School of Civil and Mechanical Engineering
Department of Civil Engineering

# Durability of Concrete Using Fly Ash as a Partial Replacement of Cement

**Pradip Nath**

**This thesis is presented for the degree of**
**Master of Philosophy in Civil Engineering**
**of**
**Curtin University**

**August 2010**

# DECLARATION

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

The following publications have resulted from the work carried out for this degree:

**Publications:**

1. Nath, P., & Sarker, P. (2010). Resistance to permeation of high strength concrete containing fly ash. Accepted for the *2nd International Symposium on Life-cycle Civil Engineering (IALCCE 2010)*, Taiwan Tech, Taipei, Taiwan, 27-31 October.

2. Nath, P., & Sarker, P. (2011). Effect of fly ash on the durability properties of high strength concrete. Accepted for the *12th East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-12)*, Hong Kong, 26-28 January.

**Signature:**

**Date:**

# ABSTRACT

Utilization of fly ash as a supplementary cementitious material adds sustainability to concrete by reducing the green house gas emission associated with cement production. Fly ash is a by-product of coal fired power stations. The properties of fly ash depend on the type of coal and its burning process. Due to the variation in composition, different fly ash affects the properties of concrete differently. Research data on the performance of concrete containing the Western Australian fly ash is scarce in literature. In this study, mechanical and durability properties of high strength concrete using Class F fly ash from Western Australia were investigated. The ACI 211.4R-08 guidelines were followed to design two series of concretes, each having one control concrete and two fly ash concretes using 30% and 40% fly ash as cement replacement. Fly ash concretes of series A were designed by adjusting the water to binder (w/b) ratio and total binder content to achieve the same strength grade of control concrete.  In series B, w/b ratio and total binder content were kept constant in all the three mixtures. Samples were water cured for 7 and 28 days; and were tested at different ages. The mechanical properties were tested by compressive strength, tensile strength and flexural strength test. The investigated durability properties were drying shrinkage, volume of permeable voids, water and air permeability, carbonation and chloride ion penetrability. The 28-day compressive strength of the concrete mixtures varied from 65 to 85 MPa. The fly ash concretes showed lower drying shrinkage than control concrete when designed with adjusted w/b ratio and the total binder content. Inclusion of fly ash reduced sorptivity and water permeability significantly at 28 days. Fly ash showed no adverse affect on air permeability of concrete. Fly ash concretes showed similar carbonation and had less chloride ion penetration as compared to the similar grade control concrete. In general, incorporation of fly ash as partial replacement of cement improved the durability properties of concrete at early age when w/b ratio was adjusted to achieve similar 28-day strength of the control concrete. The durability properties improved with the increase of fly ash content from 30% to 40% of the binder and with the increase of age. Fly ash concretes of series A achieved similar service life of control concrete in carbonation and resulted in higher service life than that of the control concrete, when chloride diffusion was considered as the dominant form of attack.

# ACKNOWLEDGEMENT

I would like to sincerely express my gratitude to Dr. Prabir Sarker. I am grateful for his unwavering support and guidance throughout the research.

I would like to acknowledge the support of SGS Australia Pty. Ltd. for this research project. I wish to thank the staff of SGS Australia Pty. Ltd. for their assistance in carrying out some tests.

I wish to thankfully acknowledge the financial support provided by CSRP (Centre for Sustainable Resource Processing). I would also like to acknowledge the cordial assistance of Dr. Dan Churach, Education Manager of CSRP.

I would like to thank Professor Hamid Nikraz for his keen support in this research.

I also gratefully acknowledge the help of all of the concrete laboratory technicians.

I wish to sincerely thank my parents for their continued inspiring love and support.

Last, but not the least, I would like to thank God, the source of all blessings.

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# NOMENCLATURE

| | | |
|---|---|---|
| $\varepsilon_{cs}$ | Design shrinkage strain | - |
| $\varepsilon_{csd}$ | Drying shrinkage strain | - |
| $\varepsilon_{cse}$ | Autogenous shrinkage strain | - |
| A | Cross sectional area / Exposed surface area | $mm^2$ |
| $A$ | Mass of oven dry specimen | gm |
| $A_b$ | Boiled absorption | % |
| $a_{ca}$ | Absorption of coarse aggregate | % |
| $a_{fa}$ | Absorption of fine aggregate | % |
| $A_i$ | Immersed absorption | % |
| B | Width of the specimen at the section of failure | mm |
| $B$ | Mass of pycnometer filled with water | gm |
| | or, Mass of saturated surface dry specimen in air | gm |
| $C$ | Mass of pycnometer filled with specimen and water | gm |
| | or, Apparent mass of saturate specimen in water | gm |
| $C_{cr}$ | Critical chloride concentration for initiating corrosion | mass % |
| $C_i$ | Initial chloride concentration in the concrete slice | mass % |
| $C_r$ | Reference chloride concentration | mass % |
| $C_s$ | Chloride concentration at the exposed surface | mass % |
| $C(x, t)$ | Chloride concentration at depth $x$ and exposure time $t$ | mass % |
| D | Diameter of specimen/average depth of the specimen | mm |
| $D$ | Density of water | $gm/mm^3$ |
| $D_{28}$ | Chloride diffusion coefficient at 28 days | $m^2/s$ |
| $D_a$ | Apparent chloride diffusion coefficient | $m^2/s$ |
| $D_a (t)$ | Diffusion coefficient at time $t$ | $m^2/s$ |
| $D_{ult}$ | Ultimate diffusion coefficient | $m^2/s$ |
| $erf$ | Error function | - |
| $erfc$ | Complementary error function | - |
| $f'_c$ | Compressive strength at 28 days | MPa, psi |
| $f_c$ | Compressive strength | MPa, psi |
| $f'_{cf}$ | Theoretical flexural strength | MPa, psi |
| $f_{cf}$ | Modulus of rupture | MPa, psi |

| | | |
|---|---|---|
| $f'_{ct}$ | Characteristic principal tensile strength | MPa, psi |
| $f_{ct}$ | Indirect tensile strength | MPa, psi |
| $f'_{cr}$ | Required average compressive strength | MPa, psi |
| H | Head of water | m |
| I | Initial current | amperes |
| $I$ | Absorption in sorptivity test | mm |
| $I_0$ | Current immediately after voltage is applied | amperes |
| $I_t$ | Current at $t$ minutes after voltage is applied | amperes |
| k | Water permeability coefficient | m/s |
| $k$ | Air permeability | $\mathrm{m}^2 \times 10^{-14}$ |
| $k_{cr}$ | Chloride penetration parameter | $\mathrm{mm/yr}^{½}$ |
| l | Thickness of the specimen | mm |
| L | Length of specimen / Span length | mm |
| $L$ | Gauge length of drying shrinkage specimen | mm |
| $L_{ds}$ | Drying shrinkage in microstrain | - |
| $L_i$ | Initial length of the shrinkage specimen | mm |
| $L_t$ | Length of the shrinkage specimen at any time t | mm |
| $m$ | Diffusion decay constant | - |
| $M_1$ | Initial weight of the dried samples | gm |
| $M_{2i}$ | Weight after immersion | gm |
| $M_{3b}$ | Weight after boiling | gm |
| $M_{4ib}$ | Weight of suspended sample in water | gm |
| $\mathrm{M_{ca}}$ | Mass of coarse aggregate | gm, kg |
| $\mathrm{M_{fa}}$ | Mass of fine aggregate | gm, kg |
| $M_t$ | Change in specimen mass at the time $t$ | gm |
| $\mathrm{M_w}$ | Mass of water | gm, kg |
| N | Exact normality of 0.05 N $\mathrm{AgNO_3}$ solution, | - |
| P | Maximum force applied | kN |
| Q | Rate of flow | $\mathrm{m^3/s}$ |
| $Q$ | Charge passed | coulomb |
| R | Resistance | Ohm |
| $S$ | Mass of saturated surface dry specimen | gm |
| $t$ | The exposure time | seconds |

| | | |
|---|---|---|
| $t_a$ | Time for the pressure change from 55 to 50 kPa below atmospheric pressure | seconds |
| V | Volume of 0.05 N $AgNO_3$ solution used for sample titration,<br>or, Voltage | ml<br>Volt |
| $V$ | Volume of air permeability apparatus including test hole | ml |
| W | Mass of pulverised concrete sample | gm |
| $w_{ca}$ | Moisture content of fine aggregate | % |
| $w_{fa}$ | Moisture content of fine aggregate | % |
| w/b | Water to binder ratio | - |
| w/c | Water to cement ratio | - |
| w/cm | Water to cementitious materials ratio | - |
| $x$ | Depth below the exposed surface | m, mm |

# ABBREVIATIONS

| | |
|---|---|
| AAR | Alkali Aggregate Reaction |
| ACI | American Concrete Institute |
| AER | Air Exclusion Rating |
| AS | Australian Standards |
| ASR | Alkali Silica Reaction |
| ASTM | American Society for Testing and Materials |
| BS | British Standard |
| CSIRO | Commonwealth Scientific & Industrial Research Organisation |
| CSRP | Centre for Sustainable Resource Processing |
| HSC | High Strength Concrete |
| LOI | Loss on Ignition |
| OPC | Ordinary Portland Cement |
| RCPT | Rapid Chloride Penetration Test |
| SCM | Supplementary Cementitious Materials |
| SSD | Saturated Surface Dry |
| VCA | Volume fraction of (oven-dry rodded) Coarse Aggregate |
| VPV | Volume of Permeable Voids |
| XRF | X-Ray Florescence |

# 1. INTRODUCTION

## 1.1. Background

Cement is the most important component of concrete. Production of cement involves an energy intensive kilning process and causes significant contribution to the green house gas emission. The current cement production of the world contributes over 1.5 billion tonnes of carbon dioxide in the atmosphere (Malhotra, 2002a). To ensure greener construction practice, it is essential to reduce the green house gas contributions from cement production or to replace cement with other environmentally friendly and efficient by-product materials.

Currently several supplementary pozzolanic materials such as fly ash, blast furnace slag and silica fume are being researched over the past few decades (Mehta, 1989). Fly ash is a by-product of coal-fired power plants and it is a pozzolanic material. When mixed with Portland cement, the products of fly ash-cement interaction are very similar to those formed by cement hydration (calcium silicate hydrate gel), but with a lower Ca/Si ratio (Escalante-Garcia and Sharp, 2004).

In the context of sustainability, partial replacement of cement in concrete with fly ash can be an effective way of reducing overall cement production, which in turn will reduce green house gas emissions. It also ensures effective utilization of currently under-utilised fly ash (Ash Development Association of Australia, 2010).

Incorporation of fly ash in partial replacement of cement shows reliable mechanical properties, e.g. compressive strength, flexural strength etc. in comparison to ordinary Portland cement (OPC) concrete (Siddique, 2004). Durability properties including water absorption, permeability and chloride penetration indicate enhanced performance with cement replacement by fly ash (Malhotra, 1990), while slightly poorer performance for carbonation was generally noted as compared to Portland cement concrete (Sisomphon and Franke, 2007).

Though fly ash is believed to enhance durability characteristics of concrete, it depends on a wide range of factors. The properties of fly ash vary with the type of coal and its combustion process. Due to the variation in composition, different fly ash affects the properties of concrete differently. For this reason, the results published in the literature vary widely with the variation of fly ash and local conditions, which may not be applicable for the other fly ash available elsewhere. Research data on the performance of concrete containing the West Australian fly ash is scarce in literature. Hence, the properties of concrete utilizing the local fly ash were studied in this research so that it can be appropriately used in construction of concrete structures in Western Australia.

## 1.2. Objectives and Scope

The focus of this research is the utilisation of locally available Western Australian fly ash for concrete structures where durability is the main design consideration. Structures in aggressive conditions such as those in marine environment, desalination plants, industrial operations, water treatment plants, sewage disposal facilities, bridges etc. need highly durable concrete. Therefore, assessing the durability of concrete incorporating the local fly ash is the main objective of this research. The specific objectives of the research are as follows:

- Determination of the workability, compressive strength and tensile strength of high strength concrete containing the local fly ash as different proportions of the binder.
- Determination of the durability properties of concrete containing the local fly ash in different proportions of the binder. The properties include drying shrinkage, sorptivity, water permeability, air permeability, carbonation and chloride penetration of concrete at different ages and subjected to different lengths of curing period.
- Assessment of the effect of fly ash in different proportions of the binder on the properties of concrete. Evaluate the appropriate mix design considerations for enhanced durability of concrete when fly ash is used as part of the binder.
- Demonstrate the effect of the local fly ash on the service life of concrete by attempting a simple method of service life estimation.

The scope of this study included testing of two series of concrete mixes; each having two fly ash-incorporated concrete and one Ordinary Portland Cement (OPC) control concrete. The proportions of fly ash to the total binder were selected as 30% and 40%. The compressive strength of these mixes was selected to be sufficient for marine structure requirement after several trial mix design and testing. The physical properties of aggregates such as particle size distribution, water absorption and specific gravity were considered in the mix design of concrete. The mechanical properties of concrete samples were tested by compressive strength test, indirect tensile strength test and flexural strength test. The durability properties were investigated by drying shrinkage test, volume of permeable voids test, sorptivity test, water permeability test, air permeability test, carbonation test, rapid chloride permeability test and chloride diffusion test. The results of the fly ash concretes were compared with those of the corresponding control OPC concretes. Based on the results of carbonation and chloride diffusion tests, analyses were carried out to estimate the service lives of the concretes and the effect of fly ash was evaluated by comparing the results of the analyses.

## 1.3. Significance

Fly ash concrete can play an important role in the context of sustainability. According to Ash Development Association of Australia (ADAA) (2010), in 2008 only 12% of the total fly ash produced in Australia was used in high value-added applications such as cementitious applications or concrete manufacture. The surplus amount of fly ash (10.1 million tonne) is typically placed into onsite storage ponds awaiting some future opportunity for economic reuse.

In Western Australia, several power stations produce large amount of fly ash each year. Three more coal-fired power stations are considered to be built in the near future. This will produce even more fly ash in Western Australia. However, the usage of fly ash by the concrete industries is still limited. Information regarding the performance of concrete using the Western Australian fly ash is scarce in literature. The huge amount of fly ash that is produced in Western Australia can be utilised potentially in the infrastructure development in this region. Thus a comprehensive study is necessary to understand the properties of concrete containing this fly ash.

This study has aimed to evaluate the durability properties of concrete incorporating the local fly ash as a partial replacement of cement.

The results of this study will be useful for designing durable concrete for structures in aggressive environments such as marine and desalination projects. Due to limited resistance against aggressive materials, concrete face early deterioration which eventually reduce service life of the structure. It requires huge maintenance and repair cost to ensure serviceability. For instance, in USA approximately 18-21 billion dollar is spent every year for repair, rehabilitation, strengthening and protection of the concrete structures (Strategic Development Council, 2006). In this context, fly ash can be utilised to improve durability of concrete without increasing cost of concrete production and further maintenance (Camoes, Aguiar and Jalali, 2003). In addition, inclusion of fly ash in concrete improves the green star rating of concrete structures. Currently, this is a very important design consideration for the development of infrastructures in Australia. The information provided by this study will help increase utilisation of the local fly ash as a replacement of cement in concrete. Thus, it will help improve sustainability of concrete structures by utilising local by-product materials.

## 1.4. Thesis Outline

The thesis is organised in six chapters:

Chapter 1 presents the objectives, scope and significance of this study with a brief background.

Chapter 2 presents the ideas and research conducted previously that are related to fly ash utilisation as a cementitious material in concrete. The factors affecting durability of concrete are also described.

Chapter 3 presents the experimental works consisting of the description of materials and the procedures of the tests conducted.

Chapter 4 presents the results and discussions of the results.

Chapter 5 presents the service life estimation of the concrete.

Chapter 6 provides the conclusions and recommendations for further research.

# 2. LITERATURE REVIEW

## 2.1. Introduction

The effect of incorporation of fly ash in concrete is described in this chapter with regards to previous works. The environmental and durability considerations of concrete production are discussed. The factors affecting the concrete durability are also described in brief.

## 2.2. Concrete production

### 2.2.1. Environmental considerations

Production of concrete uses mostly the naturally available aggregate and commercially produced cement. Thus, production of concrete affects the natural resources and environment. Both coarse and fine aggregates that are used in the concrete come mostly from the local quarries. Continuous extraction of these limited natural resources may cause natural disparity in the long run. The Portland cement production requires a large quantity of energy and it emits huge amount of carbon dioxide gas ($CO_2$) as a result of calcinations process. The calcination reactions to process 1 ton of Portland cement releases 0.53 tonnes of $CO_2$ into the atmosphere. The total $CO_2$ emission per tonne of cement production becomes about 1 tonne if carbon fuels are used as the source of energy for the production process (Lawrence, 2003). The world's cement production contributes over 7% of green house gas (Malhotra, 2002a). It has now become a major concern, as the demand of cement is increasing with the advancement of both the developing and developed nations. According to Sakai (2009), world's cement production in 2007 was estimated as 2.77 billion tonnes, with concrete production estimated as 15 billion tonnes. On the assumption that cement consumption per person will double and the population will reach nine billion in the future, world's cement production is expected to reach 7.56 billion tons. This means that approximately 6.6 billion tons of cement-originated $CO_2$ will be emitted. The increased production of cement will have severe impact on the environment with the increasing demand of raw materials and fuel for energy required for cement production. It is anticipated to deteriorate the global warming control stride.

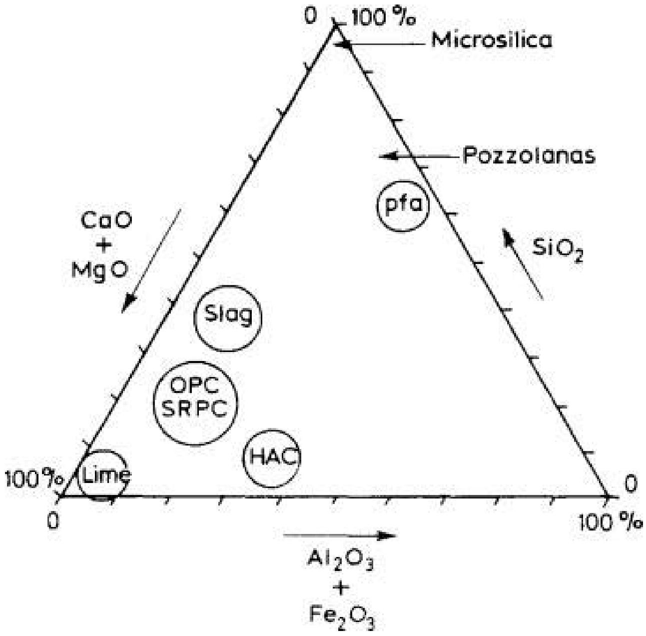
### 2.2.2. Durability of concrete

Concrete durability is defined as its resistance to weathering action, chemical attack, abrasion and other degradation processes while maintaining its desired engineering properties throughout the service life. Concrete made with traditional Portland cement is a durable material in non-aggressive mild environment. In such conditions, good resistance against harmful materials is normally achievable by proper proportioning and production. However, being a non-homogeneous porous material, concrete is susceptible to the attacks from aggressive agents such as chloride, sulphate and acid. These agents react mainly with the cement hydration products in the concrete and disintegrate the stability of concrete. The chemical degradation of cement-based materials is twofold: the dissolution of different hydrates of cement and the diffusion of dissolved species into the pore solution (Xie, Shao and Burlion, 2008). The cement hydrates (calcium hydroxide and calcium silicate hydrate) bind the aggregates in concrete. The deterioration of concrete takes place when these binder hydrates get decomposed due to aggressive chemical attack. Continuation of the deterioration eventually reduces service life of concrete structure.

## 2.3. Supplementary cementitious materials

The growing concern regarding environmental impacts of cement production leads the way to search for supplementary binder materials in concrete. Currently several supplementary pozzolanic materials are being utilised as partial replacement of cement. These materials include fly ash, blast furnace slag and silica fume (Mehta, 1989). The compositions of the various supplementary materials are different. Figure *2-1* shows the typical composition of some common supplementary cementitious materials. Fly ash contains relatively higher proportion of $SiO_2$, $Al_2O_3$ and $Fe_2O_3$ and lower CaO content as compared to slag and other cementitious materials.

Silica fume is a by-product in the reduction of high-purity quartz with coke in electric arc furnaces in the production of silicon and ferrosilicon alloys. Because of its extreme fineness and high silica content, silica fume is a very effective pozzolanic material. The addition of silica fume increases the early strength of concrete (Duval and Kadri, 1998). Silica fume serves a dual role as a filler and pozzolan (Sabir, 1997). Due to its small particle size, it can enter the spaces that exist between the particles of cement to improve packing. It contributes to the formation of calcium silicate hydrate (CSH). Silica fume could replace potentially small portions of cement due to its high reactivity with calcium hydroxide produced during the hydration of Portland cement.



pfa = pulverised fuel ash (fly ash)

OPC = ordinary Portland cement

SRPC = sulphate resisting Portland cement

HAC = high alumina cement

**Figure 2-1: Triangular diagram of common cementitious materials (Lees, 1990)**

Blast furnace slag is produced as a by-product during the manufacture of iron and steel. The production of slag has been shown to release up to 80% less green house gas emission than conventional Portland cement (Roy and Idorn, 1982). Ground granulated blast-furnace slag (GGBS) is commonly used in combination with portland cement in concrete for many applications. Concrete made with GGBS has many advantages, including improved durability, workability and economic benefits (Roy and Idorn, 1982). The drawback in the use of GGBS concrete is that its strength development is considerably slower than that of portland cement concrete. Ground granulated blast-furnace slag is therefore not commonly used in applications where high early age strength is required.

## 2.4. Fly ash

### 2.4.1. Production of fly ash

Fly ash is a by-product of the combustion of pulverised coal in thermal power plants. Figure *2-2* shows the process of producing fly ash in a power station. Coal is fed to a series of mills within a power station that pulverise the coal to a very fine powder. This pulverised coal is fed into a boiler to combust the coal to generate heat, which is then used to produce steam required for power generation. During the coal combustion process, minerals in the coal fuse to form glassy alumina-silicate spheres. These spheres remain in suspension within the flue gas from the boiler and are ultimately collected downstream by either electrostatic or mechanical precipitation. When coal is burnt in a modern pulverised fuel furnace, two types of ash are produced. The fine ash, which is recovered from the flue gas, is called fly ash (FA). This material comprises up to 90% of the total ash produced. The remainder consists of similar particles that have fused together into aggregate sized lumps. These fall to the bottom of the furnace and are known as furnace bottom ash (FBA).

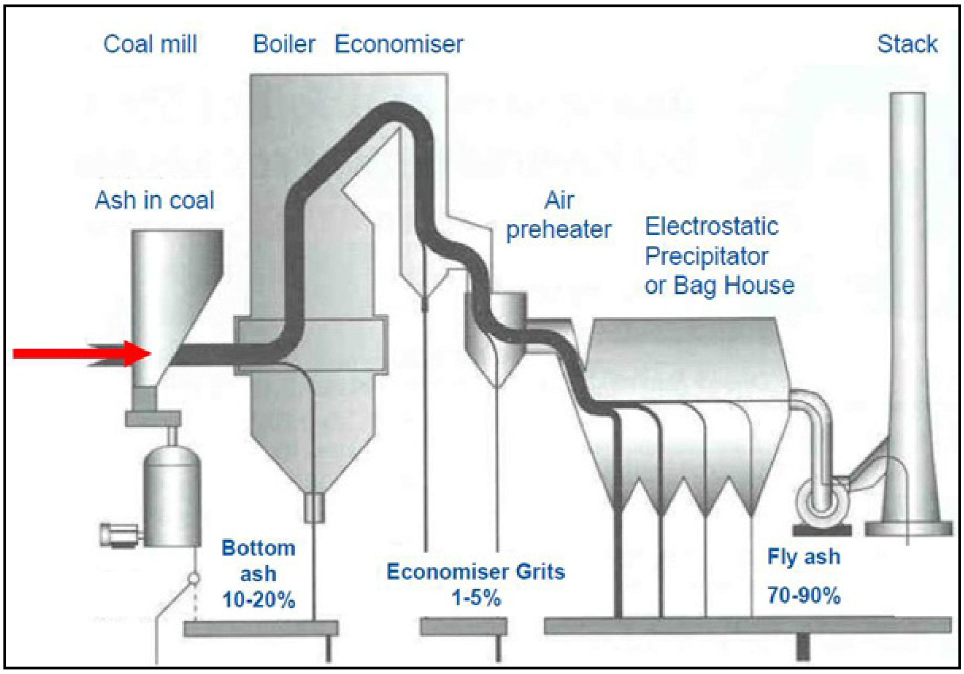


**Figure 2-2: Process of fly ash production in a coal fired power station (*Coal fired power station 1*, 2010)**

As defined by the ASTM C 618 Standard (ASTM Standards, 2008), fly ash is *'the finely divided residue that results from the combustion of ground or powdered coal and that is transported by flue gasses'*. It appears as fine grey powders consisting mostly of spherical glassy particles that are produced at very high temperature of about 1400$^{o}$C in the furnace. Particles of fly ash vary in a wide-range of shapes, the majority being spherical particularly in the smaller size range. Figure *2-3* is a typical micrograph of fly ash particles, taken using a Scanning Electron Microscope. The chemical and mineralogical compositions of fly ash are governed by the types of coal and the burning process. It mainly consists of relatively large percentage of aluminosilicate glass and crystalline phases (Bucea, Cao and Sirivivatnanon, 1996). Fly ash has pozzalonic properties and it reacts chemically with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. Fly ash can significantly improve concrete performance in various ways. More importantly, there are 80% to 90% less green house gas emissions in the production of fly ash than cement (Duxson et al., 2007).

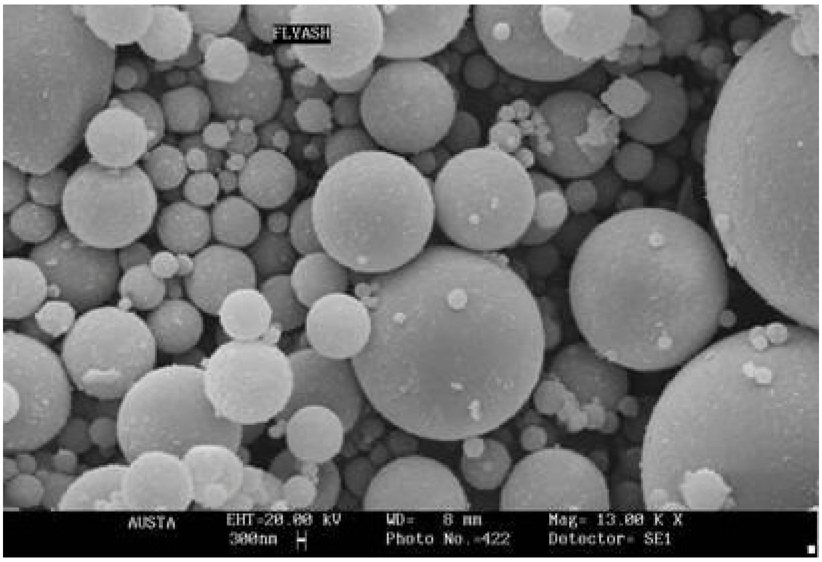


**Figure 2-3: Typical fly ash particle size and shape (*Fly ash particles,* 2010)**

### 2.4.2. Types of fly ash

Three types of fly ash were defined in ASTM C 618 (ASTM Standards, 2008): Class N, Class F and Class C. Class N fly ash includes raw or natural pozzolans such as volcanic ash, calcined clays and shales etc. Class F fly ash is typically produced from burning anthracite or bituminous coal, but may also be produced from subbituminous coal and from lignite. It is also known as low-calcium fly ash (< 10% CaO) and it has pozzolanic property. Class C fly ash is typically produced from burning lignite or subbituminous coal, and may also be produced from anthracite or bituminous coal. Class C fly ashes contain total calcium contents, expressed as calcium oxide (CaO), higher than 10%. It is also known as high-calcium fly ash. Class C fly ash has self-cementing property.

### 2.4.3. Fly ash usage

There are several applications where fly ash can be utilised for engineering and non-engineering purposes. In some applications it is used for its physical characteristics while its chemical characteristics proved most effective usage (Bucea, Cao & Sirivivatnanon, 1996). Fly ash produce a compacted mass only about 60% of that of dense sand, therefore it is ideal for backfilling retaining walls and dams over soft soil because of its high internal angle of friction, low unit mass and reduced settlement (Heidrich, 2003). As by-products of a very efficient industry, for a given power station, the types of ash have consistent properties and many potential uses. Many new potential uses have been identified by research conducted in Australia and overseas. The following are some possible applications:

- Flowable fill
- Mine and land fill
- Road base stabilisation
- Roller Constructed Concrete Dams and pavements
- Premixed Concrete
- Precast Concrete
- Concrete Road Pavements
- Concrete Masonry
- Shotcrete
- Geopolymer Concrete

The coarse furnace bottom ash (FBA) is not highly pozzolanic in nature and is less suitable for cement or concrete products. It can be used as a sand replacement, aggregate for lightweight blocks, a road-base component, and as engineered bulk fill. In recent years agricultural applications have increased in volume because of its suitability as drainage mediums.

