are given below. When developing codes, it was seen that many respondents hold similar views. However, at this stage they were recorded as different codes. Hence, in the following list some views are repeated under different code names.

Codes related to Individual Views

SL4/1 - Individual's concern is that APC is not a time-tested product.
SL4/2 - Individual needs examples of buildings constructed using APC as a proof
SL5/6 - Inside everyone there is an environmentalist
SL5/7 - Important to educate people about green products
SL6/6 - Individual would not follow social trends, but want the best in all aspects. (Majority follows social trends)
SL6/7 - For the majority, professional recommendations would help to select a new product such as APC
SL6/8 - Individual would follow his own attitudes in selecting a product (not depend on professional recommendations).
SL7/2 - Individual choosing APC depends on practicality of technology, financial, social and cultural factors.
SL8/2 - Individual would opt for familiarity and past experience due to lack of knowledge about APC,
SL8/4 - Individual would not choose APC even quality standards are confirmed, unless assurance is given
SL8/5 - Individual is hesitant to use APC for the main components of a house (walls, slabs), but may use it for minor applications (plastering).
SL9/1 - As an engineer cost is NOT the selection criteria.
SL9/3 - Individual would use APC and also recommend it to others, if quality, strength, durability requirements are satisfied
SL9/4 - Individual feels that non-familiarity is a problem for recommending APC to others.
SL9/5 - Individual would not follow social trends as they may not be correct (majority follows trend)
SL20/2 - Individual needs confirmation of standards and environmental impact important
SL24/1 - Individual is ready to do something even though there is a risk factor, but may not recommend it to others if there is a risk factor.
SL24/2 - Individual would accept APC but not recommend it to others because of the possible risk
SL25/1 - For an individual, as an engineer the main concern is properties of APC
SL28/1 - Individual would use APC and also recommend it to others, if APC confirms quality standards,

Codes related to Social Views

SL2/1 - People (society) tend to be a bit reluctant to change (that is, reluctant to use a new cement such as APC).
SL2/2 - Majority of the people (society) wait till others try APC first. After that many would be ready to try.
SL5/8 - Society would accept APC, if the people are educated
SL13/1 - For the majority (society), when building a house, cost overrules everything.
SL22/1 - Society will accept APC, if they are made aware about environmental issues.
SL34/4 - Society would look for cost factor more than eco aspects when selecting a cement.
SL35/3 - Society would accept APC, if a social trend is created by marketing campaigns.

Stage II - Discovering Concepts

In the second stage, the related coded data were grouped together and concepts began to emerge. In other words, a bottom-up approach was adopted to unearth the concepts grounded in the data. From the data, over 20 concepts emerged; three of them are given below as examples.

Coded Data Group 1

SL6/6 - Individual would not follow social trends, but want the best in all aspects (majority follows social trends).
SL7/2 - Individual choosing APC depends on practicality of technology, financial, social and cultural factors.
SL9/3 - Individual would use APC and also recommend it to others, if quality, strength, durability requirements are satisfied
SL9/5 - Individual would not follow social trends as they may not be correct (majority follows trend)
SL28/1 - Individual would use APC and also recommend it to others, if APC confirms quality standards,
SL35/3 - Society would accept APC, if a social trend is created by marketing campaigns

⇨ **Emerged CONCEPT:** Trends / culture of accepting a product
(Related to individuals as well as to society)

Coded Data Group 2

SL5/6 - Inside everyone there is an environmentalist
SL5/7 - Important to educate people about green products
SL5/8 - People would accept APC, if they are educated
SL22/1 - Society will accept APC, if they are made aware of environmental issues.

⇨ **Emerged CONCEPT: Environmental awareness/education**
(Related to individuals as well as to society)

Coded Data Group 3

SL6/6 - Individual would not follow social trends, but want the best in all aspects. (Majority follows social trends)
SL6/8 -Individual would follow his own attitudes in selecting a product (not depend on professional recommendations).
SL9/1 - As an engineer cost is NOT the selection criteria.
SL9/4 - Individual feels that non-familiarity is a problem for recommending APC to others.
SL24/1 - Individual is ready to do something even though there is a risk factor, but may not recommend it to others if there is a risk factor.
SL24/2 - Individual would accept APC but not recommend it to others because of the possible risk

⇨ **Emerged CONCEPT: Individual belief & self-identity**
(Related to individuals)

Stage III - Discovering Categories

As demonstrated above, a bottom-up approach was adopted to develop the concepts. In subsequent stages this approach was also applied to generate ‘categories’, and finally ‘theory’. However, as mentioned previously, the purpose of employing grounded theory in this research is not to unearth the theory grounded in data, but to discover the concepts grounded in the selected contexts, and thereafter to assign them to the four categories of the Integral Sustainability Framework. Hence, in this stage, a top-down approach was adopted, instead of a bottom-up one. Using these categories, a set of strategies were developed. The categories related to the four quadrants are given in **Fig 9.4**.

[UL]	**[UR]**
UL Concerns – Emotions, Beliefs, Self-identity **I**: Individual's Nature Loving Attitude **I** : Individual's Sustainability /Environmental Concerns **I**: Individual's optimistic attitude **I**: Individual's pessimistic attitude **I**: Individual's readiness to re-consider with more information **I**: Individual's hesitation about new materials **I**: Individual belief & self-identity	**UR Concerns – Price, Physical Properties** **I & S** : Concern about market price **I & S** : Specific qualities related to engineering properties **I & S** : General qualities related to engineering properties **I** : Long term effect (durable properties) **I** : Type of structure / type of application **I** : Health/risk related Issues
LL Concerns – Philosophical, Ethical, Religious World views **S**: Culture of loving nature **S**: Ethical considerations **S**: Acceptance of professional recommendations **S**: Social trends **I & S** : Trends / culture of accepting a product **S**: Culture of resistance to change **S**: Culture of readiness to change **S**: Culture of adaptability **[LL]**	**LR Concerns – Environmental, Ecological, Educational, Economic, Legal** **I & S** : Overall economic gains **I & S** : Confirmation of quality **I & S** : Proof **I** : Guarantee / assurance **I** : Environmental awareness/education **I** : Consideration of environment & ecological systems **I**: Consideration of combined effect **[LR]**
KEY: The concepts related to 'Individuals' and 'Society are indicated by letters '**I**' and '**S**'.	

Fig. 9.4 Categories Related to Four Quadrants

9.4.2.3 Requirements Emerging from Responses to Open-ended Questions

The purpose of open-ended questions is to determine the concerns of individuals and societies that had not been identified or queried through closed-ended questions. Through the analysis, it was found that individuals as well as societies have many other concerns that fall into the four quadrants of the integral sustainability framework as shown in **Fig 9.4**. The issues that need to be addressed arising from those concerns are briefly demonstrated in **Table 9.7**. Among them, the long-term effect on properties of APC, guarantee / assurance given about APC and health/risk-related issues for the user are some of the important newly identified concerns.

Table 9.7 Summary of Four Quadrant Concerns of Sri Lankan Environmentalists

	CONCERN	REQUIREMENTS
UL	**Related to Emotions, Beliefs, Self-identity**	
	Individual's optimistic attitude Individual's pessimistic attitudes Individual Belief & Self Identity ⇨	Addressing individual's psychological needs
	Individual's Nature Loving Attitude Individual's Sustainability /Environmental Concerns ⇨	Addressing individual's environmental concerns
	Individual's Hesitation about new materials ⇨	Addressing doubts about new materials (by giving assurance)
	Individual's readiness to consider with more information ⇨	Providing more information to build confidence on APC
LL	**Related to Philosophical Ethical, Religious World views**	
	Culture of resistance to change ⇨	Emphasizing similarities of APC and OPC (quality)
	Culture of readiness to change ⇨	Emphasizing differences between APC and OPC (usage of by-products as raw material)
	Culture of nature loving Considerations of environmental ethics ⇨	Emphasizing eco-friendly features , environmental ethics
	Acceptance of professional recommendations ⇨	Providing details for professionals
	Trends / culture of accepting a product ⇨	Awareness /promotional campaigns about APC
UR	**Related to Price, Physical Properties**	
	Concern about market price ⇨	Competitive market price
	General qualities related to engineering properties Specific qualities related to engineering properties ⇨	Quality standards and quality assurance
	Long term effect Type of structure / type of application ⇨	Specifications : usage, applications, limitations
	Health related issues ⇨	Safety Data Sheets, Risk Assessments, Health Assurance
LR	**Related to Ecological, Economic, Quality, Legal**	
	Overall economic gains ⇨	Cost comparisons giving overall economic gains
	Consideration of combined effect ⇨	Comparison of quality, economy, ecology
	Examples (building constructed by APC) Assurance for buildings constructed using APC ⇨	Guarantees for buildings constructed by APC
	Consideration of environment & ecological Systems ⇨	Highlighting environment & ecological benefits

Proceeding with data generated in other countries

It has been demonstrated how the set of data from Sri Lankan Environmentalists were selected and grounded theory techniques employed to generate the results shown in **Table 9.7**. This information can be further improved / amended by employing the other two sets of data, namely, sets of data from Australian Technologists and American Integralists. Also, this process can be extended to other countries as well, and continued with a snowballing effect. However, as the purpose here is only to demonstrate the procedure, the application of grounded theory for the data related to other countries has not been done.

9.5 Conclusion

The main aim of this chapter is to present the results of the investigation of the social survey, which includes individual and social concerns about selected aspects related to the integral sustainability of Alkali Pozzolan Cement (APC), and to discover any other main concerns of individuals and societies related to the four quadrants of integral sustainability framework. The findings are summarised below:

1. Generally, the individuals as well as the societies of the three countries have assigned relatively high degrees of importance to aspects favourable for the integral sustainability of APC such as market price, quality standards and impact on sustainability of the earth. Aspects unfavourable for APC, such as non-familiarity, have not been given a high degree of importance by individuals, but societies have done so. However, when overall acceptability is considered, it is seen that there is a high probability of acceptance of APC as an integral sustainable cement in all three countries, Australia, America and Sri Lanka.

2. Of all the aspects considered, individuals and societies of all three countries have given higher degrees of importance to market price, quality standards, sustainability issues and recommendation of professionals. This implies that certification of quality standards would useful.

3. There are clearly contextual differences in the assigning of degrees of importance to different aspects. In the context of Sri Lanka, ‘social trends’ is considered as important, while it is not considered so in the contexts of Australia and America.

4. Many new concerns were identified through the responses to the open-ended question. Some of the most important concerns were the long-term effect on the properties of APC, guarantee/assurance given about APC, and health/risk-related issues for the user.

5. This chapter has also demonstrated the usefulness of the application of fuzzy sets for analysing responses to closed-ended questions, and grounded theory techniques to analyse responses to open-ended questions.

6. The open-ended question generated some very important information, and hence underlines the importance of this approach in eliciting subjective information, provided that a good ‘grounded theory’ type of technique is employed for analysing it.

9.6 References

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10 Integral Sustainability of Alkali Pozzolan Cement (APC)

Overview

This chapter presents the results of the last stage of this research, which integrated both objective and subjective aspects related to Alkali Pozzolan Cement (APC) and investigated the integral sustainability of APC. For that purpose, the two frameworks developed were employed. The modified two-dimensional framework was employed to investigate the degree of integral sustainability of APC, while the newly developed three-dimensional framework was used to assess the stability of this sustainability by investigating the certainty/uncertainty of objective and subjective aspects. The overall results indicate that there is a strong possibility that APC will emerge as an integrally sustainable cement.

Key words: *Degree of integral sustainability, Stability of integral sustainability, certainty/uncertainty,*

10.1 Introduction

'Integral sustainability' is a holistic concept that integrates sustainability aspects related to objective, inter-objective, subjective and inter-subjective aspects. Accordingly, in order to develop Alkali Pozzolan Cement (APC) for 'integral sustainability', these aspects have to be considered from the initial stage of development. In other words, from the very beginning, both the objective aspects such as the properties of APC and its environmental impact, and the subjective aspects such as individual and social concerns about APC, have to be considered. Chapters 3, 4 and 5 focused on the objective aspects of APC, while Chapters 6 and 7 focused on the inter-objective aspects of APC. In order to integrate the subjective and objective aspects related to APC, the two-dimensional tetra-quadrant framework and the three-dimensional octa-octant framework were introduced in Chapter 8. In Chapter 9, an investigation of the subjective and inter-subjective aspects of APC was presented. Finally, this chapter presents the outcomes of the investigation into the integral sustainability of APC using the two aforementioned frameworks.

10.2 Aim and Objectives

The main aim of this chapter is to employ the two frameworks developed in this research to bring together all the aspects related to APC in order to investigate the degree of integral sustainability of APC and to identify areas for improvement in order to achieve/maintain this sustainability. Accordingly, the main aim can be expressed as two objectives as follows:

1. To employ the modified tetra-quadrant framework to:
   - (i) bring together subjective, inter-subjective, objective and inter-objective aspects of APC (four quadrant aspects of APC);
   - (ii) explicitly represent the contribution from each of the above aspects as quadrant entries;
   - (iii) identify the aspects to be improved in order to achieve/improve integral sustainability of APC.

2. To employ the newly developed octa-octant framework to:
   - (i) identify the certainty/uncertainty of subjective, inter-subjective, objective and inter-objective aspects of APC (four quadrant aspects of APC);
   - (i) explicitly represent the certainty/uncertainty of each of the above aspects as octant entries;
   - (ii). identify the aspects to be improved in order to minimise the uncertainty, so that the integral sustainability of APC is made relatively certain (i.e. to maintain the integral sustainability of APC).

In the process of achieving these objectives, the various aspects related to APC were reviewed and suitable indicators developed where necessary to be employed in the above frameworks.

As described in Chapter 8, the ‘modified tetra-quadrant framework’ recognises ‘spread measures’ instead of ‘point measures’ and also ‘collectives’ as well as ‘collections’. Hence, in the case of objective aspects, some statistical concepts were employed to represent the idea of 'spread measures'. In the case of subjective aspects, several fuzzy set concepts were employed and the 'spread' of perceptions was taken into account.

10.3 Employing the Tetra-quadrant Framework

The modified tetra-quadrant framework developed to integrate objective and subjective aspects related to integral sustainability was given in **Fig. 8.8** in Chapter 8. By employing this framework, the data generated through different methods were integrated through the 'Quadravial Approach', as shown in **Fig. 10.1**. Individual and social concerns about APC (depicted by 'quadratic views') were transferred to the UL and LL quadrants of the main framework respectively. Objective properties such as strength and cost were transferred to the UR quadrant, while inter-objective properties (compound entities) such as energy per unit strength and CO_2 released per unit weight were transferred to the LR quadrant.

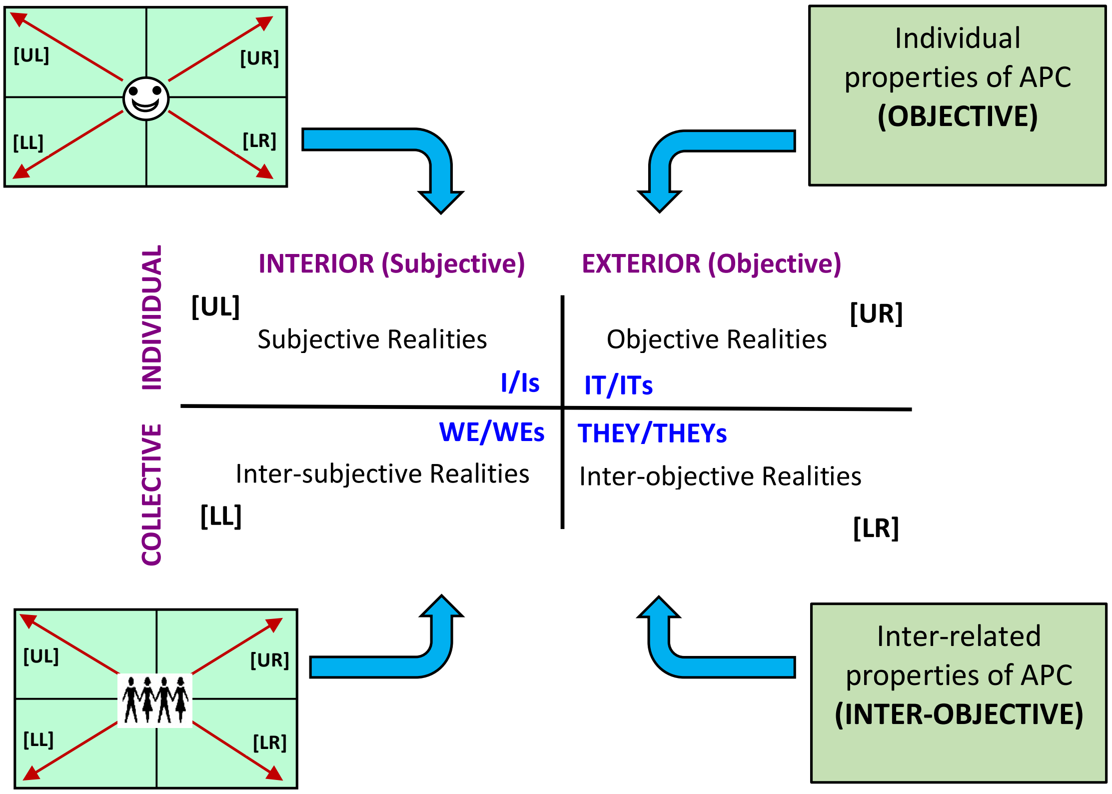


Fig. 10.1 Quadravial Approach

10.3.1 Re-viewing of Objective Aspects of APC

When developing a new cement, compressive strength is the main concern, which is an objective aspect of cement. Resistance to water absorption and chemical attack are some of the other important objective aspects. When environmental impact is considered, the amount of energy required and the carbon dioxide emissions during cement production are two of the main concerns, which are inter-objective aspects. When it comes to production, cost is one of the most important factors to be considered, which is also an objective aspect. All these concerns were taken into account when investigating the integral sustainability of APC. The results are presented below, with the sections and chapters from which results were extracted being indicated within parentheses.

Objective Aspects:

Here the mixture considered for analysis is the 'targeted mixture', which is the APC mixture 'M', with w/c = 0.3 (that is Mixture M3) under a 'controlled air curing' condition.

The information below was extracted from **Appendix A5**.

28 day Strength (*Appendix A5.1***)**
APC (air cured) 46 MPa (Var=07%) {cf OPC 57 (Var =57%)}
Sensitivity to curing change =1.15 {cf OPC 1.00}
Sensitivity w/c increase = 1.43 {cf OPC 1.42}

Water Absorption (*Appendix A5.2*)
APC (air cured) 13.7% (Var 05%) {cf OPC 11.6 %(Var =09%)}
Sensitivity to curing change =1.08 {cf OPC 1.16}
Sensitivity w/c increase = 1.55 {cf OPC 1.42}

Carbonation depth at 3 month (*Appendix A5.3*)
APC (air cured) 8.3mm (Var 08%) {cf OPC 4.0 (Var =10%)}
Sensitivity w/c decrease = 2.66 {cf OPC 1.13}

Sulphuric Attack (*Appendix A5.4*)
APC (air cured) 45.76% (Var 18%) {cf OPC 47.50% (Var =04%)}
Sensitivity w/c increase = 1.09 {cf OPC 1.44}

Embodied Energy of Cement Powder (*Table 6.4*)
APC (powder) 2.72MJ/kg (Var 21%) {cf OPC 4.79 (Var =33%)}

CO_2 Emission of Cement Powder (*Table 6.6*)
CO_2 Emission associated with APC Mixture M: Mean = 0.426 CO_2 kg/ kg (Variability = 12%)
{cf CO_2 Emission associated with OPC Mixture M: Mean = 0.894 CO_2 kg/ kg (Variability = 16%)}

The above information are summarised as,
APC (powder) 0.43 CO_2 kg/ kg (Var =12%) {cf OPC 0.89 CO_2 kg/ kg (Var =16%)}

Cost of Cement Powder (*Table 6.8*)
APC (powder) 0.26$/ kg (Var =07%) {cf OPC 0.39 $/kg/ kg (Var =08%)}

Inter-objective Aspects

The information below was extracted from Chapter 6.

<u>Embodied Energy per unit volume per unit strength</u> (Table 6.4)
APC (Mix M3) 98.8 MJ/m3/MPa (Var =29%) {cf OPC(Mix R3) 146.6 MJ/m3/MPa (Var =101%)}

<u>CO2 emission per unit volume per unit strength</u> (Table 6.6)
APC (Mix M3) 15.457 CO_2 kg /m3/MPa (Var =19%) {cf OPC(Mix R3) 27.344 CO_2 kg /m3/MPa (Var =78%)}

<u>Cost per unit volume per unit strength</u> (Table 6.8)
APC (Mix M3) 9.42 $ /m3/MPa (Var =14%) {cf OPC(Mix R3) 11.93 $ /m3/MPa (Var =69%)}

The objective and inter-objective aspects listed above were transferred to the UR and LR quadrants of the 'tetra-quadrant framework' as illustrated in **Fig. 10.1** and the output presented in **Fig. 10.4** of Section10.3.3.

10.3.2 Re-viewing of Subjective Aspects of APC

The 'quadratic approach' was adopted to generate subjective views (that is individual as well as social perceptions) regarding the integral sustainability of Alkali Pozzolan Cement (APC) as described in Chapter 9. The quadratic perceptions of individuals and societies in terms of three different contexts, namely Australia, America, and Sri Lanka, were analysed and the Degrees of Identities (DoIs) for each aspect were computed and given in **Table 9.1**, **Table 9.2** and **Table 9.3** of Chapter 9. The DoIs related to individuals and societies are presented using the tetra quadrant frameworks shown in **Fig. 10.2** and **Fig. 10.3**.

HIGHLIGHTS OF QUADRATIC VIEW OF INDIVIDUALS OF AUSTRALIA			
Non-familiarity	: ML(0.38), MH(0.40), **H(0.43)**	Market Price	: MH (0.45), **H(0.58)**
'Feel good' factor	: ML(0.39), **MH(0.45)**, H(0.43)	Quality standard	: **H(0.61),** VH(0.51)
Social Trends	: ML(0.38), **MH(0.39)**, H(0.37)	Impact on Sustainability	: MH (0.52), **H(0.56)**, VH(0.33)
Rec of Prof	: MH(0.43), **H(0.61)**, VH(0.40)	Mitigating land pollution	: MH(0.48), **H(0.56)**, VH(0.33)

HIGHLIGHTS OF QUADRATIC VIEW OF INDIVIDUALS OF AMERICA			
Non-familiarity	: **L(0.50)**, ML(0.44)	Market Price	: **MH (0.53)**, H(0.50)
'Feel good' factor	: MH(0.39), **H(0.61)**, VH(0.46)	Quality standard	: H(0.50), **VH(0.57)**
Social Trends	: ML(0.39), **MH(0.47)**, H(0.33)	Impact on Sustainability	: H(0.55), **VH(0.61)**
Rec of Prof	: MH(0.33), **H(0.57)**, VH(0.54)	Mitigating land pollution	: MH(0.36), H(0.50), **VH(0.52)**

HIGHLIGHTS OF QUADRATIC VIEW OF INDIVIDUALS OF SRI LANKA			
Non-familiarity	: L(0.33), ML(0.37), **MH(0.42),**H(0.33)	Market Price	: MH (0.44), **H(0.65)**
'Feel good' factor	: MH(0.36), **H(0.58)**, VH(0.53)	Quality standard	: MH(0.33),**H(0.58),** VH(0.48)
Social Trends	: MH(0.43), **H(0.57)**, VH(0.33)	Impact on Sustainability	: **H(0.62)**, VH(0.58)
Rec of Prof	: MH(0.33), **H(0.67)**, VH(0.50)	Mitigating land pollution	: MH(0.33), **H(0.60)**, VH(0.49)

Fig. 10.2 Highlights of Quadratic Views of Individuals of Three Countries

By analysing the information given in **Fig. 10.2**, the most important concerns were identified using a suitable cut-off level. When the DoIs of individuals were examined, a cut-off level of 0.55 was deemed appropriate for choosing the most important concerns. Accordingly, the most important concerns are listed below.

<u>Australian Individuals</u>

Quality standard	: **H(0.61),** VH(0.51)
Recommendation of professionals	: MH(0.43), **H(0.61)**, VH(0.40)
Market Price	: MH (0.45), **H(0.58)**
Impact on sustainability	: MH (0.52), **H(0.56)**, VH(0.33)
Mitigating land pollution	: MH(0.48), **H(0.56)**, VH(0.33)

<u>American Individuals</u>

Impact on sustainability	: H(0.55), **VH(0.61)**
'Feel good' factor	: MH(0.39), **H(0.61)**, VH(0.46)
Quality standard	: H(0.50), **VH(0.57)**
Recommendation of professionals	: MH(0.33), **H(0.57)**, VH(0.54)

<u>Sri Lankan Individuals</u>

Recommendation of professionals	: MH(0.33), **H(0.67)**, VH(0.50)
Market Price	: MH (0.44), **H(0.65)**
Impact on sustainability	: **H(0.62)**, VH(0.58)
Mitigating land pollution	: MH(0.33), **H(0.60)**, VH(0.49)

In the above list, the largest DoI for each concern is indicated in bold letters and these are transferred to the UL quadrant of the 'tetra-quadrant framework' as illustrated in **Fig. 10.1**, and the output presented in **Fig. 10.4** of Section 10.3.3.

The DoIs related to quadratic perceptions of the societies in the three different contexts, Australia, America, and Sri Lanka were given in **Table 9.1**, **Table 9.2** and **Table 9.3** of Chapter 9, and they are presented in the tetra quadrant frameworks in **Fig. 10.3**.

HIGHLIGHTS OF QUADRATIC VIEW OF SOCIETY OF AUSTRALIA			
Non-familiarity	: MH(0.40), **H(0.55)**	Market Price	: MH(0.38),**H(0.67),** VH(0.38)
'Feel good' factor	: ML(0.35), MH(0.48), **H(0.50)**	Quality standard	: MH(0.42), **H(0.49),** VH(0.33)
Social Trends	: MH(0.45), **H(0.55)**	Impact on Sustainability	: MH(0.46), **H(0.50)**
Rec of Prof	: MH(0.42),**H(0.63),** VH(0.40)	Mitigating land pollution	: MH(0.43),**H(0.53)**

HIGHLIGHTS OF QUADRATIC VIEW OF SOCIETY OF AMERICA			
Non-familiarity	: **MH(0.52)**, H(0.48)	Market Price	: H (0.34), V**H(0.62)**
'Feel good' factor	: L(0.33), ML(0.45), **MH(0.46)**	Quality standard	: MH(0.39),H(0.45), **VH(0.46)**
Social Trends	: ML(0.32), **MH(0.56)**, H(0.47)	Impact on Sustainability	: ML(0.43), **MH(0.53),** H(0.36)
Rec of Prof	: MH(0.49), **H(0.56)**, VH(0.40)	Mitigating land pollution	: **ML(0.46)**, MH(0.44)

HIGHLIGHTS OF QUADRATIC VIEW OF SOCIETY OF SRI LANKA			
Non-familiarity	: **L(0.50)**, ML(0.39)	Market Price	: MH (0.36), **H(0.57)**
'Feel good' factor	: MH(0.42), **H(0.49)**	Quality standard	: ML(0.33),MH(0.36), **H(0.45)**
Social Trends	: MH(0.48), **H(0.58)**, VH(0.33)	Impact on Sustainability	: MH(0.38), **H(0.52)**
Rec of Prof	: MH(0.36), **H(0.51)**, VH(0.44)	Mitigating land pollution	: MH(0.38), **H(0.45)**

Fig. 10.3 Highlights of Quadratic Views of Societies of Three Countries

Based on the Degrees of Identities (DoIs) in **Fig. 10.3**, the most important concerns of societies of the three different countries (that is information related to 'WEs' of the tetra-quadrant framework) were determined using a suitable cut-off level. When the DoIs of societies were examined, a cut-off level of 0.55 was deemed appropriate for choosing the most important concerns. The most important concerns in this case are listed below.

Australian Society

Market Price	: MH(0.38),**H(0.67),** VH(0.38)
Rec of Prof	: MH(0.42),**H(0.63),** VH(0.40)
Non-familiarity	: MH(0.40), **H(0.55)**

American Society

Market Price	: H (0.34), V**H(0.62)**
Social Trends	: ML(0.32), **MH(0.56)**, H(0.47)
Rec of Prof	: MH(0.49), **H(0.56)**, VH(0.40)

Sri Lankan Society

Social Trends	: MH(0.48), **H(0.58)**, VH(0.33)
Market Price	: MH (0.36), **H(0.57)**

In the above list, the largest DoI for each concern is indicated in bold letters, and these were transferred to the UL quadrant of the 'tetra-quadrant framework' as illustrated in **Fig. 10.1**, and the output presented in **Fig. 10.4** of Section 10.3.3.

10.3.3 Integration of Subjective and Objective Aspects of APC

The objective aspects reviewed in Section 10.3.1 and subjective aspects reviewed in Section 10.3.2 were integrated using the 'modified tetra-quadrant framework' as illustrated in **Fig. 10.1** and the output presented in **Fig. 10.4**.