#### 2.4.4. Fly ash in Australia

Fly ashes produced in Australian power stations are light to mid-grey in colour and have the appearance of cement powder. Particle sizes range from less than 1 micron to 200 micron and are irregular to spherical in shape. According to Heidrich (2003), the majority of fly ash produced in Australia is classified as F type (ASTM C 618, ASTM Standards, 2008). The main components are silica and alumina (80-85%) and CaO (< 10%). Mean compositions of Australian fly ashes are shown in Table *2-1*. About 85% of the current beneficial use of fly ash is to enhance the properties of concrete and other building materials and used to good effect with road base binders and asphalt filler.

**Table 2-1: Principal chemical constituents of Australian coal fly ashes as percentages (Heidrich, 2003)**

| | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $Na_2O$ | $K_2O$ | $SO_3$ | L.O.I.* |
|---|---|---|---|---|---|---|---|---|---|
| Mean | 61.1 | 26.2 | 4.2 | 1.7 | 0.9 | 0.8 | 1.1 | 0.2 | 2.6 |
| Std. Deviation | 6.62 | 2.48 | 3.31 | 1.74 | 0.54 | 1.05 | 0.62 | 0.19 | 2.78 |

*Loss on ignition

Australia has significant dependency on coal fired power stations for power generation as many other industrialised nations. The installed capacity operating as coal fired power stations stands at approximately 84% of total power generation for the nation. Based on the installed capacity in 1999, national electricity demand growth estimates and proposed new capacity, ash material availability is expected to increase at around 3-5% annually (Heidrich, 2003).

According to Annual membership survey report 2008 of Ash Development Association of Australia (2010), approximately 14.6 Mt (million tonnes) of Coal Combustion Products (CCP) were produced within Australasia in 2008. Only 4.584Mt (or 31%) of CCPs have been effectively utilised in various value added products or to some beneficial end over the period. On a per capita basis, this equates to about 208 kg/person recycled or reused against about 664 kg/person production. Approximately 1.787 Mt (or 12%) was used in high value-added applications such as cementitious applications or concrete manufacture. Surplus CCPs (10.1 Mt) are typically placed into onsite storage ponds awaiting some future opportunity for economic reuse.

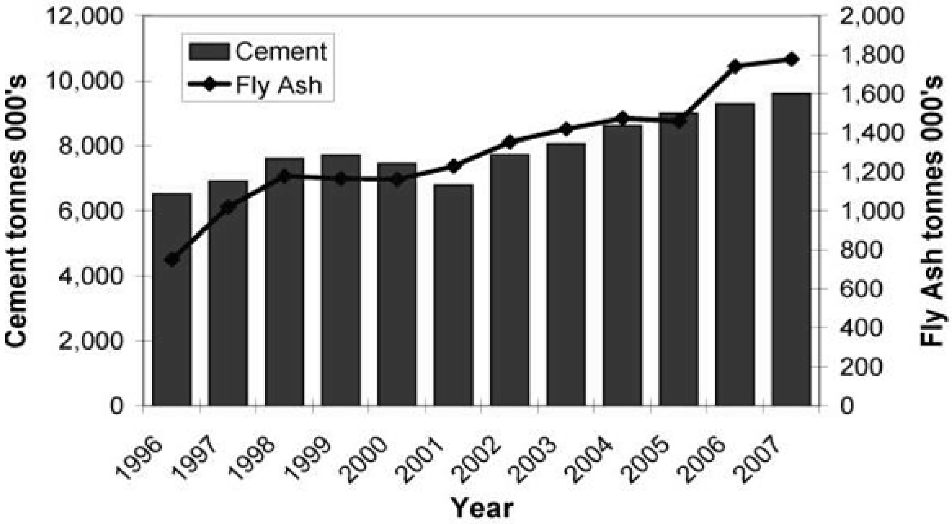


**Figure 2-4: Comparison of sale of cement and fly ash used in cementitious application (Ash Development Association of Australia, 2009)**

In Australia fly ash is normally used at a dosage of about 60-100 kg per cubic meter of concrete, which represents about 20% of the total binder (Bucea, Cao & Sirivivatnanon, 1996). Figure *2-4* shows the growth in fly ash (cementitious use) sales compared to cement sales over the past years. Fly ash sales have increased at a faster rate than cement sales over the corresponding period.

## 2.5. Use of fly ash in concrete

Although the earliest noteworthy study of the use of fly ash was in 1937, its use as a pozzolanic ingredient was recognized as early as in 1914 (*Fly ash*, 2010). Volcanic ash, which possesses similar properties to fly ash, was used as pozzolan in Roman structures such as *aqueducts* or the *Pantheon*. Its use became more common since 1980s. At first, it was used as a cost-saving measure. But over the years, the concrete industry discovered its qualitative advantages.

### 2.5.1. Reactivity of fly ash

The chemical compounds of fly ash and Portland cement are similar. Fly ash compounds are generally amorphous (glassy) due to rapid cooling, while those of cement are crystalline, formed by slower cooling (Technical Bulletin 2, 2005). The typical composition of different fly ash and Portland cement is shown in Table *2-2*. Portland cement is richer in lime (CaO) in comparison to fly ash. Fly ash has higher reactive silicates than portland cement. Portland cement is manufactured with CaO, almost 20% of which is released in a free state during hydration (Technical Bulletin 2, 2005). This free lime is available to react with fly ash in the form of water soluble Calcium Hydroxide (CaOH). The reaction product is similar to the cement hydration product calcium silicate hydrate (Figure *2-5*). Thus it is apparent that a blend of cement and fly ash will increase the amount of durable binder in the concrete.

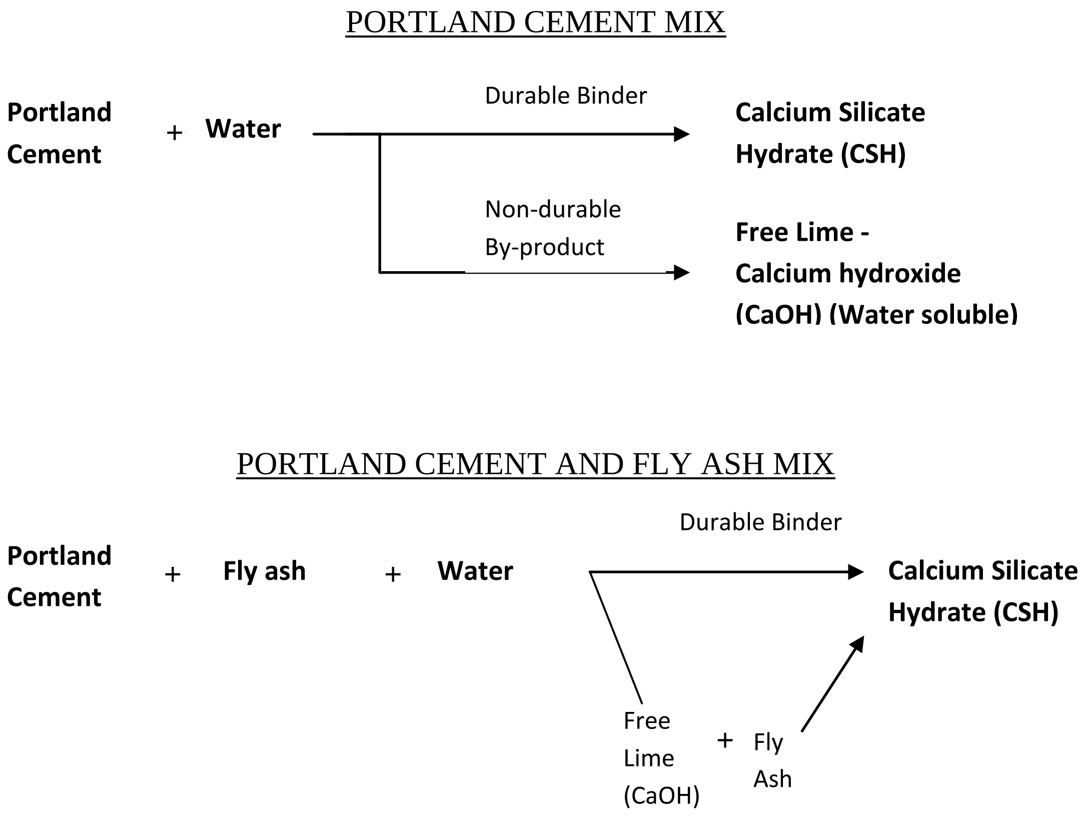


**Figure 2-5: Hydration products of cementitious binders.**

**Table 2-2: Typical chemical compounds in pozzolans and portland cement (Technical Bulletin 2, 2005)**

| Chemical compound | Pozzolan type | | | Cement |
|---|---|---|---|---|
| | Class F | Class C | Class N | |
| $SiO_2$ | 54.9 | 39.9 | 58.2 | 22.6 |
| $Al_2O_3$ | 25.8 | 16.7 | 18.4 | 4.3 |
| $Fe_2O_3$ | 6.9 | 5.8 | 9.3 | 2.4 |
| CaO | 8.7 | 24.3 | 3.3 | 64.4 |
| MgO | 1.8 | 4.6 | 3.9 | 2.1 |
| $SO_3$ | 0.6 | 3.3 | 1.1 | 2.3 |
| $Na_2O$ & $K_2O$ | 0.6 | 1.3 | 1.1 | 0.6 |

### 2.5.2. High Volume Fly Ash (HVFA) concrete

High Volume Fly Ash (HVFA) concrete was developed at Canada Centre for Mineral and Energy Technology (CANMET) in the late 1980s (Mehta, 1999). Typically, this type of concrete has a very low water to cementitious materials ratio (w/cm) and incorporates up to 55% Class F fly ash. Because of low water content, high-range water-reducing admixtures or superplasticisers are used to achieve workable slumps ranging from 150 mm to 200 mm (Malhotra, 2002b).

The use of fly ash in concrete can lead to many improvements in overall concrete performance. Firstly, fly ash reduces the amount of water needed to produce a given slump (Jiang and Malhotra, 2000). The spherical shape of fly ash particles creates a "ball-bearing" effect that fills voids and increases the workability of the mix. Its dispersive ability provides water-reducing characteristics similar to a water-reducing admixture. In addition, fly ash enables the mix to flow better in pump hoses and makes it more workable under hand finishing. Fly ash produces relatively more cementitious paste due to its lower unit weight. By its shape and dispersive action, fly ash particles create better lubrication of the aggregates which increases the flow ability of concrete (ACI Committee 211, 2008).

Having reduced quantity of cement in the mix and slow hydration, fly ash concrete generates low heat of hydration (Neville and Brooks, 1987) as compared to Portland cement concrete. Hence it reduces the amount of thermal cracks and drying shrinkage of concrete. With the development of hydration the fly ash concrete becomes denser as compared to Portland cement concrete. Thus it achieves high long term strength (Sivasundaram, Carette and Malhotra, 1990) and higher resistance to water permeation (Naik, Singh and Hossain, 1994). This makes the fly ash concrete highly resistant to aggressive materials, because most of the aggressive agents finds its way to concrete in dissolved form with water. Fly ash concrete is efficient in increasing the initiation period and reducing the corrosion rate of steel reinforcement due to chloride ingress (Bucea, Cao and Sirivivatnanon, 1996). Hence, the use of HVFA concrete can result in extended maintenance free service life of reinforced concrete structure in aggressive environments.

### 2.5.3. Limitations of using fly ash in concrete

There are some limitations of using fly ash in concrete. If concrete is made with poor quality fly ash, inadequately proportioned and cured, it becomes highly permeable, particularly in the early ages (Ramezanianpour, and Malhotra, 1995). Under such conditions, chlorides as well as moisture and oxygen penetrate the concrete and the protective layer at the reinforcing steel surface can be destroyed. Fly ash concrete shows slower setting time due to slow hydration (Bentz and Ferraris, 2010). Fly ash concretes also have low early strength due to the high alumina and iron oxide content (Mehta, 1985). This difficulty can be eliminated by using accelerating admixture in the mix.

In decorative applications, colour of fly ash may affect the aesthetics of the structure. According to Kosmatka (as cited in Dawson, n.d.), buff-coloured ash can impart a tan colour to the concrete. Although rare, some fly ash has a form of iron that can result in an orange or red colour in the concrete. This is a minor problem as long as the fly ash is uniformly distributed and all batches have equal amounts of the same ash.

## 2.6. Factors affecting durability of concrete

Concrete should be capable of withstanding the conditions, for which it has been designed, throughout the life of the structure. Hence, the durability is the most desirable property of concrete. Durability can be affected by external agents arising from the surrounding environment or by internal agents within the concrete. Causes of deterioration can be physical and chemical or both. The physical causes involve surface wearing and cracking due to external forces and volume change associated with concrete. The chemical causes of deterioration are related to the adverse reactions between harmful agents and cement hydration products. However, the physical and chemical causes are usually interdependent and mutually acting towards degradation of concrete. For instance, expansion and subsequent micro-cracking due to the physical effect of pressure from frost action in a permeable concrete will increase the permeability further and pave the way for deleterious chemical agents. Some of the deterioration mechanisms of concrete are described briefly in the following sections.

### 2.6.1. Thermal effect

Like most engineering materials, concrete has a positive coefficient of thermal expansion. The value for concrete depends both on its mix proportion and on its moisture condition at the time of temperature change. Since the aggregates and cement in the concrete mix have different thermal coefficients, the aggregate proportions and elastic properties of these two materials affect the thermal behaviour of the concrete. For a concrete containing 350 kg cement/$m^3$, with a gravel aggregate, the thermal expansion could be as high as $13\times10^{-6}$/°C, at the higher range of thermal expansion that can be assumed for normal concrete ($6\times10^{-6}$/°C – $13\times10^{-6}$/°C) (Lees, 1990). Heat of cement hydration causes the initial thermal experience of concrete. In concrete which is not insulated the heat generated is dissipated by cooling to the surroundings and slow heat evolution will cause a lower temperature rise than rapid heat output.

If the concrete can expand on heating and contract on cooling without any restraint, cracking should not occur. The problem arises when concrete is restrained against movement internally or externally. Internal restrain is common in massive mass of concrete, when variable temperature at different parts of concrete cause a temperature gradient in the concrete. External restraint exists when the movement of any part of concrete member is prevented by other adjacent rigid parts. Restraint can induce both compression and tension, but in the majority of cases the tension causes cracking (Neville and Brooks, 1987).

The magnitude of temperature effects can be reduced by using cements with supplementary cementitious materials such as fly ash and blast furnace slag.

### 2.6.2. Shrinkage

Concrete experience shrinkage due to loss of water by evaporation or by hydration of cement. Cement in its plastic state undergoes a volumetric contraction, which is known as plastic shrinkage. It is caused by evaporation of water from the surface of concrete. Even when no moisture movement to and from the set concrete is possible, autogenous shrinkage occurs due to loss of water used in hydration of cement. Autogenous shrinkage is very small, typically $50\times10^{-6}$ to $100\times10^{-6}$ (Neville and Brooks, 1987).

For workability purposes the amount of water added to the mixture is much higher than that strictly needed for hydration of concrete. Due to the presence of this excess water, the hardened concrete exposed in unsaturated air face drying shrinkage. When concrete dries, free water present in the capillary pores that is not physically bound evaporates. This process induces a relative humidity gradient in the cement paste and water moves to the empty spaces from the adjacent areas (Neville and Brooks, 1987). In consequence, cement contracts and causes stress in the concrete.

Shrinkage of hardened concrete is influenced by various factors such as aggregate types and proportions, water/cement ratio, relative humidity of surrounding air, and the size of the member. Lower shrinkage could be obtained by utilising non-shrinkable (higher modulus of elasticity) aggregates with a lower water/cement ratio in the concrete (Neville and Brooks, 1987). The incorporation of fly ash also results in lower drying shrinkage of concrete (Kumar, Tike & Nanda, 2007).

Volume changes due to shrinkage are of considerable importance, because in practice, this movement is partly or wholly restrained such as in concrete slabs laid on granular sub-bases, which provide high friction and can cause high tensile stresses. Differential shrinkage, which can occur in a concrete slab used for road construction, can also cause warping or curling and tensile stresses (Neville, 1995). If there are no joints between slabs or reinforcement in concrete, then the concrete will crack. Shrinkage of concrete is also important in prestressed concrete members, because the force in the prestressing strand is relaxed due to shrinkage.

### 2.6.3. Alkali aggregate reaction

The reactive silica constituents of the aggregate and the alkalis in the cement cause a chemical reaction known as alkali-silica reaction (ASR). Another type of deleterious reaction is alkali-carbonate reaction (ACR) which is rare. These reactions are commonly defined as Alkali-aggregate reaction (AAR). It is a major problem of concrete durability in western part of USA and some parts of UK. In Australia, alkali aggregate reaction is not common (Standards Australia, 1996a).

An alkali-silicate gel is produced in the ASR due to the reaction between the alkaline hydroxide derived from the alkalis ($Na_2O$, $K_2O$) in the cement and reactive forms of silica in the aggregate (eg: chert, quartzite, opal, strained quartz crystals). The gel increases in volume by taking up water and so exerts an expansive pressure, resulting in expansion, cracking and disruption of cement paste and characteristic 'map cracking' of the concrete (Neville and Brooks, 1987). The swelling or expansion that occurs due to water absorbed by the gel can induce tensile stresses in the concrete with a magnitude of 6-7 MPa (Lee, 2006). Since concrete is weak in tensile strength, this tensile force can lead to cracking which exposes it to increased potential penetration of harmful agents along with water.

In the case of alkali-silica reaction, the reaction usually occurs much later, possibly years after the concrete was placed. The rate at which the reaction occurs is controlled by the size of the silicious aggregate. Finer particles (20 to 30 micron) react within four to eight weeks while larger particles do so after few years.

It is recommended in UK to use minimum 25% PFA (fly ash) with Portland cement having alkali content of less than 3.0 $kg/m^3$ (Neville and Brooks, 1987). The use of pozzolanic materials in the concrete mix as a partial cement replacement can reduce the likelihood of ASR occurring as they reduce the alkalinity of the pore fluid (Shayan, Diggins and Ivanusec, 1996). The alkali present in pozzolans probably contained in the glassy structures of fly ash and take no part in the reaction with aggregates. Moreover, the silica in PFA attenuates the harmful effects of ASR.

### 2.6.4. Acid attack

Concrete is susceptible to acid attack because of its alkaline nature. Acid attack is a problem in industrial processes, in sewers and in circumstances where the concrete is exposed to rapid flows and considerable volumes of acid. Sulphur dioxide ($SO_2$), carbon dioxide ($CO_2$) and some fumes present in the atmosphere form acid in the presence of moisture. Once the concrete comes in contact with these acids, they react with the hydration products of the cement and disintegrate the concrete. The components of the cement paste break down during contact with acids and leave a soft and very weak mass. Most pronounced is the dissolution of calcium hydroxide to produce insoluble calcium salts. The aggressiveness of the acid depends on the solubility of its calcium salt (Lees, 1990). Acids such as nitric acid, hydrochloric acid and acetic acid are very aggressive as their calcium salts are readily soluble and removed from the attack front. In contrast, the salt having low solubility (e.g. salts produced by natural acid present in acid soils and humic acid) and having no solubility (e.g. calcium oxalate produced by oxalic acid) are relatively less aggressive. In this case, the surfaces of the paste exposed to the acid become coated with the insoluble salt and slow down the further reaction by filling up the pores and pathways near the surface. Sulphuric acid is very damaging to concrete as it combines an acid attack and a sulfate attack.

Concrete also can be attacked by water containing carbon dioxide in concentration of at least 50-60 ppm (Neville and Brooks, 1987). This forms the soluble salt, calcium bicarbonate. Attack is generally a surface effect since precipitation of silica gel as a result of cement hydrate dissolution inhibits further attack (Lees, 1990).

### 2.6.5. Sulphate attack

Sulphate attack is one of the most important problems concerning the durability of concrete structures. Under the sulphate environment, cement paste undergoes deterioration resulting from expansion, spalling and softening (Lauer, 1990). Sulphate attack is a complex phenomenon. This term is used to explain a series of chemical reactions between the sulphate ions and the components of hardened concrete. The products in cement paste react when they are exposed to sulphates, oxygen and moisture. Attacks are caused by the formation of gypsum (calcium sulphate) and formation of ettringite (calcium sulphoaluminate). These products occupy a greater volume than the compounds they replace. The increased volume causes expansion and disruption of concrete (Neville and Brooks, 1987).

Concretes that are in contact with sulphate-rich soil or water are vulnerable to sulphate attack. The sulphates react with both $Ca(OH)_2$ and the hydrated tricalcium aluminate ($C_3A$). The product of which are gypsum and ettringite respectively. The reaction of calcium hydroxide with dissolved sulphate ions depends on the nature of the sulphate. Magnesium sulphate is more aggressive than other sulphates, because it leads to the decomposition of calcium hydroxide as well as hydrated calcium silicates and hydrated $C_3A$. The product of the reaction is magnesium silicate that has no binding capacity. Hence magnesium sulphate reduces the strength of concrete.

Concrete containing fly ash or ground granulated blast furnace slag exhibit sulphate-resisting properties. Addition of pozzolan reduces the calcium hydroxide in cement paste and improves the permeability of concrete. This helps to increase the resistance of concrete to the attack of sulphate and other harmful solutions (Malhotra, as cited in Chindaprasirt et al. 2007). The sulphate resisting cement (ASTM, Type V) can also be used which is essentially a cement having lower amount of $C_3A$.

### 2.6.6. Carbonation

Carbonation is one of the processes by which corrosion of reinforcement initiates. The chemical reaction of carbon dioxide with the pore water in the concrete causes carbonation. The whole process involves three substances: carbon dioxide ($CO_2$), calcium phases (Ca), and water ($H_2O$). Carbon dioxide ($CO_2$) is present in the surrounding air, calcium phases are mainly calcium hydroxide ($Ca(OH)_2$) and calcium silicate hydrate (CSH) that are present in the concrete, and water ($H_2O$) is present in the pores of the concrete.

The first reaction is in the pores where carbon dioxide ($CO_2$) and water ($H_2O$) react to form carbonic acid ($H_2CO_3$):

$$CO_2 + H_2O \longrightarrow H_2CO_3$$

The carbonic acid then reacts with the calcium phases:

$H_2CO_3 + Ca(OH)_2 \longrightarrow CaCO_3 + 2H_2O$

Once the $Ca(OH)_2$ has converted and is missing from the cement paste, hydrated CSH (Calcium Silicate Hydrate – $CaO.SiO_2.H_2O$) will liberate CaO which will then also react with carbonic acid:

$H_2CO_3 + CaO \longrightarrow CaCO_3 + H_2O$

During these reactions the pH value of the concrete pore solution drops. The normal pH value of concrete is above 13 and the pH-value of fully carbonated concrete turns to below 9 (Neville and Brooks, 1987). Hence carbonation has an adverse effect on the degree of concrete alkalinity and its ability to protect the reinforcement. When pH level at the concrete near the reinforcement falls below 11, the protective passive layer of Iron Oxide on the steel surface destroys. If the concrete is permeable to the extent that carbonation reaches at the level of reinforcement, corrosion initiates provided that water and oxygen are present. Physical effects of carbonation within the concrete are usually positive. Carbonation of mature concrete densifies its structure, increases strength, and reduces permeability. However, carbonation increases shrinkage of concrete that is fully matured, which can cause additional cracking (Lees, 1990).

Carbonation is generally a slow process. The rate of carbonation increases with a high water/cement ratio, low cement content, short curing period, low strength and high permeability. It is also dependent on relative humidity (RH) of concrete. At the range of 50 to 75% RH, the carbonation rate is the highest. If the RH is below 25%, carbonation occurs at a negligible rate. At more than 75% RH, moisture in the pore restricts the penetration of $CO_2$; hence carbonation retards.

### 2.6.7. Chloride attack

Chloride ion is the most extensively reported element that causes premature corrosion of steel reinforcement (*Corrosion of embedded metals*, 2010). The chlorides in the concrete either come from the components of the fresh mix (water, sand, aggregates, additives), or from external sources such as marine environment and de-icing salts. The chlorides, present in the mix, react in different ways

(Schueremans, Gemert and Giessler, 2007): a part (about 5%) forms insoluble salts or is locked in the pores of the silicates that are insoluble in water; a part (about 85-90%) forms soluble salts (Salt of Friedel) and a part (about 5%) can be found in the concrete as free chlorides, in solution, or easily soluble by adding water.

The chlorides coming from external sources after the hardening of the concrete react very little with the solid phase of the concrete and can be found in the concrete as free chlorides. The water soluble salts (salt of Friedel) act as a stock of free chlorides. In the presence of these salts, the water in the pores will enrich itself with chlorides until a final concentration is reached that equals the product of solubility. The free chloride that remains in the pore water is responsible for the corrosion risk of the reinforced concrete structure. Presence of chloride ion above the critical limit initiates the corrosion. It causes fast and localized corrosion, called pitting corrosion. A subsequent phase is the spalling off of the concrete cover due to the expansive corrosion reaction, which leads to the full exposition of parts of the reinforcement rods to the aggressive environment. The corrosion process is faster near the cracks and fissures because of the easier access of contaminants and because of the reinforcements residing in a low alkaline environment.

Dense concrete of high alkalinity and low permeability can carry higher levels of chlorides without the occurrence of corrosion than permeable carbonated concrete (Lees, 1990). One of the measures that can be taken to improve the durability of a concrete structure is to increase the resistance of concrete to permeation of chloride ions. High-performance concrete containing silica fume, slag, or fly ash is characterized by its improved pore structure with a dense matrix and low permeability, and these factors can offer protection against aggressive materials.

### 2.6.8. Corrosion of reinforcement

Reinforced concrete becomes vulnerable to corrosion of steel when it is affected by carbonation and chloride attack. The corrosion of steel in concrete is an electrochemical process. It requires essentially three elements to occur: two different metals (which act as cathode and anode), an electrolyte and a metallic connection. In concrete two different regions of the reinforcing bar work as cathode and anode due to their electro-chemical potential difference. Concrete acts as the electrolyte and the tie bars or the rebar itself acts as the metallic connection.

At the anode region of the steel an oxidation reaction occurs, which is known as anodic reaction. The positively charged ferrous ions ($Fe^{++}$) at the anode pass into the electrolyte solution and the electrons ($e^-$) flows through the steel towards the cathode region.

Anodic/oxidation reaction: $Fe \longrightarrow Fe^{++} + 2e^-$

At cathode, electrons are combined with oxygen and moisture to form hydroxyl ion ($OH^-$). This is a reduction reaction.

Cathodic/reduction reaction: $4e^- + 2H_2O + O_2 \longrightarrow 4(OH^-)$

To maintain electric neutrality, the ferrous ions pass through the concrete pore water to the cathodic region where they react with hydroxyl ions and from $Fe(OH)_2$ (ferrous hydroxide). This product further reacts with oxygen to form higher oxide, $Fe(OH)_3$ (ferric hydroxide).

$Fe^{++} + 2OH^- \longrightarrow Fe(OH)_2$

$4Fe(OH)_2 + 2H_2O + O_2 \longrightarrow 4Fe(OH)_3$

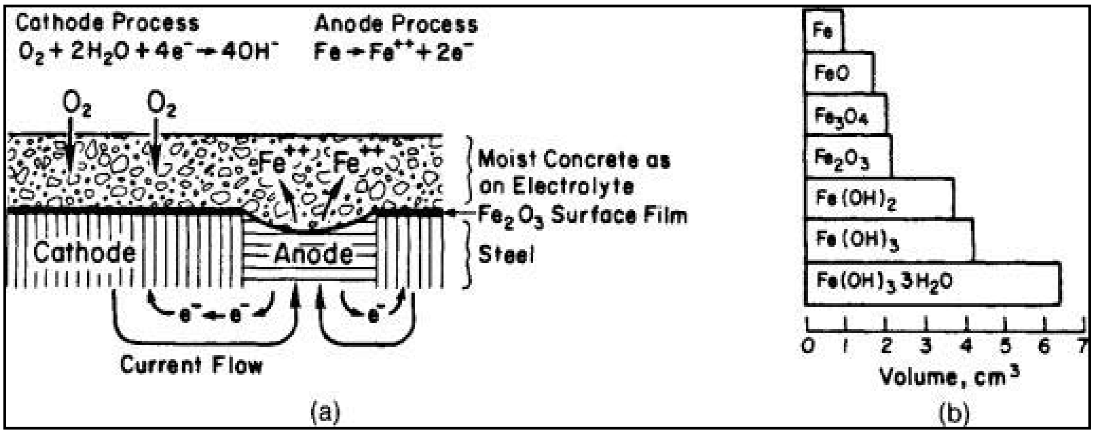


**Figure 2-5: (a) Anodic and cathodic reactions in the corrosion of steel in concrete, (b) Volumetric expansion as a result of oxidation of metallic iron. (Mehta, 1990)**

These hydroxides have higher volume than the original steel and cause internal stress within the concrete. In consequence, cracks develop to spall off the concrete cover. Figure *2-5* shows the mechanism of corrosion and the relative volume of the reaction products. In order to proceed the corrosion process at a significant rate there must be enough oxygen and water present in the vicinity of steel (Lees, 1990). Continuous availability of these elements is influenced by the porosity and permeability of concrete. An impermeable concrete can resist corrosion better than porous concretes.

## 2.7. Previous studies on the effect of fly ash in concrete

The literature is rich in publications regarding the effect of fly ash on concrete. The properties of fly ash concrete vary widely due to its variable composition and variation on mix proportions. Generally, fly ash is categorized as a normal pozzolan, a material consisting of silicate glass, modified with aluminum and iron (Papadakis, 1999). When pozzolanic materials are added in concrete, the cement hydration product $Ca(OH)_2$ (calcium hydroxide) is transformed into secondary calcium silicate hydrate (CSH) gel. This CSH gel helps the larger pores to refine into finer pores. Montgomery, Hughes and Williams (1981) suggest that, as the hydration proceeds around individual spheres of fly ash, the outward growth leads to mechanical interlocking of the hydration products. This enhanced interlinking aspect is thought to be fundamental to the strength imparting mechanism. Thus, the use of mineral admixture such as fly ash improves the quality of concrete by binding the $Ca(OH)_2$ (Papadakis & Tsimas, 2002).

On the downside, fly ash tends to have a low reaction rate when used as an admixture in concrete mixes. At 28 days, the degree of fly ash reaction rate is slightly more than 10% (Lam, Wong and Poon, 2000). Furthermore, only 20% of the fly ash reacts after 90 days. According to Gopalan (1993), one explanation for the low activity of fly ash at room temperature is that the pH of the solution 13 does not meet the requirements of fly ash, 13.3.

Papadakis and Tsimas (2002) studied the efficiency factor and design of supplementary cementitious materials (Fly ash) in concrete and reported that when fly ash substitute aggregates, the strengths are higher than that of the control concrete. When fly ash replace cement, the strength is reduced at first, but as time proceeds this gap is gradually reduced and the strength becomes higher than that of the control for fly ash with higher active silica content in comparison with the cement. An efficiency factor equal to Portland cement (k=1) was reported for pulverised fly ashes in terms of strength. In contrast, Ganesh Babu and Rao (1993) investigated the efficiency factor of fly ash in concrete, considering the strength to water/cement ratio relations, age, and percentage of replacement. The strength decreases continuously from 100 to 35% at replacement levels varying from 20 to 75% respectively. It is reported that the overall cementing efficiency depends on the age and replacement percentage.

The composition of fly ash influences the properties of concrete. Papadakis (1999) and Papadakis (2000a) investigated low-calcium and high-calcium fly ash in Portland cement systems respectively. It is reported that when aggregates are replaced by low-calcium fly ash, higher strengths are observed after 14 days; whereas in cement replacement, higher strengths are observed after 91 days (Papadakis, 1999). When aggregates are replaced by high-calcium fly ash, significantly higher strengths are observed from the beginning of the hydration, as well as higher water binding and significantly lower porosity (Papadakis, 2000a). In the case of high calcium fly ash, due to replacement of cement the strength remained constant.

In a study conducted by Ueda et al. (as cited in Jerath and Hanson, 2007) the influence of fly ash mixed into concrete as the substitute for cement or fine aggregate on corrosion behaviour of reinforcement due to both chloride attack and carbonation, was evaluated by means of electrochemical techniques. The results showed that when fly ash was mixed as the substitute for fine aggregate, restrained permeation of $CO_2$ or $Cl^-$ into concrete resulted in small corrosion loss for steel. However, when fly ash was mixed as a substitute for cement, corrosion loss of reinforcing steel was not restrained under the severe corrosion condition in this study. In other study the conclusion is different. Papadakis and Tsimas (2002) concluded that, the concrete incorporating supplementary cementitious materials, whether used as partial replacement for aggregate or cement, exhibited significantly lower total chloride content. Higher efficiency factor values against chlorides as compared with the corresponding values for strength were presented (k = 2–2.5) for fly ashes.

The study of Onera, Akyuzb and Yildiza (2005) showed that strength increases with increasing amount of fly ash up to an optimum value, beyond which strength starts to decrease with further addition of fly ash. The optimum value of fly ash is about 40% of cement. Fly ash/cement ratio is an important factor determining the efficiency of fly ash. Srinivasan, Tiwar and Banchhor (2004) showed that maintening low water to cementious material ratio is essential along with the use of a superplasticiser to obtain desired properties of strength and durability. Their investigation revealed that pore filling effect and pozzolanic properties of fly ash improve the properties of fresh and hardened concrete. In addition, aggregate grading also plays significant role in fly ash concrete properties. Jerath and Hanson (2007) researched the properties of fly ash concrete using dense and gap graded aggregates. The study shows that dense graded aggregate with fly ash content up to 45% caused higher reduction of the pore space in concrete. The same trend was also found in chloride permeability test.

Toutanjia et al. (2004) studied the effect of fly ash for short time curing period of 14 days. The addition of fly ash exhibited a reduction in compressive strength. The compressive strength decreased by as much as 50% with the addition of 30% fly ash. Mixes with fly ash showed significant increase in strength due to wet–dry exposure. Some fly ashe requires 90 days or more to achieve equal or exceed 28-day control concrete’s strength. They recommended that, because of the slow pozzolanic reactions of fly ash, continuous wet curing and favourable curing temperatures are required for proper development of strength.

Kumar, Tike and Nanda (2007) reported a study of superplasticized high-volume fly-ash concrete substituting in the order of 20 to 60% of cement. Maximum strength at the age of 90 days was developed by 40% fly ash replacement. Abrasion resistance of concrete decreased with increasing fly-ash content. However, Siddique (2003) has shown that abrasion resistance of concrete could be improved approximately by 40% over control mixture with 40% replacement of fine aggregate with Class F fly ash.

Atis (2003b) studied with 50 and 70% fly ash replacement of cement with w/b ratios ranged from 0.28 to 0.34. It showed that the inclusion of high volumes of fly ash in concrete with a low water-cementitious material ratio resulted in a reduction in the shrinkage values of up to 30% when compared to OPC concrete. Superplasticised concretes showed 50% higher shrinkage in comparison to non-superplasticised one. Kumar, Tike and Nanda (2007) reported, for superplasticised fly ash concrete with 20-60% replacement, drying shrinkage of concrete decreased with decreasing w/b ratio and increasing fly-ash content. The least shrinkage was observed with w/b ratio of 0.30 and 60% fly ash. Conversely, the study of Munday et al. and Erdogan (as cited in Atis, 2003b) revealed different findings. Munday et al. reported that the use of fly ash reduces the shrinkage in some concrete and increases it in others. Erdogan (as cited in Atis, 2003b) reported that the inclusion of fly ash in concrete generally increases the shrinkage.

Fly ash influences the pore structure of concrete in different way. By replacing up to 45% class F fly ash, reduced pore diameter and porosity of concrete were observed at 28 days, whereas fly ash-cement paste revealed increased porosity (Poon, Lam and Wong, 2000). Papadakis (1999) observed increased porosity when Class F fly ash replaced cement and decreased porosity when fly ash replaced aggregate in mortar.

Naik, Singh, and Hossain (1994) tested concretes with up to 70% Class C fly ash and obtained reduced air and water permeability of fly ash concretes at 91 days. They reported best performance for 50% fly ash replacement. Tasdemir (2003) investigated the effect of Class C fly ash as one of the mineral admixtures, replacing 10% of cement in concrete with fly ash and using w/b ratio of 0.60. Higher sorptivity coefficient was reported for fly ash concrete as compared to normal concrete at early age. However, Camoes, Aguiar, and Jalali, (2003) obtained reduced sorption coefficient by using w/b ratio in the range of 0.25-0.40 and Class F fly ash content of as high as 60% of the total binder.

Gopalan (1996) tested the sorptivity under different curing conditions. The addition of fly ash to a concrete influenced the sorptivity of the hardened concrete which strongly depended on the curing conditions. When fog cured concretes of identical strengths were considered, the sorptivity of the fly ash concrete was found to be lower than that of cement concrete. Under “drying,” the fly ash concrete had higher sorptivity than cement concrete.

Higher carbonation in fly ash concrete than in cement concrete is reported by some researchers (Chen, Sun, Zhang, and Guo, 2007; Jiang, Lin, and Cai, 2000; Khan and Lynsdale, 2002; Sisomphon and Franke, 2007). However, others reported reduced carbonation of concrete by addition of fly ash (Cabrera and Woolley as cited in Atis, 2003a). Atis (2003a) found higher carbonation for 70% fly ash and less carbonation for 50% fly ash incorporation as compared to control cement concrete. The study of Thomas, Matthews, and Haynes (2000) shows that the carbonation of concrete with 15% to 30% fly ash is similar to or slightly higher than the concrete of equivalent strength without fly ash. Concrete containing 50% fly ash carbonated at a significantly faster rate than control specimens of the same grade and the differences were particularly marked for poorly cured concretes. Papadakis (2000b) observed that, the use of fly ash as a cement replacement may result in a shortened carbonation-induced initiation stage in contrast to that as aggregate replacement.

Naik, Ramme, Kraus, and Siddique (2003) used Classes C and F fly ashes for up to 70 and 67% cement replacement respectively to study the long term performance of concrete pavements. Long term performance tests conducted using core specimens from in-place pavements showed that the concrete mixtures containing Class F fly ash exhibited higher resistance to chloride-ion penetration than those containing Class C fly ash revealing greater pozzolanic strength contribution of Class F fly ash relative to Class C fly ash.

Papadakis (2000b) reported that, the specimens incorporating fly ash, whether it substitutes aggregate or cement, exhibit significantly lower total chloride content. The use of SCM as an addition to a concrete mix, replacing either aggregates or cement, significantly lengthens the chloride-induced corrosion initiation stage. In the study of Kouloumbi and Batis (1992) it is reported that the addition of the fly ash causes an increase of the total chloride content of the corresponding specimens over the OPC mortar specimens. Nevertheless, they also noted improved corrosion behaviour of the steel reinforcing bars because fly ash reduces the free chloride content of the corresponding specimens.

Thus it can be seen from the above studies that the application of fly ash in concrete can enhance durability features, but the extent of improvement is dependent on the mix proportioning and the properties of fly ash. Therefore, this study was conducted to the determine the properties of concrete utilizing the local fly ash so that it can be appropriately used in construction of concrete structures in Western Australia.

## 2.8. Performance measures of durability

Performance of concrete may vary widely with the conditions of the surrounding environment, degree of attack and the resisting capability of concrete itself. It can be measured in the real structure as in the service, with the aid of non destructive tests. However, it will only indicate the current status of the concrete and it may not be always possible to recover the concrete from the deterioration once it is built. Hence, the local building Codes such as AS 3600-2009 (Standards Australia, 2009), provide the guidelines for durability in terms of general or special specifications. Following these guidelines it is expected to design durable concrete which can be tested for specific performance criteria. The followings are some important performance indicators of concrete durability that were used in this study.

- Drying shrinkage
- Volume of Permeable voids
- Water sorptivity
- Water permeability
- Air permeability
- Carbonation and
- Chloride diffusion

# 3. EXPERIMENTAL WORKS

## 3.1. Overview

Concrete is a widely used material in building civilisation. Availability of constituent materials in abundant and suitability to form any predefined shape with considerable strength made it a ubiquitous construction material. Properties of concrete depend on the properties of its constituents. The properties of the ingredients of the concrete may vary considerably depending on their sources. The primary objective of this research is to determine the strength and durability properties of high strength concrete containing fly ash sourced from Western Australia. Within the scope of this research, it was planned to have six different mixes, each with a characteristic strength of more than 50 MPa as recommended by AS 3600-2009 (Standards Australia, 2009) for concrete in marine and other aggressive environments. The constituents of the concrete consisted of locally available cement, aggregates, fly ash and tap water. The materials chosen for the experiment are those generally used to make concrete in construction. A conventional concrete mix design procedure was used to design the mixes using fly ash. Each mix of concrete was tested and evaluated for different mechanical and durability properties.

## 3.2. Concrete mixtures

### 3.2.1. Quality of concrete

Quality of the concrete varies widely due to the variation in mix proportion. Different forms of concrete are used for different purposes ranging from low to high performance application. The requirements for specific purpose govern the concrete mixture proportions. This project was focused on the durability of high strength concrete using fly ash as a part of binder. Durability of concrete, that is expected to achieve over the lifetime, is vastly dependent on the surrounding conditions of the structure. It is also affected by the intensity of attack from aggressive materials like chloride ion, sulphate ion, acids etc. Mixture proportions govern the pore structure of the hardened concrete and hence the penetration of the aggressive agents into concrete. The mixture proportions were determined to achieve certain 28-day compressive strength and workability of the concrete. The percentage of fly ash in the total binder was set so that a significant amount of cement replacement could be achieved without substantial reduction in strength.

### 3.2.2. Target strength

As defined by ACI 211.4R-08 (ACI Committee 211, 2008), high strength concrete should have a compressive strength more than 6000 psi (41 MPa). The compressive strength of the concrete was selected following the AS 3600-2009 (Standards Australia, 2009) requirements for most severe environment. In AS 3600-2009, structures in sea water were classified in three exposure categories: B2, C1 and C2. The most severe exposure category is C2, belongs to the structures in the tidal/splash zone. Requirements for classification C2 were used in the mix design.

According to AS 3600-2009, the minimum characteristic compressive strength of the concrete for exposure classification C1 and C2 is 50 MPa. From this characteristic strength the required design strength was determined (section 3.5.1).

### 3.2.3. Concrete mixes

Concrete mixes were selected after trial mix design and testing for required strength. Nine trial mixes were designed and tested to determine the correct proportion of final concrete mixes. These trial mixes are given in Appendix A. Two series of concrete mixes were designed according to ACI 211.4R-08 (ACI Committee 211, 2008): Series A and Series B. Each series of mixture had a control mix (OPC concrete) and two mixes with 30% and 40% fly ash of the total binder content. The variables of these mixes are shown in Table *3-1.* Fly ash concretes tend to show an optimum cement replacement level of about 40% when compressive strength requirement is in concern (Kumar, Tike and Nanda, 2007; Onera et al. 2005). Thus fly ash content is kept limited to 40% of total binder to achieve required strength grade at 28 days.

Series A concretes were proportioned so as to achieve similar minimum compressive strength of 50 MPa at 28 days. The proportions of ingredients were varied to achieve this target. Mainly the water to binder ratio (w/b) and total binder content (cement and fly ash) were adjusted. Series B concretes were designed to assess the effect of cement replacement partially with fly ash while keeping other constituents proportion as same as the corresponding OPC concrete. Since replacement of cement by fly ash usually reduces strength (Ganesh Babu and Rao, 1993), the total binder content was set to 517 kg/m$^3$ to achieve required compressive strength with 40% cement replacement with fly ash.

**Table 3-1: Mix variables of different concrete mixtures**

| Mixtures | | Binder content | | Total binder content (kg/m$^3$) | Water-binder ratio (w/b) |
|---|---|---|---|---|---|
| **Series** | **Mix ID** | **Cement (%)** | **Fly ash (%)** | | |
| A | A00 | 100 | 0 | 355 | 0.41 |
| | A30 | 70 | 30 | 440 | 0.32 |
| | A40 | 60 | 40 | 440 | 0.31 |
| B | B00 | 100 | 0 | 517 | 0.29 |
| | B30 | 70 | 30 | 517 | 0.29 |
| | B40 | 60 | 40 | 517 | 0.29 |

## 3.3. Experimental programme

The coarse and fine aggregates were tested first to determine specific properties that are required for mix design. Table *3-2* is a list of aggregate properties tested. During mixing a slump test was done as per AS 1012.3.1 (Standards Australia, 1998a) to assess workability of the fresh concrete mixes. A number of tests were performed to determine mechanical and durability properties of the concrete. These tests were chosen to assess the individual characteristics of the concrete samples such as strength and durability properties of the concrete. A complete list of the tests is given in Table *3-3*.

**Table 3-2: Properties of aggregates tested**

| **Aggregate properties** | **Standard followed** |
|---|---|
| Sieve analysis / Fineness Modulus | AS 1114.11<br>(Standards Australia, 1996c) |
| Relative density / Specific gravity | ASTM C127- 07 and ASTM C 128 -07a (ASTM Standards, 2007c) |
| Absorption | |
| Bulk density / Unit weight | ASTM C 29 / C 29M - 07<br>(ASTM Standards, 2007a) |

**Table 3-3: Tests to assess the characteristics of the various concrete mixes**

| **Properties** | **Tests** | **Assessed characteristics** | **Standard Followed** |
|---|---|---|---|
| Mechanical | Compressive strength | Development of strength | AS 1012.9<br>(Standards Australia, 1999a) |
| | Indirect tensile strength | Tensile strength capacity | AS 1012.10<br>(Standards Australia, 2000b) |
| | Flexural strength | Flexural strength capacity | AS 1012.11<br>(Standards Australia, 2000c) |
| Durability | Drying shrinkage | Shrinkage due to drying | AS 1012.13<br>(Standards Australia, 1992) |
| | Volume of permeable void (VPV) | Permeable void | AS 1012.21<br>(Standards Australia, 1999b) |
| | Sorptivity | Capillary water permeation | ASTM C 1585<br>(ASTM Standards, 2004b) |
| | Water permeability | Permeability coefficient | GHD/TEL method (n. d.) |
| | Air permeability | Air permeability | Figg’s test (Figg, 1973) |
| | Carbonation | Resistance against carbonation | *fib* CEB-FIP (2006) |
| | Rapid chloride permeability test (RCPT) | Resistance to chloride penetration | ASTM C 1202<br>(ASTM Standards, 2007d) |
| | Chloride diffusion | | NT Build 443<br>(Nordtest Method, 1995) |

## 3.4. Description of materials

The basic ingredients of concrete are cement, aggregate and water. With the development of technology, the properties of concrete have been improved by using different types of admixtures. Hence, concrete proved itself as a preferable material for construction. Typically, a concrete mix consists of about 10 to 15 percent cement, 60 to 75 percent aggregate and 15 to 20 percent water. Entrained air in many concrete mixes may also take up another 5 to 8 percent (*Cement and Concrete basics*, 2010).

While aggregates fill the major portion of concrete volume, binder materials in the presence of water form complex hydration products that unite the aggregates together. Cement is the principal binder that dominated the concrete production, but with the growing concern of global warming, supplementary cementitous materials are now being used as a replacement of cement. These materials includes various industrial by-products like fly ash, ground granulated blast furnace slag, silica fume.

Now-a-days, it has become common to utilise admixture in concrete to enhance specific characteristics of concrete. These characteristics include increased workability, high-early strength, sulphate resistance etc.

**Table 3-4: General Specification of Swan General Purpose Portland Cement - Type GP (Swan Cement, 2004)**

| Parameter | | Test method | Unit | Typical value | Range | AS 3972 – 1997 limits |
|---|---|---|---|---|---|---|
| Chemical analysis | $SiO_2$ | XRF | % | 21.1 | 20.4 – 21.8 | - |
| | $Al_2O_3$ | XRF | % | 4.7 | 4.3-5.1 | - |
| | $Fe_2O_3$ | XRF | % | 2.7 | 2.5 – 2.9 | - |
| | CaO | XRF | % | 63.6 | 62.6 – 64.6 | - |
| | MgO | XRF | % | 2.6 | 2.4 – 2.8 | - |
| | $SO_3$ | XRF | % | 2.5 | 2.2 – 2.8 | 3.5% max |
| | Loss on ignition | AS 2350.2 | % | 2.0 | 1.0 – 3.0 | - |
| | Chloride | ASTM C114 | % | 0.01 | 0.01 – 0.03 | - |
| | $Na_2O$ equiv. | ASTM C114 | % | 0.50 | 0.40 – 0.60 | - |
| Fineness index | | AS 2350.8 | $m^2/kg$ | 400 | 370 – 430 | - |
| Normal consistency | | AS 2350.3 | % | 28.5 | 27.5 – 29.5 | - |
| Soundness | | AS 2350.5 | mm | 1 | 0 - 2 | 5 mm max |
| Initial Setting time | | AS 2350.4 | min | 120 | 90 – 150 | 45 mins min |
| Final Setting time | | AS 2350.4 | min | 195 | 165 - 225 | 10 hr max |
| Compressive strength | | 3 days | MPa | 38 | 35 – 42 | - |
| | | 7 days | MPa | 47 | 44 – 51 | 25 MPa min |
| | | 28 days | MPa | 60 | 56 - 64 | 40 MPa min |

### 3.4.1. Cement

A General Purpose (GP) Portland cement conforming to AS 3972 (Standards Australia, 1997) was used to manufacture the concrete specimens. The cement was produced by Swan Cement. General specifications of the cement are given in Table *3-4*. Sealed bags of cement were stored in the laboratory on a platform above floor and were covered with plastic covering. Thus it was free from any exposure to moisture. Bags were unsealed immediately before mixing.

### 3.4.2. Fly ash

The fly ash used in this study was collected from Collie power station of Western Australia. Fly ash is produced when pulverised coal is burned. The properties of fly ash vary depending on the composition and types of coal. It can also differ in different batches. The fly ash was collected in 2008 as bulk quantity. It was stored in the storage of the laboratory in a large sealed bag. The chemical compositions were investigated at a local commercial laboratory (Ultra Trace Pty. Ltd.). The chemical and mineral compositions of the fly ash are shown in Tables *3-5* and *3-6* respectively. Compositions of three other fly ashes from different states of Australia are shown in Table *3-5* to facilitate comparison. All the fly ashes are classified as Class F fly ash or low-calcium fly ash as per ASTM C 618 (ASTM Standards, 2008).

**Table 3-5: Chemical composition of fly ash.**

| **Parameter** | **Method of test** | **Collie Fly ash (%)** | **Fly ash (Bucea et al. 1996)** | | | **Class F Fly ash* (%)** |
|---|---|---|---|---|---|---|
| | | | **FA1 (%)** | **FA2 (%)** | **FA3 (%)** | |
| $SiO_2$ | XRF | 50.50 | 52.4 | 65.1 | 53.6 | - |
| $Al_2O_3$ | XRF | 26.57 | 28.6 | 25.9 | 25.1 | - |
| $Fe_2O_3$ | XRF | 13.77 | 3.0 | 3.0 | 13.9 | - |
| $SiO_2+Al_2O_3+Fe_2O_3$ | XRF | 90.84 | 84.0 | 94.0 | 92.6 | 70.0 min |
| CaO | XRF | 2.13 | 5.3 | 1.3 | 1.6 | 10.0 max |
| MgO | XRF | 1.54 | 2.1 | 0.7 | 1.2 | - |
| $SO_3$ | XRF | 0.41 | 0.5 | 0.2 | 0.2 | 5.0 max |
| $K_2O$ | XRF | 0.77 | - | - | - | - |
| $Na_2O$ | XRF | 0.45 | - | - | - | - |
| $P_2O_5$ | XRF | 1.00 | - | - | - | - |
| Loss on ignition | - | 0.60 | 0.3 | 1.5 | 1.8 | 6.0 max |

*ASTM C 618 (ASTM Standards, 2008).

**Table 3-6: Mineral composition of fly ash**

(after William as cited in Rickard & Riessen, 2008).

| Component | Composition (wt %) |
|---|---|
| Amorphous | 61.6±0.7<br>inc. Fe (6%) |
| Quartz | 19.9 ± 0.3 |
| Mullite | 15.0 ± 0.3 |
| Hematite | 1.3 ± 0.1 |
| Maghemite | 2.2 ± 0.1 |

### 3.4.3. Fine aggregates

Natural sand was used for all the mixes. The sand was supplied by local suppliers from Baldivis sand pit.  It is widely used within the construction industry as a fine aggregate for concrete. It contains clay and fine silt content of 2% (supplier's specification). Grading of fine aggregates, as shown in Figure *3-1* was within the limits of AS 2758.1 (Standards Australia, 1998b) considering uncrushed aggregate. Fine aggregates were prepared to saturated surface dry (SSD) condition. The water absorption value of fine aggregate was 0.99% and it was within the acceptable limit of 2% as per AS 2758.1 (Standards Australia, 1998b).

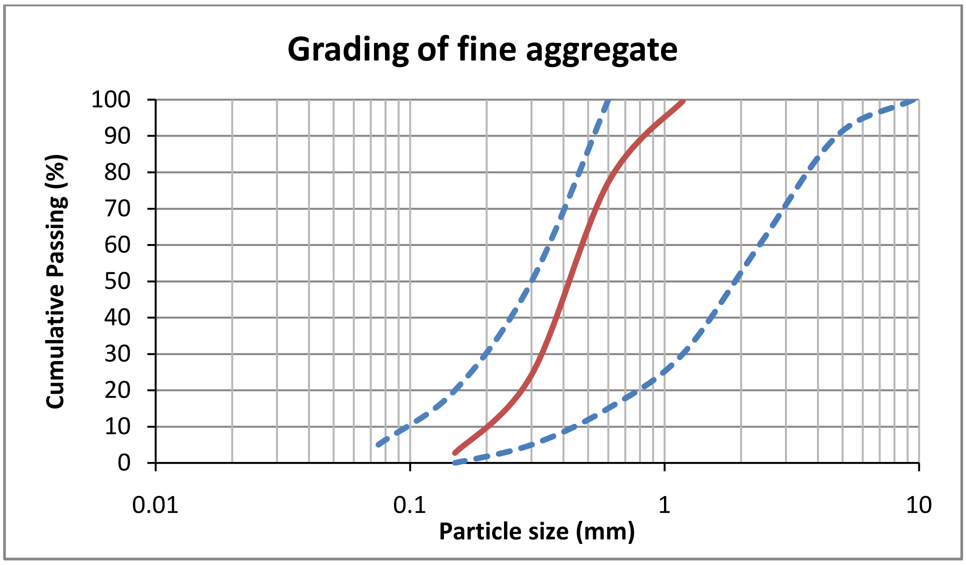


**Figure 3-1: Grading curve of fine aggregate and the limits of uncrushed aggregate as per AS 2758.1 (Standards Australia, 1998b)**

### 3.4.4. Coarse aggregates

Coarse aggregates used in this research were crushed granite, supplied from a local quarry, with nominal maximum size of 7 mm, 10 mm and 20 mm. In order to determine whether the aggregates conformed to the grading requirements under AS 2758.1 (Standards Australia, 1998b), several sieve analyses were conducted. The method is described in section 3.7.1. The results are shown in Appendix B. Water absorption of aggregates may influence the free water content in concrete mix. Thus it was measured carefully for every different size of coarse aggregates and fine aggregate. The water absorption test method is described in section 3.7.2. The results of water absorption are presented in Table *3-7*. The absorption values were well below the acceptable value 2% according to AS 2758.1 (Australian Standard 1998b).