Australian Individuals
Quality standard : **H(0.61)**
Prof. Recommendations : **H(0.61)**
Market Price : **H(0.58)**
Impact on Sustainability : **H(0.56)**
Mitigating land pollution : **H(0.56)**

American Individuals
Impact on Sustainability : **VH(0.61)**
'Feel good' factor : **H(0.61)**
Quality standard : **VH(0.57)**
Prof. Recommendations : **H(0.57)**

Sri Lankan Individuals
Prof. Recommendations : **H(0.67)**
Market Price : **H(0.65)**
Impact on Sustainability : **H(0.62)**
Mitigating land pollution : **H(0.60)**

I / Is

28 day Strength (MPa)
APC (air cured) 46 MPa *{cf OPC 57}*
Sensitivity to curing change =1.15 *{cf OPC 1.00}*
Sensitivity w/c increase = 1.43 *{cf OPC 1.42}*

Water Absorption (% weight)
APC (air cured) = 13.7 *{cf OPC 11.6 }*
Sensitivity to curing change =1.08 *{cf OPC 1.16}*
Sensitivity w/c increase = 1.55 *{cf OPC 1.42}*

Accelerated Carbonation depth (mm)
APC (air cured) = 8.3mm *{cf OPC 4.0}*
Sensitivity w/c decrease = 2.66 *{cf OPC 1.13}*

Sulphuric Attack (% weight)
APC (air cured) 33.32% *{cf OPC 44.34%}*
Sensitivity w/c increase = 1.09 *{cf OPC 1.44}*

Embodied Energy of Cement Powder (MJ/kg)
APC 2.72MJ/kg *{cf OPC 4.79}*

CO_2 Emission of Cement Powder (kg/kg)
APC 0.43 CO_2 kg/ kg *{cf OPC 0.89 CO_2 kg/ kg}*

Cost of Cement Powder ($/kg)
APC 0.26$/ kg *{cf OPC 0.39 $/kg/ kg}*

IT / ITs

WE / WEs

Australian Society
Market Price : **H(0.67)**
Prof. Recommendations : **H(0.63)**
Non-familiarity : **H(0.55)**

American Society
Market Price : **VH(0.62)**
Social Trends : **MH(0.56)**
Prof. Recommendations : **H(0.56)**

Sri Lankan Society
Social Trends : **H(0.58)**
Market Price : **H(0.57)**

THEY / THEYs

Embodied Energy per unit volume per unit strength
APC (Mix M3) 98.8 MJ/m^3/MPa
{cf OPC(Mix R3) 146.6 MJ/m^3/MPa}

CO2 emission per unit volume per unit strength
APC (Mix M3) 15.457 CO_2 kg /m^3/MPa
{cf OPC(Mix R3) 27.344 CO_2 kg /m^3/MPa}

Cost per unit volume per unit strength
APC (Mix M3) 9.42 $ /m^3/MPa
{cf OPC(Mix R3) 11.93 $ /m^3/MPa}

Fig. 10.4 Representation of Integral Sustainability of APC

10.3.4 Discussion on Tetra-quadrant Framework

With the aid of **Fig. 10.4**, the developed Alkali Pozzolan Cement (APC) was compared with the conventional Ordinary Portland Cement (OPC) through four lenses: objective, inter-objective, subjective and inter-subjective. Objective measures of APC are presented along with related measures of OPC indicated within parentheses. In generating subjective data, perceptions about APC were always generated with respect to OPC. Hence, the concerns indicated in subjective quadrants are not 'absolute concerns', but are 'relative concerns' with reference to OPC.

The upper right (UR) quadrant of **Fig. 10.4** presents the objective aspects related to APC. It is seen that APC was able to achieve reasonably good 28-day strength, around 80% of the strength of OPC. When durability properties were considered, the resistance to water absorption and carbonation is a shortcoming of APC, yet resistance to sulphuric acid attack is markedly better than that of OPC. Where environmental costs are concerned, it is seen that APC was able to reduce environmental cost by decreasing embodied energy and CO_2 emission per unit weight by the high percentages of 44% and 52% compared to OPC. In addition, the financial cost of APC is only about 65% of the cost of OPC. Accordingly, among the aspects considered from the UR quadrant of the integral sustainability framework, financial cost, environmental impact per unit weight and resistance to sulphuric attack are highly satisfactory; the strength, resistance to water absorption and resistance to carbonation are satisfactory to a lesser degree, and may have to be improved.

The lower right (LR) quadrant of **Fig. 10.4** presents the inter-objective aspects related to APC. These inter-objective aspects were found by combining environmental cost and financial cost per unit weight with unit hydrated volume and unit strength of APC. It is seen that the embodied energy and CO_2 emission per unit volume of hardened paste per unit strength were less than OPC by 33% and 44% respectively. Moreover, the cost per unit volume per unit strength is only about 79% of that of OPC. This implies that the integral sustainability of APC with respect to the LR quadrant is highly satisfactory.

The upper left (UL) quadrant of **Fig. 10.4** represents individuals' four-quadrant concerns. It seems that 'impact on sustainability' and 'professional recommendations' were considered as high concerns by individuals of all three countries, also reflected by the high DoIs indicated within parentheses. Further, 'market price', was a strong concern for both Australian and Sri Lankan individuals, also reflected by high DoIs. However, the 'feel good factor' elicited strong concern from American individuals only. Accordingly, in terms of the UL quadrant, individuals are highly concerned about 'market price', 'impact on sustainability' and 'recommendations of professionals'.

These have to be taken into account when developing APC for integral sustainability. The lower ‘market price’ and reduced (negative) ‘impact on sustainability of earth’ of APC have already been established.

The lower left (LL) quadrant of **Fig. 10.4** represents the society’s four quadrant concerns. Unlike in the case of individuals, the ‘impact on sustainability of Earth’ was not considered as a high concern by the societies of any of the countries, and therefore was not included in the lower left quadrant of **Fig 10.4**. However, just as in the case of individuals, all three societies were strongly concerned about ‘market price’, as reflected in the high DoIs. Also, the societies of America and Australia have strong concerns about ‘professional recommendations’, also reflected by high DoIs. Moreover, the societies of Sri Lanka and America have high concerns about social trends as reflected by high DoIs. Generally, it appears that in terms of the aspects related to the LL quadrant, social concerns about market price, social trends and recommendations of professionals have to be addressed when developing APC. The above findings may suggest that marketing strategies should try to create social trends, perhaps by focusing on market price and by seeking endorsements from professionals.

10.4 Employing the Octa-octant Framework

The octa-octant framework developed to determine the certainty/uncertainty issues of objective and subjective aspects related to APC was given in **Fig. 8.11** in Chapter 8. By employing this framework, certainty and uncertainty of the aspects related to each quadrant can be identified and the stability of integral sustainability of APC can be investigated.

The certainty/uncertainty of measurements is due to the randomness and incompleteness of data, while certainty/uncertainty of perceptions is due to fuzziness and incomplete knowledge regarding APC (Foley et al. 1997). This convention is used to investigate the certainty/uncertainty of the objective and subjective aspects of APC.

10.4.1 Identifying Certainty/Uncertainty of Objective Aspects

10.4.1.1 Identifying certainty/uncertainty based on randomness

Objective and inter-objective aspects of APC were determined using experimental and analytical methods described in Chapters 4, 5, 6 and 7. Randomness of measurements is reflected by 'variability of data', which refers to the spread of data. The simplest measure of variability is the 'range'. The most common measures of variability are 'variance' and 'standard deviation'. However, the variability measures that are adopted are usually determined by what is specifically required. One such measure is 'relative range of variation' which is defined as 'range to mean ratio' (Vincent 2006). In this research, to investigate certainty/uncertainity' of data, variability was defined as the difference between the upper bound and the lower bound of data, expressed as a percentage of the mean. Accordingly, low values of variability imply less randomness while high values of variability imply more randomness. Less randomness implies more certainty and more randomness implies less certainty (or more uncertainty). For the purpose of analysis, a variability of 15% was considered as the cut-off level. Accordingly, entities having variability values less than or equal to 15% were considered as less random or more certain; entities having variability values greater than 15% were considered as more random or uncertain.

The point measures of experimental results such as mean strength and water absorption of different mixtures were given in Chapters 4 and 5. The numerical values of those point measures and relevant additional information such as 'variability of point measures' and the 'average values' computed after combining different mixtures are given in **Appendix A5**. As the interest here is to obtain a general picture about the certainty/uncertainty of APC mixtures, average values are extracted from Sections A5.5 to A5.8 of **Appendix A5** and summarised in **Table 10.1**.

Table 10.1 Variability of Strength and Durability Aspects of APC Mixtures

28 day strength for air cured samples		**Water Absorption (%)**		**Carbonation depth at 3 months**		**Sulphuric Attack Indicator**	
Mean (MPa)	*Variability*	*Mean (kg/kg)*	*Variability*	*Mean (mm)*	*Variability*	*Mean (kg/kg)*	*Variability*
39	12%	18.13	05%	14.30	04%	25.98	36%

Taking the critical level of variability as 15%, the objective aspects shown in **Table 10.1** were categorised as certain and uncertain as follows:

Certain entities of Objective aspects

Water absorption of APC (Mean variability= 05%)
Carbonation of APC (Mean variability = 04%)
Strength of APC (Mean variability = 12%)

Uncertain entities of Objective Aspects

Sulphuric acid attack (Mean variability= 36%)

The above information is transferred to the octa-octant framework given in **Fig 10.5** of Section 10.4.3.

Environmental costs such as embodied energy, CO_2 released by different APC mixtures, and financial cost with their variability values, were given in Chapter 6. The costs and variability values of different mixtures were combined and the average values were computed as shown in Sections A5.9 to A5.11 in **Appendix 5**. The results are given in **Table 10.2**.

Table 10.2 Variability of Economic Aspects of APC Mixtures

EMBODIED ENERGY				CO_2 RELEASED				COST			
per unit weight of APC Powder		per unit volume per unit strength		per unit weight of APC Powder		per unit volume per unit strength		per unit weight of APC Powder		per unit volume per unit strength	
Mean *(MJ/kg)*	*Var*	*Mean* *(MJ/m³/MPa)*	*Var*	*Mean* *(Kg/kg)*	*Var*	*Mean* *(Kg/m³/MPa)*	*Var*	*Mean* *($/kg)*	*Var*	*Mean* *($/m³/MPa)*	*Var*
2.80	**22%**	**116.5**	**34%**	**0.430**	**12%**	**18.0**	**24%**	**0.26**	**07%**	**10.90**	**19%**

Taking the critical level of variability as 15%, the objective aspects shown in **Table 10.2** were categorised as certain and uncertain as follows:

Certain entities of objective Aspects

CO_2 released per unit weight (Mean variability = 12%)
Cost per unit per unit weight (Mean Variability = 07%)

Uncertain entities of objective Aspects

Embodied Energy per unit weight of APC (Mean variability = 22%)

Certain entities of inter-objective Aspects

None

Uncertain entities of inter-objective Aspects

Embodied Energy per volume per strength of APC (Mean variability = 34%)

Cost per unit per volume per strength (Mean Variability = 19%)

CO_2 released per volume per strength (Mean variability = 24%)

The above information is transferred to the octa-octant framework given in **Fig. 10.5** of Section 10.4.3.

10.4.1.2 Identifying certainty/uncertainty based on incompleteness of knowledge

The degree of certainty/uncertainty of the objective aspects of APC can also be due to the completeness/incompleteness of data about APC. It can be considered that the knowledge of chemical properties of raw materials and APC are fairly complete, hence more certain. However, the properties of commercially available raw materials are quite different from the properties of samples analysed, and can be considered as more uncertain. Similarly, the theoretical energy requirement to produce APC is more certain, while the energy needed for the actual production is uncertain. Accordingly, those aspects can be categorised based on certainty/uncertainty as follows:

Certainty based on completeness

Properties of APC constituents

Certainty based on completeness

Theoretical energy requirement to produce APC

Uncertainty based on Incompleteness

Properties of commercially available raw materials

Uncertainty based on Incompleteness

Actual production processes

The above information can be used in addition to the information given in Section 10.4.1.1. However, as this thesis focuses on the initial stage of developing APC, the completeness/incompleteness of data is not considered any further.

10.4.2 Identifying Certainty/Uncertainty of Subjective Aspects

10.4.2.1 Identifying certainty/uncertainty based on fuzziness

The identification of the degree of certainty/uncertainty of individual and social concerns about selected aspects was based on the analysis given in Chapter 9. Individual and social perceptions about the selected aspects of APC were generated in three different contexts, namely, Australia, America, and Sri Lanka. Then the perceptions were analysed by employing fuzzy sets; and the Degrees of Identity (DoIs) for each aspect were computed and presented in **Table 9.1**, **Table 9.2** and **Table 9.3** of Chapter 9 (the physical meaning of DoI was given in Chapter 9). For the purpose of interpretations, only the 'significant DoIs' which are over a cut-off level of 0.33 were considered. The 'width of spread' of the 'significant DoIs' can be considered as a measure of fuzziness of perceptions. For any specific aspect, if 'significant DoIs' come under a single linguistic label (or fuzzy curve), this means that the fuzziness of the perception is narrow or the perception is more certain. On the other hand, if 'significant DoIs' are spread over a number of linguistic labels (or fuzzy curves), this means that the fuzziness of the perception is wide or the perception is less certain (or more uncertain). Hence, by considering the 'width of spread' of 'significant DoIs', the certainty/uncertainty of perceptions of a specific aspect can be categorised. In Chapter 9, **Table 9.4** gives the 'widths of spread' of Significant DoIs. Summations of the 'widths of spreads' of 'significant DoIs' are computed and presented in **Table 10.3**.

Table 10.3 Summations of 'Widths of Spreads' of 'Significant DoIs'

Qn	AUSTRALIA		AMERICA		SRI LANKA		TOTAL		
	a	b	a	b	a	b	∑a	∑b	{ ∑a + ∑b }
Q1	2	3	2	2	2	2	**6**	**7**	**13**
Q2	2	3	2	3	3	3	**7**	**9**	**16**
Q3	3	2	2	3	2	2	**7**	**7**	**14**
Q4	3	2	3	2	3	2	**9**	**6**	**15**
Q5	3	2	2	2	4	2	**9**	**6**	**15**
Q6	3	3	3	3	3	2	**9**	**8**	**17**
Q7	3	2	3	3	3	3	**9**	**8**	**17**
Q8	3	2	3	3	3	3	**9**	**8**	**17**
TOTAL	**22**	**19**	**20**	**21**	**23**	**19**	**65**	**59**	**124**

KEY

Q1 - Market price
Q2 - Quality standard
Q3 - Impact on the sustainability of the earth
Q4 - Mitigating land pollution due to fly ash
Q5 -Non-familiarity
Q6 -'Feel good' factor
Q7 -Social trends
Q8 -Recommendations of professionals

In **Table 10.3**, the first column specifies the question numbers. The aspects considered in each question are indicated under the 'key'. In the 1st, 2nd and 3rd double columns, parts (a) and (b) give 'widths of spared' of 'Significant DoIs' of individuals and societies respectively from three counties. In order to obtain a general view about the fuzziness (or certainty/uncertainty) about the perceptions of individuals and societies, the summation of width of spreads of parts (a) and (b) were computed separately and indicated in the 4th double column. It is seen that these summations have a range between 6 and 9. Hence, for the purpose of analysis, this range can be equally divided into two by considering that values of 6 and 7 represent less fuzzy or 'certain' aspects; and that values of 8 and 9 reflect more fuzzy or 'uncertain' ones. Based on these results, for individuals as well as for society, less fuzzy (or certain) and more fuzzy (or uncertain) perceptions are identified and listed below.

Individuals: Certain aspects (that are less fuzzy)

Market Price
Quality Standard
Impact on Sustainability

Individuals: Uncertain aspects (that are more fuzzy)

Mitigating land pollution
Non-familiarity
'Feel good' factor
Social Trends
Recommendations of Professionals

Society: Certain aspects (that are less fuzzy)

Market Price
Impact on Sustainability
Mitigating land pollution
Non-familiarity

Society: Uncertain aspects (that are more fuzzy)

Quality standard
'Feel good' factor
Social Trends
Recommendations of Professionals

The above information is transferred to the octa-octant framework given in **Fig 10.5** of Section 10.4.3, which is used to investigate the 'stability' of the integral sustainability of APC.

10.4.2.2 Identifying certainty/uncertainty based on incompleteness of knowledge

The degree of certainty/uncertainty of individual and social views about different aspects of APC can arise from the completeness/incompleteness of knowledge about APC. It can be considered that when the knowledge of APC is high (or complete), then the acceptability/non-acceptability for respondent would be based on more certain grounds. However, when knowledge about APC is less (or incomplete), then the decisions are not based on certain grounds, but rather on assumptions and/or opinions. Accordingly, different outcomes can be listed as follows:

Individuals: Certainty based on completeness/incompleteness

Individual acceptability based on knowledge

Individuals: Uncertainty based on completeness/incompleteness

Individual acceptability based on assumptions and/or opinions

Society: Certainty based on completeness/incompleteness

Social acceptability based on knowledge

Society: Uncertainty based on completeness/incompleteness

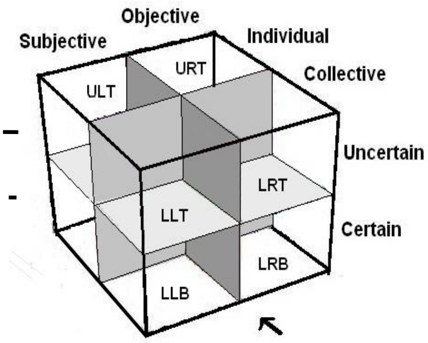
Social acceptability based on assumptions and/or opinions

The above information can be used in addition to the information given in Section 10.4.2.1. However, as this thesis focuses on the initial stage of APC development, the completeness/incompleteness of knowledge is not considered any further.

It should be noted in passing that one way in which to account for completeness/incompleteness is to elicit from respondents a ‘level of confidence’ regarding their choices (Dias and Chandratilake, 2005). This ‘level of confidence’ could be expected to be an index of respondents’ completeness of knowledge. This level of sophistication was beyond the scope of this research, and irrelevant to the research objectives.

10.4.3 Integration of Certainty/Uncertainty of Subjective/Objective Aspects

The certainty/uncertainty of objective aspects identified in Section 10.4.1 and the certainty/uncertainty of subjective aspects identified in Section 10.4.2 are integrated using the ‘three-dimensional octa-octant framework’ and presented in **Fig. 10.5**. In order to present the three-dimensional framework on a two-dimensional space, the top block of octants and bottom block of the octants are separated.



Block of Bottom Octants (Certain Octants)

[ULB] **INDIVIDUAL CONCERNS** **<u>Less Fuzzy Individual Perceptions</u>** Market Price Quality Standard Impact on Sustainability of earth	***[URB]*** **INDIVIDUAL ENTITIES** **<u>Less Random entities</u>** Water absorption of APC (var= 05%) Carbonation of APC (var =04%) Strength of APC (var = 12%) Cost per unit weight of APC powder (var = 07%) CO_2 released per unit weight (var = 12%)
SOCIAL CONCERNS **<u>Less Fuzzy Social Perceptions</u>** Market Price Impact on the Sustainability of earth Mitigating land pollution Non-familiarity ***[LLB]***	**COMBINED ENTITIES OR RELATIONSHIPS** **<u>Less Random relationships</u>** None ***[LRB]***

Block of Top Octants (Uncertain Octants)

[ULT] **INDIVIDUAL CONCERNS** **<u>More Fuzzy Individual Perceptions</u>** Mitigating land pollution Non-familiarity 'Feel good' factor Social Trends Recommendation of Professionals	***[URT]*** **INDIVIDUAL ENTITIES** **<u>More Random entities</u>** Sulphuric acid resistance (var= 36%) Embodied Energy per unit weight (var= 22%)
SOCIAL CONCERNS **<u>More Fuzzy Social Perceptions</u>** Quality standard 'Feel good' factor Social Trends Recommendation of Professionals ***[LLT]***	**COMBINED ENTITIES OR RELATIONSHIPS** **<u>More Random relationships</u>** Embodied Energy per unit vol per unit strength (var=34%) Cost per unit vol per unit strength (var = 19%) CO_2 released per unit vol per unit strength (var = 24%) ***[LRT]***

Fig. 10.5 Entries to Top and Bottom Octants of the Octa-octant Framework

10.4.4 Discussion on Employing Octa-octant Framework

The application of the three-dimensional octa-octant framework is demonstrated in **Fig. 10.5** where the block of bottom octants (certain octants) is given first; below that is the block of top octants (uncertain octants). In the octa-octant framework, the terms ‘certainty/uncertainty’ are used with a specific meaning. Here, the term ‘uncertain’ means that the values of a particular measurement or a perception about a particular concern are spread over a relatively wide region on the scale considered; ‘certain’ means that the values or perception are spread over a narrow region. Where objective and inter-objective properties are concerned, the spread over a narrow region implies high consistency. In the case of subjective (individual) and inter-subjective (social) concerns, the spread over a narrow region implies that the individuals and societies are more ‘sure’ or ‘confident’ about their concerns or decisions. From the marketing point of view, the consumers’ confidence about their decision is not important as long as they buy the product. However, according to integral sustainability philosophy, mere acceptance of a product by consumers as a result of ignorance or uncertainty would not make the product ‘integrally sustainable’. Instead, the acceptance should be a conscious choice and it should be based on more certain grounds. Hence, the aim here is to identify uncertainties associated with the objective measurements and subjective concerns, and to find ways to reduce those uncertainties.

The upper right bottom/top octants of **Fig. 10.5** present the certainty/uncertainty of objective aspects related to APC. As evident, the important objective aspects such as cost per unit weight, strength, water absorption, carbonation and CO_2 released per unit weight fall into the ‘certain’ octant (URB). Sulphuric acid resistance falls into the ‘uncertain’ octant (URT) with relatively high variability value (Var = 36%); also embodied energy per unit weight (with a much lower variability). Therefore, most of the objective aspects related to integral sustainability show stability.

The lower right bottom/top octants of **Fig. 10.5** present the certainty/uncertainty of inter-objective aspects related to APC. Here, all the aspects are in the ‘uncertain’ octant (LRT) and reflect uncertainty. These relatively high variabilities are the average variabilities of a number of APC mixtures made of fly ash and slag, namely L, M, N and P, with water/cement ratios of 0.3 and 0.4. Therefore, the reason for high average variability is that some of the mixtures have high variability values. Hence, similar groups may be grouped together during the development stage and considered separately. Such an approach would help to develop APC more precisely. By doing so, the integral sustainability of APC can be made more stable.

The upper left bottom/top octants of **Fig. 10.5** represent certainty/uncertainty of individuals' four-quadrant concerns. It is seen that three of the most important concerns, namely 'market price', 'impact on sustainability of earth' and 'quality standards' are held fairly certainly by individuals. However, perceptions of individuals about 'mitigating land pollution', 'feel good factor', 'non-familiarity', 'social trends' and 'recommendation of professionals' have inherent uncertainty. The certainty regarding 'market price', 'impact on sustainability of earth' and 'quality standards' reflect the stability of individuals' concerns. However, this does not mean that the individuals are satisfied about those aspects. It only means that they are certain that they would consider those aspects when selecting a cement. Hence, in order to establish the stability of the integral sustainability of APC, those aspects related to APC have to be confirmed and conveyed to individuals. Among the uncertain concerns, the first three are related to individuals' lack of knowledge about APC and its eco-friendliness. Hence, if individuals are well-informed, they would be able to make choices based on more certain grounds. Uncertainty about 'recommendations of professionals' may be due to their misconceptions about professionals. Hence, a different way of conveying the quality standards to consumers has to be found. Endorsements by professional bodies, such as standards institutions, might be one option.

The lower left bottom/top octants of **Fig. 10.5** represent certainty/uncertainty of society's four-quadrant concerns. It is seen that the most important concerns, namely 'market price', 'impact on sustainability of earth', 'mitigating land pollution' and 'non-familiarity' are felt fairly certainly by the societies. However, social perceptions about 'quality standard', 'recommendations of professionals', 'feel good factor' and 'social trends' have inherent uncertainty. Certainty regarding 'market price', 'impact on sustainability of earth', 'mitigating land pollution' and 'non-familiarity' reflects a stability of social concerns. Hence, as mentioned in the case of individuals, in order to establish the stability of the integral sustainability of APC, these aspects related to APC have to be confirmed and conveyed to society. Among uncertain concerns, 'quality standards' and 'recommendations of professionals' are somewhat inter-related. The society is not certain whether quality standards should or should not be considered in the selection of cement. In such situations, the 'recommendation of professionals' becomes irrelevant, and perception about it too becomes uncertain. This situation is somewhat unfavourable for APC. To overcome this problem, society has to first be educated about the importance of quality standards and thereafter be informed that APC meets those standards. Also, as in the case of individuals, the quality standards of APC may be conveyed to society through endorsements from professional bodies such as standards institutions.

10.5 Conclusions

The main aim of this chapter is to bring together all the aspects related to APC in order to investigate the degree of integral sustainability of APC and to identify the aspects to be improved to achieve/maintain such sustainability. This aim was achieved with the aid of two frameworks developed during the process of the research, namely the modified two-dimensional tetra-quadrant framework and the newly developed three-dimensional octa-octant framework. The modified tetra-quadrant framework was used to determine the four integral theory aspects, while the octa-octant framework was used to identify the certainty/uncertainty of those four aspects. The conclusions drawn are presented below separately under two headings.

<u>The conclusions drawn from the modified tetra-quadrant framework are:</u>

1. Among the aspects considered from the UR quadrant of the integral sustainable framework, financial cost, embodied energy per unit weight, CO_2 emission per unit weight and resistance to sulphuric attack are highly satisfactory. The strength, resistance to water absorption and resistance to carbonation are satisfactory to a lesser degree; hence, these properties may need to be improved. This implies that integral sustainability of APC with respect to the UR quadrant is moderately satisfactory.

2. Among the aspects considered from the LR the quadrant of the integral sustainable framework, embodied energy per unit volume per unit strength, CO_2 emission per unit volume per unit strength and cost per unit volume per strength are highly satisfactory. This implies that the integral sustainability of APC with respect to the LR quadrant is also highly satisfactory.

3. Among the aspects considered from the UL quadrant of the integral sustainable framework, generally, individual's concerns about 'market price', 'impact on sustainability' and 'recommendations of professionals' are high. Further, the first two of those concerns have already been established for APC through this research. Hence, the integral sustainability of APC with respect to the UL quadrant has already been established satisfactorily.

4. Among the aspects considered from the LL quadrant of the integral sustainable framework, generally social concerns about 'market price' and 'recommendation of professionals' are high, and the first one met for APC as described above. However, the lower social concerns about the impact on sustainability is unfavourable for APC to be get established as an integrally sustainable cement. Hence, the integral sustainability of APC with respect to the LL quadrant can be described as moderately satisfactory.

<u>The conclusions drawn from the octa-octant framework are:</u>

1. When the objective properties of APC are considered, it is seen that the important aspects such as cost per unit weight, strength, water absorption, carbonation and CO_2 released per unit weight show less variability, confirming the certainty of those properties; however, embodied energy per unit weight and resistance to sulphuric attack show greater variability. Accordingly, the integral sustainability of APC with respect to objective aspects has already been secured with relatively high stability.

2. When inter-objective properties of APC are considered, all aspects, namely the environmental impact due to CO_2 released per unit volume per unit strength, cost per unit volume per unit strength and embodied energy per unit volume per unit strength show high variability, confirming the uncertainty of those properties. Accordingly,

the integral sustainability of APC with respect to inter-objective aspects is unstable, and steps need to be taken to focus on and market a particular formulation of APC. This will reduce the uncertainty.

3. When individuals' four-quadrant concerns regarding APC are considered, it is seen that important concerns such as 'market price', 'impact on sustainability of earth' and 'quality standards' are held fairly certainly by individuals, but not about 'mitigating land pollution', 'feel good factor', 'non-familiarity', 'social trends' and 'recommendation of professionals'. Accordingly, the integral sustainability of APC with respect to subjective aspects is moderately stable.

4. When society's four-quadrant concerns regarding APC are considered, it is seen that the most important concerns, namely 'market price', 'impact on sustainability of earth', 'mitigating land pollution' and 'non-familiarity' are held fairly certainly by the societies, but not 'quality standard', 'recommendation of professionals', 'feel good factor' and 'social trends'. Accordingly, the integral sustainability of APC with respect to inter-subjective aspects is moderately stable.

5. The above findings can be summarised as follows:

Aspects	**Integral Sustainability**	**Stability of Sustainability**
Objective	Moderately satisfactory	High stability
Inter-objective	Highly satisfactory	Low stability
Subjective	Satisfactory	Moderate stability
Inter-subjective	Moderately satisfactory	Moderate stability

10.6 References

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11 Conclusions and Recommendations

The main aim of this research is 'to investigate the development of Alkali Pozzolan Cement (APC) for integral sustainability', or, to elaborate:

> *'To investigate the design and development of 'Alkali Pozzolan Cement' (APC), constituted of non-hazardous chemicals that can be cured under ambient conditions and stored as a dry powder, and to establish its integral sustainability; and also to compare APC with High Volume Fly Ash (HVFA) Cement with reference to Ordinary Portland Cement (OPC)'.*

The significance of this research can be discussed under three spheres: a general sphere, specific sphere and distinctive sphere. Conventional cement, which is commonly known as OPC, has issues related to ecological sustainability, and thus there is a general requirement to minimize the use of OPC. Consequently, an investigation into the development of Alkali Pozzolan Cement (APC), which is an alternative cement, has a general significance. Much of the current research on alternative cement contends with one or more issues related to the use of hazardous chemicals, elevated curing, and being a wet binder; hence, there is a specific requirement to develop an alternative cement which utilises a higher percentage of fly ash, consists of non-hazardous chemicals, can be cured under ambient conditions, and can be stored as a dry powder. Thus APC, which fulfils such requirements, possesses this specific significance as well. Finally, even though much research has been carried out to develop alternative cements, these studies have tended to focus mainly on technological and/or ecological sustainability. Apart from having a similar focus, this study is also concerned with other aspects related to integral sustainability; hence, it also has a distinctive significance.

11.1 Research Summary and Conclusions

The chapters of the thesis are divided into four parts. Chapter 1 gives an introduction to the research including its main aim and objectives. Chapter 2 describes a suitable research methodology to be employed to achieve the objectives of the research. Chapters 3 to 10 present the process of achieving the objectives of the research, with Chapters 3 to 7 describe the engineering aspects and Chapters 8 to 10 the integral aspects. Finally, Chapter 11, i.e. this chapter, presents a summary of the research, its outcomes, and recommendations.

The cementitious mixtures used in this research were already described in Chapter 4. However, for convenience, they are reproduced below.

APC Mixtures derived from fly ash
L = 70% (95% APC60 + 5% Na2SO4) + 30% OPC
M =70% (95% APC70 + 5% Na2SO4) + 30% OPC
N =70% (95% APC80 + 5% Na2SO4) + 30% OPC

APC Mixtures derived from slag
P = 70% (95% APC70 + 5% Na2SO4) + 30% OPC

HVFA Mixtures
C = 70% FA + 30% OPC

OPC Mixtures
R = 100%OPC

NOTES:
1. APCr = r% Pozzolan + (100-r)%Lime

2. The above dry cement powders were mixed with water, using w/c ratios of 0.3 and 0.4 and two pastes from each cement were obtained. To identify those pastes, suffixes 3 and 4 were added to the letter indicating the dry mix. For example the pastes prepared from cement M with w/c=0.3 and 0.4 were identified as M3 and M4 respectively.

At the end of the each chapter, a summary and/or conclusions related to that chapter were given; they are reproduced in Section 11.1.1 below. This is followed by the overall research summary and conclusions, which is given in Section 11.1.2.

11.1.1 Summary and Conclusions drawn from Chapters

Chapter 1: Introduction and Formulation of the Research

Alkali Pozzolan Cement (APC) is an alternative cement developed in this research. In order to investigate the integral sustainability of APC, the objective aspects related to APC (material properties, cost of production, ecological impact, etc.) as well as subjective aspects regarding APC (individual and social concerns) were to be investigated from the development stage itself.

1. A research framework that can be employed to investigate objective and subjective aspects related to APC was formulated. It suggested adopting a cyclical process instead of linear process in developing APC for integral sustainability.