**Table 3-7: Water absorption of aggregates**

| | 20 mm | 10 mm | 7 mm | Sand |
|---|---|---|---|---|
| Absorption (%) | 0.35 | 0.42 | 0.91 | 0.99 |
| Relative density (Oven dry) | 2.67 | 2.83 | 2.66 | 2.60 |

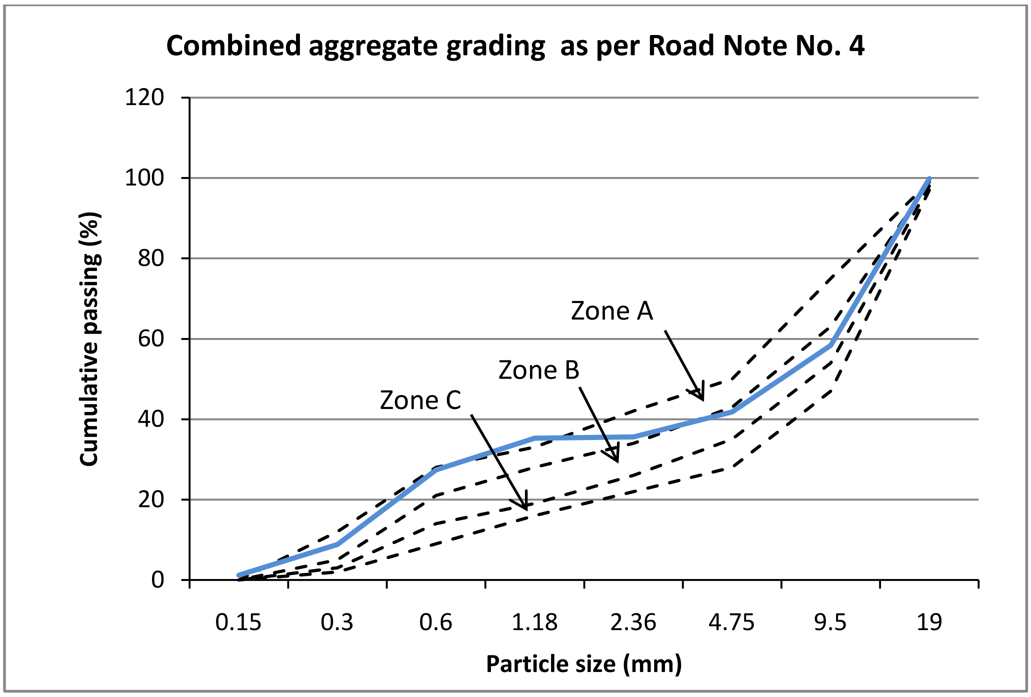


**Figure 3-2: Combined aggregate grading curve and grading limits set in Road Note no. 4 (Road research Laboratory, as cited in Sirivivatnanon et al. 1995)**

Both the 20 mm and 10 mm coarse aggregates met the criteria of single-sized aggregate and were within the ranges recommended in AS 2758.1 (Standards Australia, 1998b). The 7 mm aggregate was within acceptable deviation range of ±10%. Since it was a mixture of fine and coarse aggregates, it helped to obtain a denser combined grading. All three aggregates were combined with sand to obtain a dense graded aggregate combination. The combination of aggregates was fixed by judging individual grading of aggregates and then combining in different proportions by trial and error process. The grading limits set in Road Note no. 4 (Road research Laboratory, as cited in Sirivivatnanon, Cao, Khatri, and Bucea, 1995) were followed as a guide in this regard. The final combined aggregate volume was a combination of 41% 20 mm aggregate, 9% 10 mm aggregate and 15% 7 mm aggregate and 35% sand. Figure *3-2* shows the combined grading curve on the Road Note No. 4 grading limits. The coarser zones B and C is suitable for mixes with high binder content, but a combined grading that falls within one zone is essential to produce good workable concrete (Sirivivatnanon et al. 1995).

### 3.4.5. Water

The water used in the mixtures was taken from the Curtin University of Technology concrete laboratory which is originally the tap water supplied by potable water distributing authority of Perth, Australia. This same water was also used to cure the concrete samples after casting.

### 3.4.6. Admixture

A superplasticiser, known as ‘Rheobuild 1000’ was used. It was a naphthalene sulphonic acid-based high range water reducing admixture that helps to augment workability. This superplasticiser is more effective in dispersing the cement (Neville and Brooks, 1987) which is mainly promoted by the sulphonic acid being absorbed on the surface of cement particles, causing them to become negatively charged and thus mutually repulsive. This increases the workability at a given water-cement ratio. The admixture was supplied by BASF Chemicals. The amount of application was adjusted according to the supplier’s recommendation and the data from trial mixture.

## 3.5. Mix design methodology

### 3.5.1. Mix Design

The mix design was based on the method presented by the ACI Committee 211 (2008), "*Guide for selecting proportions for high-strength concrete using Portland cement and other cementitious materials* (ACI 211.4R-08)". "*Guidelines for the use of high volume fly ash concretes*" (Sirivivatnanon et al. 1995) was also followed to achieve final mix proportions. The design templates for all mixes are given in Appendix C.

Because the performance of high-strength concrete is highly dependent on the properties of the individual material, the proportioning procedure is meant to produce mixture proportions based on the performance of laboratory trial batches. Usually, for high strength concrete mixtures chemical admixtures are used to limit the w/b ratio. Thus many trial mixtures are often required to generate the data necessary to identify optimum mixture proportions. The mix design was done in several steps as described below. It involves designing a basic mixture containing only cement as binder and incorporating fly ash in required percentage later to produce final batches by adjustment of material quantities per unit volume.

*Step 1: Select slump and required strength*

Workability of high strength concrete requires a balance between w/cm ratio and required strength. Usually high range water reducer admixture (HRWRA) is used to achieve sufficient workability of high strength concrete as it necessitates a low w/cm ratio. An initial starting slump of 25 to 50 mm (1 to 2 inch) before adding HRWRA is recommended for high strength concrete made with HRWRA. The desired slump can be achieved by adjusting the required quantity of HRWRA during trail mixing and followed accordingly in the field. Table *3-8* shows the recommended slump.

As discussed in section 3.2.2, the compressive strength was targeted as minimum 50 MPa (7250 psi). To allow any shortcoming during mixing and subsequent reduction in strength results, the average required strength was selected using the Equation 3-1 in accordance with ACI 214R (as cited in ACI Committee 211, 2008).

$$f'_{cr} = 1.10f'_c + 700 \tag{3-1}$$

Where, $f'_{cr}$ = required average compressive strength (psi)

$f'_c$ = compressive strength (psi)

**Table 3-8: Recommended slump for concrete with and without HRWRA (ACI Committee 211, 2008)**

| **Concrete made using HRWRA** | |
|---|---|
| Slump before adding HRWRA | 1 to 2 inch. |
| **Concrete made without HRWRA** | |
| Slump | 2 to 4 inch. |

*Step 2: Select maximum size of aggregate*

ACI 318 (as cited in ACI Committee 211, 2008) states the maximum size of the aggregate should not exceed 1/5 of the narrowest dimension between the sides of forms, 1/3 of the depth of concrete elements, nor ¾ of the minimum clear spacing between reinforcing bars. Based on the strength requirement the recommended (ACI Committee 211, 2008) nominal size of coarse aggregate was ¾ to 1 inch for compressive strength less than 9000 psi. Thus the maximum size of coarse aggregate used was ¾ inch (20 mm). A combination of 20 mm, 10 mm and 7 mm nominal sized aggregate was finally employed in all mixtures.

*Step 3: Select optimum coarse aggregate content*

The optimum content of coarse aggregate depends on its strength, potential characteristics and maximum size. In proportioning normal strength concrete the optimum content of coarse aggregate is given as function of the maximum size and the fineness modulus of the fine aggregate. High strength concretes, however, have a high content of cementitious material and thus are not so dependent on the fine aggregate to facilitate consolidation of concrete. The recommended (ACI Committee 211, 2008) coarse aggregate content is expressed as a fraction of bulk density (Equation 3-2) to be used with fine aggregate of FM 2.5 – 3.2.

$$\text{Mass of coarse aggregate (per cubic yard)} = \text{VCA} \times \text{bulk density} \times 27 \qquad (3\text{-}2)$$

Where, VCA is the fractional volume of oven-dry rodded coarse aggregate (ASTM C 29/C 29M, ASTM Standards, 2007a) as indicated in the Table *3-9*.

**Table 3-9: Recommended volume of coarse aggregate per unit volume of concrete**

| **Optimum coarse aggregate content to be used with fine aggregate with fineness modulus of 2.5 to 3.2** | | | | |
|---|---|---|---|---|
| Nominal maximum size, inch | 3/8 | 1/2 | 3/4 | 1 |
| VCA | 0.65 | 0.68 | 0.72 | 0.75 |

The fineness modulus of fine part of the combined aggregate passing 4.75 mm sieve was calculated and found to be within 2.5 – 3.2. Bulk density of the oven dry rodded aggregate also determined for the combined aggregate. This value is same for all mixture in this study. Thus the value of VCA is taken as 0.72 from Table *3-9*.

*Step 4: Estimate mixing water and air content*

The quantity of water per unit volume of concrete required to produce a given slump is dependent on many factors, including the maximum size, particle shape and grading of the aggregate; the quantity of cement and fly ash and the type of chemical admixture used. Thus the exact quantity of water needs to be selected by mixing trial batches. ACI Committee 211 (2008) suggests maximum first estimate of water quantity for different maximum aggregate size and slumps considering fine aggregate with 35% void. It is 285 lb/yd$^3$ (167 kg/m$^3$) for maximum nominal size of coarse aggregate ¾ inch and slump of 1-2 inch. Since particle shape and texture of fine aggregate can affect water requirement, an adjustment was made when void content of fine aggregate is other than 35%. The Equations *3-3* and *3-4* were used to find void content in fine aggregate and to adjust water requirement respectively.

$$\text{Void content V, \%} = \left(1 - \frac{\text{bulk density}}{\text{relative densitry} \times 62.4}\right) \times 100 \qquad (3\text{-}3)$$

$$\text{Mixing water adjustment, lb/yd}^3 = (\text{V} - 35) \times 8 \qquad (3\text{-}4)$$

For selecting the water quantity, guidelines by Sirivivatnanon et al. (1995) were taken into consideration to reduce number of trial mixture. However, water content for every mixture was less than 167 kg/m$^3$.

Recommended (ACI Committee 211, 2008) air content for concrete mixture with HRWRA and maximum coarse aggregate size of 20 mm (¾ inch.) is 1.5%. This was selected for all mixes.

*Step 5: Select water to cementitious materials ratio (w/cm)*

The compressive strength of high strength concrete depends significantly on the water to cementitious materials ratio (w/cm). The ratio can be increased when HRWRA is used in the mix. The suggested w/cm values for different required strength and maximum aggregate size can be found in ACI 211.4R-08 (ACI Committee 211, 2008). According to this, the maximum w/cm ratio that can be used for 9000 psi compressive strength of concrete containing maximum size of aggregate as ¾ inch and using HRWRA is 0.35. Again, high volume fly ash concretes have w/cm ratio ranging from 0.12 - 0.16 below Portland cement concrete of equivalent grade (Sirivivatnanon et al. 1995). Thus the w/cm ratio for the control mixtures were selected first and then it was adjusted for fly ash incorporated concrete mixes of series A. For mixes of series B, same w/cm ratio of 0.29 was applied for both control and fly ash concretes.

*Step 6: Calculate content of cementitious material*

Once a w/cm ratio was selected, total content of cementitious material was then calculated by diving total water content by w/cm value.

AS 3600 Supplement 1 (Standard Australia, 1994a) suggests a minimum cement content of 400 kg/m$^3$ for exposure classification C concrete (AS 3600 Supplement 1 1994). All of the required cement (cementitious materials) values for marine grade concrete exceeded this value except the control concrete of series A. This mixture contained less than 400 kg/m$^3$ which was considered reasonable as the trial mix achieved strength more than 60 MPa (required strength) with cement content 355 kg/m$^3$ and w/cm ratio of 0.41. Hence the calculated values were used.

*Step 7: Proportioning basic mixture with no other cementitious material*

A basic mixture is proportioned first using only cement as cementitious material. The 'absolute volume method' was adopted. Volumes of air content and all materials except fine aggregate per unit volume of concrete were estimated using their relative density values. Finally the required volume of fine aggregate was calculated simply deducting total volume of all other material from unit volume of concrete. Mass of fine aggregate was then determined by multiplying with relative density.

*Step 8: Proportioning companion mixtures using fly ash*

After getting basic mixture quantities, fly ash was included in replacement of cement. ACI Committee 211 (2008) recommends 15 to 25 % replacement by mass of Portland cement with Class F fly ash and 20 to 35 % Class C fly ash for high strength concrete. However, high strength and good durability properties of concrete, having fly ash at a higher replacement level than these recommended levels, were reported in many literatures (for instance, Malhotra, 1990; Naik et al. 1994; Sivasundaram et al. 1990). Thus, in this study the fly ash replacement level was selected as 30% and 40% of the total binder.

Due to difference in relative density of Portland cement and fly ash, the volume of cementitious materials per unit volume of concrete will vary with the fly ash content, even though the mass of cementitious materials remains constant. Therefore for each mixture, the volume of cementitious materials was calculated by adding the volume of cement and the volume of fly ash. Consequently the volume of fine aggregate was adjusted by absolute volume method.

*Step 9: Trial mixtures*

Final selection of mix proportions necessitates several trial mixtures for individual design. For time constraint, the most favourable mixture was selected considering values in the guidelines (Sirivivatnanon et al. 1995) and other literature. Trial mixes were done accordingly to check for any adjustment.

The mass of aggregate estimated in previous steps was calculated considering relative density in oven dry condition. Thus it is required to adjust the exact quantity of aggregates when they contain moisture. For this, prior to mixing, the moisture contents of aggregates were checked and final free water was adjusted as follows:

$$\text{Fine aggregate, wet} = M_{fa} \times (1 + w_{fa}) \tag{3-5}$$

$$\text{Coarse aggregate, wet} = M_{ca} \times (1 + w_{ca}) \tag{3-6}$$

$$\text{Final water requirement} = M_w - M_{fa} \times (w_{fa} - a_{fa}) - M_{ca} \times (w_{ca} - a_{ca}) \tag{3-7}$$

Where,
$M_w$ = mass of water
$M_{fa}$ = mass of fine aggregate
$w_{fa}$ = moisture content of fine aggregate
$a_{fa}$ = absorption of fine aggregate
$M_{ca}$ = mass of coarse aggregate
$w_{ca}$ = moisture content of fine aggregate
$a_{ca}$ = absorption of coarse aggregate

*Step 10: Adjust trial mixture proportions*

Based on the results on the trial mixtures several adjustments can be made such as slump, HRWRA application rate, coarse aggregate content and grading, and w/cm ratio. The trial mixtures in this study resulted in sufficient strength. However, the aggregate grading and admixture dosage were adjusted to achieve better workability which consequently improved other properties as well.

The procedure used for mix design is summarised in Table *3-10*.

**Table 3-10: Mix design procedure of concrete containing fly ash**

**(ACI Committee 211, 2008)**

| **Procedure** | **Required** | **Designed** |
|---|---|---|
| Data collection | Aggregates: relative density (Oven dry), absorption, fineness modulus, bulk density.<br>Cement and fly ash: types, relative density<br>Admixture : HRWRA properties | Determined and collected |
| Slump required | 25-50 mm before applying HRWRA<br>About 150 mm after applying HRWRA | Step 1 |
| Strength required | Minimum 50 MPa for marine exposure | Step 1 |
| Maximum size of aggregate | Recommended 20 – 25 mm for compressive strength < 9000 psi (62 MPa) | Step 2 |
| Coarse aggregate content | As per Table *3-9* | Step 3 |
| Water estimate | Recommended max. 167 kg/m$^3$ using HRWRA and fine aggregate with 35% void | Step 4 |
| Water adjustment | If fine aggregate void content is other than 35% | Step 4 |
| Air content | Recommended 1.5% | Selected |
| w/cm ratio | Recommended max. 0.35 using HRWRA | Step 5. Selected from literature and guidelines |
| Cementitious material content | Recommended min. 400 kg/m$^3$ (AS 3600 Supplement 1-1994) | Step 6 |
| Fly ash content | Recommended 15-25% class F fly ash | Designed as 30% and 40% |
| Fine aggregate content | Calculate by absolute volume method | Step 8 |
| Water adjustment for moisture in aggregate | If moisture content in aggregate is other than its absorption | Step 9 |
| Final mix | Trial mix adjustment | Step 10 |

### 3.5.2. Mixture proportions

Two series of concrete mixture were proportioned (section 3.3), each having three mixtures. The mix design described in previous section was followed. The quantities of fine and coarse aggregates were determined considering oven dry. Saturated surface dry (SSD) weights of aggregates were adjusted before mixing by checking the moisture contents. Superplasticiser dosage was applied according to the results obtained in the trial mixes. Table *3-11* shows the quantities used per cubic meter of each mixture.

**Table 3-11: Mixture proportions of the concrete mixtures**

| | **Series A** | | | **Series B** | | |
|---|---|---|---|---|---|---|
| **Mix ID** | **A00** | **A30** | **A40** | **B00** | **B30** | **B40** |
| Fly ash (%) | 0 | 30 | 40 | 0 | 30 | 40 |
| Cement (Kg/m$^3$) | 355 | 308 | 264 | 517 | 362 | 311 |
| Fly Ash (Kg/m$^3$) | 0 | 132 | 176 | 0 | 155 | 207 |
| Coarse aggregate - 20 mm (Kg/m$^3$) | 746 | 746 | 746 | 746 | 746 | 746 |
| Coarse aggregate - 10 mm (Kg/m$^3$) | 166 | 166 | 166 | 166 | 166 | 166 |
| Coarse aggregate - 7 mm (Kg/m$^3$) | 273 | 273 | 273 | 273 | 273 | 273 |
| Sand (Kg/m$^3$) | 740 | 661 | 665 | 594 | 570 | 561 |
| Water (Kg/m$^3$) | 145.5 | 141 | 136.5 | 150 | 150 | 150 |
| Superplasticiser (Kg/m$^3$) | 4.27 | 3.97 | 3.96 | 5.64 | 4.00 | 3.53 |
| w/cm | 0.41 | 0.32 | 0.31 | 0.29 | 0.29 | 0.29 |

The coarse aggregate quantities were same for every mixture, because similar grade of aggregate was used for mix design. The optimum coarse aggregate content as recommended in Table *3-9* was kept constant for all mixtures. Water to cementitious materials ratio (w/cm) was varied in concretes of series A and kept constant for concretes of series B as described in section 3.2.3.

## 3.6. Preparation of concrete

Concrete properties can be greatly influenced by the concrete production techniques. Utmost care was taken to ensure uniform mixing standard for all the mixes. A total of six concrete mixes were prepared.

### 3.6.1. Preparation of materials

The preparation of material mainly involves the aggregate preparation. Both coarse and fine aggregates were used in saturated surface dry (SSD) condition. It is very important, because moisture content of aggregate affects the actual free water content in the mix. If the aggregate is too dry, it absorbs water from the mix and reduces water/cement ratio as well as workability of concrete. On the other hand if the aggregate is wet in excess of its absorption, it contributes excess water in the mix which increase water/cement ratio; consequently, concrete properties deteriorate.

**Figure 3-3: Preparation of fine aggregate for SSD condition.**

The coarse aggregate was soaked in water for 24 hours and let it to dry in the air until the SSD condition is reached. Due to difficulties in bringing the large quantity of aggregate to the SSD condition especially in the winter season, an alternative approach was taken. The aggregates were stored in the sealed container when it was close to SSD condition. The moisture content was checked before actual mixing and the water content was adjusted accordingly (section 3.5.1). For this, approximately 1 kg aggregate was taken from the sealed container prior to casting, weighed and placed in an oven at 105°C for a period of 24 hours. The oven dry sample was weighed again and the moisture content of the aggregate was determined as a percentage.

Since the fine aggregate was already moist in the stack, it was not soaked again. Instead air drying was performed under the laboratory shed to achieve moisture content close to that at SSD condition.  Similar procedure of coarse aggregate was applied also for the fine aggregate to check moisture content prior to mixing. Figure *3-3* shows fine aggregates being dried in the laboratory air.

**Figure 3-4: Different types of moulds: (i) flexural strength test mould, (ii) drying shrinkage test mould, (iii) tensile strength test mould and (iv) compressive strength test mould**

### 3.6.2. Mould for casting test specimens

Moulds were prepared before concrete mixing for casting samples. Four different types of moulds were used. A cylindrical mould of 100 mm diameter and 200 mm height was used to cast samples for compressive strength, sorptivity, water permeability, volume of permeable void (VPV), rapid chloride penetration (RCPT) and chloride diffusion test. A cylindrical mould of 150 mm diameter and 300 mm height was used to cast sample of tensile strength test.

For drying shrinkage test, rectangular prisms were cast in the mould with dimension of 75 × 75 × 285 mm. Another mould of dimensions 100 × 100 × 400 mm was used to cast rectangular prism for testing flexural strength and air permeability.

The Figure *3-4* shows different types of mould used in this study.

Every mould was properly cleaned and tightened to maintain exact dimension during casting. The inner surfaces of the moulds were coated with a concrete releasing agent to facilitate demoulding process after hardening of concrete. The releasing agent was a mixture (1:1) of general purpose oil and liquid polishing wax.

### 3.6.3. Concrete mixing and sample casting

Concrete was mixed according to the mixing procedure outlined in AS 1012.2 (Standards Australia, 1994b). Concrete ingredients were mixed in a motor driven laboratory pan mixer with a capacity of 70 litres. The mixer pan has less surface area compared to conventional large tilting drum mixers. Hence it reduces the loss of finer material due to adherence on the surface during mixing.

Each concrete mix was prepared in two batches due to the limitation of mixer pan capacity. Prior to the first batch of each mix the pan was moistened so that it does not adsorb any free water from the mix. The coarse aggregate was loaded first in the pan followed by sand. Aggregates were mixed for 1 minute. Then cement was loaded followed by fly ash. The whole mix was thoroughly mixed for 4-5 minutes. Water was added slowly while the mixing was in progress (Figure *3-5*). Superplasticiser was added along with the mixing water.

The mixing was continued until all the materials were thoroughly mixed. Then a slump test was done in accordance with AS 1012.3.1 (Standards Australia, 1998a). The concrete used for slump test was rejected and was not used for sample casting. The mixtures were designed after trial mixture. Hence, no adjustment of water was necessary.

**Figure 3-5: Water mixed with superplasticiser is being added in the running mixer.**

**Figure 3-6: Moulds on the vibration Table**

The specimens were cast immediately using the freshly mixed concrete. All the moulds except the tensile test mould (150×300 mm cylinder) were filled in two layers. Tensile test mould was filled in three equal layers. After pouring each layer, the moulds were compacted on a vibration table (Figure *3-6*). The time of vibration is monitored so that the concrete does not get segregated due to over vibration. The vibration was stopped when there is very few bubbles liberating and aggregates are just dipped in the mortar. Then another layer of concrete was poured and vibrated. After filling the final layer, excess over flown material were removed from the top surface of the mould and smoothened using a trowel.

### 3.6.4. Demoulding and curing details

The cast specimens were demoulded on the day after casting at approximately 18 to 24 hours of mixing. Care was taken with demoulding to ensure that none of the specimens were damaged. Especially the drying shrinkage samples were removed from mould with great care so that the studs at the both end do not get loose. Then the samples were placed in the curing tanks filled with water as in Figure *3-7*. The curing room was always maintained a constant temperature of 23°C and relative humidity of 60 ± 10%. The specimens were generally cured in the curing tanks up to maximum 28 days of age. The VPV test, sorptivity test and air permeability test were conducted on samples facing two curing regime:

- Regime I: Samples were cured under water up to 28 days of age and after that cured in the curing room environment (23°C and 60 ± 10% RH) until test.
- Regime II: Samples were cured under water up to 7 days of age and after that cured in the curing room environment (23°C and 60 ± 10% RH) until test.

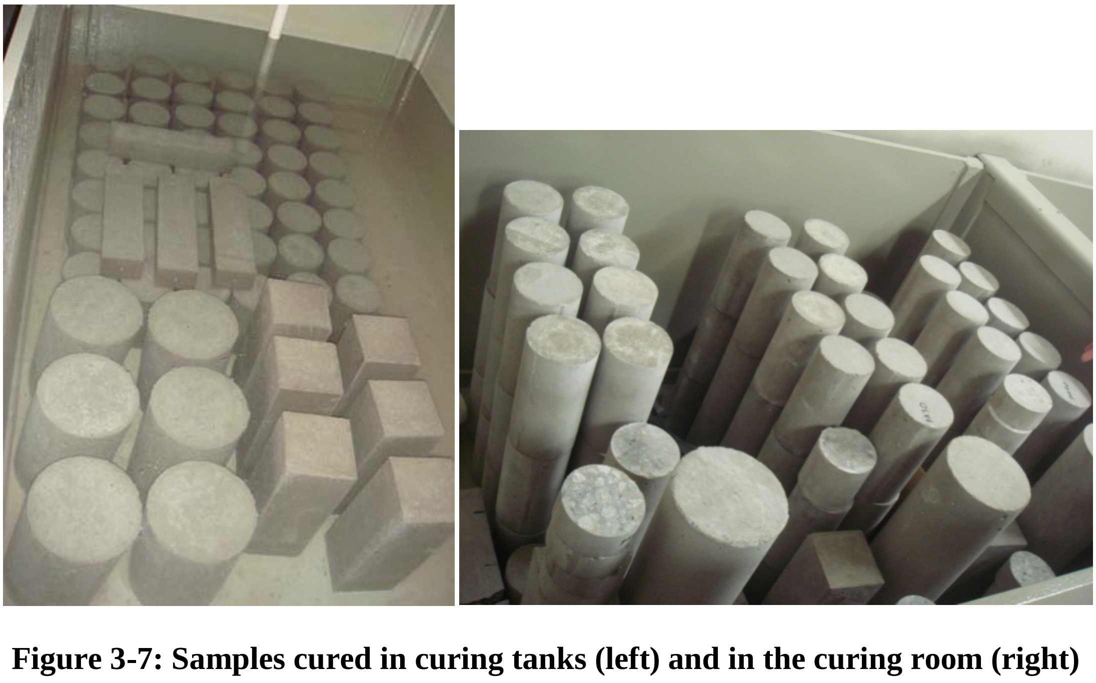


**Figure 3-7: Samples cured in curing tanks (left) and in the curing room (right)**

The curing periods were varied with the specific requirement of the tests. The starting time of actual test also varied depending on the test procedure for different tests. The details are provided to the relevant procedures in Section 3.7. Tests that were done within 28 days of age were performed on samples taken directly from the curing tank.

## 3.7. Test methods

### 3.7.1. Particle size distribution

Sieve analysis was done to determine particle size distributions of fine aggregate and three coarse aggregates of nominal size 20 mm, 10 mm and 7 mm. The method presented in AS 1141.11-1996 (Standards Australia, 1996c) was followed for sieve analysis.

*Fine Aggregate*

Approximately 1 kg of sand sample was collected from the stack randomly and put in the oven at 105$^{o}$C. For sieve analysis, 500 gm of oven dried fine aggregate was taken. The sand sample was divided into two parts (each part not less than 150 gm as recommended by AS 1141-11) to facilitate sieving and tested separately. Sieves of 2.36 mm, 1.18 mm, 600 μm, 300 μm and 150 μm were used and placed on the mechanical shaker in order of decreasing size from the top to bottom. The sample was then placed on the top sieve and the shaker was started to run for about ten minutes. The samples retained on each sieve were then checked by sieving manually for 1 minute. Sieving was considered completed when no more than additional 1% by mass of the residue on any individual sieve passed during hand sieving. Care was taken to keep the mass of retained particle on any particular sieve within maximum permitted in AS 1121.11-1996 (Standards Australia, 1996c). The mass retained on each sieve was then measured and represented as a percentage of the total sample.

*Coarse Aggregate*

Similar procedure as in the fine aggregate was applied for sieve analysis of the coarse aggregates. The samples were oven dried and approximately 5 kg of 20 mm, 2 kg of 10 mm and 2 kg of 7 mm aggregate were sieved. Every sample was divided into several parts meeting minimum requirement (3 kg 20 mm, 800 gm 10 mm and

500 gm 7 mm) for sieving. The sieves used for coarse aggregate sieving were 30 cm in diameter and the sieve aperture sizes used were 26.5 mm, 19 mm, 9.5 mm, 4.75 mm, 2.36 mm, and 1.18 mm. The mechanical shaker was run for 10 - 15 minutes. Sieves were checked for any particle to facilitate passing through. Masses of the retained aggregate were recorded.

### 3.7.2. Water absorption and relative density of aggregates

The relative density and water absorption of aggregate were tested using ASTM standard. ASTM C127-07 (ASTM Standards, 2007b) was used for coarse aggregate and ASTM C 128-07a (ASTM Standards, 2007c) was used for fine aggregate.

*Fine aggregate*

Approximately 1 kg of sand was taken and kept immersed under water. After 24 ± 4 hours the excess water was decanted carefully to prevent loss of fines. A hand-held drier was used to prepare Saturated Surface Dry (SSD) sample while stirring the sample continuously. The SSD condition was checked using a special mould (a frustum of cone with 90 ± 3 mm dia at bottom, 40 ± 3 mm dia at top and 75 ± 3 mm height) and a tamping tool. The aggregate was placed into the mould when it appeared to be surface dry. It was tamped 25 times with the tamping tool. The mould was then lifted vertically. Slight slumping of the moulded fine aggregate indicates surface dry condition; otherwise it retains the moulded shape. This check was done at frequent intervals.

When the sample reached to surface dry condition, about 500 gm of sample was put in the oven to measure water absorption. The remaining sample was used to determine relative density of fine aggregate following Gravimetric (Pycnometer) procedure.