2. Considering the key aspects that have to be investigated, eight research goals (or research objectives) were formulated.

Chapter 2: Development of Integrated Research Methodology

The positivist paradigm is the standard research paradigm commonly used in the domains of science and engineering. However, it was noted that the positivist paradigms alone could not be employed in this research since this research is related to engineering as well as integral philosophy.

1. Potential and limitations of employing positivist and non-positivists paradigms in this research were investigated. The positivist paradigm could be used to investigate the objective properties of APC, but it could not be used to investigate socially and culturally constructed perceptions regarding APC. Non-positivist paradigms are

useful to understand/investigate differences in subjective meanings regarding APC, but they could not be used to investigate the objective properties of APC.

2. An integrated research methodology suitable for research related to engineering and integral philosophy, which could be used to investigate the integral sustainability of APC, was developed by combining positivist with non-positivist paradigms, which include quantitative as well as qualitative research methods.

Chapter 3: Design of Alkali Pozzolan Cement (APC)

The first objective of the research was to design APC with alkali materials, pozzolanic materials and other non-hazardous materials to yield satisfactory compressive strength, and compare it with HVFA with reference to OPC. The research began with a basic APC mixture consisting of 70% fly ash and 30% lime.

1. Strength development of the basic APC mixture (containing 70% fly ash and 30% lime) was very low. Microstructural investigations revealed that this was due to the non-activation of the pozzolanic reaction.

2. Compressive strength at 28 days was considerably increased when activators were used, mainly through the improvement of pozzolanic reactivity, but early compressive strength was still low. Of the activators tried, 5% Na_2SO_4 proved to be the best when combined with scaffolding.

3. Adding 30% of OPC as a scaffolding material improved the strengths of both the basic and activated APC mixtures. However, scaffolding alone did not improve the pozzolanic reaction. When both scaffolding and activation were employed, a dense CSH/CASH gel structure was obtained and the APC mixture reached strengths comparable to the reference OPC mixture.

4. Microstructural investigations revealed that improvements due to scaffolding and activation were reflected in the grape-cluster-like formation in the SEM images and the presence of the elements Ca, Si, Al and O in the EDS graphs (suggesting the

formation of CSH/CASH), and in the enhanced humps at 2-theta values of 21.5° and 32° in the XRD curves.

5. The best APC mixture was one, the composition of which can be expressed as 70% (95% APC70 + 5% Na2SO4) + 30% OPC, where APC70 is a mixture of 70% fly ash and 30% lime. Of the three curing conditions employed, the highest 28-day strength was achieved by the ambient curing condition.

6. Of the four factors that were varied in order to improve the strength of APC mixtures, scaffolding was found to be the most significant statistically, followed by chemical activation (with Na_2SO_4) and age (i.e. variation from 3 to 28 days). Temperature (i.e. variation from entirely ambient to 15 hours curing at 60^{o}C) was found to be significant for 3-day but not for 28-day strengths.

7. Although some further fine tuning may be required to arrive at the optimum constituent percentages, this work has demonstrated that a 'non-hazardous dry cement powder', comparable in strength to OPC and needing only ambient temperature curing, can be developed using fly ash, lime, OPC and a Na_2SO_4 activator.

Chapter 4: Structural and Microstructural Properties of APC

The second objective of the research was to investigate the structural and microstructural properties of APC, and compare them with those of HVFA with reference to OPC. Accordingly, APC mixtures derived from different pozzolanic materials, namely fly ash and slag, in different proportions, were mixed with different w/c ratios of 0.3 and 0.4, and their structural and microstructural properties were experimentally investigated. The main focus of interest was APC mixture M, the composition of which can be expressed as 70% (95% APC70 + 5% Na2SO4) + 30% OPC, where APC70 is a mixture of 70% fly ash and 30% lime.

1. The initial setting time and final setting time of the APC mixture M is close to those of the reference OPC mixture, the difference being only about 10%.

2. APC does not require elevated-temperature curing even though it contains a significantly high volume of pozzolan; it does not require water curing to gain strength. In fact, APC performs better under air curing, which is its main advantage.

3. In general, under air-curing conditions, the 28-day strength of APC mixtures are over 85% higher than that of HVFA mixtures. This confirms the suitability of APC over HVFA when compressive strength is considered. The APC mixtures also achieve around 75% of the strength of corresponding OPC mixtures.

4. APC mixtures derived from slag gave higher strengths than those derived from fly ash. One reason for this is that slag contains 32.6% CaO, while fly ash contains only 1.6% of CaO. This implies the possibility of improving strength of APC by using high-CaO pozzolans such as slag or high calcium fly ash (Class C fly ash). The other reason for the greater strength is that slag contains more amorphous silica than fly ash, as reflected in XRD curves.

5. Strength increased somewhat from APC60 to APC80 through APC70, and this was reflected in the hydrate-bound water quantities obtained from thermal analysis too.

6. The HVFA mixes showed the greatest sensitivity to changes in w/c ratio, while APC and OPC mixes were less sensitive. The w/c = 0.4 mixes were more sensitive to changes in curing, while the HVFA mixes were improved by heat curing.

7. XRD curves of hydrated samples showed the formation of C-S-H by 'broad humps' at the relevant 2θ values (around 29^o and 32^o). XRD curves of APC samples very clearly indicated that these broad humps become more pronounced with time (with a reduction of the alite and belite peaks and an increase in the portlandite peak), implying that the formation of C-S-H (and C-A-S-H) continues over a long duration up to 112 days, both through the direct hydration of OPC constituents C_3S and C_2S, and through the reaction of $Ca(OH)_2$ with the fly ash.

8. SEM images of APC samples indicate that fly ash particles were smooth and clear at early ages, but were ‘eaten up’ by $Ca(OH)_2$ to form C-S-H over time. This too confirms that the hydration process of APC continues over a long period of time. The presence of the element Al in the EDS graphs, in addition to the elements Ca, Si and O, indicate that the hydration of APC samples produces C-A-S-H in addition to C-S-H.

9. Thermal Analysis confirmed the findings of XRD and SEM analysis on the continuation of hydration processes in APC over a long period of time. DTA and DSC curves do not reflect crystallization of hydrated products.

10. It was possible to find a reasonably good general correlation between hydrate bound water and compressive strength, whatever the mix type or age.

11. Overall, it can be concluded that APC is a reasonably good alternative to OPC that does not need water curing, and that its compressive strength is much higher than that of the HVFA tested (incorporating a similar percentage of OPC).

Chapter 5: Durability Properties of Alkali Pozzolan Cement (APC)

The third objective of the research was to investigate the durability properties of APC, and compare them with those of HVFA (C) with reference to OPC (R). Here, durability properties were investigated through selected tests, namely water absorption of relatively young (28 day old) specimens, sulphuric acid attack on mature (1 year old) specimens, sodium chloride ion penetration of mature (1 year old) specimens, and carbonation of mature (1 year old) specimens.

1. Resistance to water absorption of APC mixture M was greater than that of HVFA Mixture C, but slightly less than that of OPC mixture R. The reason is that the hydration process of APC is faster than that of HVFA, but slower than OPC. Therefore, the degree of pore structure filling by C-S-H would decrease in the order of OPC, APC and HVFA, and porosity decreases in the same order. Among fly ash-based APC samples, water absorption of the mixture L was the greatest. The reason

could be that it has the greatest proportion of lime, and unreacted lime would get leached away, thus making samples more porous. Water absorption of APC mixtures derived from fly ash and slag are similar. The reason would be that their porosities are similar due to similar hydration processes.

2. The Sensitivity to w/c ratio for water absorption of APC mixture M is slightly less than that of HVFA mixture C and OPC mixture R. The reason could be that the lime in APC could contain CaO in addition to $Ca(OH)_2$. Then some of the excess water would react with CaO to form $Ca(OH)_2$, which would also be involved in pozzolanic reactions, rather than increasing the porosity. Hence, a slight increase of w/c would not increase water absorption of APC to a greater extent as in the cases of HVFA and OPC. Sensitivity to w/c of APC mixture N is clearly higher than that of APC mixtures L and M, under both curing conditions. Of the APC mixtures, mixture N has the least quantity of lime; hence, it needs less water than the others for the hydration process. Excess water would increase porosity, and sensitivity to w/c for water absorption would be higher in N than in others.

3. Resistance to sulphuric acid attack of APC samples was greater than that of OPC samples, but less than that of HVFA samples. APC and HVFA samples have only 30% of OPC, and therefore have less C_3AH_{12} than OPC samples. Therefore, the subsequent formation of expansive ettringite would be less than that in OPC. Even though APC and HVFA have the same quantity of C_3AH_{12}, the ettringite formed would expand into the relatively larger pore structure of HVFA without exerting expansive stresses on the internal structure and damaging the sample. As a result, even though damage caused to APC samples is less than that of OPC, it is greater than that of HVFA. Resistance to sulphuric acid attack of fly ash-based APC mixtures L, M and N and slag-based APC mixture P as are similar, because both groups have the same quantity of C_3AH_{12}.

4. When sensitivity to the w/c ratio for sulphuric acid attack was considered, it was seen that in all mixtures, the damage due to sulphuric attack was higher in the samples made with w/c=0.3 than with w/c=0.4. The reason is that when w/c ratio increases, samples become more porous, thus providing more room for ettringite to expand into; hence, the damage cause by expansive stresses becomes less.

5. Resistance to the sodium chloride ion penetration depth of APC samples was greater than that of OPC samples, but less than that of HVFA samples. Both APC and HVFA samples have OPC and fly ash, and differences in the size and shape of the two materials make the paste structure more tortuous, obstructing the penetration of chloride ions. Also, OPC samples have free OH^- ions due to $Ca(OH)_2$ released during the hydration process while APC samples have free OH^- ions due to the added lime; hence, chloride ion penetration occurs through ion exchange in those samples. However, in HVFA, the greater part of $Ca(OH)_2$ released during hydration gets involved in pozzolanic reactions, and hence the free-$Ca(OH)_2$ is either very much less or non-existent. Hence, chloride ion penetration through ion exchange becomes less. As a result, the depth of chloride ion penetration decreases in the order of OPC, APC and HVFA. In APC mixtures L, M and N, the proportion of lime decreases in that order; and as a result, free OH^- ions decrease. Hence, chloride penetration through ion-exchange decreases in the same order.

6. When sensitivity to w/c ratio for sodium chloride ion penetration is considered, it is seen that sensitivities are greatest in HVFA sample C and APC sample N. In HVFA mixture C and APC mixture N, the quantity of $Ca(OH)_2$ is less, and hence water consumed in pozzolanic reactions is also less. Therefore, a greater part of excess water would increase porosity, rather than being involved in hydration reactions. As a result, sensitivity to w/c of those samples becomes significantly high.

7. Resistance to carbonation of APC samples is greater than that of HVFA samples, but less than that of OPC samples. HVFA samples are more porous than OPC and APC samples, and have less free $Ca(OH)_2$ than OPC and APC samples. Hence, CO_2 penetrates easily and the limited $Ca(OH)_2$ gets carbonated sooner which means that the carbonated region deepens quickly. On the other hand, OPC samples are less porous, and have more free $Ca(OH)_2$; hence, the carbonated region deepens slowly. Conditions in APC fall in between HVFA and OPC; hence, the carbonation results also reflect a median position. Thus, resistance to carbonation decreases in the order of OPC, APC and HVFA. In fly ash-based APC samples L, M and N, the free $Ca(OH)_2$ decreases in that order, and depth of carbonation increases in the same order. Slag based-APC samples are less porous than fly ash-based APC samples.

Further, they have more free $Ca(OH)_2$ (since slag has more CaO than fly ash). As a result, resistance to carbonation is greater in the slag based-APC sample P, than in fly ash-based ones.

8. When sensitivity to w/c ratio on carbonation is considered, it is seen that for all mixtures, sensitivity is greater at 3 months than at 1 month. It is also seen that APC and HVFA samples are more sensitive than OPC ones. Initially, all samples have a relatively high quantity of free $Ca(OH)_2$. However, with time, free $Ca(OH)_2$ decreases due to the carbonation process and also due to pozzolanic reactions (in APC and HVFA samples). Therefore, with the passage of time, the remaining limited $Ca(OH)_2$ is carbonated faster in more porous samples than in less porous ones. Hence, in all samples sensitivity to w/c is higher at 3 months than at 1 month. APC and HVFA samples are more porous than OPC ones, and when w/c increases, their porosity increases further. Hence, sensitivity to w/c of APC and HVFA is greater than that of OPC.

Chapter 6: Ecological & Financial Costs of APC

The fourth objective of the research was to investigate economic aspects with respect to ‘ecological cost’ and ‘financial cost’ of APC, and compare them with those of HVFA with reference to OPC. Accordingly, in this study, energy requirements to produce cementitious mixtures, CO_2 emissions during the production of mixtures and financial costs of producing mixtures were computed and compared. These investigations were done according to two criteria: the first one was based on unit weight of dry cement powder, and the second one was based on unit volume per unit strength of hydrated cement.

1. When embodied energy of dry cementitious powders are considered, the embodied energy per unit weight of the fly ash based APC group is 2.7 MJ/kg, while that of the OPC group is about 4.8 MJ/kg. That is, embodied energy per unit weight of APC mixtures are only about 57% of the OPC ones. When hydrated pastes are considered, the embodied energy per unit volume per unit strength of the fly ash based APC group is around 119 $MJ/m^3/MPa$, while that of the OPC group is about

165 MJ/m^3/MPa; this means that APC's percentage is only about 72% of OPC. This implies that, regardless of whether the basis of calculation of the embodied energy is per unit weight or per unit volume per unit strength, APC is a very much less energy intensive material than OPC.

2. When CO_2 emission of dry cementitious powders are considered, the CO_2 emission per unit weight for fly ash based APC group is 0.4 kg of CO_2/kg of cement, while that of OPC group is about 0.9 kg of CO_2/kg of cement. That implies that CO_2 emissions per unit weight of APC mixtures are only about 48% of that of OPC ones. When hydrated pastes are considered, CO_2 per unit volume per unit strength of fly-ash-based APC is around 19 kg/m^3/MPa, while that of OPC group is about 31 kg/m^3/MPa, indicating that APC's amount is only about 60% of OPC's amount.

3. When the financial cost of dry cementitious powders are considered, the fly ash based APC group is approximately about 0.26 $/kg, while the OPC group is about 0.39 $/kg. That is, the financial cost of APC powder is only about 66% of the cost of OPC. When financial cost per unit volume per unit strength of hydrated pastes are considered, fly ash based APC is around 11.32 $/m^3/MPa, while OPC is about 13.44 $/m^3/MPa. In other words, APC's financial cost is only about 84% of OPC's financial cost.

4. The HVFA mixtures show better performance than the APC ones for embodied energy, CO_2 emissions and cost, when considering a 'per unit weight' basis, but APC ones perform better in all three when considering a 'per unit volume per unit strength' basis.

5. There is a little to choose between indices of the slag based APC and the corresponding fly ash based one.

<u>Chapter 7: Cross-tabulation of APC and HVFA with OPC</u>

The fifth objective of the research was to bring together all the aspects considered before (technological aspects with respect to structural and durability properties as well as economic aspects with respect to ecological and financial economy) of APC, and compare them with those of HVFA with reference to OPC. The technological aspects considered are 28-day compressive strength, water absorption, accelerated carbonation, weight change due to sulphuric attack and chloride ion penetration; and these aspects were investigated according to three criteria, namely performance, robustness with respect to w/c and robustness with respect to curing. The economic aspects considered for comparison are economy with respect to embodied energy, economy with respect to CO_2 emission and economy with respect to financial cost; and they were investigated according to two criteria, namely cost per unit weight and cost per unit volume per unit strength.

1. When performance is considered, the APC mixture M is better than the HVFA mixture C with respect to three of the most important aspects, namely strength, resistance to water absorption and carbonation. Also the APC mixture M performs better than OPC mixture R with respect to resistance to sulphuric acid attack and chloride ion penetration.

2. Generally, the performance of the three APC mixtures L, M and N are more or less similar for all the aspects, namely strength, resistance to water absorption, carbonation, acid attack and chloride ion penetration.

3. When the performance of groups is considered, again the APC group is better than the HVFA group with respect to strength, resistance to water absorption and carbonation. Also, the APC group performs better than the OPC group with respect to resistance to sulphuric acid attack and chloride ion penetration.

4. Although the notion of robustness was considered for analysis, in general, differences in robustness within the groupings were not that significant. It could be said that, in general, robustness is greater against changes in curing than against changes in w/c ratio.

5. When economic aspects based on unit weight of dry cement were considered, the APC mixture M is more economical than the OPC mixture R, in all three economic aspects, namely embodied energy economy, CO_2 emissions economy and financial

economy. Moreover, when the same aspects were examined based on unit volume per strength of hardened cement, the APC mixture M is unquestionably better than the OPC mixture R as well as the HVFA mixture C.

6. When economic aspects were examined based on unit volume per strength of hardened cement, it was seen that all three APC mixtures L, M and N are equally economical in all three aspects.

7. When economic aspects based on unit weight of dry cement are considered, the APC group is more economical than OPC in all three economic aspects. When the same aspects were examined based on unit volume per strength of hardened cement, the APC group is very clearly more economical than the HVFA group and the OPC group.

Chapter 8: Development of Integral Sustainability Frameworks

The sixth objective of the research was to develop frameworks to investigate the integral sustainability of APC, and compare it with that of HVFA with reference to OPC. Accordingly, a need arose to develop an integral sustainability framework capable of integrating the four aspects of sustainability related to the four quadrants of the integral framework. Moreover, in order to differentiate 'collections' and 'collectives', a necessity arose to modify the pronouns of the standard tetra quadrant framework. In addition, to investigate the 'stability' of integral sustainability of APC, a totally new three-dimensional framework has been developed. Finally, the application of the above modified frameworks to APC has been illustrated.

1. An integral sustainability framework with the 4Es of sustainability, that is, economical, ecological, existential and ethnological sustainability, can be used as the basis for this research.

2. The basic pronouns related to the four quadrants of the standard tetra-quadrant framework have been modified as I(s), WE(s), IT(s) and THEY(s), in order to recognise and differentiate 'collections of individuals' from 'collectives of

individuals'. With the aid of this framework, the 'collection of views related to APC' and 'collective views related to APC' can be generated and analysed.

3. In analysing subjective information, it is believed that qualitative estimates having 'step-scales' or clear-cut boundaries are not appropriate, since subjective preferences do not have clear-cut boundaries. Hence, a 'fuzzy scale' with fuzzy boundaries has been proposed for analysing subjective information.

4. In analysing objective information, the inadequacy of 'point measures' that give single values has been recognised; hence, the 'spread of measures' has been proposed to reflect uncertainty.

5. A third dimension has been added to the two-dimensional tetra-quadrant framework and the three-dimensional octa-octant framework derived. The third dimension added was the 'certain – uncertain' dichotomy. This three-dimensional octa-octant framework can be used to differentiate 'certain' and 'uncertain' aspects of subjective and objective information related to APC.

6. The 'integral sustainability' of 'Alkali Pozzolan Cement' (APC) can be effectively assessed with the aid of the modified integral frameworks.

7. The two-dimensional tetra-quadrant framework with modified pronouns and uncertainty estimates, and the newly developed three-dimensional octa-octant framework, are both general theoretical frameworks that can be used for assessing the integral sustainability not only of APC, but other products, services and entities as well.

<u>Chapter 9: Investigation of Subjective Aspects of APC</u>

The seventh objective of the research was to investigate individual and social concerns (subjective and inter-subjective concerns, according to integral theory terminology) about the integral sustainability of APC, and to discover any other main concerns of individuals and societies related to the four quadrants of integral sustainability framework. Individual and social concerns regarding different aspects related to integral sustainability of APC, were determined in the contexts of Australia, America, and Sri Lanka.

1. Generally, the individuals as well as the societies of the three countries have assigned relatively high degrees of importance to aspects favourable for the integral sustainability of APC such as market price, quality standards and impact on sustainability of the earth. Aspects unfavourable for APC, such as non-familiarity, have not been given a high degree of importance by individuals, but societies have done so. However, when overall acceptability is considered, it is seen that there is a high possibility of acceptance of APC as an integral sustainable cement in all three countries, Australia, America and Sri Lanka.

2. Of all the aspects considered, individuals and societies of all three countries have given higher degrees of importance to market price, quality standards, sustainability issues and recommendation of professionals. This implies that certification of quality standards would useful.

3. There are clearly contextual differences in assigning degrees of importance to different aspects. In the context of Sri Lanka, 'social trends' is considered as important, while it is not considered so in the contexts of Australia and America.

4. Many new concerns were identified through the open-ended questions. Among them, the long-term effect on properties of APC, guarantee / assurance given about APC, and health/risk-related issues for the user, are some of the important ones.

5. This chapter has also demonstrated the usefulness of the application of fuzzy sets for analysing responses to closed-ended questions, and grounded theory techniques to analyse responses to open-ended questions.

6. The open-ended question generated some very important information, and hence underlines the importance of this approach in eliciting subjective information, provided that a good 'grounded theory' type of technique is employed for analysing it.

Chapter 10: Integral Sustainability of Alkali Pozzolan Cement (APC)

The eighth objective of the research was to employ the two frameworks developed during the research, to integrate all the aspects related to APC in order to investigate the degree of integral sustainability of APC, and to identify the aspects to be improved to achieve/maintain integral sustainability of APC. This aim was achieved with the aid of two frameworks developed during the research, namely the modified two-dimensional tetra-quadrant framework and the newly developed three-dimensional octa-octant framework. The modified tetra-quadrant framework was used to recognise the four integral theory aspects, while the octa-octant framework was used to identify the certainty/uncertainty of those four aspects. The conclusions drawn through the two frameworks are presented separately below under two headings.

The conclusions drawn from the modified tetra-quadrant framework are:

1. Among the aspects considered from the UR quadrant of the integral sustainable framework, financial cost, embodied energy per unit weight, CO_2 emission per unit weight and resistance to sulphuric attack are highly satisfactory. The strength, resistance to water absorption and resistance to carbonation are satisfactory to a lesser degree; hence, these properties may need to be improved. This implies that integral sustainability of APC with respect to the UR quadrant is moderately satisfactory.

2. Among the aspects considered from the LR the quadrant of the integral sustainable framework, embodied energy per unit volume per unit strength, CO_2 emission per unit volume per unit strength and cost per unit volume per strength are highly satisfactory. This implies that the integral sustainability of APC with respect to the LR quadrant is also highly satisfactory.

3. Among the aspects considered from the UL quadrant of the integral sustainable framework, generally, individual's concerns about 'market price', 'impact on sustainability' and 'recommendations of professionals' are high. Further, the first

two of those concerns have already been established for APC through this research. Hence, the integral sustainability of APC with respect to the UL quadrant has already been established satisfactorily.

4. Among the aspects considered from the LL quadrant of the integral sustainable framework, generally social concerns about 'market price' and 'recommendation of professionals' are high, and the first one met for APC as described above. However, the lower social concerns about the impact on sustainability is unfavourable for APC to be get established as an integrally sustainable cement. Hence, the integral sustainability of APC with respect to the LL quadrant can be described as moderately satisfactory.

<u>The conclusions drawn from octa-octant framework are:</u>

1. When objective properties of APC are considered, it is seen that the important aspects such as cost per unit weight, strength, water absorption, carbonation and CO_2 released per unit weight show less variability, confirming the certainty of those properties; however, embodied energy per unit weight and resistance to sulphuric attack show greater variability. Accordingly, the integral sustainability of APC with respect to objective aspects has already been secured with a relatively high stability.

2. When inter-objective properties of APC are considered, all aspects, namely environmental impact due to CO_2 released per unit volume per unit strength, cost per unit volume per unit strength and embodied energy per unit volume per unit strength show high variability, confirming the uncertainty of those properties. Accordingly, the integral sustainability of APC with respect to inter-objective aspects is unstable, and steps need to be taken to focus on and market a particular formulation of APC. This will reduce the uncertainty.

3. When individuals' four-quadrant concerns regarding APC are considered, it is seen that important concerns such as 'market price', 'impact on sustainability of earth' and 'quality standards' are held fairly certainly by individuals, but not about 'mitigating land pollution', 'feel good factor', 'non-familiarity', 'social trends' and

'recommendation of professionals'. Accordingly, the integral sustainability of APC with respect to subjective aspects is moderately stable.

4. When society's four-quadrant concerns regarding APC are considered, it is seen that the most important concerns, namely 'market price', 'impact on sustainability of earth', 'mitigating land pollution' and 'non-familiarity' are held fairly certainly by the societies, but not 'quality standard', 'recommendation of professionals', 'feel good factor' and 'social trends'. Accordingly, the integral sustainability of APC with respect to inter-subjective aspects is moderately stable.

5. The above findings can be summarised as below:

Aspects	**Integral Sustainability**	**Stability of Sustainability**
Objective	Moderately satisfactory	High stability
Inter-objective	Highly satisfactory	Low stability
Subjective	Satisfactory	Moderate stability
Inter-subjective	Moderately satisfactory	Moderate stability

11.1.2 Overall Research Summary and Conclusions

The main aim of this research was 'to investigate the development of Alkali Pozzolan Cement (APC) for integral sustainability'. Accordingly, first of all, an integral research framework was developed by combining positivist with non-positivist paradigms in order to research objective as well as subjective aspects related to APC. The experimental work was started with the basic APC mixture consisting of 70% fly ash and 30% lime. Two critical issues, namely, slow activation of fly ash and slow hardening process, were identified. The first issue was resolved by adding activating materials (5% Na2SO4) to the basic APC mixture and the second issue was overcome by adding a scaffolding material (30% OPC). This led to formulate the practical APC mixtures using different pozzolanic materials in different proportions comprising non-hazardous chemicals, which can be cured under normal conditions and stored as a dry powder.

Structural properties were investigated based on the compressive strength; while microstructural properties of mixtures were investigated using microstructural techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDS) and thermal analysis (TG, DTG, DTA and DSC). The results of APC mixtures were also compared with the results of High Volume Fly Ash (HVFA) cement and Ordinary Portland Cement (OPC) mixtures. In general, under air curing conditions, the 28-day strength of APC mixtures are over 85% higher than that of HVFA mixtures, and only around 25% less than corresponding OPC mixtures. XRD, SEM, TG, DTG, DTA and DSC results confirmed the development of microstructure of APC. Accordingly, it can be concluded that when structural and microstructural development are considered, APC is a better alternative to OPC than HVFA.

The durability properties of APC were investigated using several important durability tests, namely, water absorption, acid attack, chloride ion penetration and carbonation; moreover, the durability properties of APC were compared with those of HVFA cement and OPC mixtures. Resistance to water absorption and carbonation of APC were greater than those of HVFA but less than OPC, while resistance to sulphuric acid attack and chloride ion penetration were greater than those of OPC but less than HVFA. Accordingly, it can be concluded that APC secures a median position regarding the above durability properties, and is arguably a more versatile option than OPC or HVFA.

Ecological costs of mixtures were computed based on energy requirement to produce cementitious mixtures and CO_2 emission during production of mixtures. Financial costs were computed based on the cost of producing the mixtures. APC mixtures were compared with HVFA with reference to OPC, based on two criteria. The first criteria was based on unit weight of dry cement powder, and the second was based on the unit volume per unit strength of hydrated cement. According to the first and second criteria, energy requirements of APC were 57% and 72% of OPC respectively; CO_2 emissions associated with APC were 48% and 60% of OPC respectively; financial costs of APC are 66% and 84% of OPC respectively. The HVFA mixtures show better performance than the APC ones for embodied energy, CO_2 emission and financial cost when considering a ‘per unit weight’ basis, but the APC ones perform better in all three when considering a 'per unit volume per unit strength' basis. Accordingly, it can be concluded that, when cost per unit volume per unit strength is considered, both the ecological and financial costs of APC are much less than those of OPC and HVFA.

Individual and social concerns regarding different aspects of APC related to integral sustainability were investigated in three different contexts, namely, Australia, America and Sri Lanka, using a questionnaire. Responses to closed-ended and open-ended questions were analysed using fuzzy sets and 'grounded theory' techniques respectively. Generally, it appears that there is a strong possibility that APC will be accepted as an integral sustainable cement by individuals and societies in all three contexts, even though there were some minor variances due to contextual differences in those countries.

Finally, the degree of integral sustainability of APC and aspects to be improved to enhance/maintain the stability of integral sustainability of APC were investigated with the aid of two frameworks developed in the research, namely the modified two-dimensional tetra-quadrant framework and the three-dimensional octa-octant framework. The two-dimensional framework confirmed that aspects related to the four quadrants of integral sustainable framework of APC were satisfactory, with inter-objective aspects such as ecological sustainability being highly satisfactory. The three-dimensional octa-octant framework indicated that the integral sustainability of APC is relatively stable; in particular, objective aspects such as strength and durability properties exhibit high stability. Overall, findings indicate that there is a strong possibility that APC will emerge as an integrally sustainable cement.

11.2 Originality of the Research

1. Integral research paradigm

   The integral research paradigm developed in this research is suitable for integrated research projects combining both positivist aspects (such as engineering) and non-positivist aspects (such as sociology, psychology, philosophy).

2. Dry powder form of alternative cement

Alkali Pozzolan Cement (APC) which is developed in this research is an alternative cement that utilises a higher percentage of fly ash. The distinctive characteristic of APC is that it is not constituted of hazardous chemicals, can be cured under ambient conditions, and can be stored as a dry powder.

3. Conceptualization of APC behaviour

The strength development of APC was conceptualized as assisted by activation and scaffolding, their significance estimated, and corroborated with strength and microstructural investigations. This conceptualization can serve as a framework for future research in hybrid cements.

4. Recognition of ‘collective’ and ‘collection’ forms of ‘I’

Linguistically and logically, the pronoun ‘I’ indicates a singular individual form. However, the pronoun ‘we’ is different and complex. Linguistically, the pronoun ‘we’ is considered as ‘collection of the individuals’; hence, linguistically the pronoun ‘we’ is plural. However, logically, the pronoun ‘we’ is a ‘collective form of individuals’ and it reflects one singular collective group; hence, logically the pronoun ‘we’ is not plural but singular. Differentiation between ‘collection’ and ‘collective’, and recognition of two forms of ‘I’, namely ‘collective’ and ‘collection’ forms of ‘I’, unveil new perspectives of issues.

5. Modified Integral Frameworks

The three-dimensional octa-octant framework proposed in this research incorporates a certainty-uncertainty axis in addition to the subject-objective and individual-collective one and opens up a new dimension for assessing the integral sustainability of products and services.

6. Integrated method of fuzzy sets and grounded theory techniques

In this research, fuzzy sets and grounded theory techniques were employed as complementary methods in analysing responses to closed-ended and open-ended questions, respectively. This integrated method is useful for investigating perceptions of products and services.

7. Accounting for uncertainty

The appreciation of uncertainty in both objective and subjective aspects is given prominence in the overall assessment of integral sustainability. Diverse ways of reducing uncertainty are also recognized, such as more comprehensive testing for objective aspects and better marketing or quality certification for subjective aspects.

11.3 Recommendations for Future Research

During this research, a number of research questions arose. However, they were not addressed in detail as they were beyond the scope of this research. However, those questions generate new areas to be researched. The recommendations for future research are to:

1. Investigate whether the concept of Alkali Pozzolan Cement (APC) can be extended to other pozzolanic materials such as agricultural ash (such as rise husk ash and sugar cane ash), natural ash (such as volcanic ash) and other industrial ashes (such as silica fume and red mud). If this is successful, APC can be produced in agricultural countries as well as in countries that have natural pozzolan, and therefore minimise the use of OPC globally.

2. Determine the effect of using pure quicklime instead of commercially available lime, which has been derived from quicklime via a grinding and slaking process. As quicklime is more reactive than commercially available lime, it may be more favourable for pozzolanic reaction. Further, the heat generated due to the reaction of quicklime with water can accelerate the pozzolanic reaction.

3. Investigate the feasibility of using Na_2SO_4 rich soluble minerals (such as thenardite and mirabilite) instead of the chemical form of Na_2SO_4 as the activating material in the production of APC. If this is successful, those minerals can be used whenever the Na_2SO_4 obtained from by-products of chemical industries is inadequate.

4. Investigate the feasibility of using non-hazardous Na_2CO_3 (which also reacts with $Ca(OH)_2$ to produce NaOH within the mixture) as an activating chemical instead of Na_2SO_4. That would reduce the $CaSO_4$ formed within the hydrated mixture, which is an advantage when it comes to durability properties such as resistance to sulphuric acid attack. Further, $CaCO_3$ formed within the hydrated mixture acts only as a filler without any adverse effect.

5. Investigate and assess the effect of pre-heat treatment on basic APC powder. Glass phases of fly ash are broken and activated when heated. Hence, if a mixture of lime and fly ash is heated, lime and fly ash would react and could produce a dry cementitious compound that would harden when water is added. If this is successful, activating materials and scaffolding materials might not be needed or might be needed in lesser quantities.

6. Identify the other aspects related to properties of cement, which have not been investigated in this research, and to search for a formula for APC compromising its properties, ecological impact and cost. Such complementary investigations are extremely useful for the completeness of the research.

7. Conduct a comprehensive investigation of the integral sustainability of the optimum APC mixture determined from the above, taking more objective properties and more individual and social concerns into account. Such an investigation would help to develop APC for integral sustainability more realistically.

8. Determine the possibility of commercially manufacturing APC by utilising the findings of all the above. The process may include the use of quicklime instead of commercially available lime and also the use of clinker instead of OPC as a scaffolding material. In addition, the activated APC mixture may be mixed with hot clinker (before cooling it down) to obtain the advantage of heat to break glass phases and activate fly ash.

9. Extend the research on ‘APC binding system’ into ‘APC mortar’ and ‘APC concrete’ systems of different mix-proportions with and without chemical

admixtures; to investigate their structural and microstructural properties; durability properties; and especially their workability for practical use.

10. Modify the integral framework appropriately to accommodate new developments in the discourse of reality which states that 'reality emerges as a result of the interaction of subject and object'. Recognition of this new reality might open a totally new window for the research and development of products such as APC.

11. Investigate the application of the newly developed three-dimensional octa-octant framework by defining conceptual-functional dichotomy as the third dimension to generate different means of achieving desired functional properties by upgrading the conceptualisation of APC.

"Research is what I'm doing when I don't know what I'm doing".
Wernher Von Braun
(Winner of National Medal of Science USA in 1975)

"If we knew what it was we were doing, it would not be called research, would it?"
Albert Einstein
(Winner of Nobel Prize for Physics in 1921)

APPENDICES

Appendix A1

A1 Thermal Analysis

Information given in Appendix A1 is related to 'Thermal Analysis' in Chapter 4. Thermo Gravimetric graphs (TG graphs), Derivative Thermo Gravimetric graphs (DTG graphs), Differential Thermal Analysis graphs (DTA graphs) and Differential Scanning Calorimeter graphs (DSC graphs) of hydrated samples of different cementitious mixtures are presented in Appendix A1. In addition, determination of percentage weight losses with respect to dry weights is demonstrated.

A1.1 Determination of Percentage Weight Losses

As described in Section 4.5.6.1 of Chapter 4, the following temperature ranges were considered to compute percentage weight losses of samples.

30 - 105 °C : Desorption
105 - 420 °C : Dehydration
420 - 550 °C : Dehydroxylation
550 - 1007°C : Decarbonation

Percentage weight losses indicated in TG graphs in Section A1.2 of this Appendix are associated with non-dry hydrated cement samples. Hence, percentages with respect to dry samples have to be determined as demonstrated below.

Specimen Calculations

Consider the TG-DTG graph of APC Mixture M3 at 3 days given in **Fig. A1.1** of this Appendix. The percentage weight losses are indicated on the TG curve. They are,

between 30 - 105 °C = 10.520 %
between 105 - 420 °C = 5.327%
between 420 - 550 °C = 2.570%
between 550 - 1007°C = 3.424%

(Note that, above percentages are associated with non-dry sample of M3)

It is assumed that the free water in the sample get completely removed by 105 °C. Hence the weight of the dry sample can be calculated by deducting the weight of free-water.

Percentage weight loss between 30-105 °C = 10.52%

Take weight of non-dry sample as 100 g
Then weight loss between 30-105 °C = 10.52 g
Hence, weight of free water in the sample = 10.52 g
Therefore, weight of dry sample = 100 g - 10.52 g = 89.48 g

Based on the 'dry weight', percentage weight losses are calculated. They are,

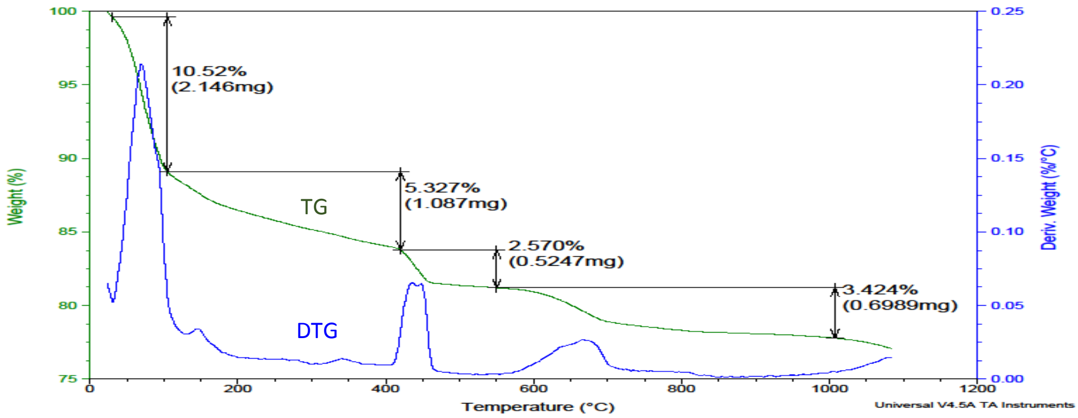
between 30 - 105 °C = (10.520/89.48)x100 % = 11.756%
between 105 - 420 °C = (5.327/89.48)x100 % = 5.953%
between 420 - 550 °C = (2.570/89.48)x100 % = 2.872%
between 550 - 1007°C = (3.424/89.48)x100 % = 3.827%

Similarly, percentage weight losses with respect to dry weights of all samples are calculated and they are tabulated in **Table 4.5** in Chapter 4.

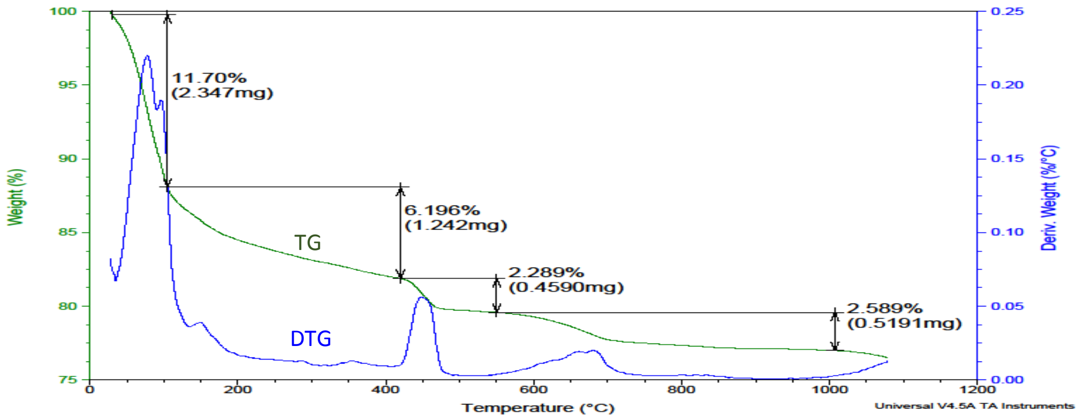
A1.2 TG-DTG graphs

A1.2.1 TG-DTG graph of APC Mixture M3

TG-DTG: M3-3day



TG-DTG: M3-28day



TG-DTG: M3-112day

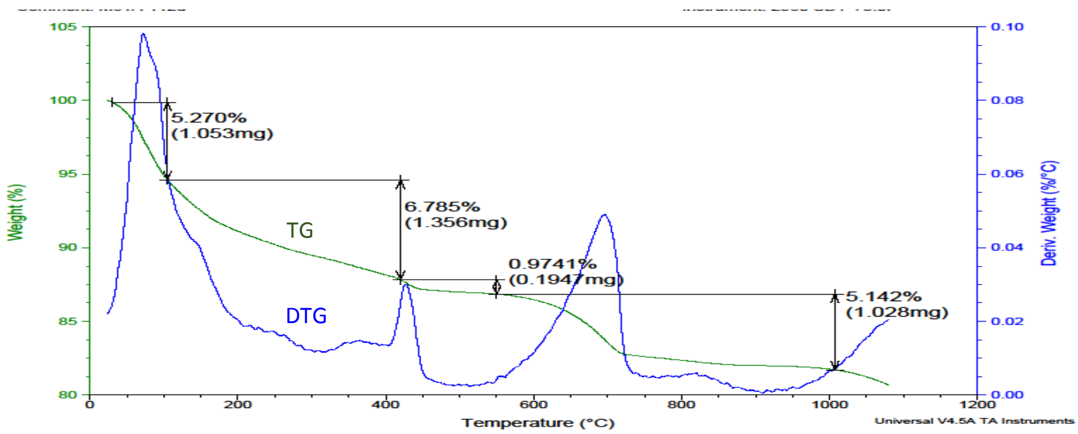
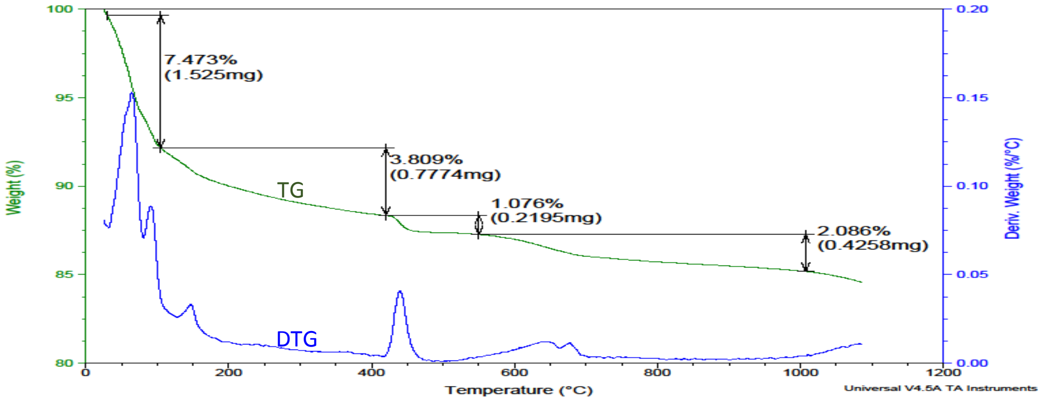


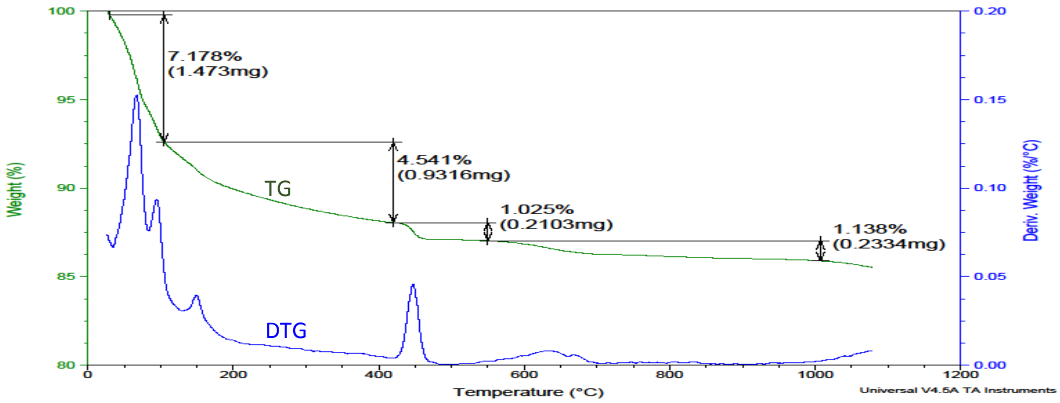
Fig. A1.1 TG-DTG graphs for APC Mixture M3 at 3, 28 and 112 days

A1.2.2 TG-DTG graphs of HVFA Mixture C3

TG-DTG: C3-3day



TG-DTG: C3-28day



TG-DTG: C3-112day

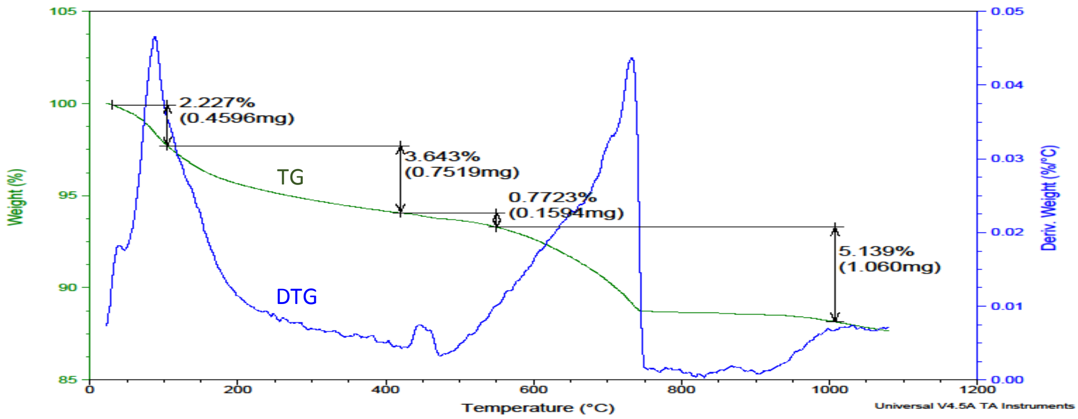


Fig. A1.2 TG-DTG graphs for HVFA Mixture C3 at 3, 28 and 112 days

A1.2.3 TG-DTG graphs of OPC Mixture R3

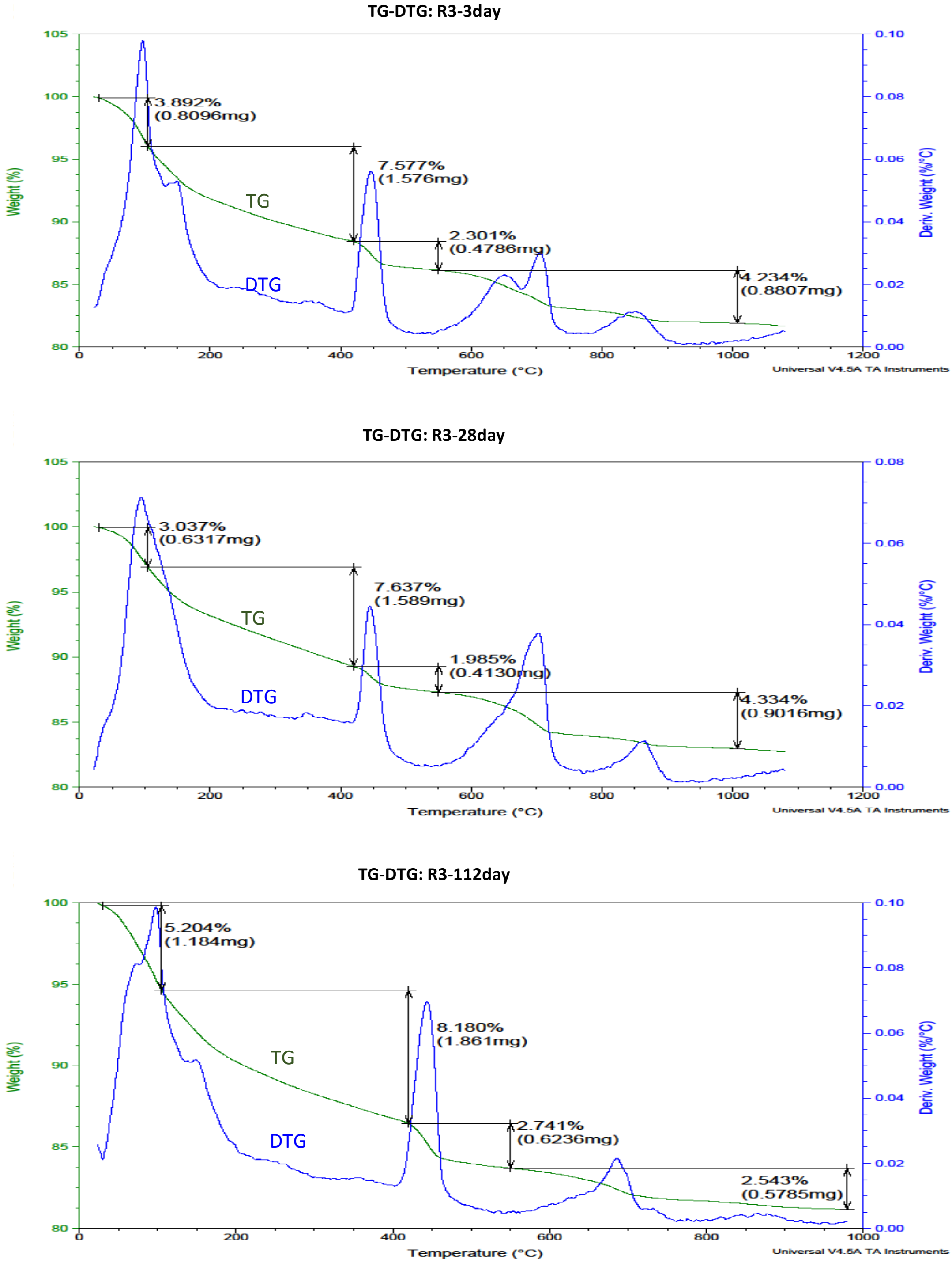


Fig A1.3 TG-DTG graphs for OPC Mixture R3 at 3, 28 and 112 days

A1.2.4 TG-DTG graphs of APC Mixture M4

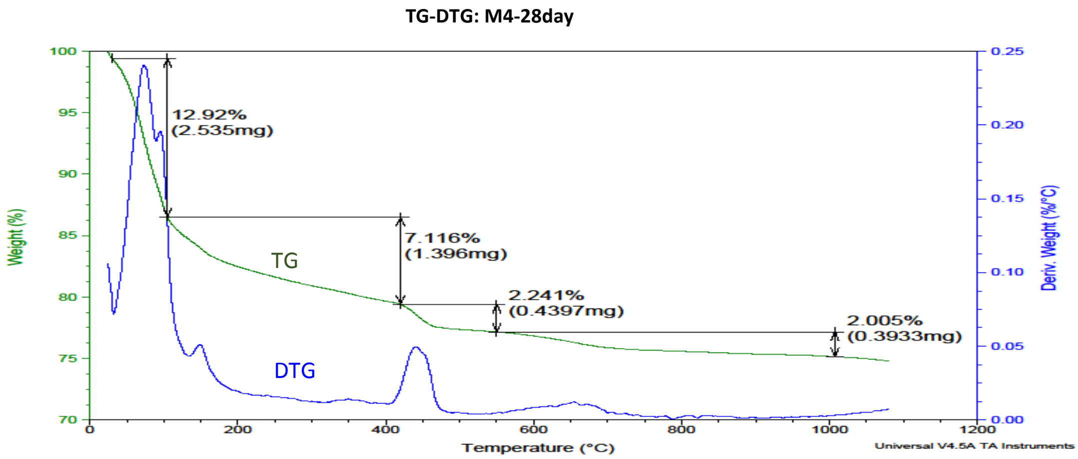


Fig. A1.4 TG-DTG graphs for APC Mixture M4 at 28 days.

A1.2.5 TG-DTG graphs of APC Mixture L3

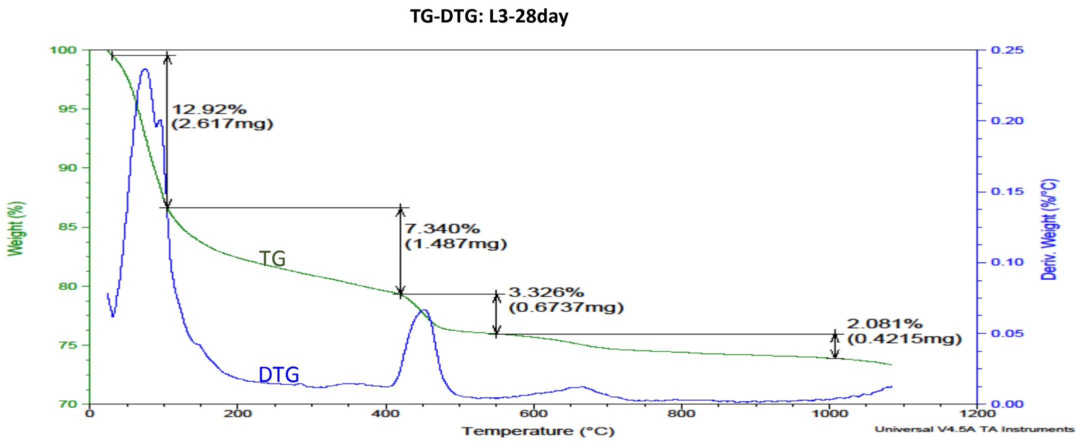


Fig. A1.5 TG-DTG graphs for APC Mixture L3 at 28 days.

A1.2.6 TG-DTG graphs of APC Mixture N3

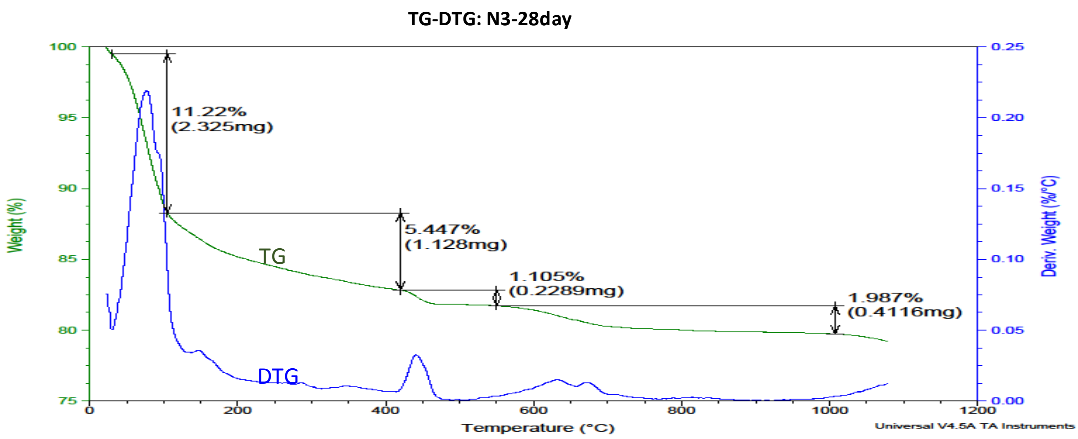


Fig. A1.6 TG-DTG graphs for APC Mixture N3 at 28 days.

A1.3 TG-DTA graphs

A1.3.1 TG-DTA graphs of APC Mixture M3

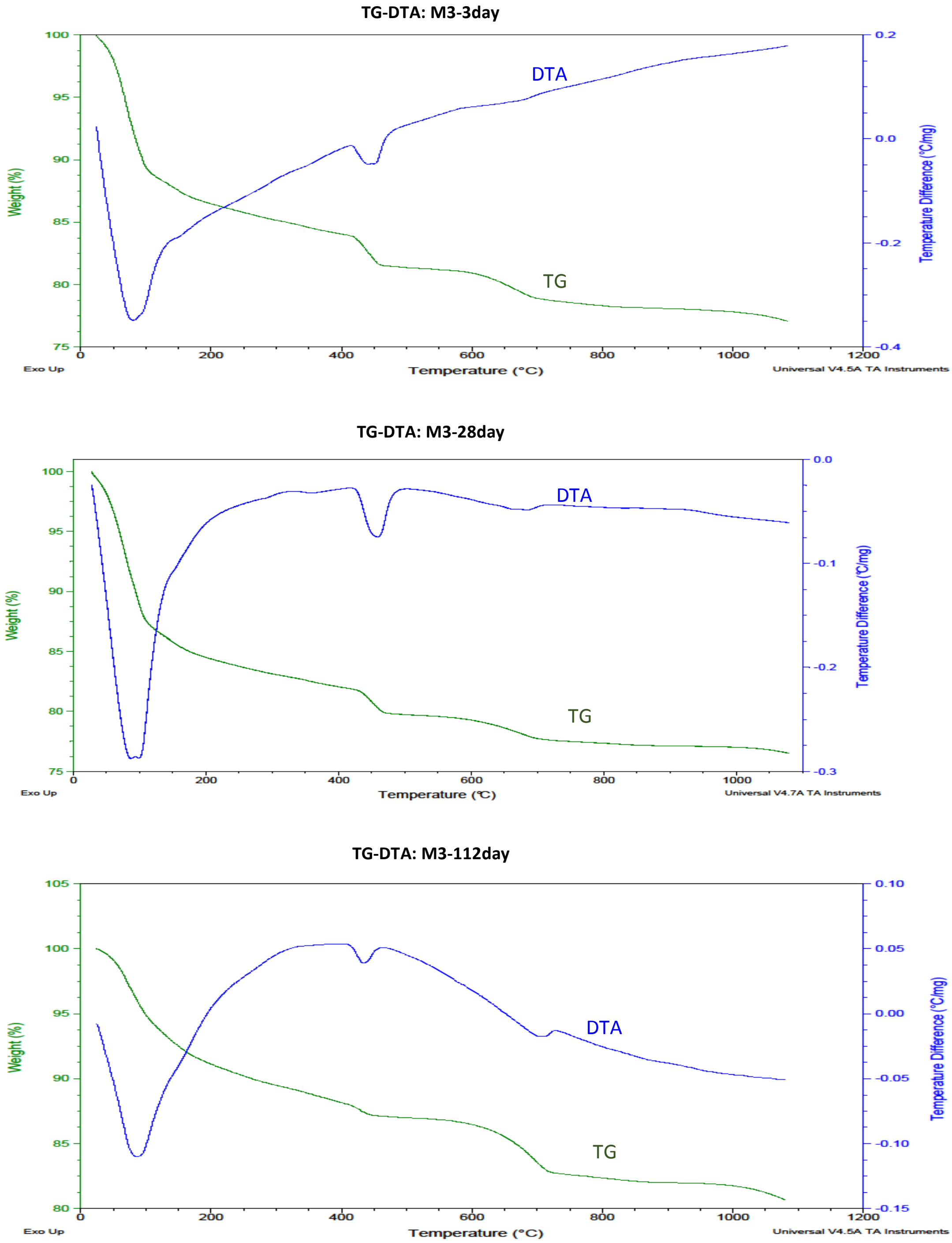
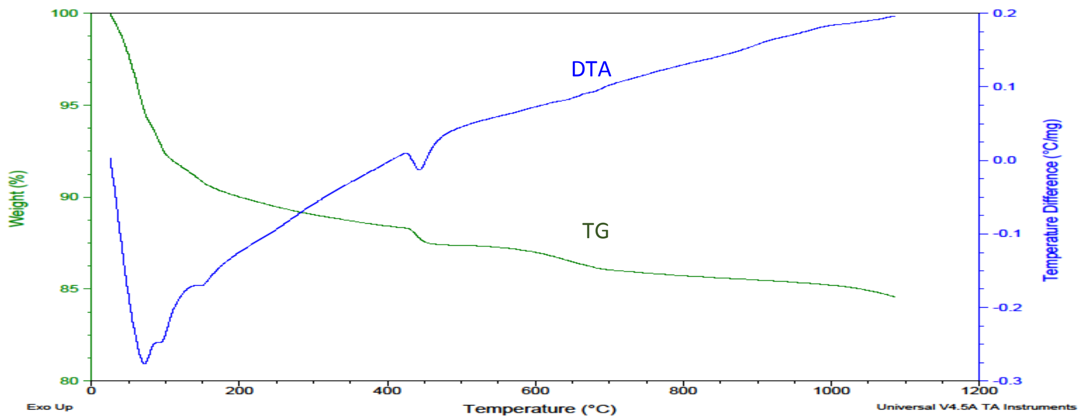


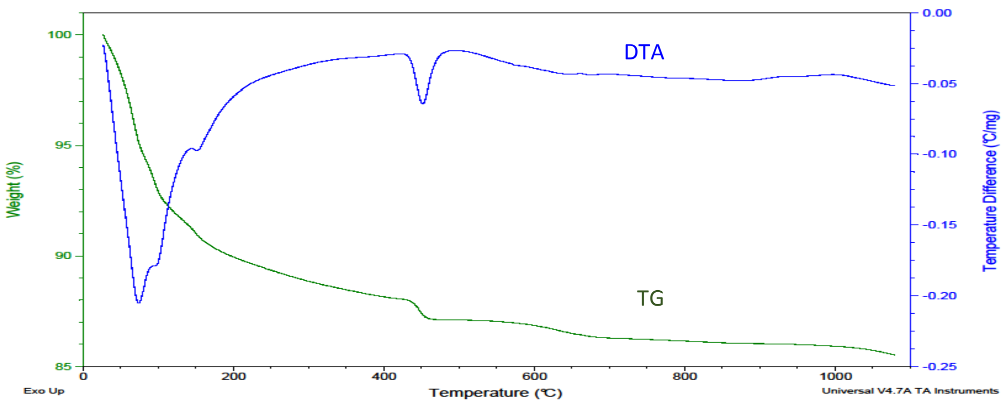
Fig. A1.7 TG-DTA curves of APC mixture M3