A pycnometer was filled partially and about 500 ± 10 gm surface dry sand was poured in it. The entrapped air bubbles were eliminated by agitating and rolling the pycnometer manually. Then it was filled with water up to its calibrated capacity at room temperature and mass was recorded. The pycnometer was then washed, dried, and cooled in room temperature to measure its empty mass. Finally the mass of the pycnometer filled to its calibrated capacity with water at room temperature was taken.

The water absorption and relative density of the fine aggregate can be calculated using the Equations *3-8, 3-9* and *3-10* (ASTM C 128-07a).

$$Absorption, \% = \frac{S-A}{A} \times 100 \tag{3-8}$$

$$Relative\ Density\ (specific\ gravity)(OD) = \frac{A}{B+S-C} \tag{3-9}$$

$$Relative\ Density\ (specific\ gravity)(SSD) = \frac{S}{B+S-C} \tag{3-10}$$

Where, *A* = mass of oven dry specimen, gm
*S* = mass of saturated surface dry specimen, gm
*B* = mass of pycnometer filled with water, gm
*C* = mass of pycnometer filled with specimen and water, gm

*Coarse aggregate*

According to standard requirement about 3 kg of 20 mm, 2 kg of 10 mm and 7 mm coarse aggregates were taken and kept immersed under water for 24 ± 4 hours. After this time, aggregates were removed from water and excess water was wiped off by rolling the aggregate on the absorbent paper until all visible films of water were removed. The mass of surface dry samples in air was recorded. The same sample was then weighed under water to determine apparent mass in water. The samples were then dried in the oven to a constant mass at 105$^{o}$C. Weight of the sample was taken after cooling to a temperature comfortable to handle.

Water absorption and relative density of coarse aggregate were calculated using the Equations *3-11*, *3-12* and *3-13* (ASTM C127-07).

$$Absorption, \% = \frac{B-A}{A} \times 100 \tag{3-11}$$

$$Relative\ Density\ (specific\ gravity)(OD) = \frac{A}{B-C} \tag{3-12}$$

$$Relative\ Density\ (specific\ gravity)(SSD) = \frac{B}{B-C} \tag{3-13}$$

Where, $A$ = mass of oven dry specimen in air, gm

$B$ = mass of saturated surface dry specimen in air, gm

$C$ = apparent mass of saturate specimen in water, gm

### 3.7.3. Workability test

Workability is an important property of fresh concrete. The subsequent mechanical and durability properties of hardened concrete depend on proper placement and compaction of wet concrete which can be significantly affected by its workability. Poor workability may lead to stiff concrete that is difficult to pump, place and finish properly. Consequently concrete becomes too porous and have poor resistance to permeation of water and aggressive agents. Thus it is essential to consider workability in the mix design to ensure ease of placement and durability of concrete. Testing for workability of fresh concrete was done in accordance with the method presented in AS 1012.3.1-1998 (Standards Australia, 1998a). A mould with the dimension of 300 mm in height, 100 mm top diameter and 200 mm bottom diameter is used to measure the slump of fresh concrete. The following steps were followed in the slump test:

- The slump mould, base plate and temping rod were moistened initially.
- The mould was fixed firmly by standing on the two plates at the bottom.
- The concrete mix was then poured in three equal layers in the mould. Each layer was compacted using a temping rod (600 mm length and 15 mm diameter). Twenty five blows of the temping rod were applied so that it penetrated just past the previous layer.
- After levelling the top surface, the mould was lifted vertically in about three seconds without any lateral of tortional displacements.
- The mould was then placed beside the slumped concrete and vertical displacement of concrete was measured from the top of the mould at centre and edges of the top surface of concrete. The average of these measurements is reported as the slump value.

### 3.7.4. Compressive strength test

Compressive strength was tested on the cylindrical samples of 100 mm diameter and 200 mm depth. The testing procedure for compressive strength was based on the Australian Standard AS 1012.9-1999 (Standards Australia, 1999a). Specimens were kept under water until 28 days for curing and then stored in laboratory environment (23°C) for rest period until the test. All compressive strength tests were conducted using the Controls MCC8 (Multifunctional Computerised Control Console) Machine of 3000 kN capacity. It was electronically operated and the data were acquired from its software. The procedure used to test the specimens is as follows:

- Top surface of cylinders were capped using sulphur to eliminate any roughness (Figure *3-8*).
- The specimen was placed in the centre of the lower plate on the machine and information regarding the specimen was entered in the program of the machine before staring test.
- The loading rate was kept fixed as 0.333 MPa/sec (approximately 20 ± 2 MPa/min) for compressive strength test and it was applied constantly to the specimen until failure. Figure *3-9* shows a specimen being tested in the machine.
- The machine recorded the maximum force exerted and calculated the compressive strength using the given values of cylinder dimensions that was provided beforehand.

**Figure 3-8: Compressive strength test specimens after sulphur capping**

**Figure 3-9: Compressive strength test machine with a sample under loading.**

Each test consisted of three to four cylinders and the compressive strength was taken as the average of the specimen values to the nearest 0.5 MPa. The compressive strength of the sample can be calculated using Equation 3-14 (AS 1012.9-1999).

$$f_c = \frac{1000 \times \mathrm{P}}{\mathrm{A}} \qquad (3\text{-}14)$$

Where, $f_c$ = Compressive strength (MPa),

P = Maximum force applied (kN),

A = Cross sectional area ($mm^2$).

### 3.7.5. Indirect tensile strength test

Indirect tensile strength test is one of the tests to determine the tension capacity of concrete. In this test load is applied in the form of compression that indirectly turn out tensile stress in the specimen. The test was done according the AS 1012.10-2000 (Standards Australia, 2000b). This test is also known as the ‘Brazilian test’ or ‘splitting test’. Samples of 150 mm diameter and 300 mm length were tested at the age of 7 days, 28 days and 335 days using the Control MCC8 machine. The test involved the following steps:

- An oil and grit free, straight and even test plane was selected to facilitate uniform loading. Average diameter was measured at the test plane. Length at the test plane also measured.
- The specimen was placed on the hardwood bearing strips in the bottom part of testing rig and the upper part of the testing rig was fixed on the specimen. It was ensured that the sample was loaded centrally on its longitudinal axis at either edge of the test plane. Figure *3-10* shows a specimen fixed in the testing rig.
- A constant force at a rate of 1.5 ± 0.15 MPa/min was then applied to the specimen until failure. The loading was shock free as an automated machine was used.

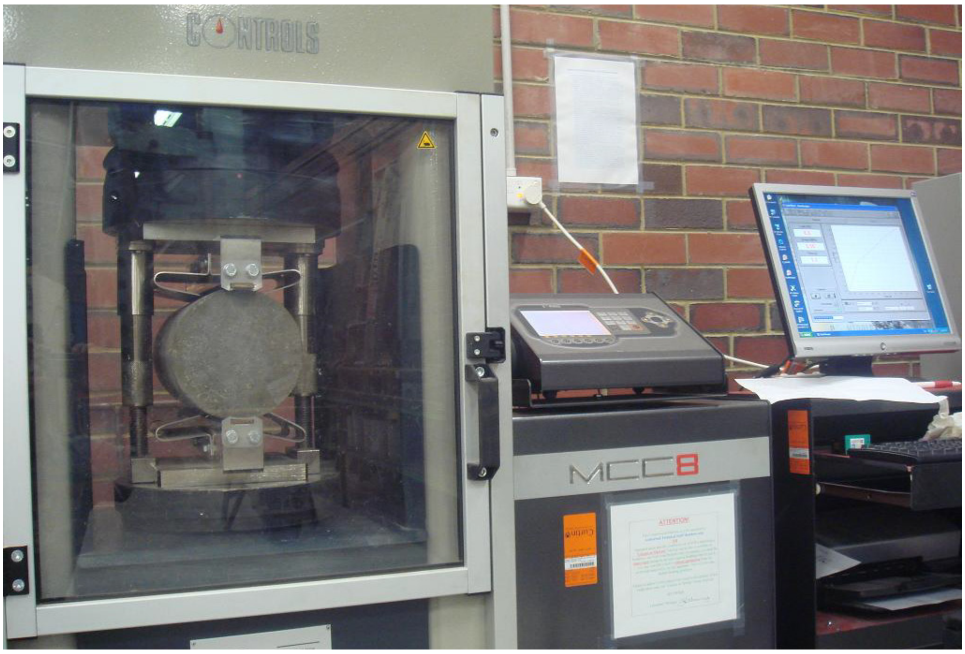


**Figure 3-10: Indirect tensile strength test in progress**

- The load at failure was recorded and tensile strength induced indirectly was calculated using Equation 3-15 (AS 1012.10-2000). Two specimens were tested at every age and average strength was reported.

$$f_{ct} = \frac{2000\mathrm{P}}{\pi \mathrm{LD}} \qquad (3\text{-}15)$$

Where, $f_{ct}$ = Indirect tensile strength (MPa), P = Maximum applied force (kN),

L = length of specimen (mm)

D = diameter of specimen (mm).

### 3.7.6. Flexural tensile strength test

Testing for flexural strength, also known as the modulus of rupture, was conducted following the method presented in AS 1012.11-2000 (Standards Australia, 2000c). The test involves beam specimens of dimensions 100 mm × 100 mm × 400 mm loaded in pure bending to fail due to flexural stress. Figure *3-11* shows a beam being tested in the Controls MCC8 machine. Two specimens were tested for each mix.

**Figure 3-11: Flexural strength test in progress**

The specimen was placed on the supporting roller of the machine. The supporting rollers were set at 300 mm (L) apart and at the same distance from either ends of the specimen. Then the loading rollers at the top of machine were brought into contact of the top surface of the specimen. Loading rollers were adjusted to seat on the third points (L/3) of the supporting span. The force was then applied at a constant rate of 0.0167 MPa/sec. The maximum load sustained before failure and the average dimensions at the failure surface were recorded. The modulus of rupture was determined by applying the Equation 3-16 (AS 1012.11-2000).

$$f_{cf} = \frac{1000 \times \mathrm{PL}}{\mathrm{BD}^2} \tag{3-16}$$

Where, $f_{cf}$ = modulus of rupture (MPa),
P = maximum applied force (kN),
L = span length (300 mm)
B = average width of the specimen at the section of failure (100 mm),
D = average depth of the specimen at the section of failure (100 mm).

### 3.7.7. Drying shrinkage test

The excess water in the concrete evaporates when subjected to dry conditions and cause drying shrinkage of concretes. Drying shrinkage can restrict the size of structural members and the location of control joints that are used to prevent initial cracking of the structure. Cracking due to drying shrinkage is a common form of crack in concrete, particularly in dry climate of Western Australia (Papworth, Rodney, and Trinder 2007). Hence, it bears an important consideration in concrete durability design. Reducing the drying shrinkage will reduce the associated cracking and reduce the risk of having large member in structure as well as concrete pavements.

The design shrinkage strain of concrete ($\varepsilon_{cs}$) can be determined according to AS 3600-2009 (Standards Australia, 2009) by three methods (a) from measurements on similar local concrete; (b) by tests after eight weeks of drying modified for long-term value, in accordance with AS 1012.13 (Standards Australia, 1992); or (c) by calculation in accordance with Clause 3.1.7.2 (AS 3600-2009). The methods (b) and (c) were followed in this study.

*Method (b):*

The method of AS 1012.13 – 1992 (Standards Australia, 1992) was followed to measure the drying shrinkage of the samples prepared in the laboratory. The test method involves three prism specimens (75mm × 75 mm × 280 mm) to be dried in specified condition and checking of the length change with time. A stainless steel gauge was cast into each end of the specimen along the line coinciding the principal axis of the prism. The detail procedure is as presented below:

- Specimens were cured in normal water in the curing tank for 7 days after demoulding within 24 hours of casting.
- At an age of 7 days, the specimens were removed one at a time from the curing tank and wiped the surface dry with a damp cloth. Gauge studs at both ends were also cleaned.

**Figure 3-12: Length of drying shrinkage specimen being measured by a horizontal length comparator.**

- The surface dry specimen was then placed in a horizontal length comparator (Figure *3-12*) so that its axis was aligned with the measuring anvil. The micrometer reading was taken. The specimen was replaced again in the same direction and the reading was recorded. The same process was repeated until at least five consecutive reading were within 0.00005 inch of the average measurement (The accuracy of the micrometer was 0.0001 inch). The average reading was noted as the initial length of the specimen. The readings were taken within 2 mins of removing the specimen from water.
- The specimens were then placed on the drying shelf keeping at least 2 inch distance from all face. The drying was carried out in the curing room with a standard temperature of 23$^{o}$C and a relative humidity of 60 ± 10%.

- The length measurement for each specimen was taken at a specified period of drying at 7, 14, 21, 28, 56, 120 and 180 days.
- The reference bar length was recorded every time at the beginning and end of the measurement, and the average of this length was subtracted to obtain actual length measurement at any specified time. Finally the length change was found using Equation 3-17.

$$L_{ds} = \frac{(L_t - L_i)}{L} \times 10^6 \tag{3-17}$$

Where, $L_{ds}$ = Drying shrinkage in microstrain

$L_t$ = Length of the individual specimen at any specified time t (mm)

$L_i$ = Initial length of the individual specimen (mm)

$L$ = Gauge length (250 mm)

- For each drying period for one sample of concrete, the average drying shrinkage was calculated using only the individual results which were within ± 40 microstrain of the median value of three results.

*Method (c):*

The method (c) for calculating design shrinkage strain is outlined here from AS 3600-2009 (Standard Australia, 2009).

The design shrinkage strain of concrete ($\varepsilon_{cs}$) is the sum of the chemical (autogenous) shrinkage strain ($\varepsilon_{cse}$) and the drying shrinkage strain ($\varepsilon_{csd}$) as shown in Equation 3-18. The design shrinkage strain ($\varepsilon_{cs}$) has a range of ±30%.

$$\varepsilon_{cs} = \varepsilon_{cse} + \varepsilon_{csd} \tag{3-18}$$

The autogenous shrinkage strain shall be taken as Equation 3-19.

$$\varepsilon_{cse} = \varepsilon_{cse}{}^{*} \times (1.0 - e^{-0.1t}) \tag{3-19}$$

Where, t is the time (in days) after setting and $\varepsilon_{cse}{}^{*}$ is the final autogenous shrinkage strain given by Equation 3-20.

$$\varepsilon_{cse}{}^{*} = (0.06 f_c' - 1) \times 50 \times 10^{-6} \tag{3-20}$$

At any time $t$ (in days) after the commencement of drying, the drying shrinkage strain shall be taken as Equation 3-21.

$$\varepsilon_{csd} = k_1 k_4 \varepsilon_{csd.b} \tag{3-21}$$

$$k_1 = \frac{\propto_1 t^{0.8}}{t^{0.8} + 0.15 t_h} \tag{3-22}$$

$$\propto_1 = 0.8 + 1.2 e^{-0.005 t_h} \tag{3-23}$$

Where, $t$ is time in days, $t_h$ is the hypothetical thickness of any member ($t_h = 2A_g/u_e$, $A_g$ = gross area and $u_e$ is the exposed perimeter), $k_4$ is equal to 0.7 for an arid environment, 0.65 for an interior environment, 0.6 for a temperate inland environment and 0.5 for a tropical or near-coastal environment.

The basic drying shrinkage ($\varepsilon_{csd.b}$) is given by

$$\varepsilon_{csd.b} = (1 - 0.008 f_c') \times \varepsilon_{csd.b}{}^{*} \tag{3-24}$$

Where, the final drying basic shrinkage strain ($\varepsilon_{csd.b}{}^{*}$) depends on the quality of the local aggregates and shall be taken as 800 × $10^{-6}$ for Sydney and Brisbane, 900 × $10^{-6}$ for Melbourne and 1000 × $10^{-6}$ elsewhere.

### 3.7.8. Volume of permeable voids (VPV) test

Concrete is a porous material and its permeability property is a function of the extent of permeable voids. The volume of permeable void in concrete was determined in accordance with AS 1012.21-1999 (Standards Australia, 1999b). The method can also be used to determine two forms of absorption in addition to the apparent volume of permeable voids (AVPV), namely boiled absorption ($A_b$) and immersed absorption ($A_i$). The three tests are progressive from one to the others, starting with immersed absorption.

The test was conducted for two curing regimes: regime I and regime II. Samples of regime I were cured under water for 28 days before leaving in the laboratory environment for the period until the test. Samples of regime II were cured under water for 7 days and after that they were taken off the water to cure in the laboratory air until test dates at 28 days and 180 days of age.

The test procedure is as follows:

*Immersed absorption:*

- The cylinder (100 mm diameter and 200 mm depth) samples were cut using a water cooled diamond saw into four equal slices of about 45 mm thickness.
- The samples were wiped dry and weighed to an accuracy of 0.1 g and placed in an oven initially for a period of 24 hours at a temperature of 105°C. After 24 hours the samples were removed from the oven, allowed to cool in a desiccator, weighed and placed back into the oven again. This weight check was repeated every day until the difference between two successive weights was less than 1 gm.
- The last weight of the samples was recorded as $M_1$ to the nearest 0.1 g and the samples were placed in a water bath maintained at a temperature of 23 ± 2°C. The samples were kept immersed for at least 48 hours.
- After 48 hours the samples were surface dried and weighed. The samples were then immersed back into the water and checked the weight after 24 hours. This process was continued until two successive weights produced a difference in weight of less than 1 gm.
- The final weight after immersion was recorded as $M_{2i}$ to the nearest 0.1 gm. At this stage the immersed absorption ($A_i$) can be calculated using the Equation 3-25 (AS 1012.21-1999).

$$A_i = \frac{(M_{2i} - M_1)}{M_1} \times 100\% \tag{3-25}$$

Where, $M_1$ = weight of the oven dried samples (gm)

$M_{2i}$ = saturated weight after immersion (gm)

*Boiled absorption and apparent volume of permeable void:*

- The surface dried samples were placed in a water bath at room temperature, and boiled for 5.5 ± 0.5 hours.
- After boiling, the water bath was switched off and the samples while still submerged were allowed to cool naturally to room temperature (Figure *3-13*).

- After at least 14 hour, the samples were removed from the water bath, surface dried and recorded the weight as $M_{3b}$.

**Figure 3-13: VPV samples left in water bath for cooling (left) and weighed under water (right)**

- The samples were then suspended in water to determine the mass under water at room temperature (Figure *3-13*). This weight was noted as $M_{4ib}$. The boiled absorption ($A_b$) and the apparent volume of permeable void (AVPV) were calculated using Equation 3-26 and Equation 3-27 respectively (AS 1012.21-1999).

$$A_b = \frac{(M_{3b} - M_1)}{M_1} \times 100\% \tag{3-26}$$

$$\text{AVPV} = \frac{(M_{3b} - M_1)}{(M_{3b} - M_{4ib})} \times 100\% \tag{3-27}$$

Where, $M_{3b}$ = weight of the samples after boiling and cooling (gm)

$M_{4ib}$= weight of the samples suspended in water (gm)

### 3.7.9. Water sorptivity test

The capillary suction property of concrete was tested with the sorptivity test. Testing for water sorptivity was based on the method ASTM C 1585 - 04 (ASTM Standards, 2004b) that was developed by Hall (1989). The method is intended to determine the susceptibility of an unsaturated concrete to the penetration of water. The tests were done at two ages: at 28 days and at 180 days after casting of the specimens. Curing regime I (28 days water curing) and curing regime II (7 days water curing) were employed to the samples as described in section 3.6.4. The test involves the properly conditioned and sealed specimens to be set in touch of water and measuring the change of mass at specified intervals of time. The detailed steps of the test are described below:

- The specimens were cut at the depth of 50 mm from the top of a cylinder (100 mm diameter and 200 mm depth). Two replicate samples were used.
- Conditioning of samples: Samples were put in the oven at 105°C to have a constant mass before the test. Weights were checked at every 24 hour. When the difference of two successive weights was less than 0.1%, specimens were put in the desiccators for cooling and weights of the cool specimens were recorded to the nearest 0.01 gm.
- The diameter and depth of the specimen were recorded as an average of at least four readings.
- The specimens were then sealed to control evaporation from the non-exposed curved surface and one flat surface leaving the other flat face open. The open face was the cut surface and was exposed to water during the test. Transparent scotch tape was used for sealing. Weights of the sealed specimen were recorded as initial mass to the nearest 0.01 gm.
- Water was taken in a tray at room temperature and support devices were placed to support specimens at the specified level.

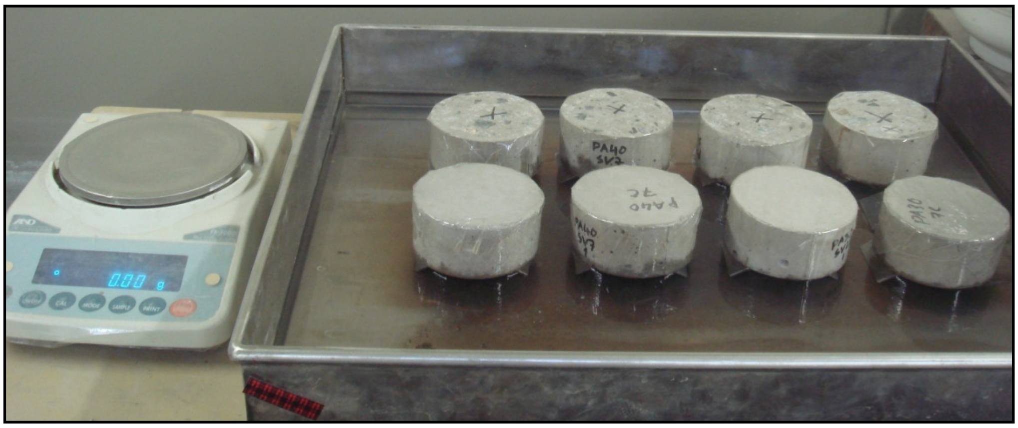


**Figure 3-14: Sorptivity test arrangement**

- The exposed surface of the specimens was set in contact of water so that it dipped 1-3 mm in the water (Figure *3-14*).
- The time of the first contact with water was recorded. The specimen was taken off the water after certain time, wiped the surface dry with damp cloth and weighed within 15 seconds of removing from water. After weighing the specimen was replaced on the support device and restarted the timing.
- Mass of the specimen and time of contact with water were recorded precisely. Same process was repeated at an interval of 1, 5, 10, 20, 30 min and every hour up to 6 hours of initial contact to water.
- Level of water was maintained within 1-3 mm above the contact surface for the whole duration of the test.
- Equation 3-28 was used to calculate the absorption which was plotted against square root of time to find the rate of water absorption (ASTM C 1585 – 04). The slope of the best-fit line of the plot represents the rate of absorption. The initial rate of absorption was calculated using reading of the first 6 hours. Average of two similar specimens was reported.

$$I = \frac{M_t}{\mathrm{A} \times D} \tag{3-28}$$

Where, $I$ = the absorption (mm)

$M_t$ = the change in specimen mass at the time t (gm)

A = the exposed area of the specimen (mm$^2$)

D = the density of water (gm/mm$^3$)

### 3.7.10. Water permeability test

Water permeability test conducted in this study provide the permeability properties of concrete samples when it is subjected to a high pressure head. The test determines the permeability coefficient of the concrete samples by measuring the flow of water through the concrete. The test was carried out in accordance with the GHD/TEL method, which was originally developed by Taywood engineering Ltd. (TEL).

Two replicate samples for each mixes were tested. Samples were cut from two different concrete cylinder specimens. The test involves passing high pressure water from one face to other face of the sample and recording the rate of flow over 7 days.

The permeability coefficient was obtained using the Darcy's Equation (Equation 3-29) as per GHD/TEL method.

$$k = \frac{Q \times L}{A \times H} \tag{3-29}$$

Where, k = Permeability coefficient (m/s)

Q = Rate of flow ($m^3/s$)

A = Cross sectional area of the specimen ($m^2$)

L = depth of specimen (m)

H = Head of water (m)

The procedure used to determine the permeability is as follows:

- The cylinder (100 mm diameter and 200 mm depth) samples were demoulded after 24 hours of casting and then immersed in water for curing.
- At the age of 28 days, the samples were cut into a slice of 50 mm thickness. The slice was taken from the middle of a cylinder to avoid any edge effect. As a general guide to obtaining a representative result, the minimum diameter of sample should not be less than twice the maximum aggregate size.
- The slices were wiped off and were placed in an oven, set at 105°C. The mass of the sample was checked every day until they reached a constant weight (less than 0.1% mass change per 24 hour period). The samples were weighed in hot condition. When constant weight was achieved, the samples were cooled in a desiccator and the cooled weight was recorded.
- After sealing the top and bottom face of the sample with an adhesive film, the curved surfaces of slices were coated with an epoxy resin and allowed to set. The adhesive films were removed from both faces and then the samples were put into a desiccator until test.
- The epoxy mounted sample was weighed and then put in the brass sleeve to fix it firmly with the o-ring of the sleeve.
- The sleeve and the sample were then placed in the permeability rig with bolts tightened up uniformly.

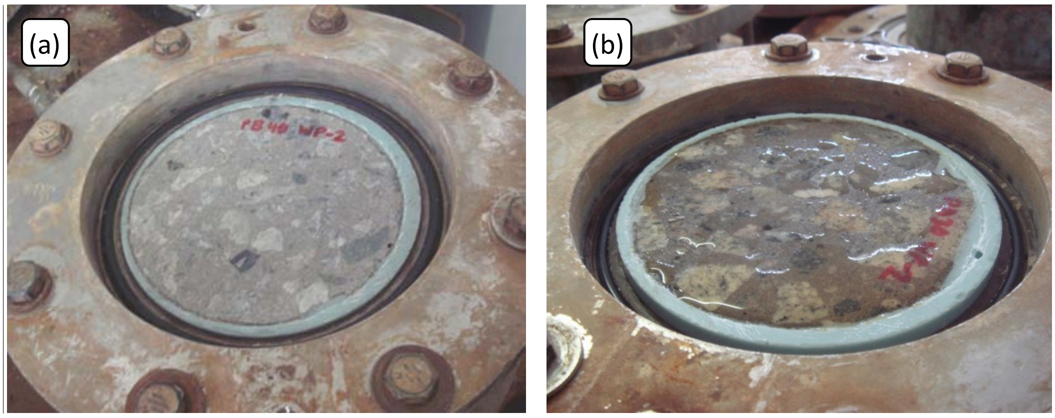


**Figure 3-15: Specimens fixed in the rig and pressurised (a) before saturation, (b) after saturation and prior to capping**

**Figure 3-16: Water permeability test arrangement.**

- Water at 950 kPa (96.5 m head) was then applied through the rig to the bottom side of the sample. The time when the water was applied was recorded.
- The sample was observed until the entire face of the exposed surface was saturated (Figure *3-15*).

- After reaching saturation, the exposed face of the sample was capped tightly to prevent any leaking and a graduated pipette of 1-2 mm capacity was placed in the dedicated cap opening (Figure *3-16*).
- The flow rate of the water was then measured through the pipette and recorded for a period of one week once a day.
- After seven days, the final reading was taken and the sample was removed from the rig. The sample was surface dried and weighed.

Only the reading of 7th day was used assuming that all of the pores in the concrete are saturated and the flow through the specimens has reached a constant rate after seven days. Earlier readings enable to check the consistency of the flow till seven day. An average of two specimens for each mix is reported to the nearest $0.01\times10^{-12}$ m/s.

### 3.7.11. Air permeability test

The ingress of air and moisture into the concrete can cause corrosion of the steel reinforcement and lead to a deterioration in concrete strength. Therefore, a measure of the ease of movement of liquid and gases through the surface layer of the concrete is as important as strength to assess concrete soundness.

A method developed by John Figg (Figg, 1973) was followed to determine air permeability of concrete. An automated test apparatus (produced by NDT James Instruments Inc) was used for this test. The air permeability test involves measuring the time taken for air to flow into a known volume of a sealed, evacuated chamber in the concrete, reducing the vacuum from 55 kPa to 50 kPa. This time is a measure of air permeability of concrete.

The moisture content of the concrete has a major effect on permeability. Thus after water curing samples were kept in the curing room environment (23°C and 60±10% RH) until the test date. Tests were performed at the age of about 130 days. The test procedure is described below:

- Preparation of test hole: Three test holes of 10 mm diameter and about 40 mm deep were drilled using a masonry drill fitted with a tungsten carbide bit.

Holes must not be less than 30 mm (1-1/4”) apart or less than 30 mm from the edge of the concrete. Loose dust from the holes was blown out with a rubber bulb blower. Then a molded silicon rubber plug of about 20 mm depth was inserted into each test hole, making sure that the top flange of the plug is seated securely on the concrete surface.

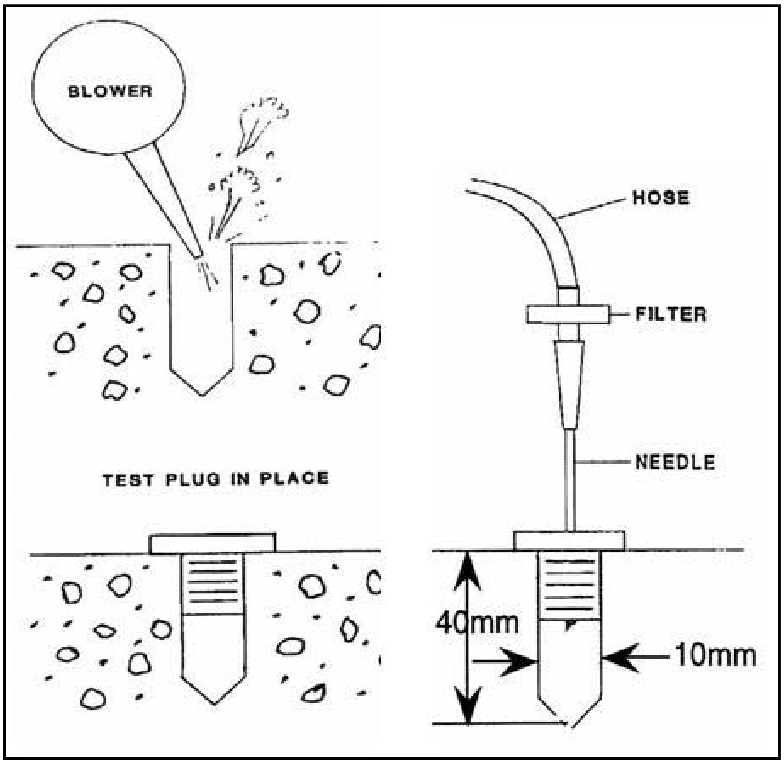


**Figure 3-17: Preparation of test hole for air permeability test.**

- The hypodermic needle was inserted through the silicon rubber plugged hole so that the hollow needle just protruded through the bottom of the plug (Figures *3-17*). The needle was connected to the instrument with a pipe and a hand vacuum pump also attached to the instrument to extract the air from the test hole.
- The power of the instrument was switched on and reset the timer display to zero.
- Turning the vacuum valve on, the system was exhausted to a vacuum in excess of 55 kPa below atmospheric pressure. During this operation the red LED indicating -50 kPa, then that indicating -55 kPa should light up.

- When vacuum is reduced to -55 kPa by infiltration of air into the test cavity, the left LED would go out and the timer would commence to run. When vacuum is reduced to -50 kPa, the right LED would go out and timer would stop. Figure *3-18* shows an air permeability test in progress.

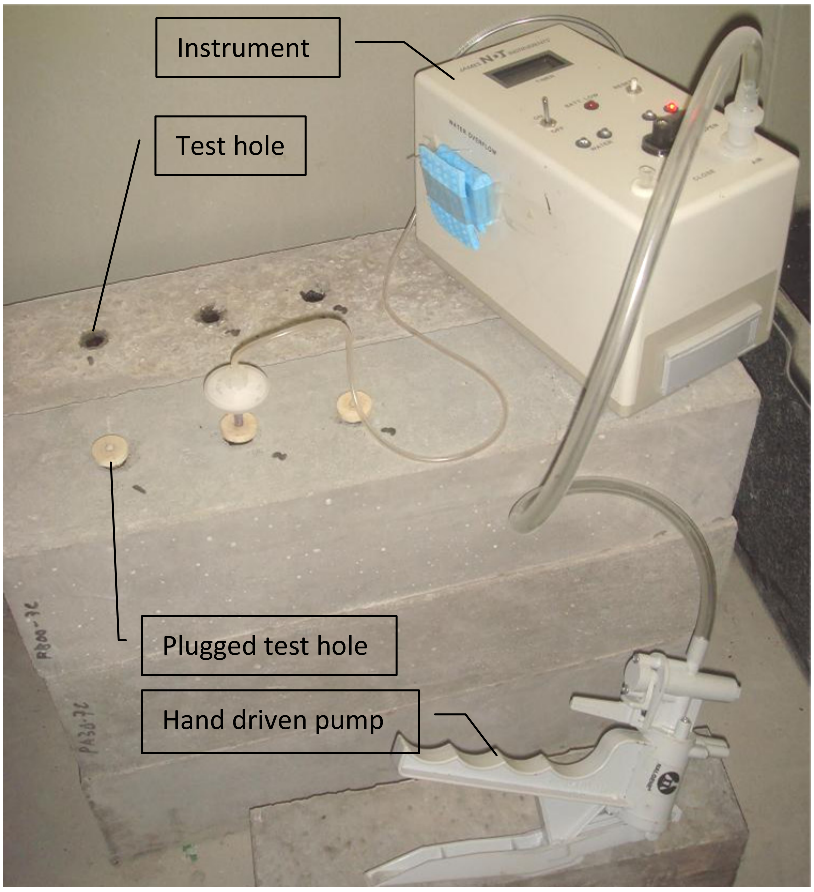


**Figure 3-18: Air permeability test in progress**

- The timer reading was noted in seconds. This is the time for a 5 kPa pressure change within the test hole from a -55 kPa to -50 kPa below atmospheric pressure.
- Air exclusion rating (AER) and air permeability (*k*) were then calculated using Equation 3-30 and Equation 3-31 respectively. Air ingress rate (ml/s) is expressed in more conveniently as a reciprocal; air exclusion rating (s/ml). Finally intrinsic air permeability (*k*) can be calculated considering standard dimensions of test cavity and the corrected viscosity of air (Figg, 1989).

$$\text{Air Exclusion Rating (AER)} = t_a / \left( \left[ \frac{55V}{50} - 1 \right] \times \frac{52.5}{100} \right) \quad (3\text{-}30)$$

$$\text{Air Permeability}, k = (5.14 \times 10^{-11}) / t_a \quad (3\text{-}31)$$

Where, $t_a$ = time (seconds) for the pressure change from
55 kPa to 50 kPa below atmospheric pressure
$V$ = volume of apparatus including test hole (ml);
for standard Poroscope V = 77.1 ml

### 3.7.12. Carbonation test

Carbonation of concrete is an important factor to affect its durability. Concrete that is exposed to the higher concentration of carbon dioxide than usual concentration in the atmosphere (0.039% by volume) is more vulnerable to the carbonation induced deterioration. Hence it is required to consider the carbonation in service life design of concrete structures. Carbonation is a gradual process as $CO_2$ propagates through the reinforcement cover depth and reacts with the pore solution which in turn reduces alkalinity of concrete. Corrosion initiates in the reduced alkalinity due to depassivation of protective layer on the steel. The time of corrosion initiation due to carbonation depends on the concrete’s resistance to gas penetrability. However, the rate of carbonation also depends on moisture condition of the protective layer, location of structural member, climatic variation etc.

The measurement of carbonation at the ambient condition at any particular age of structure can be an indication of level of carbonation. The rate of carbonation hence can be determined by measuring depth of carbonation at different ages. But earlier carbonation indicators are essential for prior assessment of the concrete’s performance. Hence carbonation test is usually conducted in accelerated condition by measuring carbonation rate of concrete samples subjected to very high $CO_2$ concentration other than normal concentration (0.03%) in the atmosphere. Different $CO_2$ concentration in accelerated condition was reported in the literature, for instance, 2% by *fib* model code (*fib* CEB-FIP, 2006), 3% by Papadakis and Tsimas (2000), 5% by Atis (2003), 10% by Thomas et al. (2000), 20% by Jiang et al. (2000).

In this study an attempt was made to assess service life of the concrete mixes in terms of carbonation. The *fib* model code for service life design (*fib* CEB-FIP, 2006) was applied. In this model an accelerated method of carbonation measurement was recommended as the reference method using 2 vol.-% to avoid as much as possible the formation of phases which normally are not formed under natural carbonation conditions (e.g. vaterite). The following procedure was followed:

- Concrete specimen of size 100×100×400 mm were prepared and cured under tap water with a temperature of 23$^{o}$C ($T_{ref}$) for overall seven days (reference curing period).
- After seven days, the specimens were removed from the water and stored in the laboratory climate ($T_{ref}$ 23$^{o}$C, relative humidity $RH_{ref}$ 60 ± 10%). This curing pattern resemble Curing regime II in this study.
- At the age of 28 days the specimens were placed in a carbonation chamber with the standardised laboratory climate ($T_{ref}$ 23$^{o}$C, relative humidity $RH_{ref}$ 65%). In the chamber the specimens were exposed to a $CO_2$ concentration of 2.0% vol.-% during 28 days. Figure *3-19* shows the samples placed in the carbonation chamber.

**Figure 3-19: Carbonation chamber with specimens inside**

- After 28 days of exposure the specimens were split and depth of carbonation was measured at the plane of rupture using an indicator solution of 1%

Phenolphthalein. The carbonated area remains colourless due to reduced alkalinity while other area indicates as pink due to high alkalinity.

- At least four depths from each edge were taken and the mean value was reported as carbonation depth. Top surface and the bottom surface were ignored. Because, top surface was the trowelled surface, thus the depth of actual carbonation may be affected. The bottom face was not exposed.

### 3.7.13. Rapid chloride permeability test

Chloride ion increases the vulnerability of concrete to corrosion. The rapid method for testing of chloride ion penetration was followed as per ASTM C 1202-07 (ASTM Standards, 2007d). This method consists of monitoring the amount of electrical current passed through a 51 mm thick concrete slice during a 6-hour period of time. A potential difference of 60 V DC is maintained across the ends of the specimen. The test procedure is summarised below:

- The samples were water cured for 28 days.
- At the end of curing period, a 51 ± 3 mm thick slice of concrete was cut from the top of a 100 mm diameter concrete cylinder using a water-cooled diamond saw. Two specimens were cut from two different cylinders.
- The slices were surface dried and coated on the curved surface with epoxy resin. The two flat surfaces were kept exposed.
- Then the specimens were placed in vacuum desiccators keeping two end faces of the specimens exposed. The desiccator was sealed and the vacuum pump was started. The vacuum was maintained for 3 hours (Figure *3-20*).
- With the vacuum pump still running, deionised water was poured in the dessicator with the aid of funnel and stopcock. The vacuum pump was run for another one hour.
- The specimens were then kept soaked under water for 18 ± 2 hours. After that, the specimens were removed from water and blotted off any excess water.
- The specimens were then mounted on the two-part test cell and sealed with high viscosity specimen-cell sealant and left overnight for curing the sealant.

- On the next day, the cell containing the top surface was filled with 3% NaCl solution and the other that contains cut face of the specimen was filled with 0.3 N NaOH solution. The NaCl solution cell was then connected to the negative terminal of the power supply while the other cell was attached to the positive terminal (Figure *3-20*).

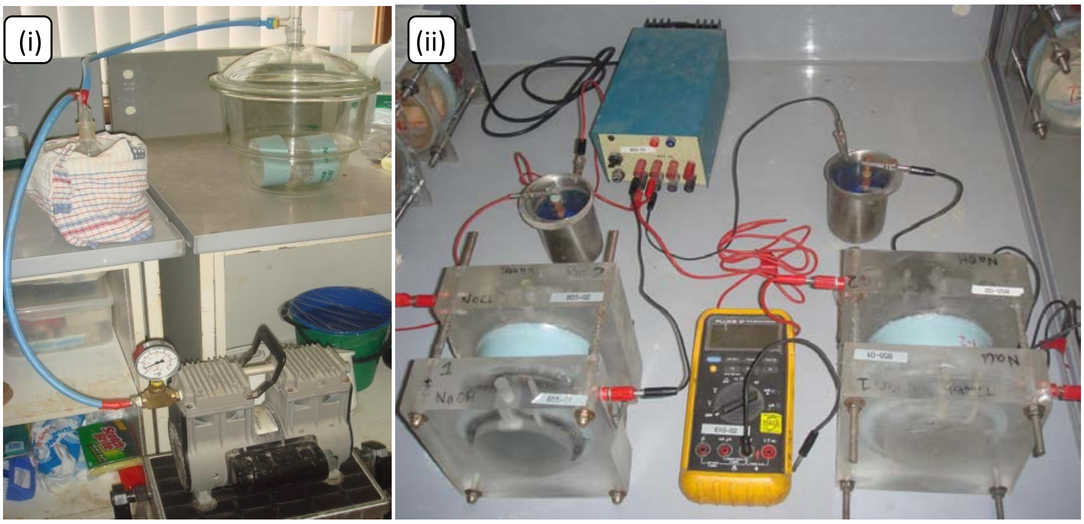


**Figure 3-20: Rapid chloride permeability test setup (i) specimens in the desiccators under vacuum, (ii) Specimens mounted in the test cell are being tested**

- A colorimeter (which contains $CuSO_4$ solution and a copper stick that acts as anode) was inserted in the circuit to check the total charge passed in terms of copper deposit. Weight of colorimeter was taken before setting in the circuit.
- Power supply was turned on and set to 60 V, and initial current was recorded using a multimeter.
- Subsequent readings of current were taken at every 30 minutes up to 6 hours.
- The colorimeter was rinsed, dried and weighed.

The total charge passed was calculated using Equation 3-32 (ASTM C 1202-07)

$$Q = 900(I_0 + 2I_{30} + 2I_{60} + \ldots\ldots\ldots + 2I_{330} + I_{360}) \qquad (3\text{-}32)$$

Where, $Q$ = charge passed (coulomb)
$I_0$ = current immediately after voltage is applied (amperes)
$I_t$ = current at t minutes after voltage is applied (amperes)

In case of the diameter of the specimen other than standard 3.75 in (95 mm), the charge passed values should be adjusted by Equation 3-33 (ASTM C 1202-07).

$$Q_s = Q_x \times \left(\frac{3.75}{x}\right)^2 \tag{3-33}$$

Where, $Q_s$ = charge passed through 3.75 inch diameter specimen (coulombs)
$Q_x$ = charge passed through $x$ inch diameter specimen (coulombs)
$x$ = diameter of the specimen (inch)

### 3.7.14. Chloride diffusion test

Durability of marine structure is mainly affected by the chloride attack. Resistance of concrete samples to permeation of chloride ion was tested through chloride diffusion test. It was carried out in accordance with the NT Build 443 (Nordtest Method, 1995) which resembles the method ASTM C 1556 – 04 (ASTM Standards, 2004a). This test provides a method of accelerated testing to determine the resistance of a hardened concrete to the penetration of chloride ions.

The test uses test specimens to be coated every face leaving only one surface exposed to the sodium chloride solution for a specified exposure period after which thin layers are ground off parallel to the exposed surface and tested for chloride content in each layer. The apparent chloride diffusion coefficient and projected surface chloride-ion concentration are then calculated using the initial chloride content and at least six related values of chloride-ion content at depths below the exposed surface.

Three slices of the sample were used for the test and one other slice is used to determine initial chloride content. The samples used were about 50 mm thick and were cut from the middle part of the 100 mm diameter concrete cylinder. Three different cylinders were cut to get three slices of specimen for every concrete mixture. The procedure of the test is mainly divided into two phases: sample preparation and chloride analysis. The procedures followed for each phase are presented below:

*Samples preparation:*

- Demoulded samples were cured under water for 28 days. Then the samples were cut into slices. Three replicate specimens were cut from three concrete cylinders of the same concrete mix. One slice was taken from the bottom part of a cylinder and stored in the laboratory for measuring background chloride content during analysis.
- The samples were air dried and coated with epoxy resin on every surface leaving only one flat face exposed to allow chloride penetration during the exposure. Epoxy coating was allowed to set overnight.
- Coated samples were then placed in the $Ca(OH)_2$ saturated water (curing tanks) for a period of time until a constant mass was reached.
- When the mass difference reached less than 0.1%, the specimens were rinsed with tap water and immersed into a Sodium Chloride solution in sealed containers for a specified exposure period. The chloride solution was made by dissolving sodium chloride in deionised water. The concentration of the solution was 165 ± 1 gm NaCl per litre. The ratio between the exposed area ($cm^2$) of samples and the volume of exposure liquid ($dm^3$) was maintained in between 20 - 45 which met the allowable limit of minimum 20 and maximum 80. The container was placed in the temperature controlled laboratory ($23^oC$ ± $2\ ^oC$) during the exposure.
- The exposure period is specified in the test standard as minimum 35 days. However, it was extended up to 56 days for the early age tests and 5 months for the later age of tests. In selecting the minimum exposure period several factors were taken into account such as type of binder (fly ash) used, water to cementitious materials ratio, and maturity (Note-9, ASTM C1556-04).
- Upon removal of the samples after the period of exposure, they were rinsed properly to remove any deposit on the surface and placed in a profiling rig (Figure *3-21*). A hand held profiler was used to grind 8 layers of 2 mm profile intervals up to a depth of 16 mm from the centre of the exposed face of the sample. The ground concrete of each layer was collected in an individual paper bag and the rig and the sample were thoroughly cleaned of dust and grits from the previous layer.

- The ground samples were then placed in an oven, set at 105°C, for 24 hours after which they were placed in a desiccator to keep free of moisture.
- The slice that was preserved for background chloride determination was also ground by crushing and placing into the oven before storing in the desicator.

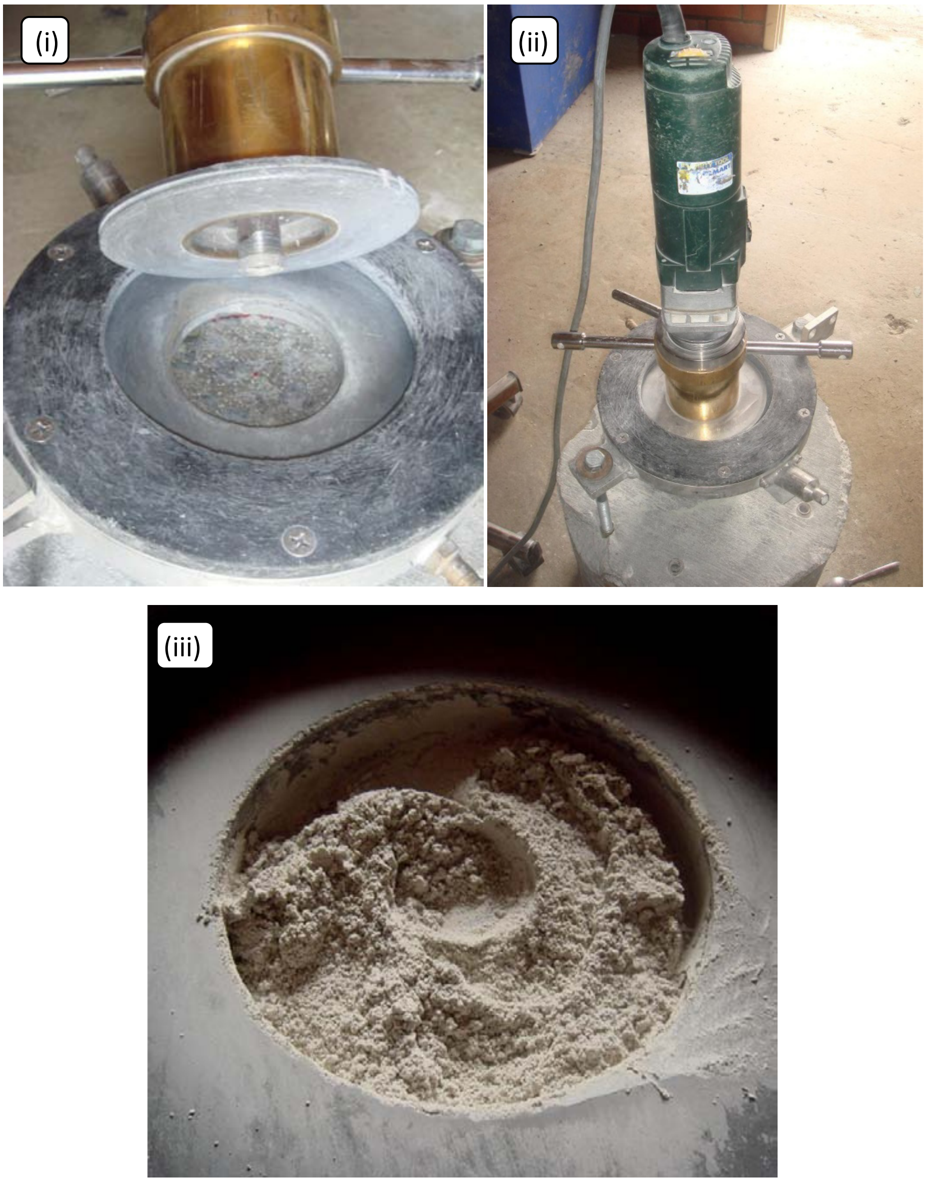


**Figure 3-21: Profiling of the chloride diffusion test specimens**
**(i) Specimen fixed in the rig and rotary grinding tip of the profile grinder**
**(ii) Profile grinder in place before grinding**
**(iii) Ground material on the specimen ready to collect.**

### *Chloride analysis:*

The analysis involved measuring the chloride content in the ground samples obtained from different layers of the concrete specimen. A potentiometric titration method was used to determine the acid soluble chloride content of each sample. An auto-titrator (TIM 860 titration manager) was used that utilize 0.05M silver nitrate solution as a titrate. One Chloride, Silver/Sulphide Ion Selective electrode and a Potentiometer are placed in the solution along with the pipette that dispenses the AgNO3 solution. The auto titrator measures the millivolt (mV) readings in addition to the amount of $AgNO_3$ required for precipitating chloride in the solution as silver chloride.

**Figure 3-22: Titration in progress using an auto titrator.**

All the ground specimens require to be digested in the acid and then the titration procedure commenced. The detail procedure is as follows:

- The ground samples of each layer were weighed as about 3-7 gm in a 250 ml beaker. The amount of each sample weighed out was recorded to an accuracy of 0.0001 gm.

- Approximately 25 ml of deionised water was added to each sample. 70% concentrated Nitric Acid (the reagent) as about 10 ml was then mixed with the samples. After mixing properly approximately 50 ml of hot (less than 100°C) deionised water was added to the beakers which were then immediately placed on a hotplate.
- The samples were heated to a point just before boiling and then allowed to cool to room temperature.
- Once the samples had reached room temperature the beaker was set on the auto titrator putting the electrode and potentiometer tips dipped in the solution in such way that they do not touch the sample at the bottom of the beaker. The titrator was then started and magnetic stirrer of the machine was set on to help titration process (Figure *3-22*).
- After finishing titration volume of silver nitrate solution was recorded and the chloride concentration by mass of concrete was measured to the nearest 0.001% using the Equation 3-34.

$$\mathrm{Cl}\ (\%) = \frac{3.545 \times \mathrm{V} \times \mathrm{N}}{\mathrm{W}} \qquad (3\text{-}34)$$

Where, V = volume of 0.05 N $AgNO_3$ solution used for sample titration (ml),
N = exact normality of 0.05 N $AgNO_3$ solution,
W = mass of sample (gm)

Similar procedure was also carried out for the background samples as well as calibration checks of the auto-titrator after every 8 runs. All calibration checks were within the acceptable range.

The values of surface chloride concentration and apparent chloride diffusion coefficient were determined by fitting the Equation 3-35 (NT Build 443) to the measured chloride contents by means of a non-linear regression analysis in accordance with the method of least squares fit.

$$C(x,t) = C_s - (C_s - C_i).erf\left(\frac{x}{\sqrt{4.D_a.t}}\right) \qquad (3\text{-}35)$$

Where, $C(x, t)$ = chloride concentration measured at depth $x$ and exposure time $t$ (mass %)

$C_s$ = projected chloride concentration at the interface between the exposure liquid and test specimen that is determined by the regression analysis, (mass %),

$C_i$ = initial chloride-ion concentration of the cementitious mixture prior to submersion in the exposure solution (mass %)

$x$ = depth below the exposed surface (to the middle of a layer) (m)

$D_a$ = apparent chloride diffusion coefficient ($m^2/s$)

$t$ = the exposure time (seconds)

$erf$ = error function defined in Equation 3-36

$$erf(z) = \frac{2}{\sqrt{\pi}} . \int_0^z e^{-u^2} du \tag{3-36}$$

# 4. RESULTS AND DISCUSSION

## 4.1. Introduction

The results of the tests on six concrete mixtures are discussed in this chapter. Both the fly ash and control concretes of two series were tested to investigate the mechanical and durability properties. The tests were conducted at different ages of the concrete samples. The durability tests included drying shrinkage, volume of permeable voids (VPV), sorptivity, water permeability, rapid chloride permeability and chloride diffusion test. VPV, sorptivity and air permeability tests were performed on the concrete samples subjected to two different curing regimes. Compressive and indirect tensile strength tests were done at various ages up to eleven months and flexural strength test was done at the age of 28 days. The effect of cement replacement by fly ash is discussed with respect to the corresponding control concretes at different test ages and for different duration of curing.

## 4.2. Workability of fresh concrete

The workability of fresh concrete mix was measured by slump test according to the AS 1012.3.1 Standard (Standards Australia, 1998). The results of average slump and amount of superplasticiser used are shown in Table *4-1* and Figure *4-1*.

**Table 4-1: Slump values of different concrete mixtures**

| Mixtures | | Binder content | | Water to binder ratio (w/b) | Slump (mm) | Super-plasticiser (kg/m$^3$) |
|---|---|---|---|---|---|---|
| Series | Mix ID | Cement (%) | Fly ash (%) | | | |
| A | A00 | 100 | 0 | 0.41 | 140 | 5.11 |
| | A30 | 70 | 30 | 0.32 | 170 | 4.77 |
| | A40 | 60 | 40 | 0.31 | 185 | 4.75 |
| B | B00 | 100 | 0 | 0.29 | 150 | 6.77 |
| | B30 | 70 | 30 | 0.29 | 175 | 4.80 |
| | B40 | 60 | 40 | 0.29 | 160 | 4.24 |

**Table 4-2: Permissible tolerance of slump as per AS 1379-2007 (Standards Australia, 2007)**

| Specified slump, mm | Tolerance, mm |
|---|---|
| < 60 | ± 10 |
| ≥ 60 ≤ 80 | ± 15 |
| ≥ 80 ≤ 110 | ± 20 |
| ≥ 110 ≤ 150 | ± 30 |
| > 150 | ± 40 |

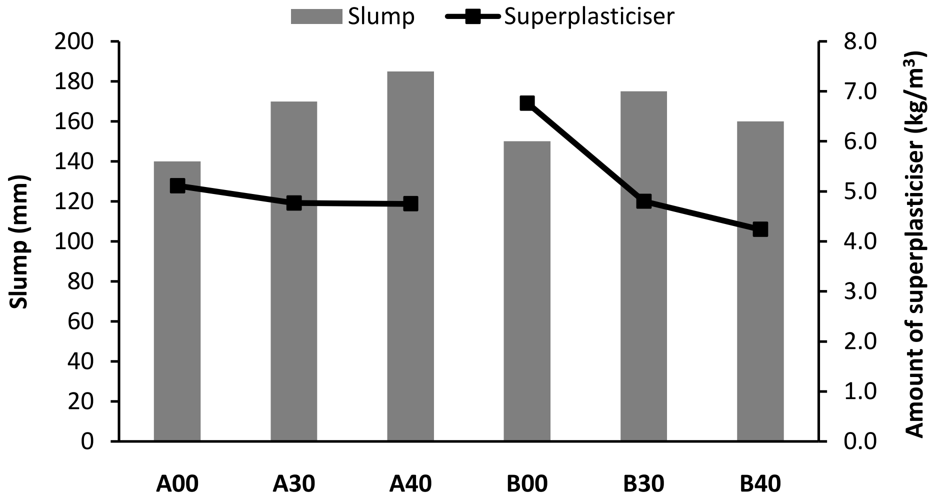


**Figure 4-1: Slump of different concrete mixtures and corresponding amount of superplasticiser**

The results indicate that the slumps of fly ash incorporated concretes are higher than that of the control concrete in both series A and B. All slump values except that of mix A40 were within the tolerable limits of slumps for specified slump ≥ 110 ≤ 150 mm as per the AS 1379 – 2007 (Standards Australia, 2007). Table *4-2* shows the specified limits of AS 1379-2007.

In the concretes of series A, amounts of superplasticiser were set constant (900 ml per 100 kg of cementitious materials) in initial design. It was increased during mixing of the control concrete (A00) to achieve the minimum slump, as it contained less amount of finer ingredients in the binder as compared to the fly ash concrete mixtures. Fly ash concretes (A30 and A40) having lower w/b ratio and superplasticiser content, achieved higher slump as compared to mix A00. Therefore, inclusion of fly ash increased the workability of the fresh concrete. Slump increased with the increase of fly ash content for the similar amount of superplasticiser.