A1.3.2 TG-DTA graphs of HVFA Mixture C3

TG-DTA: C3-3day



TG-DTA: C3-28day



TG-DTA: C3-112day

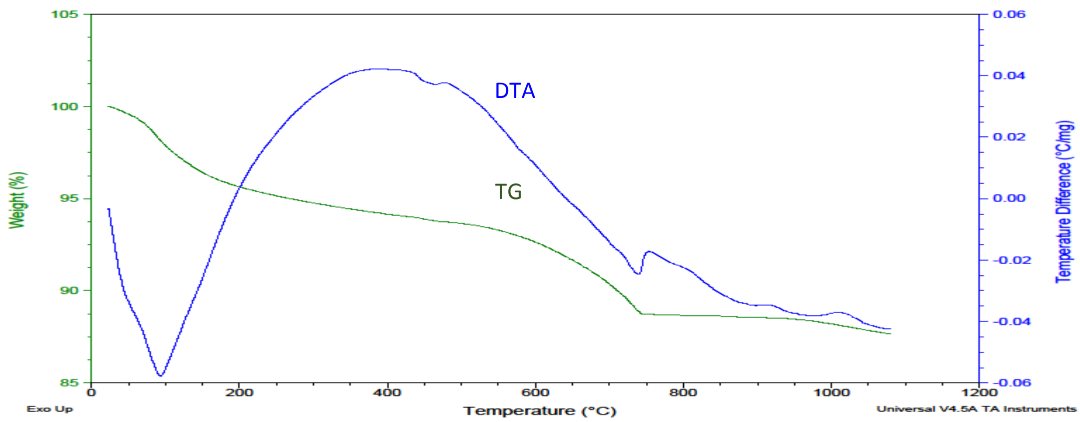
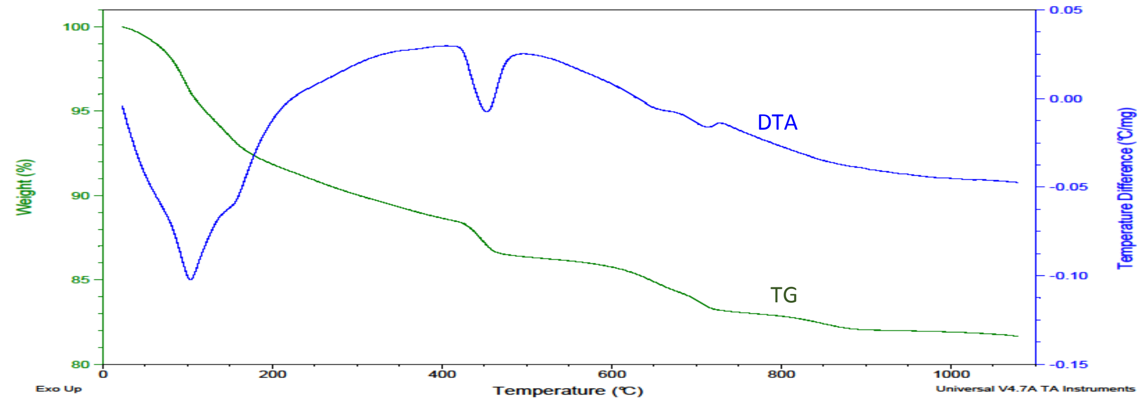


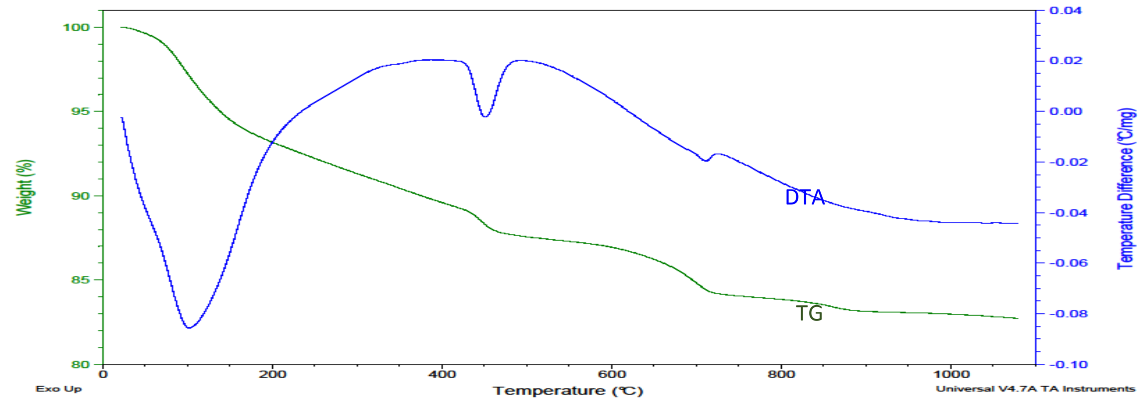
Fig. A1.8 TG-DTA curves of HVFA mixture C3

A1.3.3 TG-DTA graphs of OPC Mixture R3

TG-DTA: R3-3day



TG-DTA: R3-28day



TG-DTA: R3-112day

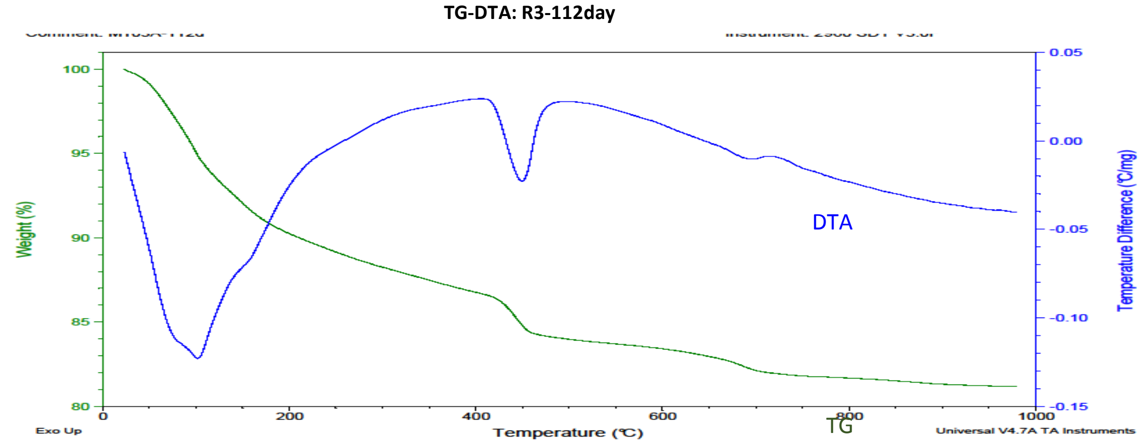


Fig. A1.9 TG-DTA curves of OPC mixture R3

A1.3.4 TG-DTA graphs of APC Mixture M4

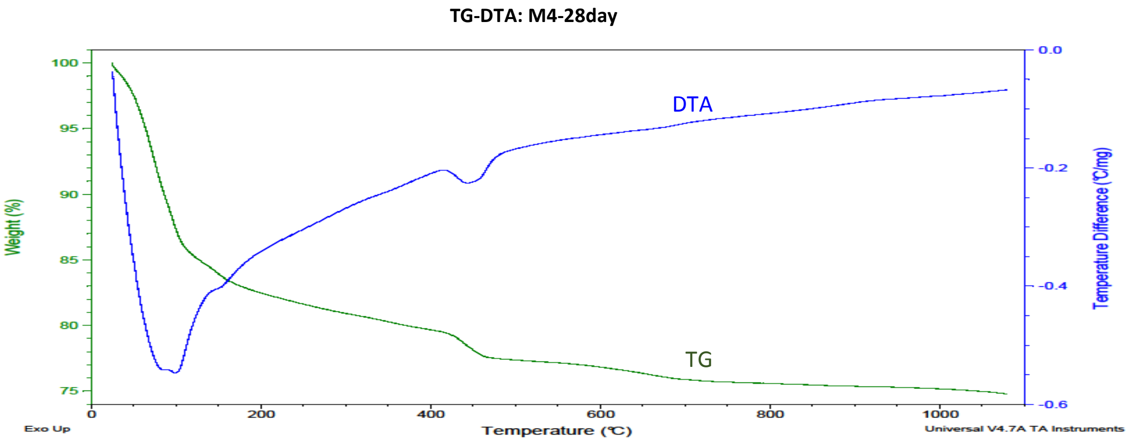


Fig. A1.10 TG-DTA curves of APC mixture M4

A1.3.5 TG-DTA graphs of APC Mixture L3

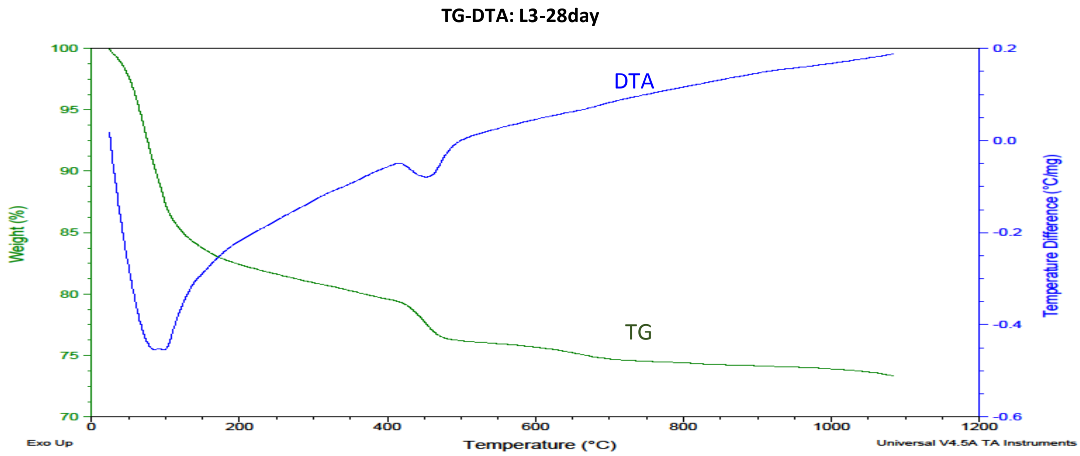


Fig. A1.11 TG-DTA curves of APC mixture L3

A1.3.6 TG-DTA graphs of APC Mixture N3

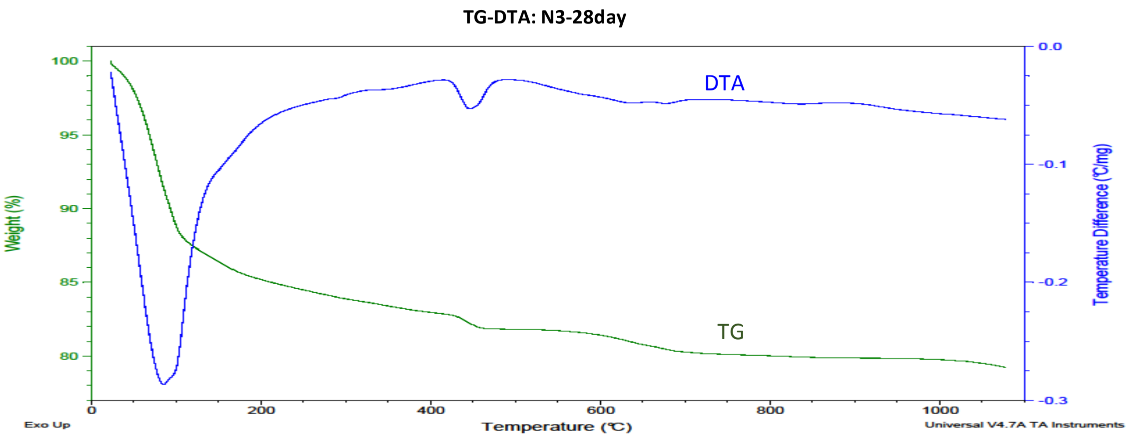
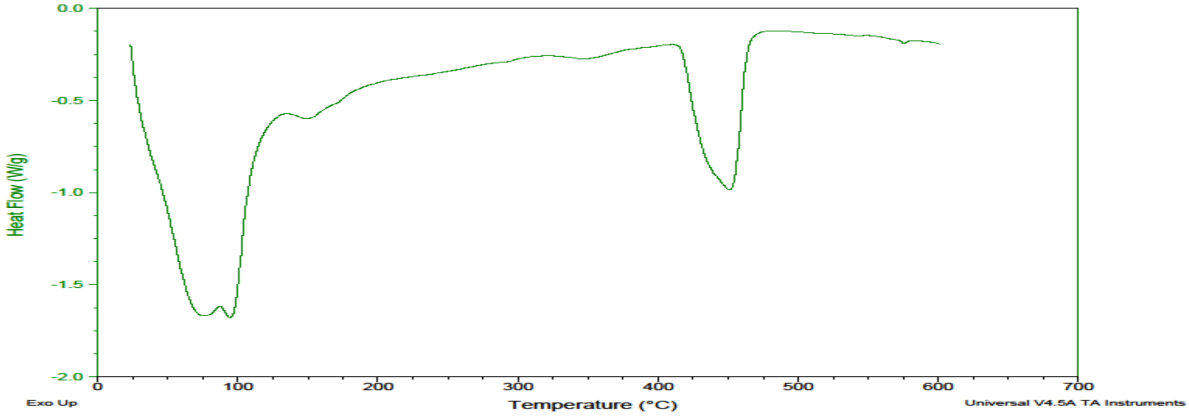


Fig. A1.12 TG-DTA curves of APC mixture N3

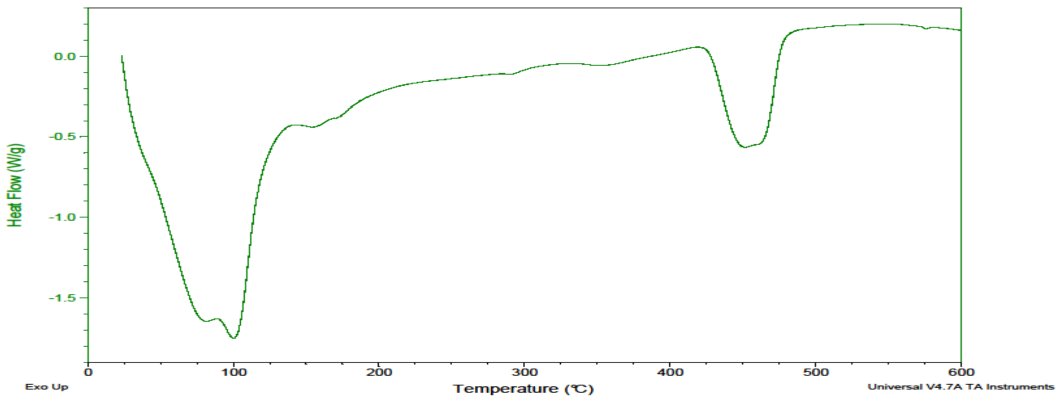
A1.4 DSC graphs

A1.4.1 DSC graphs of APC Mixture M3

DSC: M3-3day



DSC: M3-28day



DSC: M3-112day

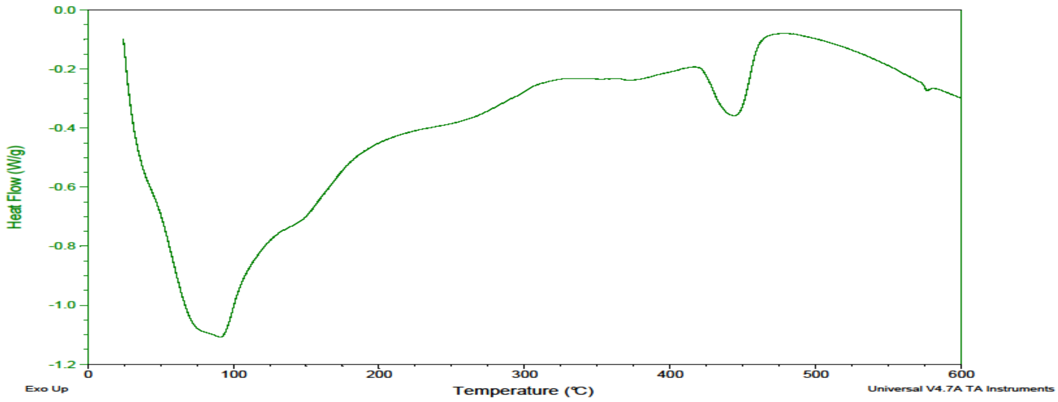


Fig. A1.13 DSC curves of APC mixture M3

A1.4.2 DSC graphs of HVFA Mixture C3

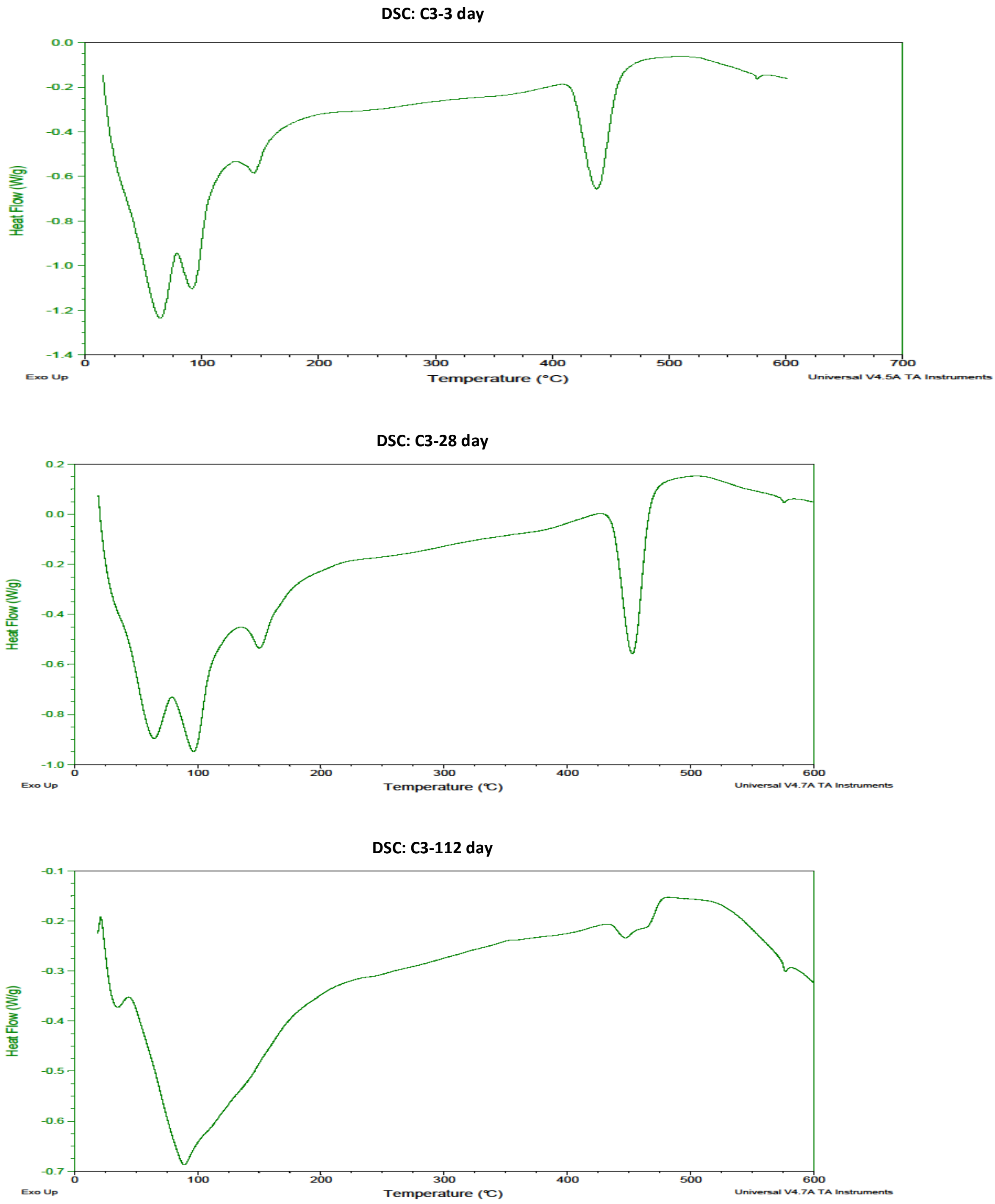


Fig. A1.14 DSC curves of HVFA mixture C3

A1.4.3 DSC graphs of OPC Mixture R3

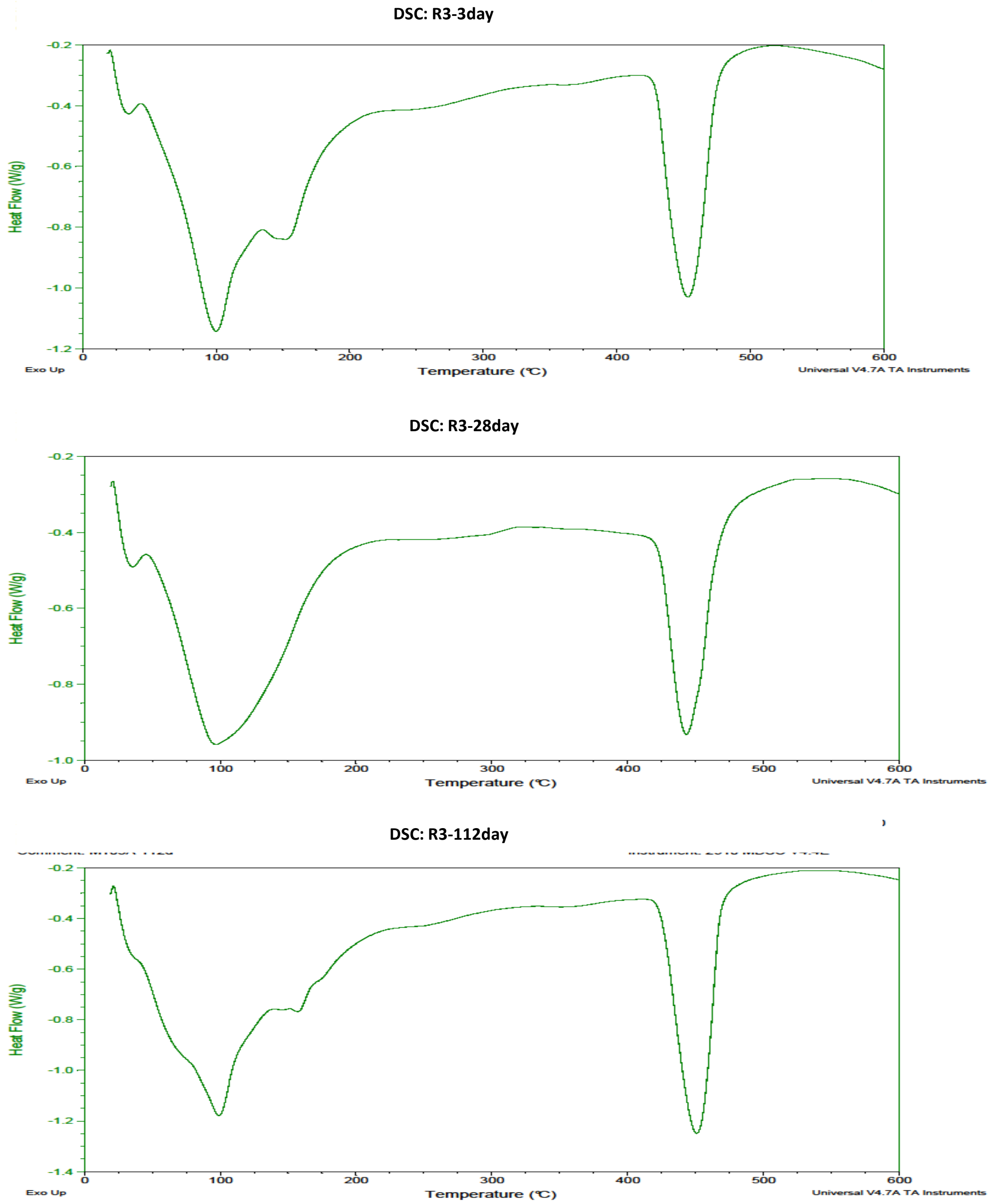


Fig. A1.15 DSC curves of OPC mixture R3

A1.4.4 DSC graphs of APC Mixture M4

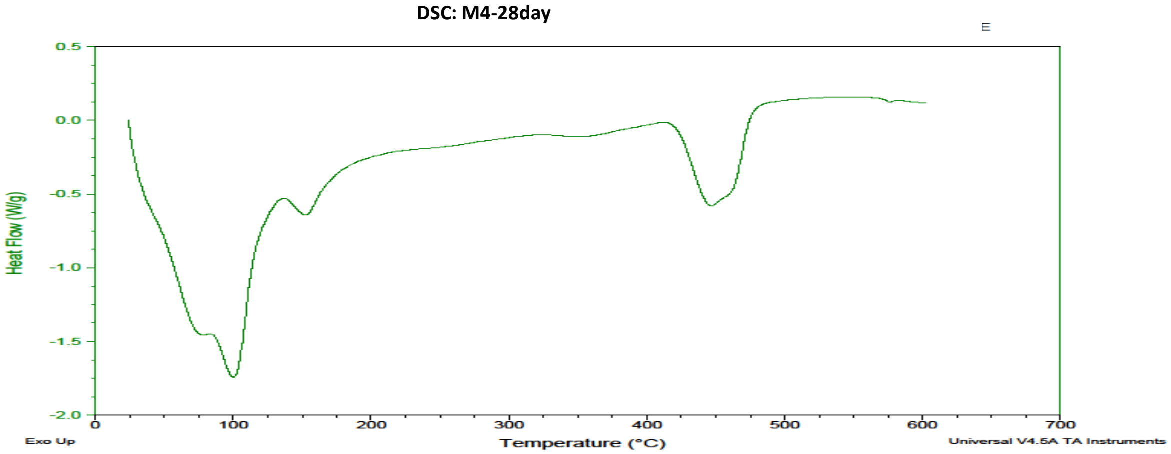


Fig. A1.16 DSC curves of APC mixture M4

A1.4.5 DSC graphs of APC Mixture L3

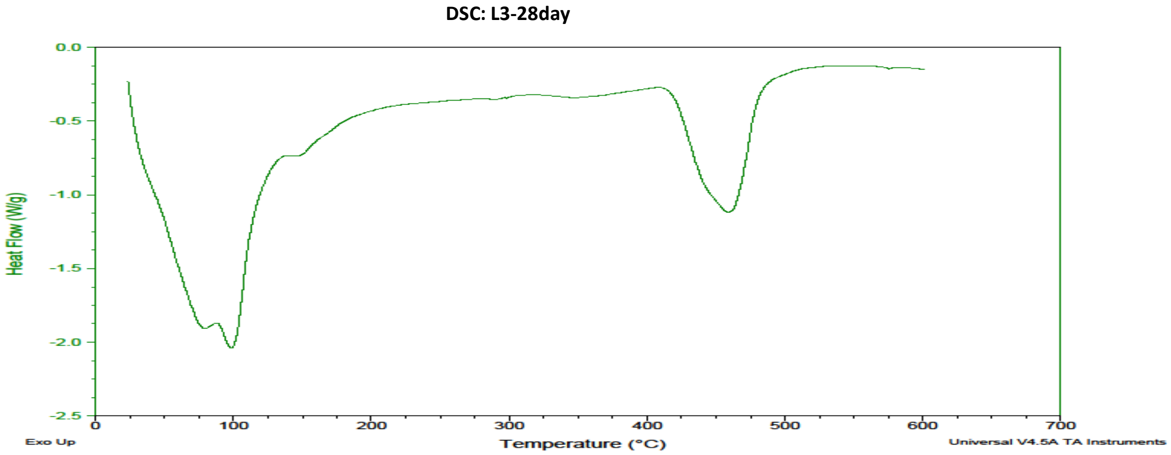


Fig. A1.17 DSC curves of APC mixture L3

A1.4.6 DSC graphs of APC Mixture N3

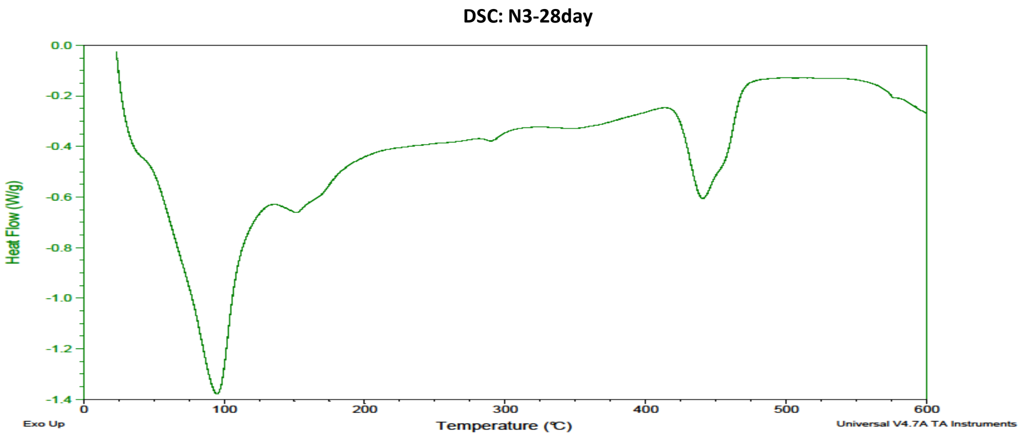


Fig. A1.18 DSC curves of APC mixture N3

Appendix A2

A2 Volumes of hydrated pastes

Information given in Appendix A2 is related to Chapter 6. Volumes of hydrated pastes were experimentally determined by preparing different mixtures according to given w/c ratios and measuring their volumes; they are given in below.