Concretes of series B were designed with similar mix proportion except partial replacement of cement by fly ash in two mixtures. The amount of superplasticiser was reduced with increasing amount of fly ash in concrete. The fly ash concretes achieved higher values of slump as compared to the control concrete (B00). The slump of mix with 40% fly ash (B40) decreased slightly as compared to the mix with 30% fly ash (B30). However, the slump drop was 9% for a superplasticiser drop of 12%.

In general, the inclusion of fly ash in concrete improved the workability. In both series, the fly ash concretes required less amount of superplasticiser for the same value of slump than the corresponding control concretes. This is because the fly ash particles are more spherical than the cement particles and they offer less resistance to movement as compared to the cement particles. Thus, fly ash requires less water or superplasticiser to slide in the concrete and facilitate higher workability.

## 4.3. Mechanical properties of concrete

### 4.3.1. Compressive strength

Compressive strength is the most desirable characteristics of concrete before considering other properties. It indicates primary quality of concrete for any particular application. Generally enhanced durability properties can be obtained with the concretes of higher compressive strength. The mixes prepared in this study were designed to achieve 28-day compressive strength more than 50 MPa as recommended by AS 3600-2009 (Standards Australia, 2009) for the most severe environment. The compressive strength results from 3 days to 335 days are shown in Table *4-3*. Detail data set is given in Appendix D. Figures *4-2* and *4-3* show the plot of strength over the ages of series A and B respectively. The initial strength developments of all the concretes are presented in Figure *4-4*. The percentage strength developments of the fly ash concretes with respect to corresponding control concrete are plotted in Figure *4-5*.

**Table 4-3: Compressive strength results**

| Mixture | | Compressive strength (MPa) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Series** | **Mix ID** | **3 days** | **7 days** | **28 days** | **56 days** | **91 days** | **210 days** | **335 days** |
| A | A00 | 47.0 | 57.0 | 69.0 | 77.5 | 78.0 | 78.5 | 79.5 |
| | A30 | 46.0 | 58.0 | 73.0 | 90.5 | 92.5 | 96.0 | 99.5 |
| | A40 | 41.0 | 50.5 | 65.5 | 88.0 | 88.5 | 90.0 | 97.0 |
| B | B00 | 67.5 | 70.5 | 85.5 | 96.0 | 101.0 | 101.5 | 102.5 |
| | B30 | 44.5 | 59.5 | 73.5 | 93.0 | 96.5 | 98.5 | 99.5 |
| | B40 | 41.0 | 52.0 | 69.0 | 89.0 | 89.5 | 92.5 | 100.5 |

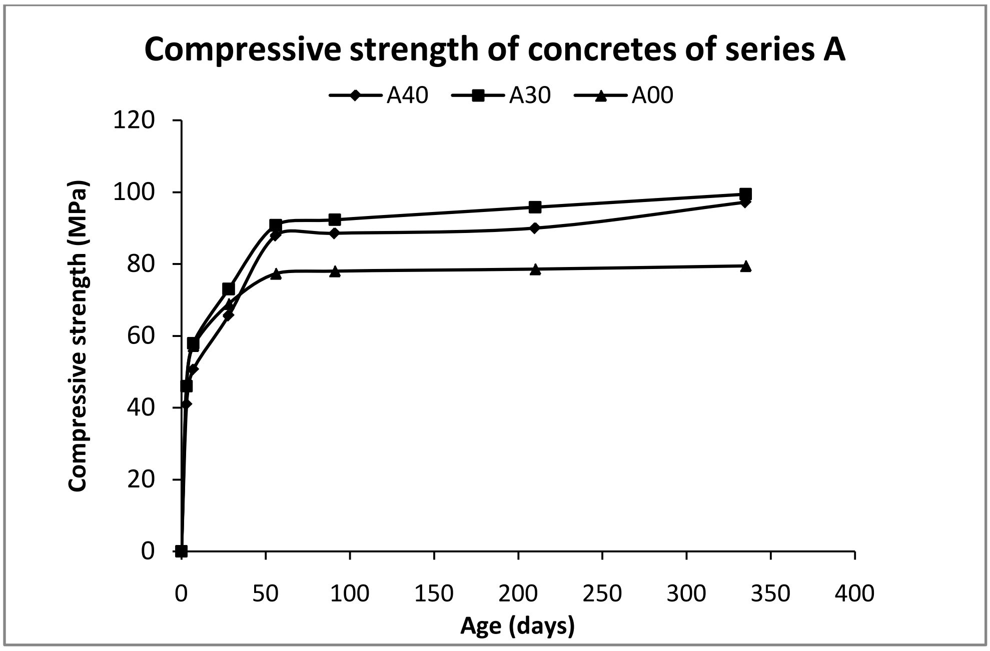


**Figure 4-2: Development of compressive strength of concretes (series A)**

In series A, the fly ash concretes (A30 and A40) gained similar strength of control concrete at 28 days, as intended in the mix design. At 56 days, both the fly ash concretes gained more than 110% of the control concrete's strength (Figure *4-5*). After 56 days, the fly ash concretes continued to gain strength, while the control concrete’s strength remained steady until the age of 335 days. At 335 days, both 30% and 40 % fly ash concretes gained more than 120% strength of the control concrete.

Strength of concretes in series B has been decreased for the inclusion of fly ash in place of cement while keeping w/b ratio and the amount of total binder constant (Figure *4-3*). However, from Figure *4-5* it is clear that, the fly ash concretes achieved more than 80% of the control concrete’s strength at 28 days which reached 92% and 96% of control concrete’s strength at 56 days for 40% and 30% fly ash content respectively. At 335 days, both 30% and 40% fly ash concretes gained similar strength which is 97% of that of the control concrete. Thus, compressive strength has not been affected significantly in the later age due to incorporation of fly ash.

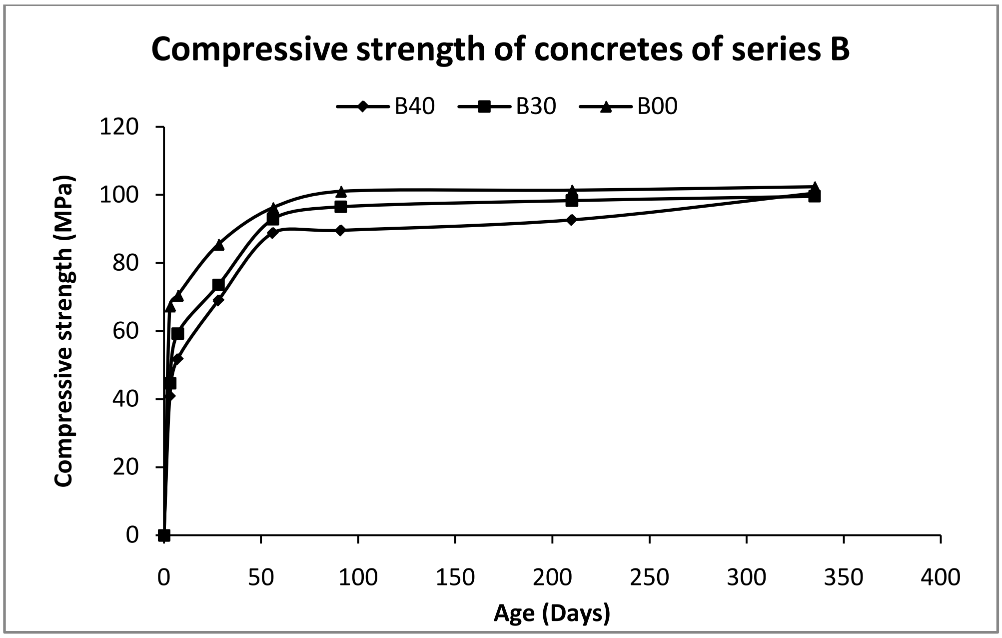


**Figure 4-3: Development of compressive strength of concretes (series B)**

The results indicate that incorporation of fly ash in concrete has decreased strength at the earlier age as compared to that of control concrete, but at later stage they have either gained more strength (series A) or reached very close (series B) to the control concrete strength depending on the mixture proportions. Generally, concretes with 30% fly ash have shown higher strength gain than that of 40% fly ash. The strength of fly ash concretes in both series developed at a higher rate than that of control concrete until the age of 56 days. From Figure *4-4* it is clear that, significant part of strength of fly ash concretes was developed during 28 to 56 days. It implies the notable strength development capability of fly ash concrete due to pozzolanic reaction after 28 days in contrast to normal cement concrete. The trend of strength development of the fly ash concretes is similar to those shown in other studies (Poon et al. 2000; Siddique, 2004).

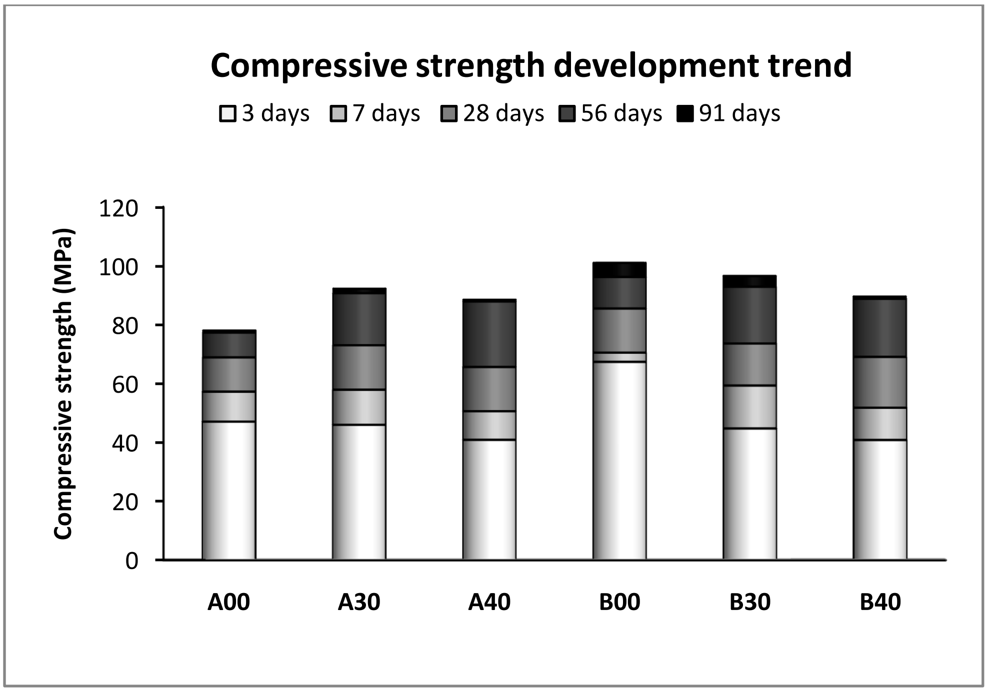


Figure 4-4: Compressive strength development trend over time

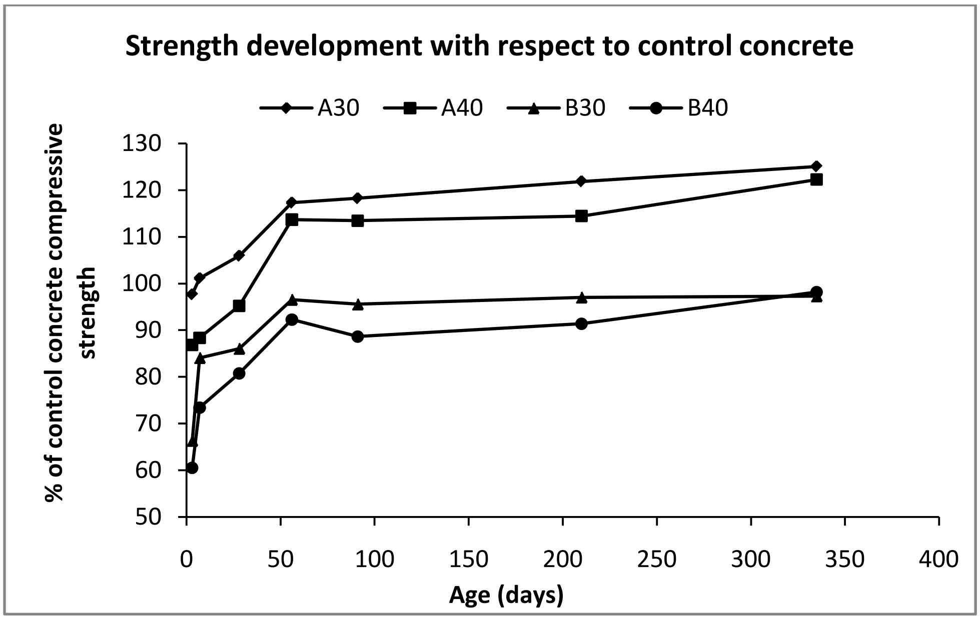


Figure 4-5: Strength development as compared to reference (control) concrete

### 4.3.2. Indirect tensile strength

Though concrete is not designed primarily to carry tensile load due to its very limited capacity to bear tension, it is sometimes capitalised in few applications. Tensile strength is related to the shrinkage, bond and shear behaviour of concrete. Tensile stress develops in concrete due to differential movements such shrinkage which often results in cracking and impairment of durability (Neville and Brooks, 1987). It is difficult to test concrete in direct (uniaxial) tension because of gripping problem at the end of specimen and high probability of eccentric loading. Consequently tensile strength of concrete is generally tested in the form of indirect tension (splitting) and flexural tension (modulus of rupture). The methodology of these tests as per Australian Standard was described in Section 3.7.5 and Section 3.7.6.

Different methods of tension test provide different results, the flexural tension being the highest value with splitting tension and direct tension following in decreasing order (Neville and Brooks, 1987). However, in absence of test results, these tensile strength values can be estimated by using theoretical equations that is based on 28 days compressive strength ($f'_c$). AS 3600 provides Equation 4-1 to estimate the characteristic principal tensile strength ($f'_{ct}$).

$$f'_{ct} = 0.4\sqrt{f'_c} \tag{4-1}$$

**Table 4-4: Indirect tensile strength (splittting tensile) results**

| Mixture | | Indirect tensile strength (MPa) | | | |
|---|---|---|---|---|---|
| **Series** | **Mix ID** | **7 days** | **28 days** | **335 days** | **Theoretical value at 28 days** |
| A | A00 | 3.4 | 3.8 | 5.1 | 3.3 |
| | A30 | 4.2 | 4.4 | 5.7 | 3.4 |
| | A40 | 3.5 | 3.8 | 5.9 | 3.2 |
| B | B00 | 4.3 | 4.4 | 6.3 | 3.7 |
| | B30 | 3.9 | 4.2 | 5.0 | 3.4 |
| | B40 | 3.6 | 4.1 | 5.7 | 3.3 |

The results of indirect tensile strength at early age up to 28 days and at late age of 335 days are given in Table *4-4*. The test data are given in Appendix E. Theoretical tensile strength at 28 days was calculated using Equation 4-1 and included in the table. Figures *4-6* and *4-7* show comparisons of the results for series A and B respectively.

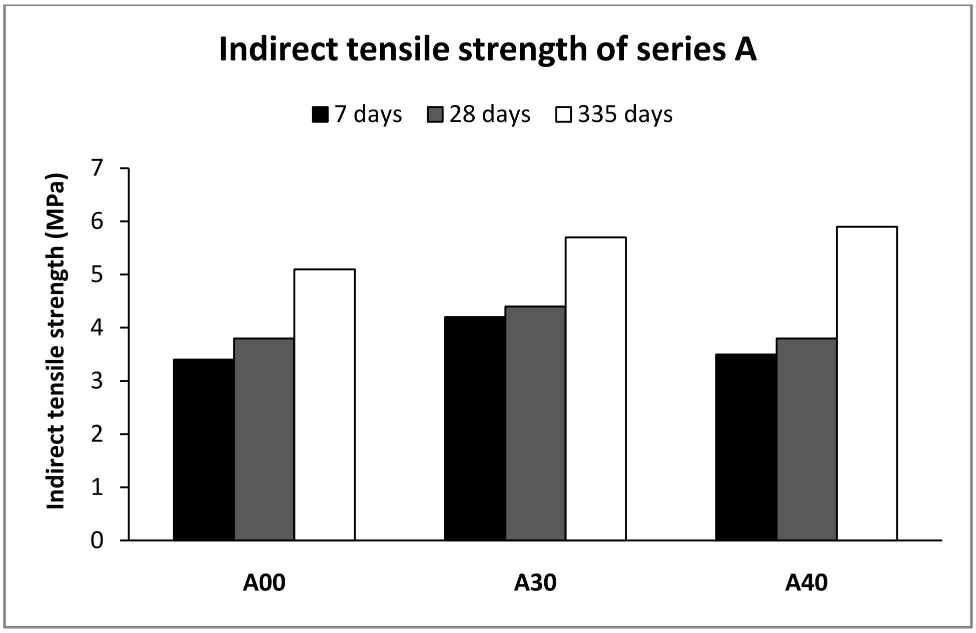


**Figure 4-6: Indirect tensile strength of concretes (series A)**

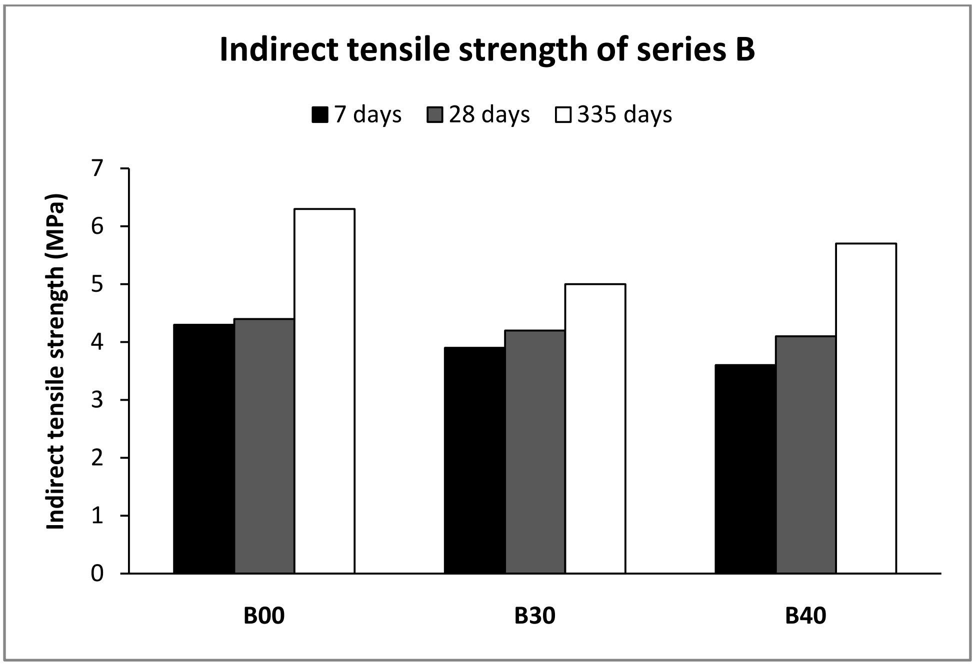


**Figure 4-7: Indirect tensile strength of concretes (series B)**

It can be seen from the results that, for every mix, experimental value of 28 days tensile strength was more than that calculated theoretically. The tensile strength increased with the increase of age of the specimens.

The concretes in series A were designed to have similar compressive strength at 28 days. The tensile strength results followed similar trend of compressive strength. At 7 days, Mix A30 and A40 reached 95% and 92% of 28-days strength, while the control concrete achieved 89%. At 28 days, mix A30 exceeded the control concrete strength and mix A40 achieved same strength of control concrete. After 335 days, fly ash concretes surpassed control concrete by more than 10%. Concrete with 40% fly ash had the most increment. The rate of strength gain was higher for the fly ash concretes than that of the control concrete.

In case of series B (Figure *4-7*), due to incorporation of fly ash in place of cement with constant w/b ratio and constant total binder content, the tensile strength decreased with respect to control concrete. The trend of the results is similar to that reported by Siddique (2004). Fly ash concretes developed strength at a rate slightly slower than that of control concrete. At 7 days, mix B00, B30 and B40 gained 98%, 93% and 88% of 28-day strength respectively. These rates are faster than corresponding rates of compressive strength. At 28 day concretes with 30% (B30) and 40% fly ash (B40) achieved 95% and 93% of control concrete’s strength respectively.

### 4.3.3. Flexural strength

As discussed in the previous section, the flexural strength is another measure of the tensile capacity of concrete. It involves measuring strength of concrete subjected to bending load. The flexural strength was measured at 28 days in accordance with the AS 1012.11 Standard (Standards Australia, 2000c). In addition, the theoretical flexural strength was calculated using Equation 4-2 as provided in AS 3600 (Standards Australia, 2009) to determine flexural strength based on 28 days compressive strength.

$$f'_{cf} = 0.6\sqrt{f'_c} \tag{4-2}$$

The results of 28 days flexural strength obtained in the test and by the theoretical equation are given in Table *4-5*. Figures *4-8* and *4-9* are the charts showing the results of series A and series B concretes respectively. The test data are given in Appendix F.

**Table 4-5: Flexural strength results to the nearest 0.1 MPa**

| Mixture | | Flexural strength at 28 days (MPa) | |
|---|---|---|---|
| **Series** | **Mix ID** | **Experimental** | **Theoretical** |
| A | A00 | 7.2 | 5.0 |
| | A30 | 8.0 | 5.1 |
| | A40 | 6.1 | 4.9 |
| B | B00 | 9.9 | 5.6 |
| | B30 | 7.3 | 5.2 |
| | B40 | 6.7 | 5.0 |

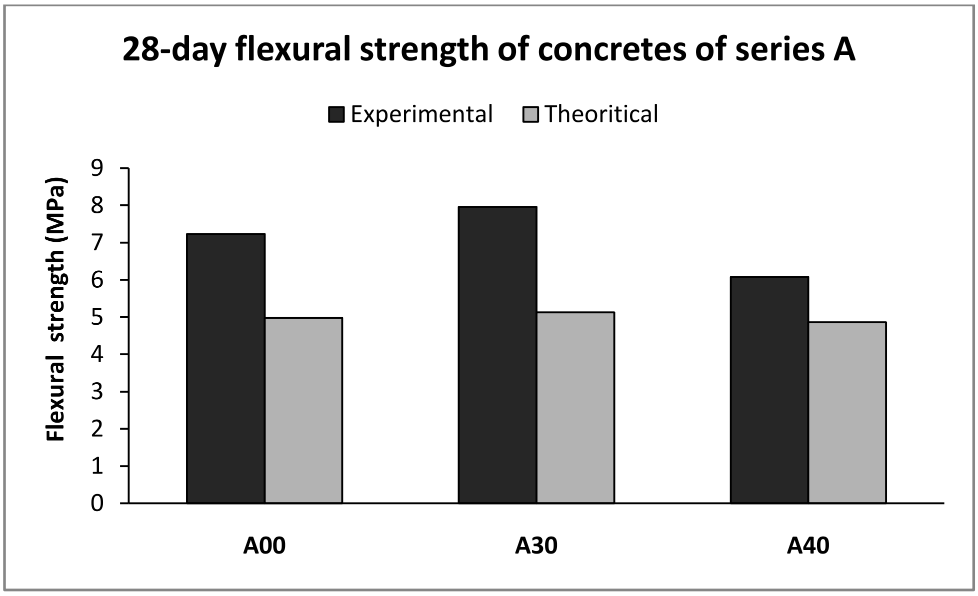


**Figure 4-8: Flexural strength of concretes (series A) at 28 days**

Fly ash incorporated concretes of series A had flexural strength in the range of ±15% of control concrete’s (A00) strength. The strength of A40 is lower than that of the control concrete. Similar 28-day result for A40 was also observed in compressive and indirect tensile strength which exceeded control concrete's (A00) strength at later ages. This trend is expected, because mix A40 contain higher amount of fly ash and slightly lower w/b ratio than mix A30.

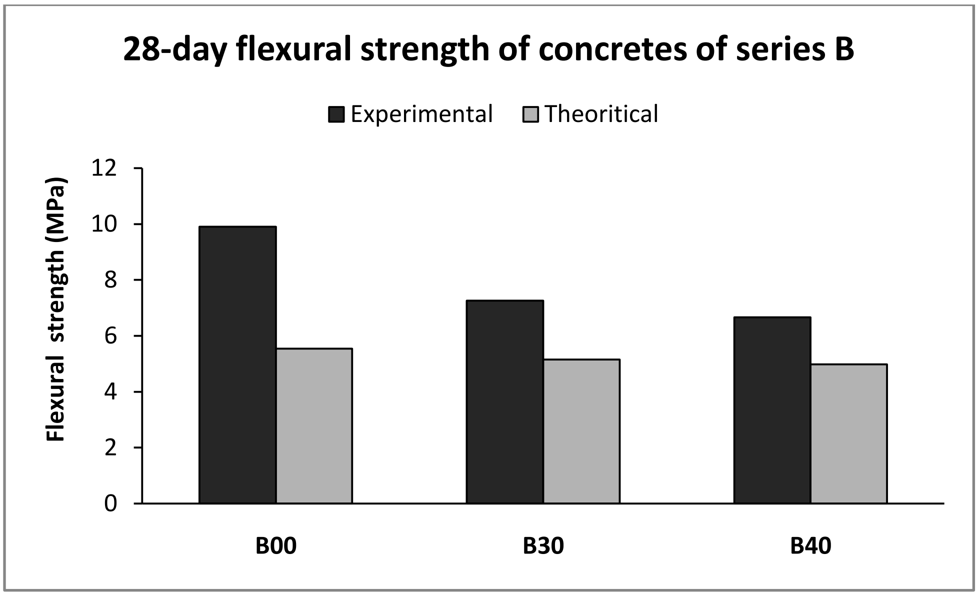


Figure 4-9: Flexural strength of concretes (series B) at 28 days

In series B, fly ash concretes presented lower flexural strength as compared to the control concrete (B00). Mix with 30% fly ash (B30) and 40% fly ash (B40) achieved about 74% and 68% of control concrete's strength at 28 days respectively. Thus it is evident that inclusion of fly ash without varying other mix proportions decreased the flexural strength at 28 days, which is also observed in the results of compressive and tensile strengths.

The flexural tensile strength values were higher than indirect tensile strength values of corresponding mixes as indicated by Neville and Brooks (1987). The trend of the effect of fly ash on the 28-day flexural strength of concretes in both series is similar to that of compressive strength. All mixtures showed higher strength in test than that predicted by Equation 4-2. In both series, concrete with 30% fly ash has shown higher flexural strength than that of concrete with 40% fly ash. It is due to slower pozzolanic reaction of fly ash in concrete at 28 days.

## 4.4. Durability Properties

### 4.4.1. Drying shrinkage

The drying shrinkage was measured in accordance with the AS 1012.13 standard (Standards Australia, 1992). The method is described in section 3.7.7. Three specimens were tested for each mix and the shrinkage was calculated by using the 7-day readings as the reference length. The measurements were continued up to 180 days. The design shrinkage strain at 56 days was also calculated in accordance with the design shrinkage strain calculation of AS 3600-2009 (method (c) in section 3.7.7).

The effect of incorporation of fly ash in concrete on drying shrinkage of series A and series B are shown in Figures *4-10* and *4-11* respectively. Shrinkage values obtained by laboratory experiments and those obtained by calculating in accordance with AS 3600-2009 (clause 3.1.7.2) are presented in Table *4-6*. Detailed data set is given in Appendix G.

**Table 4-6: Shrinkage strain of concrete mixtures at 56 days**

| **Mixtures** | | **Shrinkage strain (microstrain)** | | |
|---|---|---|---|---|
| **Series** | **Mix ID** | **Experimental value (AS 1012.13)** | **Calculated value as per AS 3600-2009 (clause 3.1.7.2)** | **calculated / experimental** |
| A | A00 | 399 | 485 | 1.21 |
| | A30 | 355 | 473 | 1.33 |
| | A40 | 356 | 494 | 1.39 |
| B | B00 | 346 | 437 | 1.26 |
| | B30 | 330 | 472 | 1.43 |
| | B40 | 355 | 485 | 1.37 |

It can be seen from the figures, that most of the shrinkage in all the concrete samples took place within 56 days from casting. Concrete incorporating fly ash have shown less drying shrinkage than the control concrete when they were designed with variable w/b ratio and total binder content to achieve similar 28 days compressive strength (series A). This is because of the lower w/b ratio in the fly ash concretes.

Shrinkage was similar for fly ash concretes and control concrete of series-A up to 21 days (Figure *4-10*). After that, the rate of shrinkage decreased for the fly ash incorporated concretes to reach a 10% lower value than that of the control concrete at 56 days and afterwards. At 180 days, the concrete containing 40% fly ash (A40) achieved slightly lower shrinkage than the concrete containing 30% fly ash (A30).