Mix No	Description			Vol of paste per 1 kg of cement (m^3/kg)
	Composition of Dry Mixture	Type of pozzolan	w/c	
L3	70%[95%APC60+5%Na_2SO_4]+30%OPC	fly ash	0.3	6.25E-04
L4	70%[95%APC60+5%Na_2SO_4]+30%OPC	fly ash	0.4	7.00E-04
M3	70%[95%APC70+5%Na_2SO_4]+30%OPC	fly ash	0.3	6.00E-04
M4	70%[95%APC70+5%Na_2SO_4]+30%OPC	fly ash	0.4	6.75E-04
N3	70%[95%APC80+5%Na_2SO_4]+30%OPC	fly ash	0.3	6.00E-04
N4	70%[95%APC80+5%Na_2SO_4]+30%OPC	fly ash	0.4	6.75E-04
P3	70%[95%APC70+5%Na_2SO_4]+30%OPC	slag	0.3	6.25E-04
C3	70%[100%APC100]+30%OPC	fly ash	0.3	5.75E-04
C4	70%[100%APC100]+30%OPC	fly ash	0.4	6.50E-04
R3	100%OPC	none	0.3	5.75E-04
R4	100%OPC	none	0.4	6.50E-04
KEY : APCr = r% Fly Ash + (100-r)%Lime				

Appendix A3

A3 Questionnaire

Curtin University

Questionnaire on 'Alkali Pozzolan Cement' (APC)

Department of Civil Engineering, Curtin University, Australia

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DEMOGRAPHIC DATA

1. Information about the location in which you presently live:

(a) Country : ……………………………………………………………………

(b) State / Province : ……………………………………..………………………

(c) How long have you been living in this country? (*Please underline*)

Less than 1 year
Between 1 and 5 years
More than 5 years

2. Your occupation : …………………………….…………………………………....

(a) Is your occupation related to the building industry?

Yes → Go to section (b) of this question

No → Go to next question (Question No. 3 of Demographic Data)

(**b**) If your occupation is related to the building industry, what describes your occupation best?

Architect
Civil Engineer
Quantity Surveyor
Property Developer / Builder
Real Estate Agent /Seller
Other (please write)……………………………………………………….…………………

3. How would you describe your level of concern about issues related to the environment and the sustainability of planet earth?

(Please indicate your response by putting a cross (X) in the relevant cell. Please note that the 'central' category 'medium' has been divided into 'medium low' and 'medium high).

Very Low	Low	Medium		High	Very High
		Med Low	Med High		

Please proceed to next page →

SUBJECT RELATED QUESTIONS

<u>Please read this before responding to questions:</u>

The purpose of this questionnaire is to investigate how people consider different aspects when they are introduced to an unknown new cement. For this purpose, we have selected a relatively unknown new cement called 'Alkali Pozzolan Cement' (APC) which is still at the research stage.

In this questionnaire, question numbers 1-9 have the same format - an 'introductory statement' and two sub-sections, namely (a) and (b).

- The 'introductory statement' of each question presents aspects related to 'Alkali Pozzolan Cement' (APC).
- In section (a), we ask you to indicate the degree of importance that **<u>you</u>** would assign to the given aspect in selecting the new cement over the conventional cement, if you were to build your own house.
- In section (b), we ask you to indicate the degree of importance that you think **<u>the society you presently live in</u>** would assign to the given aspect in selecting the new cement, over conventional cement, in order to build houses.
- Please indicate your responses by putting a cross (X) in the relevant cell in the mini-tables given in each section. Please note that the 'central' category 'medium' has been divided into 'medium low' and 'medium high'.

SECTION 1

In responding to the questions 1 to 8, please consider **<u>only the aspect given</u>** in that question.

Q 1: Aspect - Market Price

Assume the new cement (APC) is significantly cheaper than conventional cement because of its lower production cost (say 30% cheaper than conventional cement).

(a). What degree of importance would **<u>you</u>** assign to the above aspect in selecting the new cement over the conventional cement, if you were to build your own house?

Very Low	Low	Medium		High	Very High
		Med Low	Med High		

(b). In your view, what degree of importance do you think **<u>the society you presently live in</u>** would assign to the above aspect in selecting the new cement, over conventional cement, in order to build houses?

Very Low	Low	Medium		High	Very High
		Med Low	Med High		

Q 2: Aspect – Quality Standards

Assume that strength and durability properties of the new cement (APC) conforms to required standards.

(a). What degree of importance would **you** assign to the above aspect in selecting the new cement over the conventional cement, if you were to build your own house?

Very Low	Low	Medium		High	Very High
		Med Low	Med High		

(b). In your view, what degree of importance do you think **the society you presently live in** would assign to the above aspect in selecting the new cement, over conventional cement, in order to build houses?

Very Low	Low	Medium		High	Very High
		Med Low	Med High		

Q 3 : Aspect - Impact on the Sustainability of the Earth

The new cement (APC) causes a less adverse impact on the sustainability of the earth since quantities of natural resources used are relatively less; also carbon dioxide released during the manufacturing process is relatively less. (say adverse impact is 30% less than conventional cement).

(a). What degree of importance would **you** assign to the above aspect in selecting the new cement over the conventional cement, if you were to build your own house?

Very Low	Low	Medium		High	Very High
		Med Low	Med High		

(b). In your view, what degree of importance do you think **the society you presently live in** would assign to the above aspect in selecting the new cement, over conventional cement, in order to build houses?

Very Low	Low	Medium		High	Very High
		Med Low	Med High		

Q 4 : Aspect - mitigating land pollution due to fly ash

The main raw material used in manufacturing the new cement is fly ash, which is a by-product of coal power stations. It is known that fly ash is dumped in vacant lands, and hence causes land pollution. Therefore, utilization of fly ash in manufacturing the new cement (APC) provides a solution to land pollution due to fly ash.

(a). What degree of importance would **you** assign to the above aspect in selecting the new cement over the conventional cement, if you were to build your own house?

Very Low	Low	Medium		High	Very High
		Med Low	Med High		

(b). In your view, what degree of importance do you think **the society you presently live in** would assign to the above aspect in selecting the new cement, over conventional cement, in order to build houses?

Very Low	Low	Medium		High	Very High
		Med Low	Med High		

Q 5 : Aspect – Non-familiarity

Conventional cement has been used in the building construction industry over decades, and hence it is a very familiar building material. However the new cement (APC) has not been introduced yet and hence it is a non-familiar cement. Some would not like to select certain materials, purely because they are not familiar with them.

(a). What degree of importance would **you** assign to the above aspect in selecting the new cement over the conventional cement, if you were to build your own house?

Very Low	Low	Medium		High	Very High
		Med Low	Med High		

(b). In your view, what degree of importance do you think **the society you presently live in** would assign to the above aspect in selecting the new cement, over conventional cement, in order to build houses?

Very Low	Low	Medium		High	Very High
		Med Low	Med High		

Q 6 : Aspect – "Feel good" factor

The new cement (APC) causes a less adverse impact on the environment and the sustainability of the earth than conventional cement. Hence using the new cement might give you a sense of satisfying an obligation towards the environment and future generations; in other words it may make you "feel good".

(a). What degree of importance would **you** assign to the above aspect in selecting the new cement over the conventional cement, if you were to build your own house?

Very Low	Low	Medium		High	Very High
		Med Low	Med High		

(b). In your view, what degree of importance do you think **the society you presently live in** would assign to the above aspect in selecting the new cement, over conventional cement, in order to build houses?

Very Low	Low	Medium		High	Very High
		Med Low	Med High		

Q 7 : Aspect – Social Trends

Assume that there is a social trend for using the new cement (APC) (maybe because it has a less adverse environmental impact)

(a). What degree of importance would **you** assign to the above aspect in selecting the new cement over the conventional cement, if you were to build your own house?

Very Low	Low	Medium		High	Very High
		Med Low	Med High		

(b). In your view, what degree of importance do you think **the society you presently live in** would assign to the above aspect in selecting the new cement, over conventional cement, in order to build houses?

Very Low	Low	Medium		High	Very High
		Med Low	Med High		

Q 8 : Aspect - Recommendations of Professionals

Assume that professionals in the building industry, such as architects and engineers recommend the use of new cement (APC) in place of conventional cement [because of its adverse impact on the environment and sustainability of the earth is less, and because it conforms to required quality standards].

(a). What degree of importance would **you** assign to the above aspect in selecting the new cement over the conventional cement, if you were to build your own house?

Very Low	Low	Medium		High	Very High
		Med Low	Med High		

(b). In your view, what degree of importance do you think **the society you presently live in** would assign to the above aspect in selecting the new cement, over conventional cement, in order to build houses?

Very Low	Low	Medium		High	Very High
		Med Low	Med High		

SECTION 2

In responding to question 9, please consider the **combined effect of all the aspects given above in questions 1 to 8**.

Q 9: Aspect – Overall Acceptability of the new cement

In real situations, in selecting a product, people do not consider related aspects separately, but rather consider related aspects as a whole, and decide the degree of acceptability of the product. Assume the acceptability of the new cement (APC) mainly depends on the related aspects mentioned in questions 1 to 8 above, which are summarized below.

1. Lower market price of new cement
2. Conforming to required quality standards
3. Less adverse impact on the sustainability of the earth
4. Use of fly ash (industrial by-product), as a raw material provides solution to land pollution
5. 'Non-familiarity' with the new cement
6. "Feel good" factor arising from using the new cement
7. Social trends for using new cement
8. Recommendations of Professionals for using new cement

(a). Having become aware about the above aspects, what are the chances that **you** will accept the new cement over the conventional cement, if you were to build your own house ?

Very Low	Low	Medium		High	Very High
		Med Low	Med High		

(b). In your view, what are the chances that **the society you presently live in** will accept the new cement over the conventional cement to build houses?

Very Low	Low	Medium		High	Very High
		Med Low	Med High		

SECTION 3

Q 10 : Additional Information

If you are happy to describe the reasons for selecting the above responses **or** if you wish to express any other views, please indicate them below. Attach more sheets if the space provided is insufficient.

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Thank you for spending your valuable time to complete this questionnaire.

Appendix A4

A4 Determination of Degrees of Identity (DoIs)

Information given in Appendix A4 is related to Chapter 9. The theoretical background and method of computing DoIs were described in detail in Section 9.4.1.1.

The complete fuzzy set F is defined by the general equation,

$F = [x_i, \mu_F(x_i) \mid x_i = x_1 \ldots x_n]$

where $\mu_F(x_i)$ is the support allocated to x_i in F; this indicates the degree to which x_i belong to F.

Six fuzzy sets have been defined to cover the linguistic range VL to VH. A particular curve can be denoted by F_r. Then the Degree of Identity (DoI) of the mean response with a selected fuzzy curve F_r is defined as,

$DoI(M, F_r) = |M \cap F_r| / |F_r|$ where M = Mean responses, F_r = Fuzzy curve considered

Here,

$M \cap F_r = [x_i, \min(\mu_F(x_i), \mu_M(x_i))]$

$|F_r| = \sum \mu_F(x_i), x_i = x_1 \ldots x_n$

$|M \cap F_r| = \sum \min(\mu_F(x_i), \mu_M(x_i)), x_i = x_1 \ldots x_n$

Here the operator || represents the relevant area of the fuzzy set.

In all cases we will have, $0 \leq DoI(M, F_r) \leq 1$

<u>Specimen Calculation</u>

Consider the responses obtained for Q5(a) of the questionnaire from the group of 'Australian Technologists'.

Firstly, each response is presented as a fuzzy curve. For example, if a particular participant had responded as 'High' for Q5(a), it is presented as below.

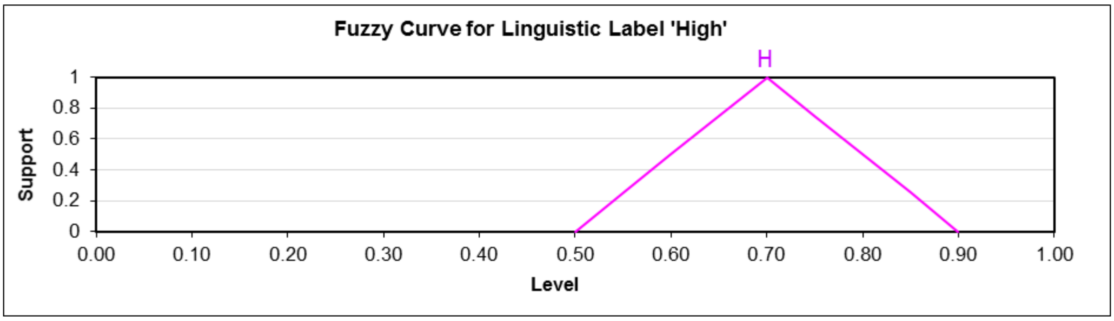


Fig. A4.1 Fuzzy Curve for Linguistic Label 'High'

Thereafter, fuzzy curves related to all the responses for Q5(a) are superimposed and the 'cumulative response curve' or the 'frequency curve' for Q5(a) is obtained, and it is given below.

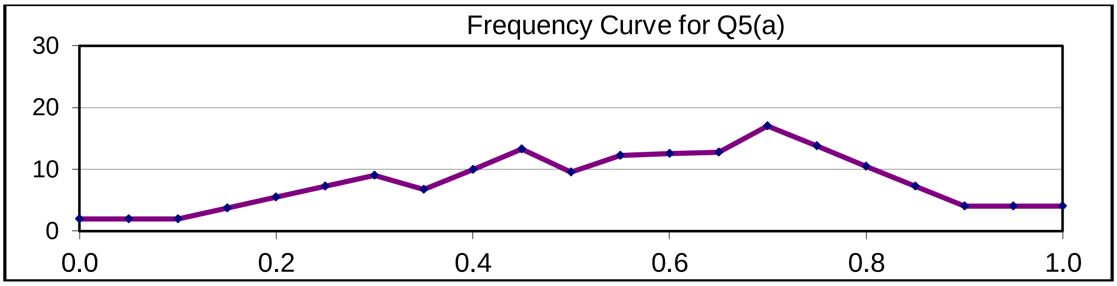


Fig. A4.2 Frequency Curve for Q5(a)

Dividing the ordinates of the frequency curve by the number of responses for Q5(a), the ordinates (y coordinates) of the 'mean curve' are determined. Valid number of responses for Q5(a) from Australia was 51. Accordingly, the ordinates of the mean curve were computed by dividing the ordinates of frequency curve by 51, and they are given below.

Ordinates of Mean Curve for Q5(a)

X=	**0.00**	**0.05**	**0.10**	**0.15**	**0.20**	**0.25**	**0.30**	**0.35**	**0.40**	**0.45**	**0.50**	**0.55**	**0.60**	**0.65**	**0.70**	**0.75**	**0.80**	**0.85**	**0.90**	**0.95**	**1.00**
Y=	0.04	0.04	0.04	0.07	0.11	0.14	0.18	0.13	0.20	0.26	0.19	0.24	0.25	0.25	0.33	0.27	0.21	0.14	0.08	0.08	0.08

Thereafter, the mean curve M is plotted over the fuzzy set as shown below.

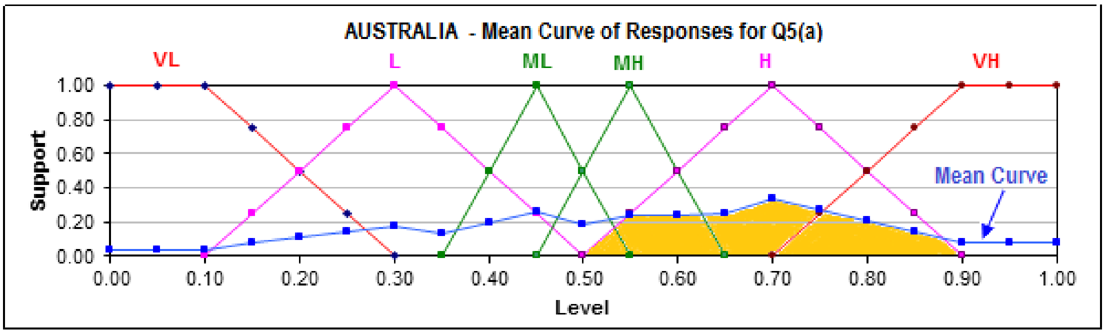


Fig. A4.3 Mean Curve for Q5(a) and Fuzzy Set

Next, the Degrees of Identity (DoI) of mean responses with each fuzzy curve is determined.

For example, consider the fuzzy curve that represent the linguistic label 'high' (H).
i.e. the fuzzy curve considered (F_r) = H

The mean curve M intersects the fuzzy curve H at (0.55, 0.24) and (0.88, 0.11).

The region of the intersection of the mean curve M and the fuzzy curve H has been highlighted in Fig. A4.3.

Then the Degree of Identity (DoI) of mean responses with the fuzzy curve H is defined as,

DoI(M, H) = **|** M∩ H **| / |** H **|** where M = Mean responses
H = Fuzzy curve considered

Here the operator **||** represents the relevant area of the fuzzy set.

Area under fuzzy curve H	= **|** H **|** = 0.2000 square units
Area under mean curve M	= **|** M **|** = 0.1627 square units
Area of the region of intersection of M and H	= **|** M∩ H **|** = 0.0857 square units

Degree of Identity of mean with fuzzy curve H	= (M ∩ H) / | H |
	= 0.0857/ 0.200
	= 0.43

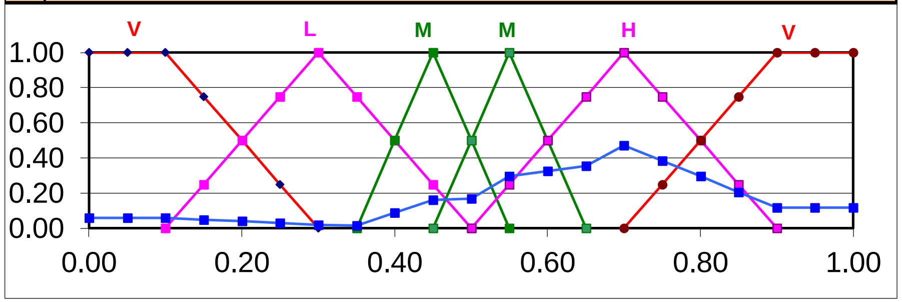
That is, DoI of Q5(a) with the fuzzy curve H is 0.43. Similarly, DoIs of Q5(a) with other fuzzy curves were computed. DoIs of Q5(a) with fuzzy curves VL, L, ML, MH, H and VH are 0.11, 0.27, 0.38, 0.40, 0.43 and 0.20 respectively. By adopting the same method, DoIs for parts (a) and (b) of all questions [Q1 to Q9 of the questionnaire] were determined.

Mean curves for responses from Australia, America and Sri Lanka are given in **Sections A4.1, A4.2** and **A4.3** of this Appendix. The DoIs for the responses obtained for all the questions [Q1 to Q9] from Australia, Sri Lanka and America were computed and tabulated in **Table A4.1**, **Table A4.2** and **Table A4.3** of this Appendix.

A4.1 Mean Curves for Responses from Australia

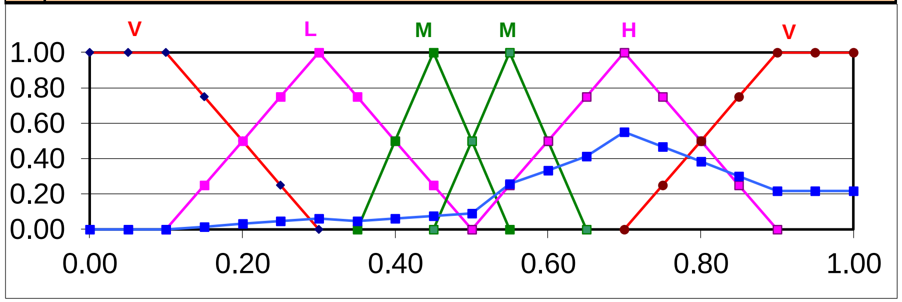
Mean Curve for Responses from Australia for Q1a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.06	0.06	0.06	0.05	0.04	0.03	0.02	0.01	0.09	0.16	0.17	0.29	0.32	0.35	0.47	0.38	0.29	0.21	0.12	0.12	0.12



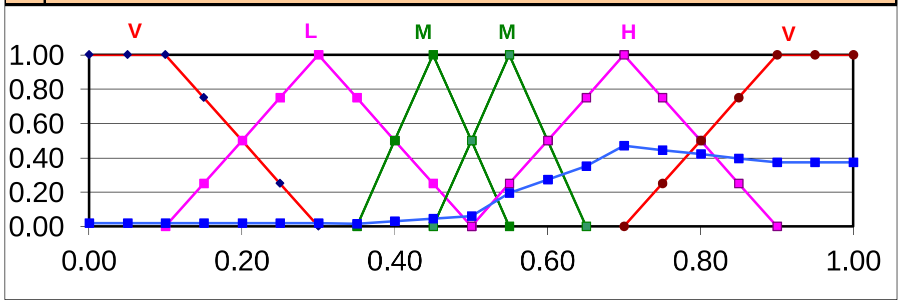
Mean Curve for Responses from Australia for Q1b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.01	0.03	0.04	0.06	0.04	0.06	0.07	0.09	0.25	0.33	0.41	0.55	0.47	0.38	0.30	0.22	0.22	0.22



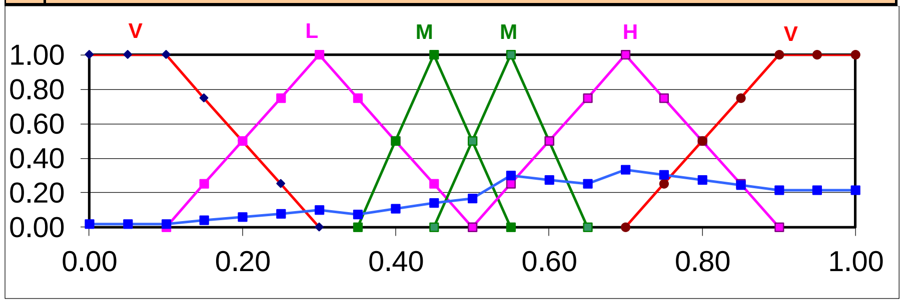
Mean Curve for Responses from Australia for Q2a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.03	0.04	0.06	0.20	0.27	0.35	0.47	0.45	0.42	0.40	0.37	0.37	0.37



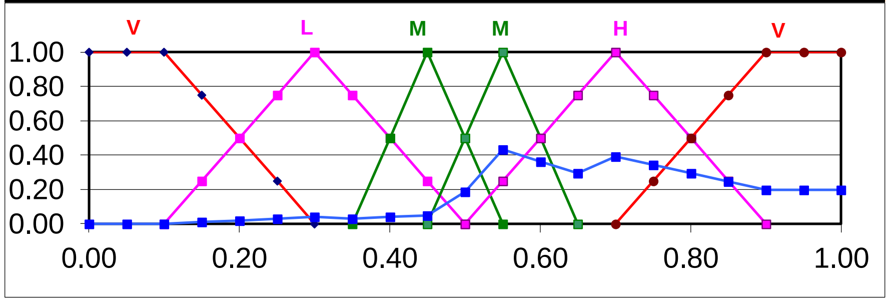
Mean Curve for Responses from Australia for Q2b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.02	0.02	0.02	0.04	0.06	0.08	0.10	0.07	0.11	0.14	0.17	0.30	0.27	0.25	0.33	0.30	0.27	0.25	0.22	0.22	0.22



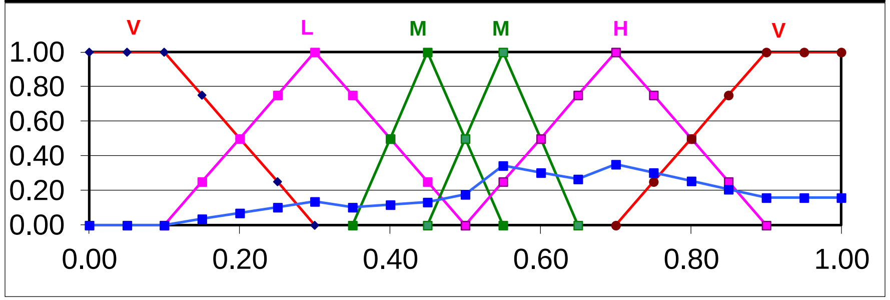
Mean Curve for Responses from Australia for Q3a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.01	0.02	0.03	0.04	0.03	0.04	0.05	0.19	0.43	0.36	0.29	0.39	0.34	0.29	0.25	0.20	0.20	0.20



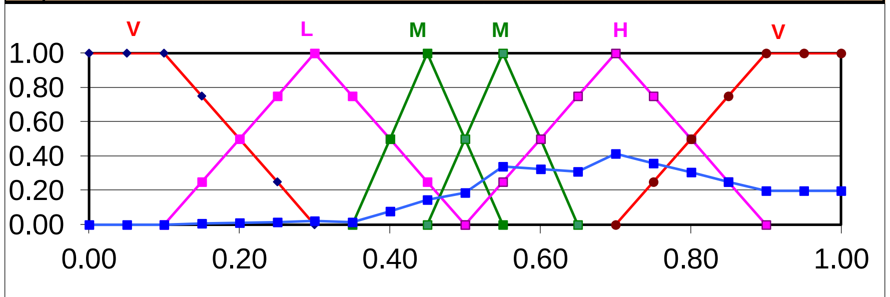
Mean Curve for Responses from Australia for Q3b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.03	0.07	0.10	0.14	0.10	0.12	0.13	0.18	0.34	0.30	0.26	0.35	0.30	0.25	0.21	0.16	0.16	0.16



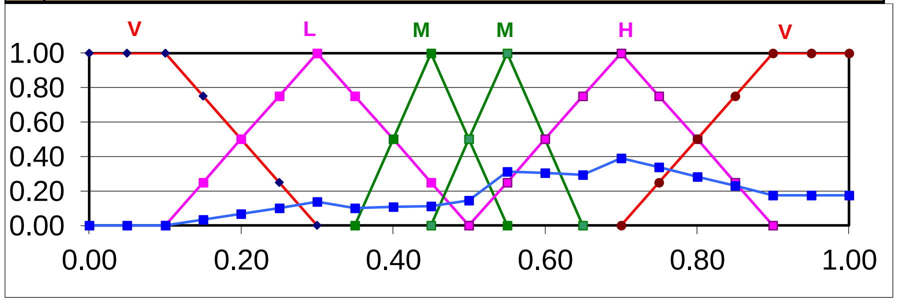
Mean Curve for Responses from Australia for Q4a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.01	0.08	0.14	0.19	0.34	0.32	0.31	0.41	0.36	0.30	0.25	0.20	0.20	0.20



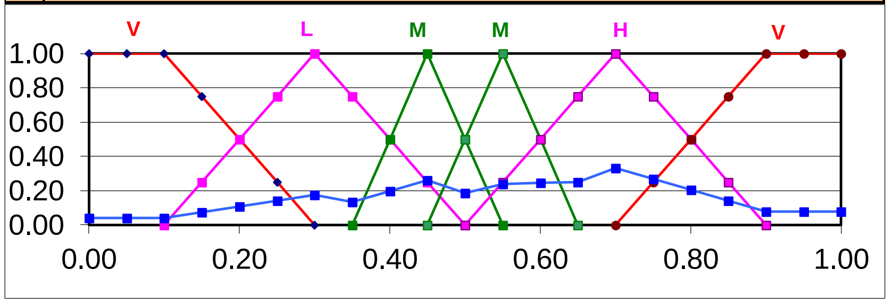
Mean Curve for Responses from Australia for Q4b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.03	0.07	0.10	0.14	0.10	0.11	0.11	0.15	0.31	0.30	0.29	0.39	0.34	0.28	0.23	0.18	0.18	0.18



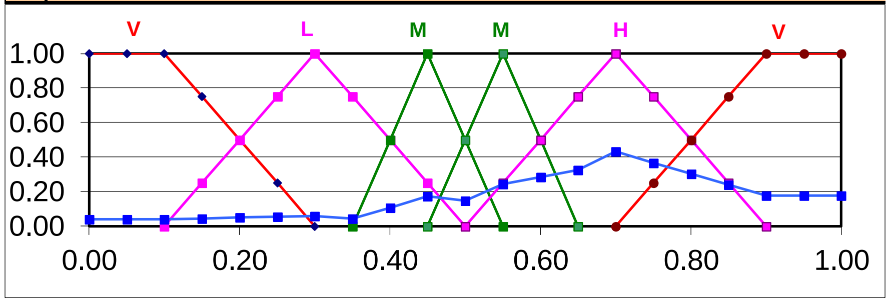
Mean Curve for Responses from Australia for Q5a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.04	0.04	0.04	0.07	0.11	0.14	0.18	0.13	0.20	0.26	0.19	0.24	0.25	0.25	0.33	0.27	0.21	0.14	0.08	0.08	0.08



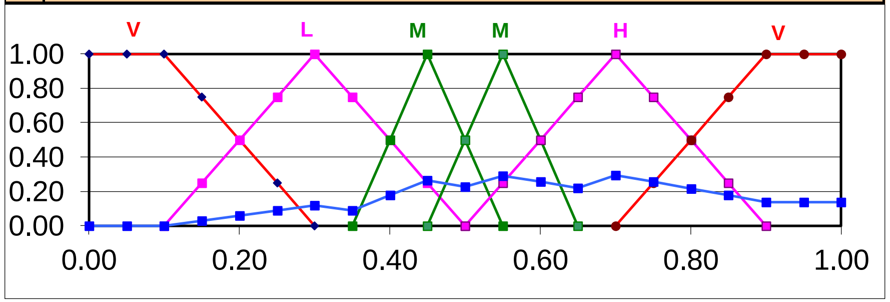
Mean Curve for Responses from Australia for Q5b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95
Y=	0.04	0.04	0.04	0.04	0.05	0.05	0.06	0.04	0.11	0.17	0.15	0.25	0.28	0.32	0.43	0.37	0.30	0.24	0.18	0.18



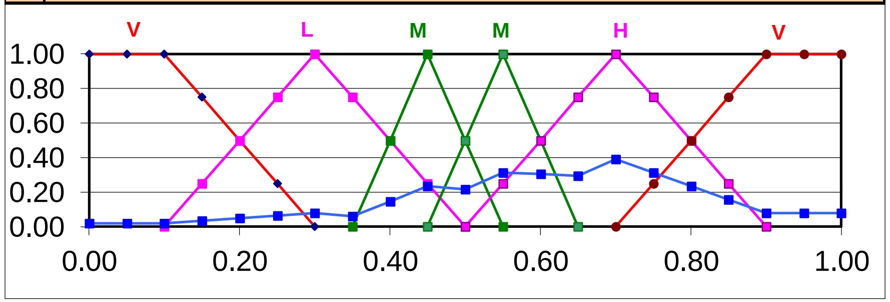
Mean Curve for Responses from Australia for Q6a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.03	0.06	0.09	0.12	0.09	0.18	0.26	0.23	0.29	0.25	0.22	0.29	0.25	0.22	0.18	0.14	0.14	0.14



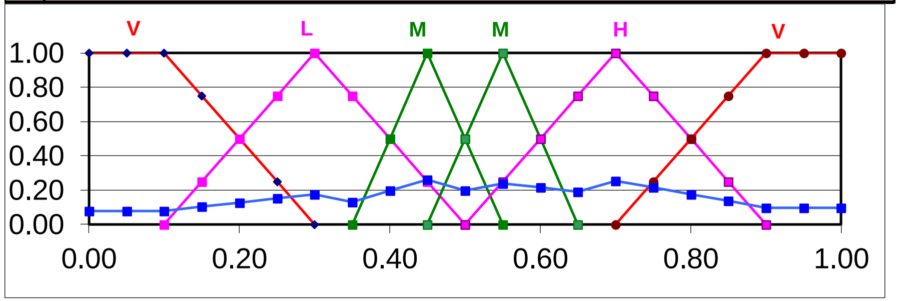
Mean Curve for Responses from Australia for Q6b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.02	0.02	0.02	0.03	0.05	0.06	0.08	0.06	0.15	0.24	0.22	0.31	0.30	0.29	0.39	0.31	0.24	0.16	0.08	0.08	0.08



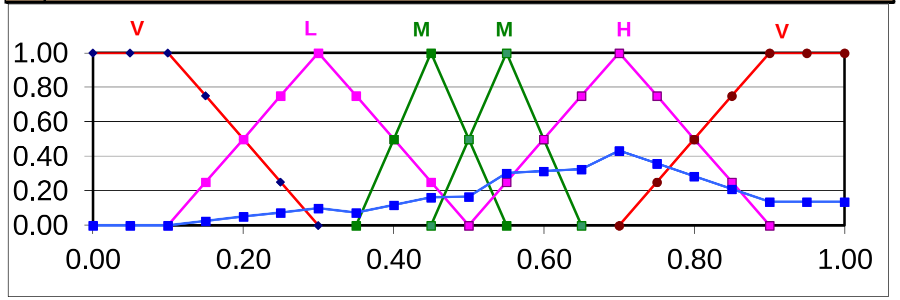
Mean Curve for Responses from Australia for Q7a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.08	0.08	0.08	0.10	0.13	0.15	0.18	0.13	0.20	0.26	0.20	0.24	0.22	0.19	0.25	0.22	0.18	0.14	0.10	0.10	0.10



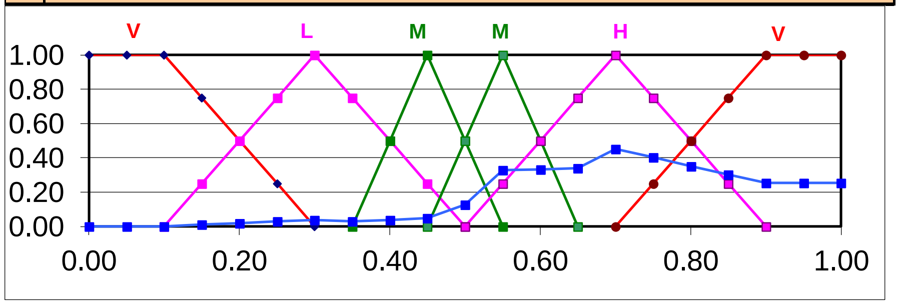
Mean Curve for Responses from Australia for Q7b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.02	0.05	0.07	0.10	0.07	0.12	0.16	0.17	0.30	0.31	0.32	0.43	0.36	0.28	0.21	0.14	0.14	0.14



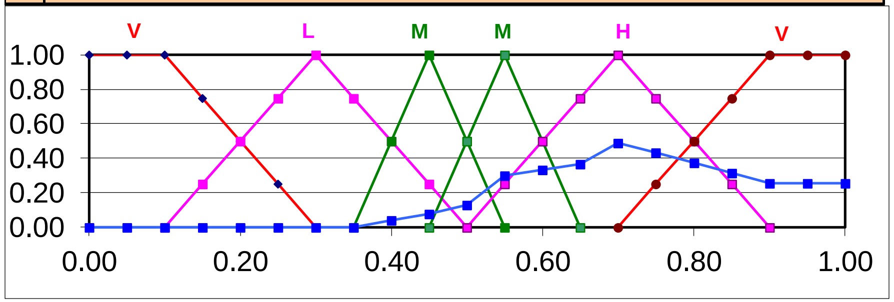
Mean Curve for Responses from Australia for Q8a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.01	0.02	0.03	0.04	0.03	0.04	0.05	0.13	0.33	0.33	0.34	0.45	0.40	0.35	0.30	0.25	0.25	0.25



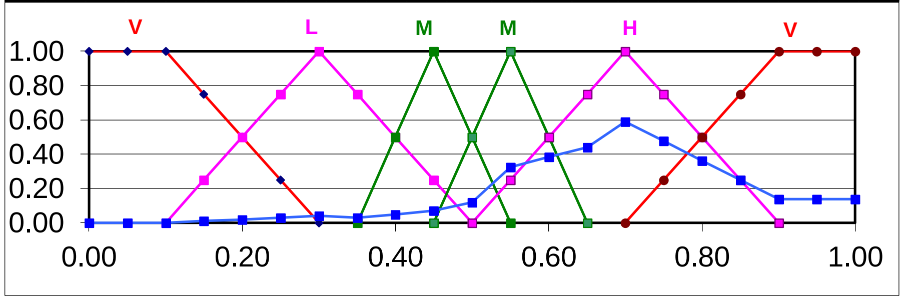
Mean Curve for Responses from Australia for Q8b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.08	0.13	0.30	0.33	0.37	0.49	0.43	0.37	0.31	0.25	0.25	0.25



Mean Curve for Responses from Australia for Q9a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.01	0.02	0.03	0.04	0.03	0.05	0.07	0.12	0.32	0.38	0.44	0.59	0.48	0.36	0.25	0.14	0.14	0.14



Mean Curve for Responses from Australia for Q9b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.02	0.04	0.06	0.08	0.06	0.08	0.10	0.20	0.42	0.36	0.31	0.41	0.34	0.26	0.19	0.12	0.12	0.12

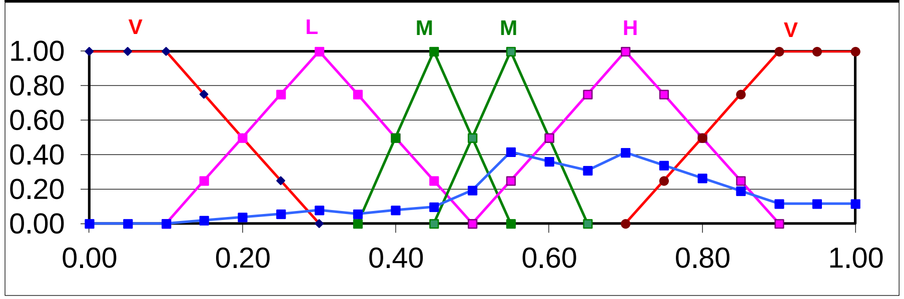


Table A4.1 DoIs for Australian Technologists

AUSTRALIA														
Sectn	Q	Part (a) - Individuals						Part (b) - Society						
		VL	L	ML	MH	H	VH	VL	L	ML	MH	H	VH	
1	Q1	0.07	0.11	0.25	0.45	0.58	0.27	0.03	0.09	0.16	0.38	0.67	0.38	
	Q2	0.03	0.05	0.10	0.31	0.61	0.51	0.06	0.16	0.26	0.42	0.49	0.33	
	Q3	0.02	0.07	0.19	0.52	0.56	0.33	0.06	0.18	0.28	0.46	0.50	0.28	
	Q4	0.01	0.08	0.25	0.48	0.56	0.33	0.06	0.18	0.25	0.43	0.53	0.31	
	Q5	0.11	0.27	0.38	0.40	0.43	0.20	0.07	0.14	0.26	0.40	0.55	0.32	
	Q6	0.05	0.20	0.39	0.45	0.43	0.25	0.06	0.17	0.35	0.48	0.50	0.22	
	Q7	0.15	0.29	0.38	0.39	0.37	0.20	0.04	0.16	0.28	0.45	0.55	0.28	
	Q8	0.02	0.06	0.16	0.43	0.61	0.40	0.00	0.04	0.16	0.42	0.63	0.40	
2	Q9	0.02	0.07	0.17	0.45	0.69	0.31	0.04	0.12	0.24	0.53	0.55	0.26	

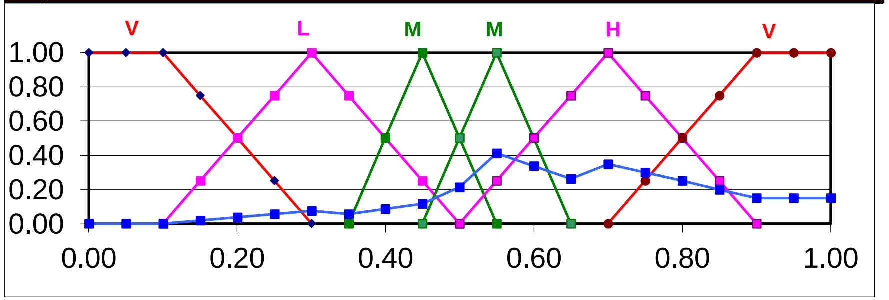
KEY

Q1 - Market price
Q2 - Quality standards
Q3 - Impact on the sustainability of the earth
Q4 - Mitigating land pollution due to fly ash
Q5 - Non-familiarity
Q6 - 'Feel good' factor
Q7 - Social trends
Q8 - Recommendations of professionals
Q9-Overall acceptability

A4.2 Mean Curves for Responses from America

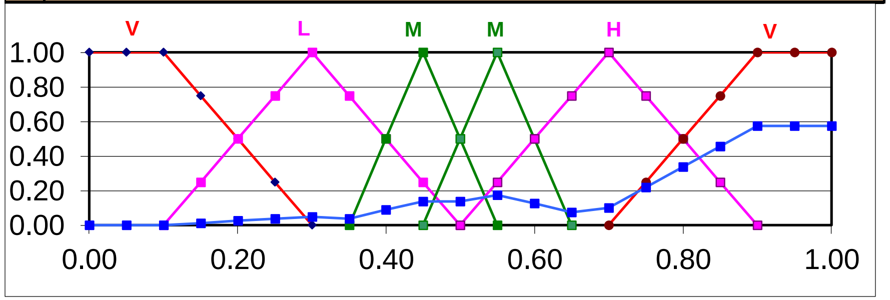
Mean Curve for Responses from America for Q1a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.02	0.04	0.06	0.08	0.06	0.09	0.12	0.21	0.41	0.34	0.26	0.35	0.30	0.25	0.20	0.15	0.15	0.15



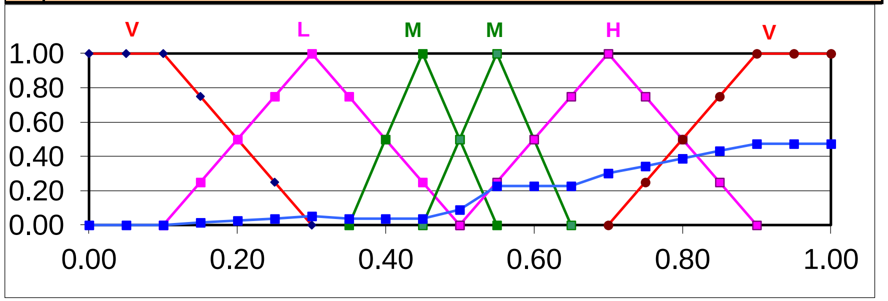
Mean Curve for Responses from America for Q1b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.01	0.03	0.04	0.05	0.04	0.09	0.14	0.14	0.18	0.13	0.08	0.10	0.22	0.34	0.46	0.58	0.58	0.58



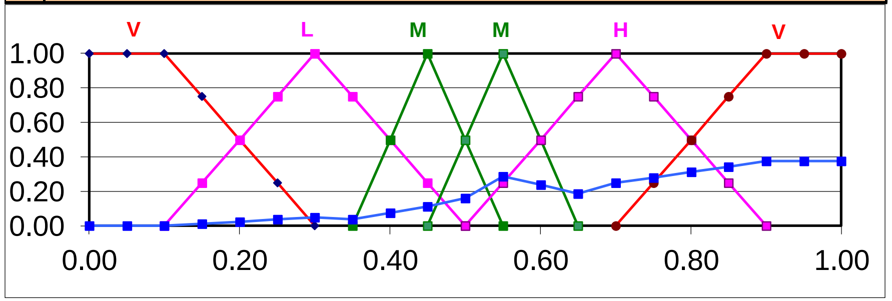
Mean Curve for Responses from America for Q2a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.01	0.03	0.04	0.05	0.04	0.04	0.04	0.09	0.23	0.23	0.23	0.30	0.34	0.39	0.43	0.48	0.48	0.48



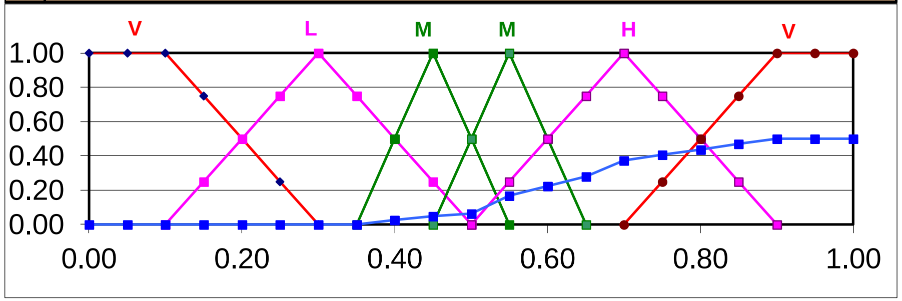
Mean Curve for Responses from America for Q2b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.01	0.03	0.04	0.05	0.04	0.08	0.11	0.16	0.29	0.24	0.19	0.25	0.28	0.31	0.34	0.38	0.38	0.38



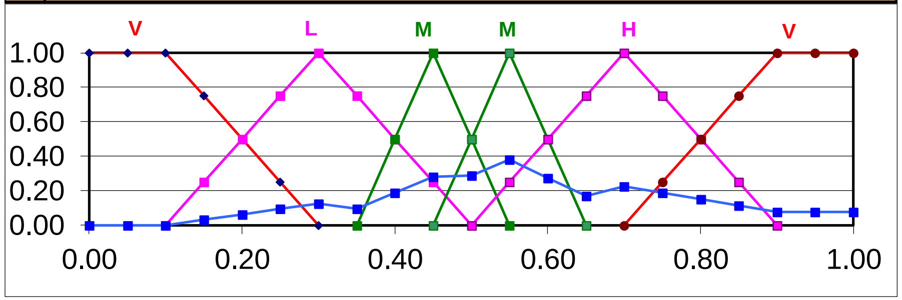
Mean Curve for Responses from America for Q3a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.05	0.06	0.17	0.23	0.28	0.38	0.41	0.44	0.47	0.50	0.50	0.50



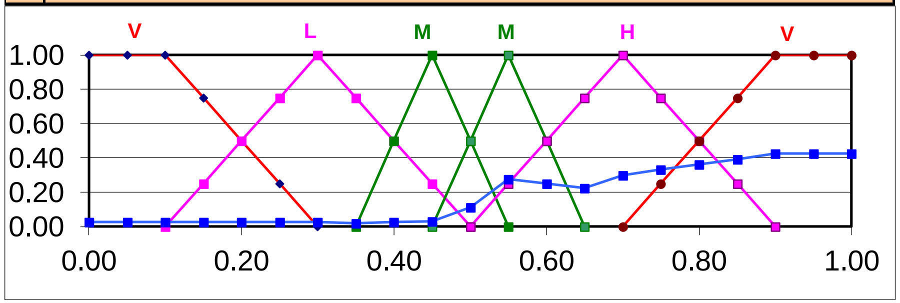
Mean Curve for Responses from America for Q3b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.03	0.06	0.09	0.13	0.09	0.19	0.28	0.29	0.38	0.28	0.17	0.23	0.19	0.15	0.11	0.08	0.08	0.08



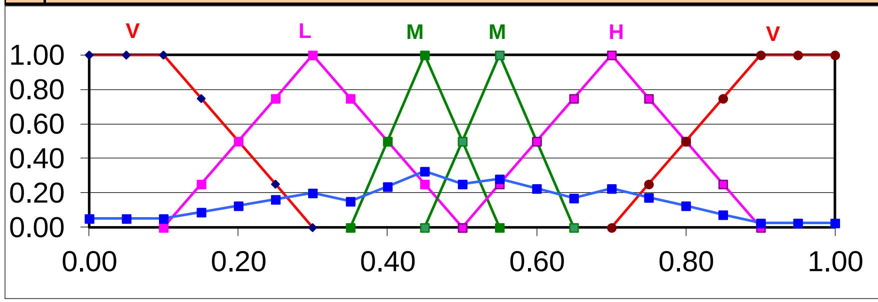
Mean Curve for Responses from America for Q4a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.03	0.03	0.11	0.28	0.25	0.23	0.30	0.33	0.36	0.39	0.43	0.43	0.43



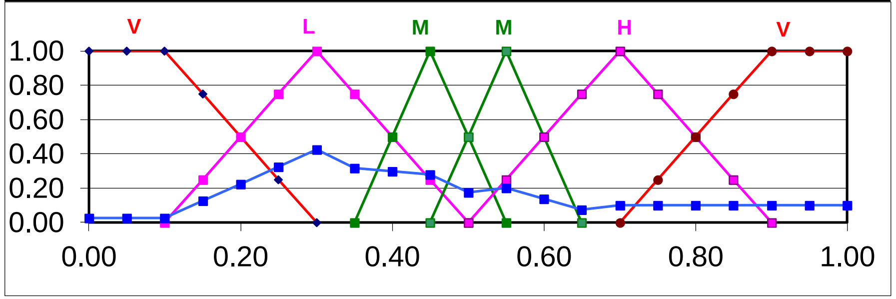
Mean Curve for Responses from America for Q4b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.05	0.05	0.05	0.09	0.13	0.16	0.20	0.15	0.24	0.33	0.25	0.28	0.23	0.17	0.23	0.18	0.13	0.08	0.03	0.03	0.03



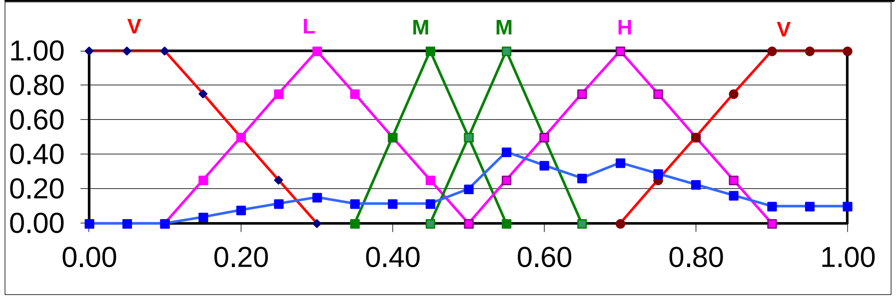
Mean Curve for Responses from America for Q5a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.03	0.03	0.03	0.13	0.23	0.33	0.43	0.32	0.30	0.28	0.18	0.20	0.14	0.08	0.10	0.10	0.10	0.10	0.10	0.10	0.10



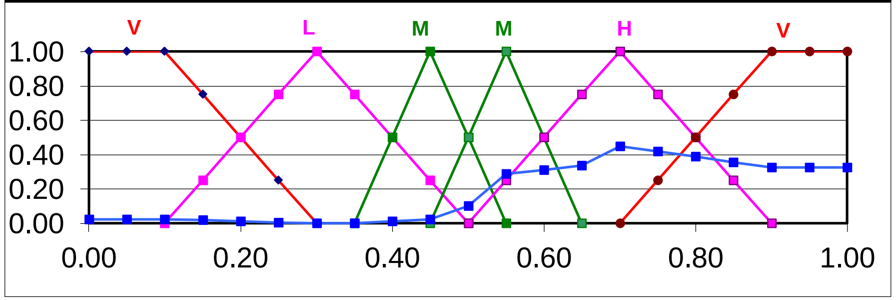
Mean Curve for Responses from America for Q5b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.04	0.08	0.11	0.15	0.11	0.11	0.11	0.20	0.41	0.34	0.26	0.35	0.29	0.23	0.16	0.10	0.10	0.10



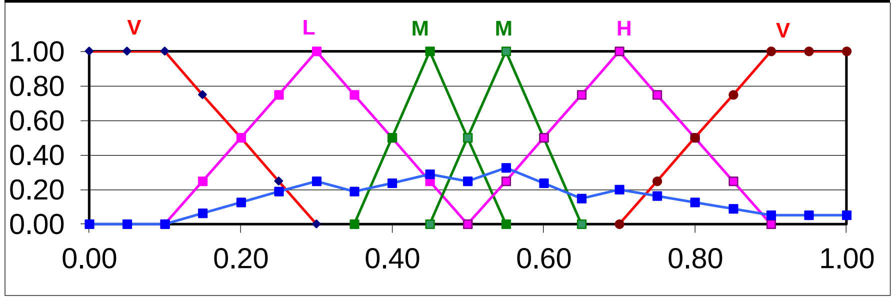
Mean Curve for Responses from America for Q6a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.03	0.03	0.03	0.02	0.01	0.01	0.00	0.00	0.01	0.03	0.10	0.29	0.31	0.34	0.45	0.42	0.39	0.36	0.33	0.33	0.33



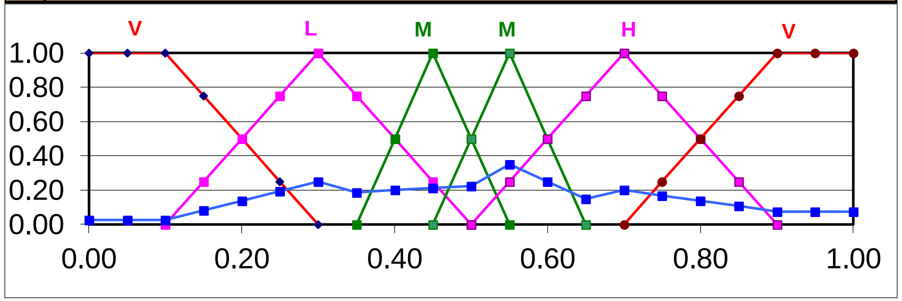
Mean Curve for Responses from America for Q6b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.06	0.13	0.19	0.25	0.19	0.24	0.29	0.25	0.33	0.24	0.15	0.20	0.16	0.13	0.09	0.05	0.05	0.05



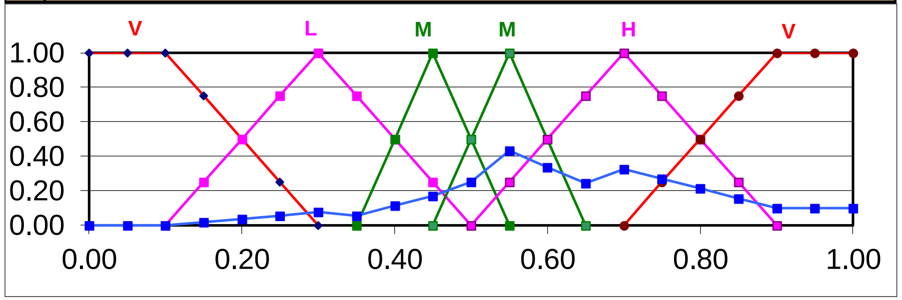
Mean Curve for Responses from America for Q7a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.03	0.03	0.03	0.08	0.14	0.19	0.25	0.19	0.20	0.21	0.23	0.35	0.25	0.15	0.20	0.17	0.14	0.11	0.08	0.08	0.08



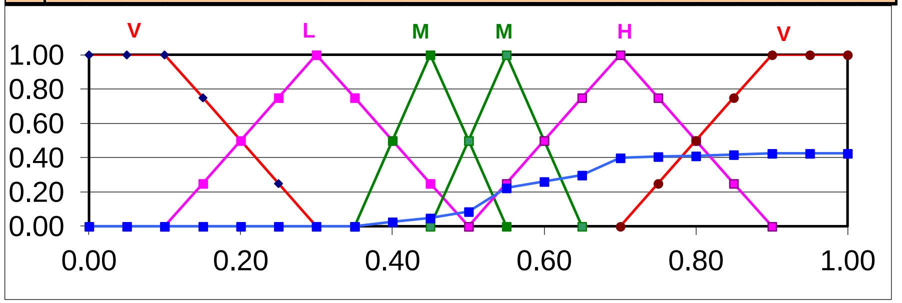
Mean Curve for Responses from America for Q7b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.02	0.04	0.06	0.08	0.06	0.11	0.17	0.25	0.43	0.34	0.24	0.33	0.27	0.21	0.16	0.10	0.10	0.10



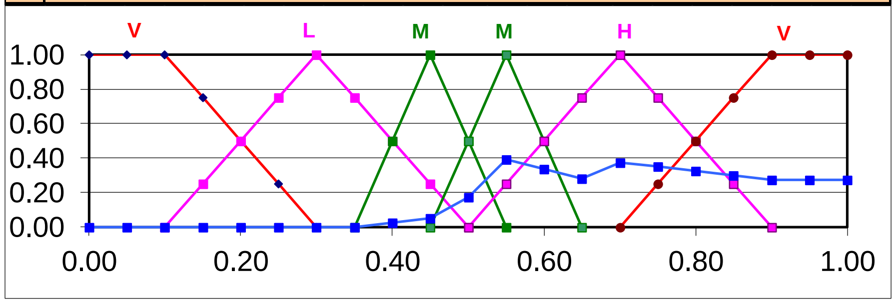
Mean Curve for Responses from America for Q8a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.05	0.09	0.23	0.26	0.30	0.40	0.41	0.41	0.42	0.43	0.43	0.43



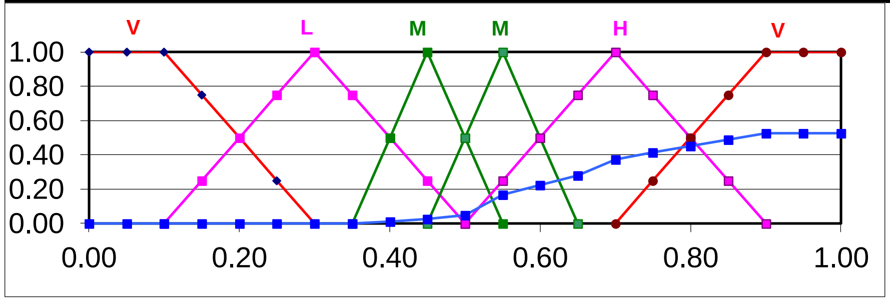
Mean Curve for Responses from America for Q8b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.05	0.18	0.39	0.34	0.28	0.38	0.35	0.33	0.30	0.28	0.28	0.28



Mean Curve for Responses from America for Q9a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.05	0.17	0.23	0.28	0.38	0.41	0.45	0.49	0.53	0.53	0.53



Mean Curve for Responses from America for Q9b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.01	0.03	0.04	0.05	0.04	0.11	0.19	0.25	0.39	0.30	0.21	0.28	0.25	0.23	0.20	0.18	0.18	0.18

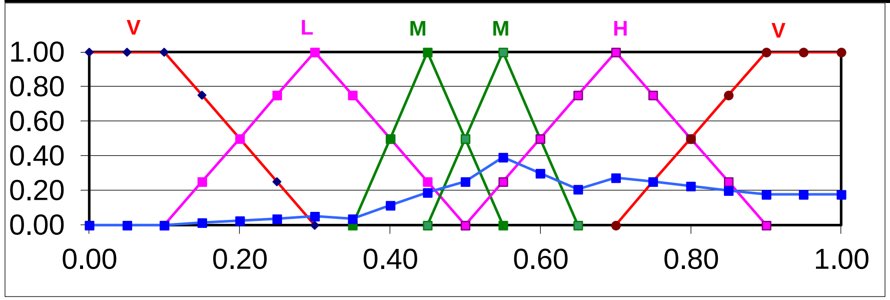


Table A4.2 DoIs for 'American Integralists'

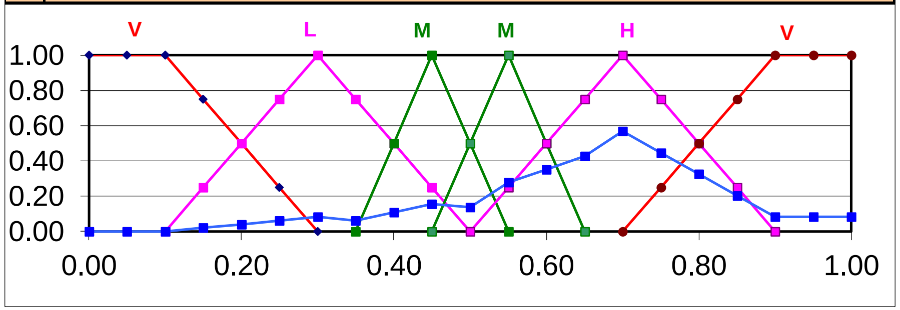
AMERICA														
Sectn		Part (a) - Individuals						Part (b) - Society						
	Q	VL	L	ML	MH	H	VH	VL	L	ML	MH	H	VH
1	Q1	0.03	0.12	0.26	0.53	0.50	0.27	0.02	0.10	0.22	0.26	0.34	0.62
	Q2	0.02	0.07	0.13	0.31	0.50	0.57	0.02	0.10	0.22	0.39	0.45	0.46
	Q3	0.00	0.02	0.10	0.27	0.55	0.61	0.06	0.21	0.43	0.53	0.36	0.17
	Q4	0.04	0.06	0.13	0.36	0.50	0.52	0.13	0.32	0.46	0.44	0.32	0.12
	Q5	0.17	0.50	0.44	0.31	0.22	0.14	0.07	0.19	0.28	0.52	0.48	0.23
	Q6	0.02	0.03	0.11	0.39	0.61	0.46	0.10	0.33	0.45	0.46	0.32	0.13
	Q7	0.12	0.32	0.39	0.47	0.33	0.16	0.03	0.14	0.32	0.56	0.47	0.22
	Q8	0.00	0.03	0.12	0.33	0.57	0.54	0.00	0.03	0.17	0.49	0.56	0.40
2	Q9	0.00	0.01	0.07	0.26	0.55	0.63	0.02	0.12	0.32	0.52	0.44	0.28

KEY
Q1 - Market price
Q2 - Quality standards
Q3 - Impact on the sustainability of the earth
Q4 - Mitigating land pollution due to fly ash
Q5 - Non-familiarity
Q6 - 'Feel good' factor
Q7 - Social trends
Q8 - Recommendations of professionals
Q9-Overall acceptability

A4.3 Mean Curves for Responses from Sri Lanka

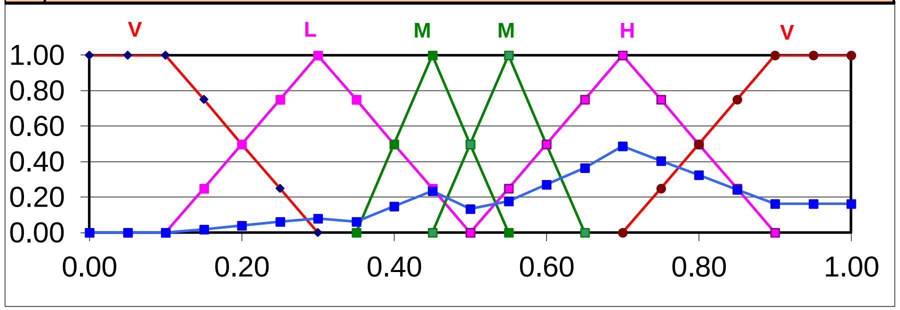
Mean Curve for Responses from Sri Lanka for Q1a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.02	0.04	0.06	0.08	0.06	0.11	0.16	0.14	0.28	0.35	0.43	0.57	0.45	0.32	0.20	0.08	0.08	0.08



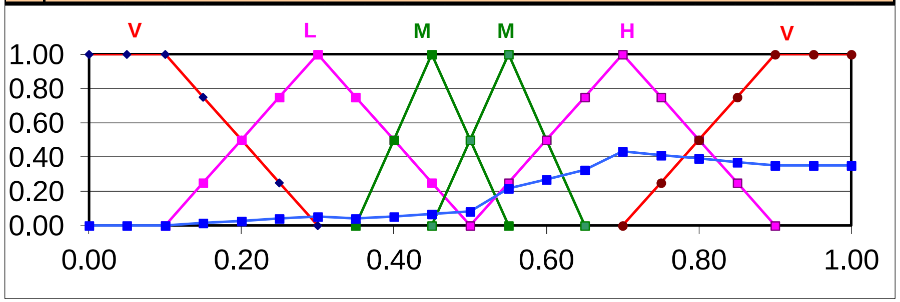
Mean Curve for Responses from Sri Lanka for Q1b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.02	0.04	0.06	0.08	0.06	0.15	0.24	0.14	0.18	0.27	0.36	0.49	0.41	0.32	0.24	0.16	0.16	0.16



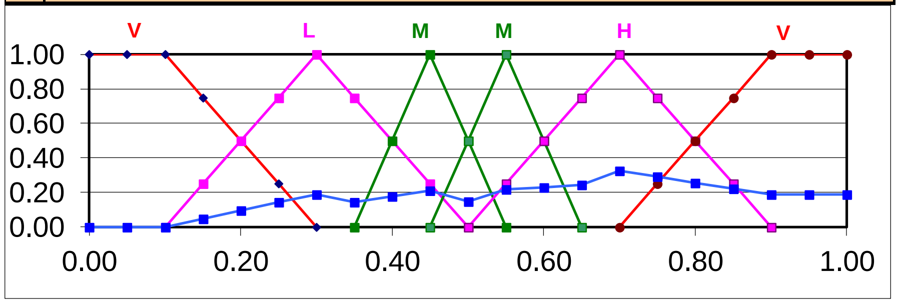
Mean Curve for Responses from Sri Lanka for Q2a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.01	0.03	0.04	0.05	0.04	0.05	0.07	0.08	0.22	0.27	0.32	0.43	0.41	0.39	0.37	0.35	0.35	0.35



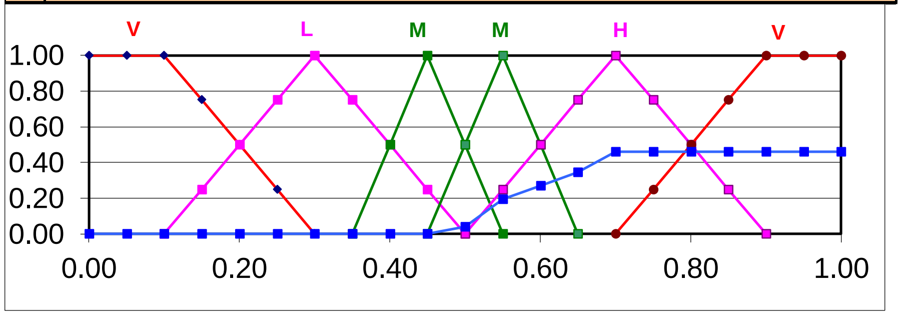
Mean Curve for Responses from Sri Lanka for Q2b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.05	0.09	0.14	0.19	0.14	0.18	0.21	0.15	0.22	0.23	0.24	0.32	0.29	0.26	0.22	0.19	0.19	0.19



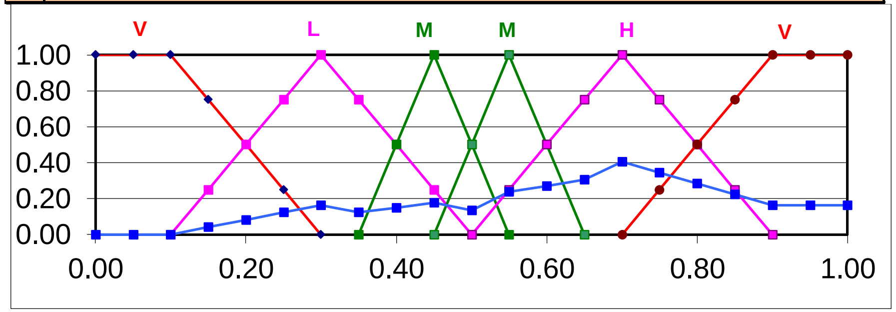
Mean Curve for Responses from Sri Lanka for Q3a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.20	0.27	0.34	0.46	0.46	0.46	0.46	0.46	0.46	0.46



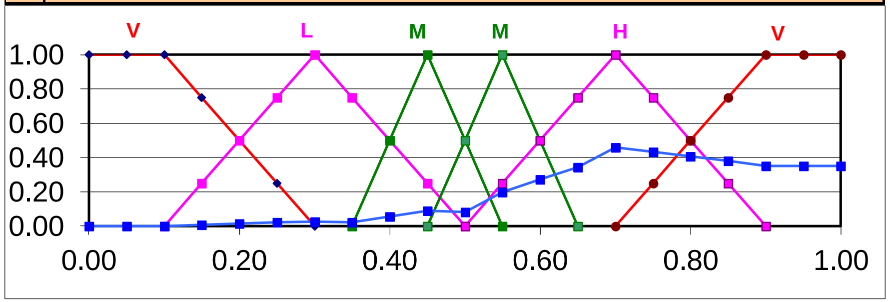
Mean Curve for Responses from Sri Lanka for Q3b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.04	0.08	0.12	0.16	0.12	0.15	0.18	0.14	0.24	0.27	0.30	0.41	0.34	0.28	0.22	0.16	0.16	0.16



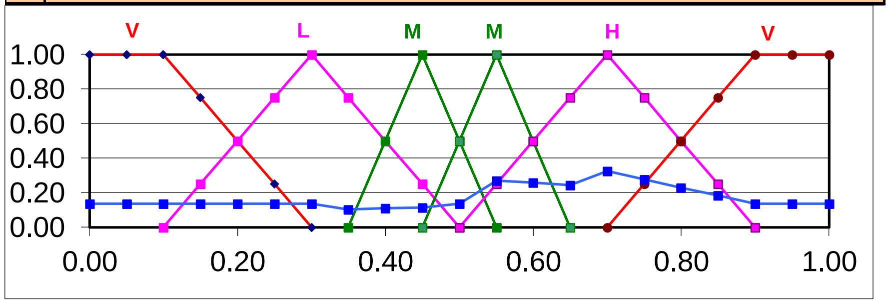
Mean Curve for Responses from Sri Lanka for Q4a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.01	0.01	0.02	0.03	0.02	0.05	0.09	0.08	0.20	0.27	0.34	0.46	0.43	0.41	0.38	0.35	0.35	0.35



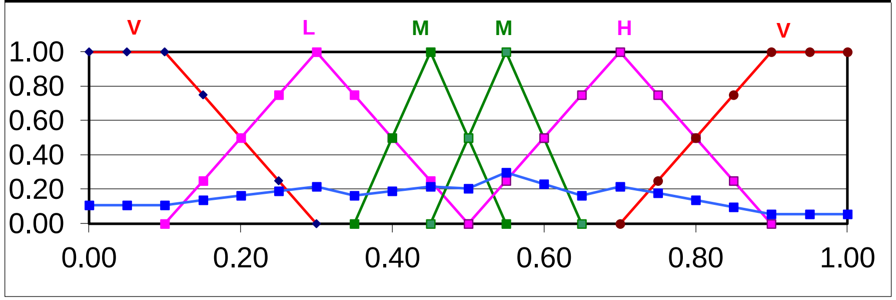
Mean Curve for Responses from Sri Lanka for Q4b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.10	0.11	0.11	0.14	0.27	0.26	0.24	0.32	0.28	0.23	0.18	0.14	0.14	0.14



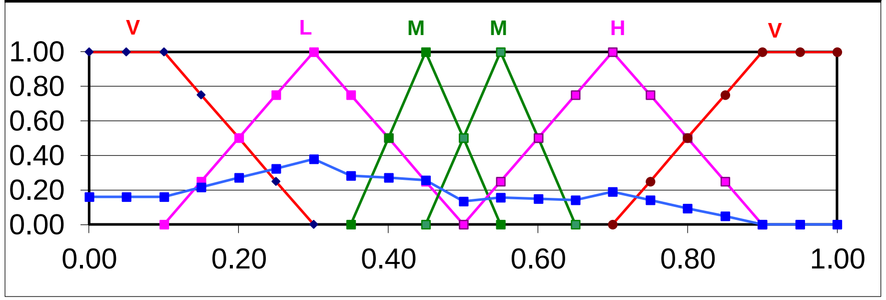
Mean Curve for Responses from Sri Lanka for Q5a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.11	0.11	0.11	0.14	0.16	0.19	0.22	0.16	0.19	0.22	0.20	0.30	0.23	0.16	0.22	0.18	0.14	0.09	0.05	0.05	0.05



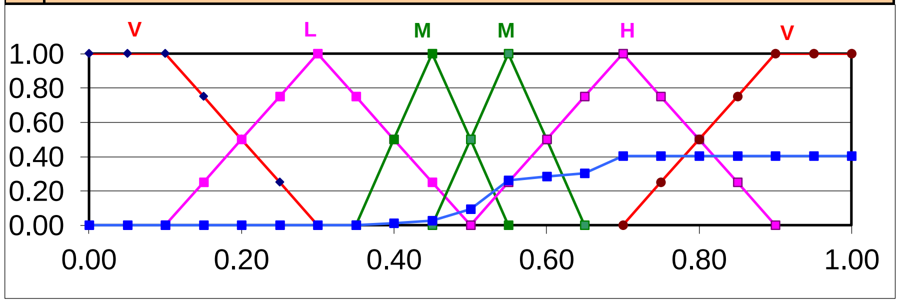
Mean Curve for Responses from Sri Lanka for Q5b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.16	0.16	0.16	0.22	0.27	0.32	0.38	0.28	0.27	0.26	0.14	0.16	0.15	0.14	0.19	0.14	0.09	0.05	0.00	0.00	0.00



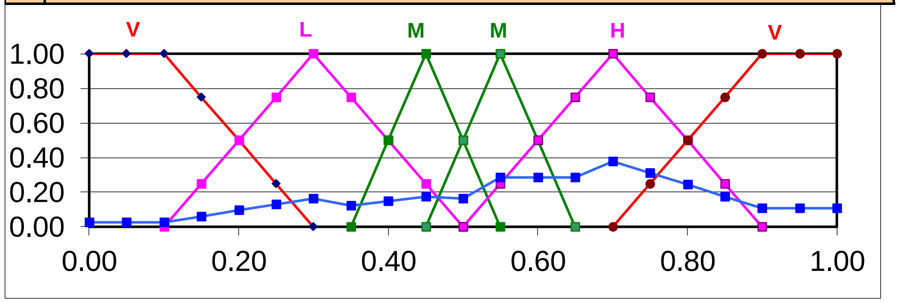
Mean Curve for Responses from Sri Lanka for Q6a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.09	0.26	0.28	0.30	0.41	0.41	0.41	0.41	0.41	0.41	0.41



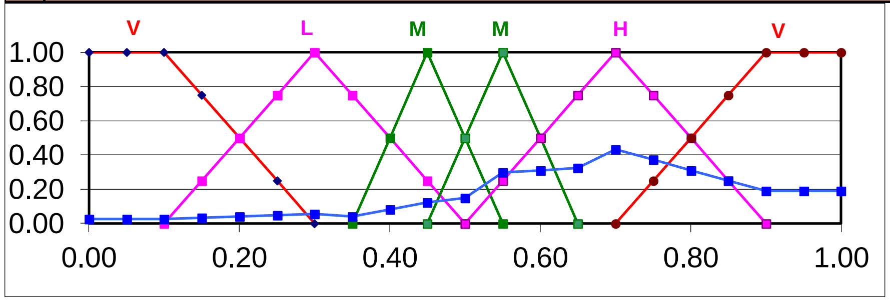
Mean Curve for Responses from Sri Lanka for Q6b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.03	0.03	0.03	0.06	0.09	0.13	0.16	0.12	0.15	0.18	0.16	0.28	0.28	0.28	0.38	0.31	0.24	0.18	0.11	0.11	0.11



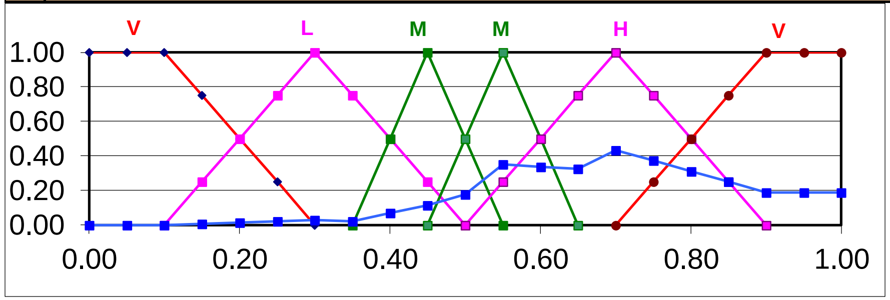
Mean Curve for Responses from Sri Lanka for Q7a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.03	0.03	0.03	0.03	0.04	0.05	0.05	0.04	0.08	0.12	0.15	0.30	0.31	0.32	0.43	0.37	0.31	0.25	0.19	0.19	0.19



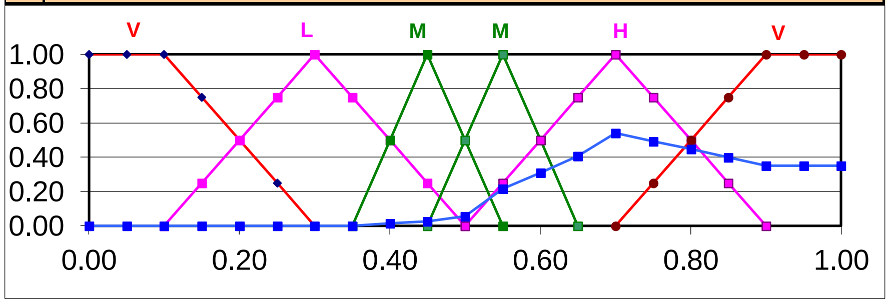
Mean Curve for Responses from Sri Lanka for Q7b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.01	0.01	0.02	0.03	0.02	0.07	0.11	0.18	0.35	0.34	0.32	0.43	0.37	0.31	0.25	0.19	0.19	0.19



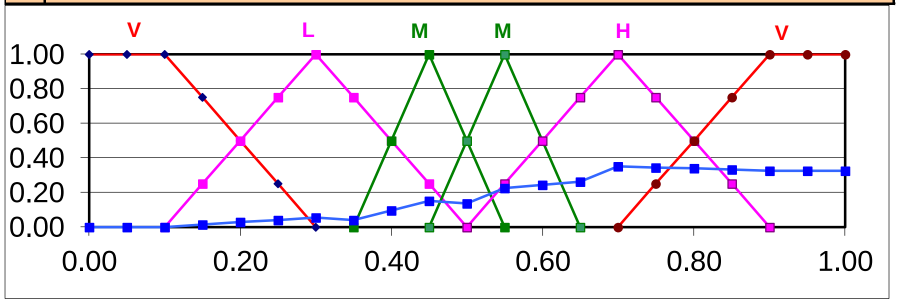
Mean Curve for Responses from Sri Lanka for Q8a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.05	0.22	0.31	0.41	0.54	0.49	0.45	0.40	0.35	0.35	0.35



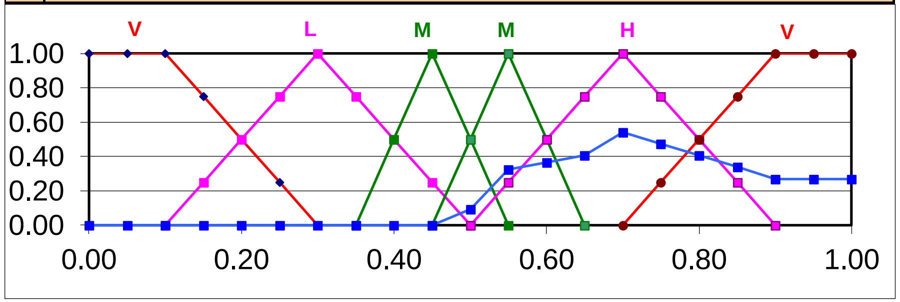
Mean Curve for Responses from Sri Lanka for Q8b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.01	0.03	0.04	0.05	0.04	0.09	0.15	0.14	0.22	0.24	0.26	0.35	0.34	0.34	0.33	0.32	0.32	0.32



Mean Curve for Responses from Sri Lanka for Q9a

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.32	0.36	0.41	0.54	0.47	0.41	0.34	0.27	0.27	0.27



Mean Curve for Responses from Sri Lanka for Q9b

X=	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Y=	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.12	0.22	0.22	0.31	0.30	0.28	0.38	0.32	0.26	0.20	0.14	0.14	0.14

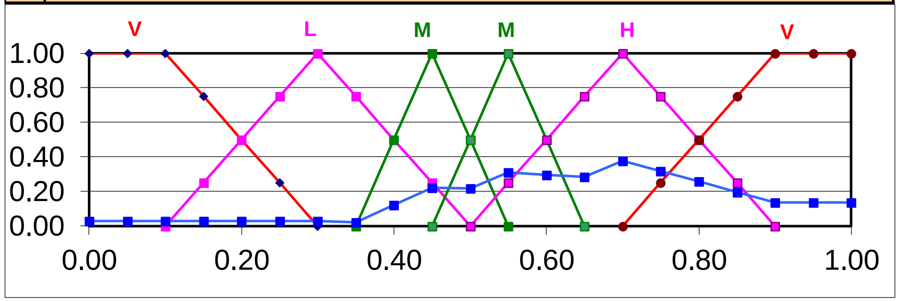


Table A4.3 DoIs for 'Sri Lankan Environmentalists'

SRI LANKA													
Sectn		Part (a) - Individuals						Part (b) - Society					
	Q	VL	L	ML	MH	H	VH	VL	L	ML	MH	H	VH
1	Q1	0.04	0.14	0.25	0.44	0.65	0.26	0.04	0.16	0.30	0.36	0.57	0.32
	Q2	0.03	0.08	0.15	0.33	0.58	0.48	0.08	0.25	0.33	0.36	0.45	0.31
	Q3	0.00	0.00	0.05	0.29	0.62	0.58	0.07	0.22	0.29	0.38	0.52	0.30
	Q4	0.01	0.06	0.15	0.33	0.60	0.49	0.19	0.23	0.24	0.38	0.45	0.25
	Q5	0.20	0.33	0.37	0.42	0.33	0.14	0.29	0.50	0.39	0.28	0.24	0.08
	Q6	0.00	0.02	0.11	0.36	0.58	0.53	0.10	0.23	0.30	0.42	0.49	0.24
	Q7	0.05	0.12	0.23	0.43	0.57	0.33	0.01	0.08	0.23	0.48	0.58	0.33
	Q8	0.00	0.02	0.08	0.33	0.67	0.50	0.03	0.11	0.23	0.36	0.51	0.44
2	Q9	0.00	0.01	0.09	0.42	0.68	0.43	0.04	0.12	0.32	0.47	0.51	0.27

KEY

Q1 - Market price
Q2 - Quality standards
Q3 - Impact on the sustainability of the earth
Q4 - Mitigating land pollution due to fly ash
Q5 - Non-familiarity
Q6 - 'Feel good' factor
Q7 - Social trends
Q8 - Recommendations of professionals
Q9-Overall acceptability

Appendix A5

A5 Objective Properties of APC

Information given in this Appendix A5 is related to Chapter 10. Compositions of cementitious mixtures are given below.

Mix. No	Description		
	Composition of Dry Mixture	Type of Pozzolan	w/c
L3	70%[95%APC60+5%Na_2SO_4]+30%OPC	fly ash	0.3
L4	70%[95%APC60+5%Na_2SO_4]+30%OPC	fly ash	0.4
M3	70%[95%APC70+5%Na_2SO_4]+30%OPC	fly ash	0.3
M4	70%[95%APC70+5%Na_2SO_4]+30%OPC	fly ash	0.4
N3	70%[95%APC80+5%Na_2SO_4]+30%OPC	fly ash	0.3
N4	70%[95%APC80+5%Na_2SO_4]+30%OPC	fly ash	0.4
P3	70%[95%APC70+5%Na_2SO_4]+30%OPC	slag	0.3
C3	70%[100%APC100]+30%OPC	fly ash	0.3
C4	70%[100%APC100]+30%OPC	fly ash	0.4
R3	100%OPC	none	0.3
R4	100%OPC	none	0.4
KEY : APCr = r% Pozzolan + (100-r)%Lime			

The mixture considered for analysis is the 'targeted mixture'**,** which is the APC mixture 'M', with w/c = 0.3 under 'controlled air curing' condition; along with the 'reference mixture' (100% OPC) with w/c=0.3.

A5.1 Compressive Strength Test

Mix	Air Cured		Water Cured	
	28d Strength (MPa)	Variability	28d Strength(MPa)	Variability
M3	46	07%	40	30%
M4	32	03%	27	19%
R3	57	57%	56	12%
R4	40	06%	54	17%

<u>**Targeted Mixture:** APC Mixture M with w/c=0.3 and air cured; that is M3</u>
28 day Strength : Mean =46 MPa ; Variability = 7%
Sensitivity to air curing to water curing = 46/40 = 1.15
Sensitivity to w/c of 0.3 to 0.4 (for air cured) = 46/32 = 1.437

<u>**Reference Mixture:** OPC Mixture R with w/c=0.3 and air cured; that is R3</u>
28 day Strength : Mean =57 MPa ; Variability = 57%
Sensitivity to air curing to water curing = 57/56 = 1.0
Sensitivity to w/c of 0.3 to 0.4 (for air cured) = 57/40 = 1.425

A5.2 Water Absorption Test

Mix	Air Cured		Water Cured	
	Water Absorption (% weight)	Variability	Water Absorption (% weight)	Variability
M3	13.7	05%	12.6	02%
M4	21.2	13%	16.8	03%
R3	11.6	09%	10.0	30%
R4	19.2	04%	15.4	35%

Target Mixture: APC Mixture M with w/c=0.3 and air cured; that is M3
Water Absorption : Mean =13. 7%; Variability = 05%
Sensitivity to air curing to water curing = 13.7/12.6 = 1.08
Sensitivity to w/c of 0.4 to 0.3 (for air cured) = 21.2/13.7 = 1.55

Reference Mixture: OPC Mixture R with w/c=0.3 and air cured; that is R3
Water Absorption : Mean =11.6%; Variability = 09%
Sensitivity to air curing to water curing = 11.6/10.0 = 1.16
Sensitivity to w/c of 0.4 to 0.3 (for air cured) = 19.2/11.6 = 1.65

A5.3 Carbonation Test

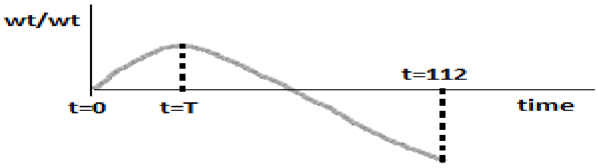
Mix	Air Cured	
	Carbonated depth (mm)	Variability
M3	8.33	08%
M4	22.17	02%
R3	4.04	10%
R4	4.58	29%

Targeted Mixture: APC Mixture M with w/c=0.3 and air cured; that is M3
Carbonation of air cured M3 samples : Mean =8.3 mm; Variability =08%
Sensitivity to w/c of 0.4 to 0.3 (for air cured) = 22.17/8.33 = 2.66

Reference Mixture: OPC Mixture R with w/c=0.3 and air cured; that is R3
Carbonation of air cured R3 samples : Mean =4.0 mm; Variability =10%
Sensitivity to w/c of 0.4 to 0.3 (for air cured) = 4.58/4.04 = 1.13

A5.4 Sulphuric Acid Test

When a sample was immersed in sulphuric acid, first its weight increases up to a maximum value and after that it drops as in figure below. Weights were recorded over a period of 4 months (112 days), and weight change per unit weight was calculated over the period.



W_0 – absolute weight before immersion;
W_t – absolute weight achieved at time 't'

Weight at time t, reference to weight at immersion, per unit weight $(U_{t,0}) = [(W_t - W_0)/W_0]*100\%$

Note that $U_{0,0} = [(W_0 - W_0)/W_0]*100\% = 0$

$U_{112,0}$ = Weight at time t=112 days, reference to weight at immersion, per unit weight

If time taken to achieve maximum weight is t=T

$U_{T,0}$ = Max weight, reference to weight at immersion, per unit weight
$U_{112,0} = U_{t,0}$ at t= 112 days = $[(W_{112} - W_0)/W_0]*100\%$
$U_{T,0}$ = maximum $\{U_{t,0}\}$ = Max $\{[(W_t - W_0)/W_0]*100\%\} = [(W_T - W_0)/W_0]*100\%$

$U_{112,T}$ = Weight at time t=112 days, reference to max weight, per unit weight

⇨ $U_{112,T} = (U_{112,0} – U_{T,0}) = [(W_{112} - W_0)/W_0]*100\% - [(W_T - W_0)/W_0]*100\%$

Mix	Weight at 112d wrt initial weight		Weight at 112d wrt max weight	
	Mean	Variability	Mean	Variability
M3	33.32%	29%	45.76%	18%
M4	18.50%	66%	41.81%	27%
R3	44.34%	06%	47.50%	04%
R4	29.63%	07%	32.91%	02%

Targeted Mixture: APC Mixture M with w/c=0.3 and air cured; that is M3
Weight change index was calculated based on weight at 112day, reference to max weight
Weight change Index : Mean =45.76% ; Variability = 18%
Sensitivity to w/c of 0.3 to 0.4 (for air cured) = 45.76/41.81 = 1.09

Reference Mixture: OPC Mixture R with w/c=0.3 and air cured; that is R3
Weight change index was calculated based on weight at 112day, reference to max weight
Weight change Index : Mean =47.50% ; Variability = 04%
Sensitivity to w/c of 0.3 to 0.4 (for air cured) = 47.50/32.91 = 1.44

A5.5 Compressive Strength and Variabilities of APC Mixtures

28 day compressive strengths of air cured APC mixtures and the relevant variabilities are given below.

Mix	L3	L4	M3	M4	N3	N4	P3	Mean
Strength (MPa)	50	26	46	32	42	28	50	**39**
Variability	13%	21%	07%	03%	25%	07%	05%	**12%**

A5.6 Water Absorption and Variabilities of APC Mixtures

Water absorption of air cured APC mixtures and the relevant variabilities are given below.

Mix	L3	L4	M3	M4	N3	N4	P3	Mean
Water Absorption (%)	16.0	25.8	13.7	21.2	12.6	23.3	14.3	**18.13**
Variability	02%	03%	05%	13%	07%	02%	03%	**05%**

A5.7 Carbonation Depths and Variabilities of APC Mixtures

Carbonation Depths at 3 months of air cured APC mixtures and the relevant variabilities are given below.

Mix	L3	L4	M3	M4	N3	N4	P3	Mean
Carbonation Depth (mm)	8.25	17.17	8.33	22.17	13.67	24.50	6.04	**14.30**
Variability	04%	02%	08%	02%	05%	00%	04%	**04%**

A5.8 Sulphuric Attack Indicators and Variabilities of APC Mixtures

Basis of the calculations are given in A5.4 above in this Appendix

Mix	Weight at 112d wrt initial weight		Weight at 112d wrt max weight	
	Mean	*Variability*	*Mean*	*Variability*
L3	-42.23	-09%	52.31	07%
L4	-12.48	-63%	34.85	25%
M3	-33.32	-29%	45.76	18%
M4	-18.50	-66%	41.81	27%
N3	-41.14	-09%	54.43	03%
N4	-2.82	-66%	26.43	18%
P3	-31.36	-13%	37.36	08%
Mean	**-25.98**	**-36%**	**41.85**	**15%**

NOTE: When 'weight changes' are needed, absolute values (modules) of mean and variability figures shown in the table are taken.

A5.9 Embodied Energy of Different Cementitious Mixtures

Mix	Embodied Energy per unit weight of dry cement powder		Embodied Energy per unit volume of cement paste per unit strength	
	Mean (MJ/kg)	Variability	Mean (MJ/m3/MPa)	Variability
L3	3.079	19%	97.9	34%
L4	3.079	19%	169.2	43%
M3	2.720	21%	98.8	29%
M4	2.720	21%	127.9	24%
N3	2.361	23%	93.8	48%
N4	2.361	23%	124.3	30%
P3	3.261	27%	103.4	33%
Mean	**2.80**	**22%**	**116.5**	**34%**

A5.10 Carbon dioxide Emission of Different Cementitious Mixtures

Mix	CO_2 emission unit weight of dry cement powder		CO_2 emission per unit volume of cement paste per unit strength	
	Mean (kg/kg)	Variability	Mean (kg/m3/MPa)	Variability
L3	0.477	11%	15.2	25%
L4	0.477	11%	26.2	34%
M3	0.426	12%	15.5	19%
M4	0.426	12%	20.0	15%
N3	0.374	13%	14.9	37%
N4	0.374	13%	19.7	20%
P3	0.454	14%	14.4	19%
Mean	**0.43**	**12%**	**18.0**	**24%**

A5.11 Cost of Different Cementitious Mixtures

Mix	Cost per unit weight of cement powder		Cost per unit volume of cement paste per unit strength	
	Mean ($/kg)	Variability	Mean ($/m3/MPa)	Variability
L3	0.285	7%	9.050	21%
L4	0.285	7%	15.642	30%
M3	0.259	7%	9.421	14%
M4	0.259	7%	12.195	10%
N3	0.234	7%	9.299	31%
N4	0.234	7%	12.319	14%
P3	0.264	7%	8.370	12%
Mean	**0.260**	**7%**	**10.900**	**19%**