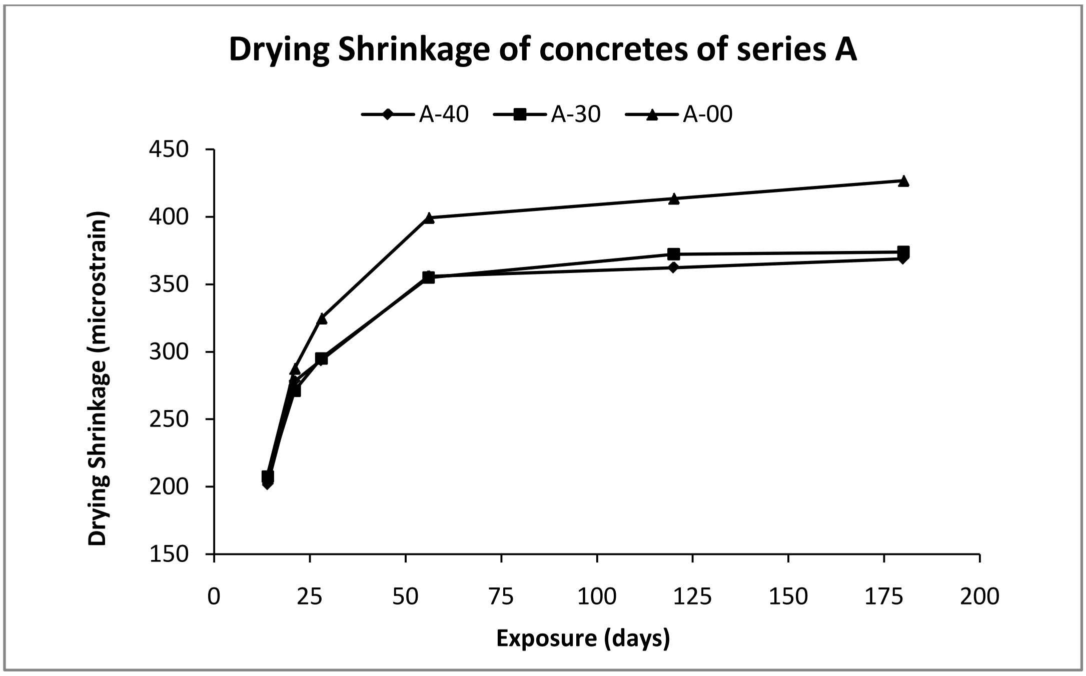


**Figure 4-10: Drying shrinkage of concretes (series A)**

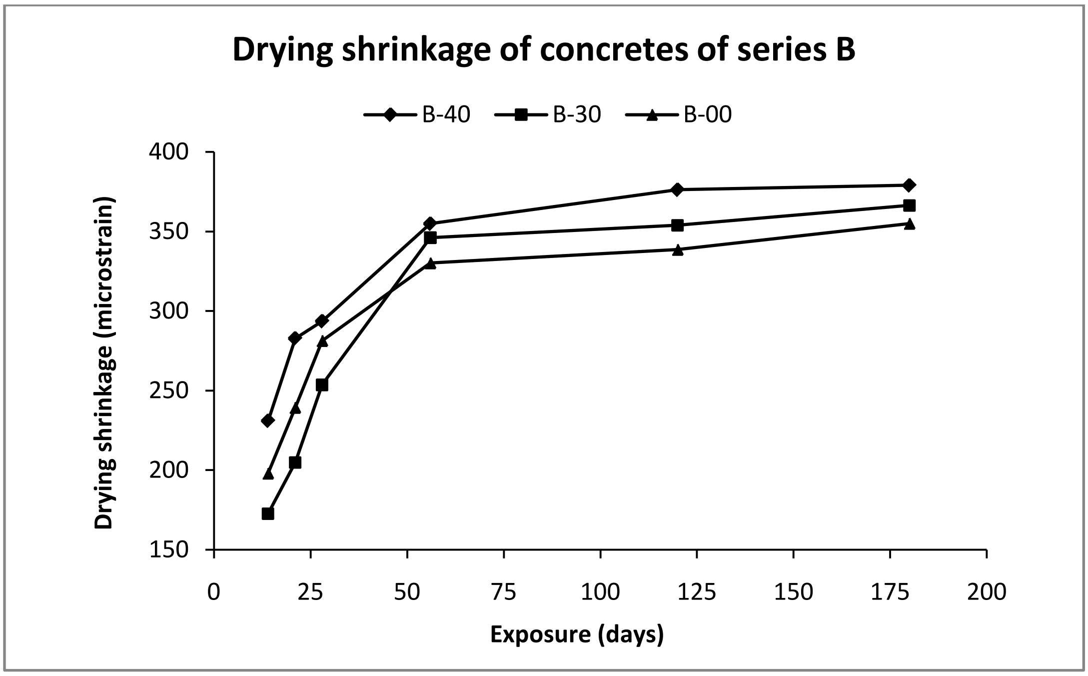


**Figure 4-11: Drying shrinkage of concretes (series B)**

In Series B, shrinkage values of the fly ash concretes (B30 and B40) were higher than that of the control concrete (B00) until 28 days (Figure *4-11*). After that, the rate of shrinkage decreased for fly ash concretes and reached a value similar to that of the control concrete at 56 days. The shrinkage values of both of the fly ash concretes were very close (within 4%) to that of control concrete up to 180 days. Concrete with 30% fly ash showed less shrinkage than that with 40% fly ash. The fly ash concrete requires less water to produce similar effect of cement concrete (Jiang and Malhotra, 2000). In series B all the mixtures had same water content. This resulted in higher amount of free water in the fly ash concretes. Hence drying shrinkage increased with the increase of fly ash. In their study, Munday, Ong, Wong, and Dhir (as cited in Atis, 2003b) also found increase of drying shrinkage for fly ash incorporation in some concrete. This result signifies the need of adjustment in mix proportions when it incorporates fly ash as partial replacement of cement.

The values of shrinkage in all the specimens at 56 days were well below the $1000\times10^{-6}$ as specified by the AS 1379-2007 Standard (Standards Australia, 2007) for normal and special class of concrete. The experimental values for all concrete samples are lower than the design shrinkage values calculated as per AS 3600-2009 (Standards Australia, 2009) (Table *4-6*). Though these calculated shrinkage values have a range of ±30%, the experimental values lie in the lower margin of calculated shrinkage values. It can be seen from Table *4-6* that the calculation of design shrinkage by using the AS 3600 Standard is more conservative for fly ash concrete than for the control concrete.

### 4.4.2. Volume of permeable void (VPV) and water absorption

The main factor controlling the penetrability of aggressive agents in concrete is the pore structure of concrete. The aggressive agents penetrate through the interconnected capillary pores and other void systems within the hardened concrete. Fly ash, being a very fine particle, acts as microfiller as well as a pozzolanic material (Poon et al. 2000). Thus it enhances the microstructure of concrete by reducing pore volume, which depends on many factors such as fly ash content, curing, age, and mix proportions. Volume of permeable void was determined at two different ages of concretes; at 28 days and at 180 days. These ages were selected to measure VPV values after initial normal curing period at early age (28 days) and at a mature age (180 days). This is expected to reflect the change in VPV values over the age due to inclusion of fly ash in concrete. The tests were done using samples that were water-cured for 28 days (curing regime I) and 7 days (curing regime II). Water absorption after immersion and boiling was also measured. The classification recommended by VicRoads, as shown in Table *4-7* is used to rate the quality of concrete.

The test results at 28 days and 180 days are shown in Tables *4-8* and Table *4-9* respectively. Figure*s 4-12* and *4-13* represent permeable voids of different mixes and curing regimes for series A and series B respectively. Detail test data are given in Appendix H.

**Table 4-7: VicRoads classification for concrete durability based on the volume of permeable void (VPV) of vibrated cylinders (Concrete Institute of Australia, 2001)**

| VPV(%) | Rating |
|---|---|
| <11 | Excellent |
| 11-13 | Good |
| 13-14 | Normal |
| 14-16 | Marginal |
| >16 | Bad |

**Table 4-8: Permeable voids and absorption of concrete mixtures at 28 days**

| Mixtures | | Curing regime I (28 days water cured) | | | Curing regime II (7 days water cured) | | |
|---|---|---|---|---|---|---|---|
| Series | Mix ID | Immersed absorption (%) | Boiled absorption (%) | AVPV (%) | Immersed absorption (%) | Boiled absorption (%) | AVPV (%) |
| A | A00 | 4.4 | 4.5 | 10.4 | 4.5 | 4.5 | 10.6 |
| | A30 | 4.3 | 4.4 | 10.3 | 4.4 | 4.4 | 10.3 |
| | A40 | 4.4 | 4.5 | 10.4 | 4.3 | 4.4 | 10.3 |
| B | B00 | 4.3 | 4.4 | 10.3 | 4.4 | 4.4 | 10.4 |
| | B30 | 4.7 | 4.8 | 11.1 | 4.9 | 5.0 | 11.5 |
| | B40 | 4.8 | 4.8 | 11.2 | 4.8 | 4.8 | 11.2 |

**Table 4-9: Permeable voids and absorption of concrete mixtures at 180 days**

| Mixtures | | Curing regime I (28 days water cured) | | | Curing regime II (7 days water cured) | | |
|---|---|---|---|---|---|---|---|
| **Series** | **Mix ID** | **Immersed absorption (%)** | **Boiled absorption (%)** | **AVPV (%)** | **Immersed absorption (%)** | **Boiled absorption (%)** | **AVPV (%)** |
| A | A00 | 4.3 | 4.4 | 10.2 | 4.4 | 4.5 | 10.4 |
| | A30 | 4.0 | 4.2 | 9.8 | 4.3 | 4.4 | 10.3 |
| | A40 | 4.2 | 4.3 | 10.1 | 4.3 | 4.4 | 10.3 |
| B | B00 | 4.1 | 4.1 | 9.7 | 4.3 | 4.3 | 10.1 |
| | B30 | 4.4 | 4.5 | 10.6 | 4.6 | 4.6 | 10.8 |
| | B40 | 4.5 | 4.6 | 10.8 | 4.6 | 4.6 | 10.9 |

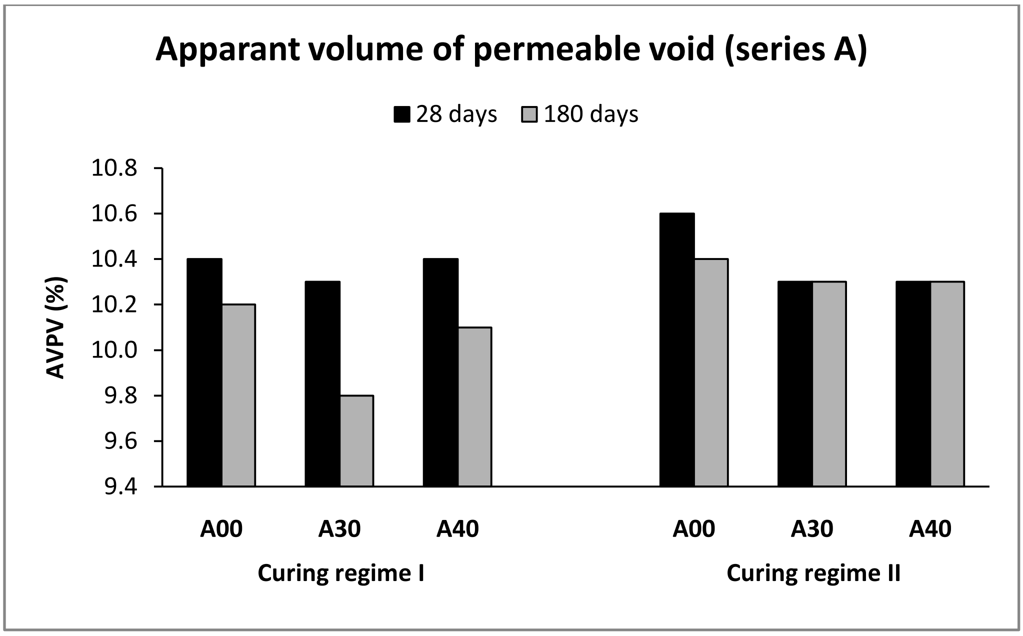


**Figure 4-12: Comparison of permeable void volume of concretes (series A)**

The mixture proportions of the concretes of series A were designed to achieve similar 28-day compressive strength. This also resulted in almost same volume of permeable void in fly ash concretes (A30 and A40) at the age of 28 days for curing regime I (28 days cured). Figure *4-12* shows that, concrete with 30% fly ash (A30) achieved slightly lower permeable void as compared to the control concrete (A00) and concrete with 40% fly ash (A40). However, at 180 days both the mix A30 and

A40 achieved lower permeable void than that of control concrete. Fly ash concrete samples that were cured for 7 days (curing regime II) achieved lower permeable void as compared to control concrete. No significant variation in VPV values were observed for fly ash concretes after 180 days.

In series B (Figure *4-13*), the fly ash concretes (B30 and B40) have shown higher VPV values as compared to the control concrete (B00), for both the curing regimes. The VPV increased with the increase of fly ash. This is due to replacing cement with fly ash while keeping the w/b ratio constant. The results are similar to those observed by Papadakis (1999), who found increased porosity when Class F fly ash replaced cement in concrete. After 180 days, the VPV values decreased for all samples maintaining similar trend of the 28 days results.

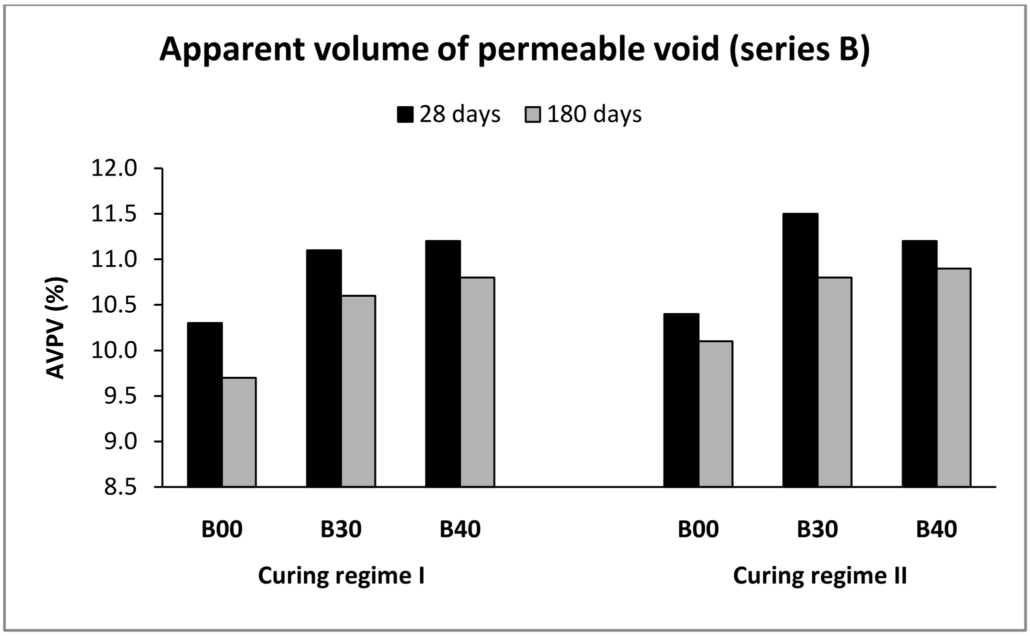


**Figure 4-13: Comparison of permeable void volume of concretes (series B)**

In general, volume of permeable voids of concrete samples cured in water for 28 days are less than that of samples cured for 7 days. This was expected as hydration for a longer period resulted in a denser structure of the concrete. The VicRoads specification (Table *4-7*) allows rounding down the test result of VPV to the nearest whole number when it is equal to or less than 0.5 above the maximum recommended value. Considering this provision, VPV of the fly ash concretes of series B met the limit of 11% for “Excellent” rating at 28 days. Hence, all the concretes in this study achieved ‘Excellent’ rating according to Table *4-7.*

In both series of concrete, the volume of permeable voids decreased at 180 days of age from that at 28 days of age. It indicates densification of the microstructure of concrete due to continued hydration with the increase of age.

Immersed absorption and boiled absorption values followed the similar trend of VPV. The boiled absorption values are slightly higher than immersed absorption. This is usual, because boiling operation facilitate access of water into the pore by eliminating entrapped air in the pores of concrete. When samples were cured for 28 days, the immersed absorption values varied in the range of 4.3 - 4.4% in series A and 4.3 - 4.8% in series B at 28 days. The absorption decreased further at 180 days.

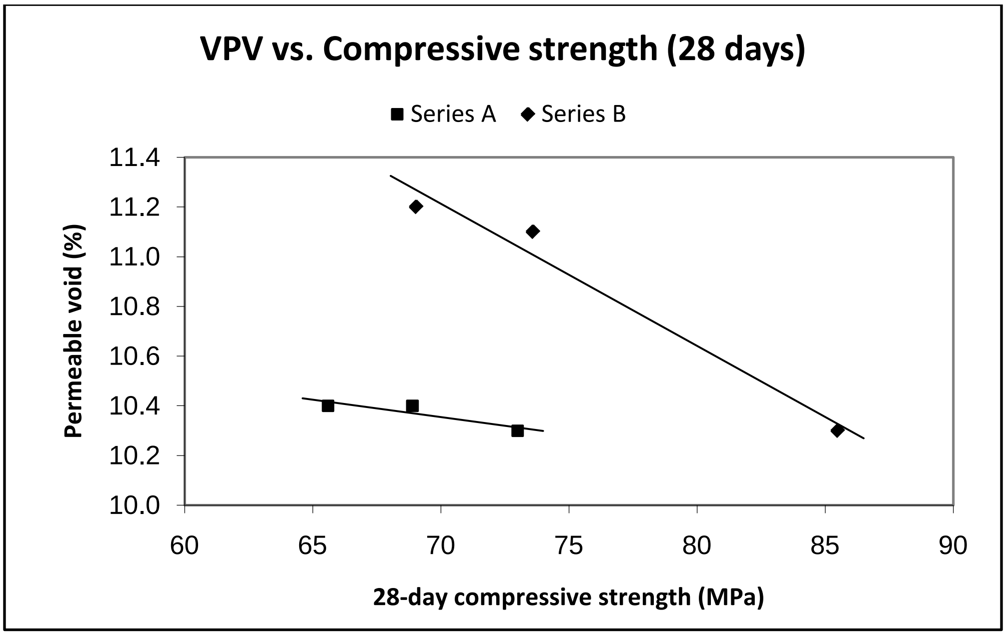


**Figure 4-14: Relationship of compressive strength and VPV**

Compressive strength of concrete is usually influenced by the volume of voids in the concrete. The 28-day compressive strengths for both the series of concretes are plotted against the volume of permeable voids in Figure *4-14.* It can be seen from this figure that compressive strength decreased linearly with the increase in void contents of the concrete. Dinakar, Babu and Santhanam (2008) have reported similar trend for self compacting concretes containing fly ash.

### 4.4.3. Water sorptivity

Water provides the medium by which many aggressive agents are transported into concrete. It also affects the initiation and rate of some deterioration process such as carbonation. Other deterioration processes such as chloride ingress, and chemical attack and corrosion of steel can be controlled by restricting the movement of moisture in the concrete. For many structures, the primary transport mechanism is considered to be absorption of surface water due to capillary suction, particularly in their early life.

The sorptivity of concrete is a quantity that measures the flow of fluids into the unsaturated concrete. The sorptivity test gives an indication of concrete's resistance against capillary permeation for assessing the pore structure. Detailed procedure of the test is outlined in section 3.7.9. Samples cured in water for 7 days (curing regimes II) and 28 days (curing regime I) were tested at 28 days and 180 days. The rate of absorption is measured using the readings of initial period of 6 hours. The rate of water absorption is defined as the slope of the line that is the best fit to the absorption plotted against the square root of time. Two replicate specimens for each mix were tested and the average rate of sorption was measured to the nearest $0.1 \times 10^{-4}$ mm/sec$^{1/2}$. Papworth and Grace (1985) recommended the typical values of water permeability and sorptivity for various performance classes of concrete (Table *4-10*). These recommendations are used in this study to rate the quality of the concretes.

**Table 4-10: Concrete performance classification (Papworth and Grace, 1985)**

| **Test method** | **Performance limits** | | |
|---|---|---|---|
| | **Poor** | **Acceptable** | **Very good** |
| Water permeability, m/s | $> 10^{-10}$ | $10^{-10}$ to $10^{-12}$ | $< 10^{-12}$ |
| Sorptivity, mm/min$^{1/2}$<br>($\times 10^{-4}$ mm/s$^{1/2}$) | > 0.2<br>(> 258.2) | 0.1 to 0.2<br>(129.1 to 258.2) | < 0.1<br>(< 129.1) |

Table *4-11* shows the initial sorptivity coefficient for each mix. The graphs and data for all of the samples are given in Appendix I. Figures *4-15* and *4-16* show the comparison of initial sorptivity coefficients of series A and series B concretes respectively. Results of 28 days and 180 days test for both curing regimes are shown in these figures.

**Table 4-11: Sorptivity test results**

| Mixture | | Sorptivity coefficient ($\times 10^{-4}$ mm/s$^{1/2}$) | | | |
|---|---|---|---|---|---|
| | | **Curing regime I (28 days water cured)** | | **Curing regime II (7 days water cured)** | |
| **Series** | **Mix ID** | **28 days** | **180 days** | **28 days** | **180 days** |
| A | A00 | 174.0 | 140.0 | 196.2 | 128.8 |
| | A30 | 107.0 | 105.3 | 124.2 | 112.5 |
| | A40 | 125.8 | 87.1 | 111.2 | 105.0 |
| B | B00 | 138.3 | 107.5 | 183.6 | 105.2 |
| | B30 | 128.8 | 106.2 | 133.3 | 114.3 |
| | B40 | 108.1 | 100.3 | 120.1 | 99.7 |

Concretes in series A, that achieved similar strength at 28 days, have shown significant reduction of sorption due to inclusion of fly ash (Figure *4-15*). At 28 days mix A40 of curing regime I (28 days water curing) showed slightly higher absorption than mix A30. However, after 180 days, the sorptivity of mix A40 reached 17% lower than that of mix A30. Sorptivity dropped by 25% and 37% of the control concrete’s value for 30% and 40% fly ash concrete respectively. Concretes of curing regime II (7 days water curing) also have shown lower sorption of fly ash incorporated concrete at both 28 days and 180 days.

In series B, inclusion of fly ash with constant w/b and constant total binder content in the mix has decreased absorption slightly (Figure *4-16)*. The sorptivity decreased with the increase of fly ash content in the concrete. For concretes with 30% and 40% fly ash and 28 days curing (curing regime I), sorptivity at 28 days reduced by 6% and 21% of that of the control concrete (B00) respectively. The rate of sorptivity of fly ash concrete tends to be similar to that of control concrete over the age up to 180 days. Fly ash concretes that were cured for 7 days (curing regime II) also showed reduced rate of sorption at early age of 28 days.

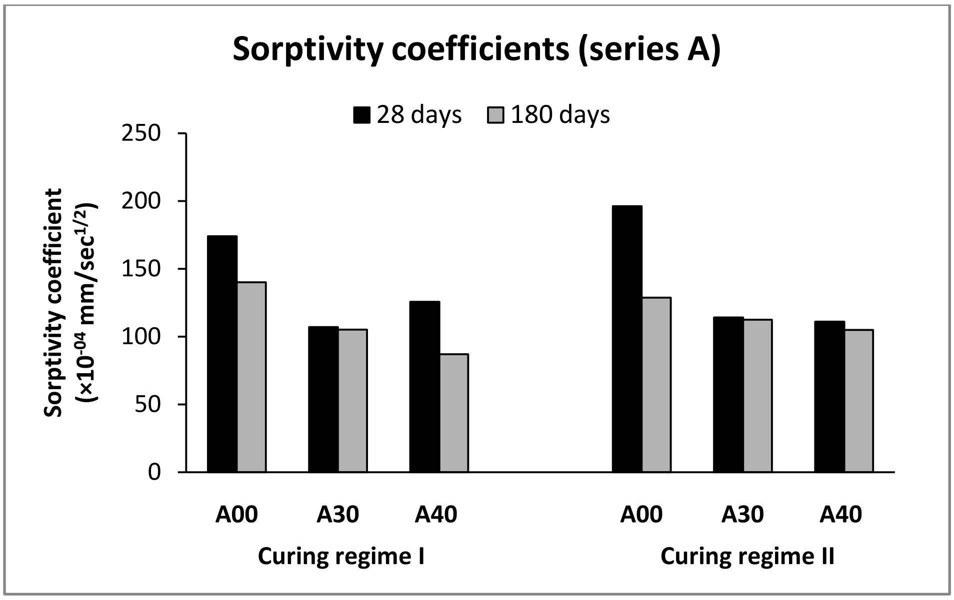


**Figure 4-15: Comparison of sorptivity coefficients of concretes (series A)**

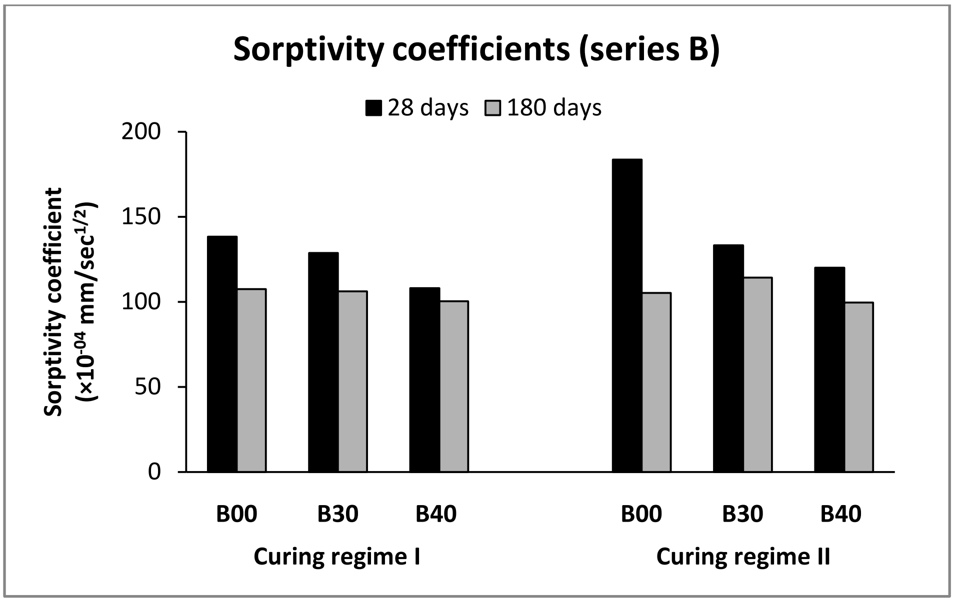


**Figure 4-16: Comparison of sorptivity coefficients of concretes (series B)**

In general, the results indicate that incorporation of fly ash has resulted in less sorption in comparison to the control concrete at 28 days in both series. The sorptivity results are in agreement with that reported by Camoes, Aguiar and Jalali (2003). The reduction in sorptivity was higher when inclusion of fly ash in the mix was combined with reduced w/b ratio and accordingly adjusted total binder content (series A). Fly ash contributed in reducing absorption by filling up the micro-pore through pozzolanic reaction. It also acts as a micro-aggregate (Poon et al. 2000).

With this dual action, fly ash blocked the capillary pore systems in the concrete and improved the resistance to permeation (Marsh, Day and Bonnet, 1985). The rate of sorption was influenced by the initial curing period. Sorptivity reduced with the increase in curing period from 7 to 28 days. Fly ash concrete usually requires intensive curing to achieve enhanced impermeability (Khan and Ayers, 1993; Ramezanianpour and Malhotra, 1995).

The values of sorptivity coefficients of fly ash concretes are less than 0.1 mm/min$^{1/2}$ (129.1×10$^{-4}$ mm/s$^{1/2}$), which is rated as a concrete of 'very good' performance (Table *4-10*) according to Papworth and Grace (1985).

### 4.4.4. Water permeability

Water permeability is the process which defines the ease of movement of water through a penetrable medium. Concrete is a porous material, hence water permeation is considered as an important mechanism for the transport of harmful materials (chloride, sulphate, acids etc.) into concrete. Water permeability can be a major factor for concrete structures under water or that comes in contact of water frequently due to flooding or tidal effect. It is also an indication of the quality of the concrete, and its susceptibility to other forms of penetration such as chloride diffusion and water sorptivity. Concrete of lower water permeability is always desirable to prevent it from early deterioration. The water permeability of concrete using local fly ash as a part of the binder has been investigated in this study.

Water permeability was tested by measuring the uniaxial flow of water passing under high pressure through the concrete sample. The method is described in section 3.7.10. The test was conducted at 28 days and 180 days. The average of two replicate samples is presented for each mix except the values of mix B30 and B40 at 180 days. In these mixes, the individual results of two samples were not within the recommended coefficient of variation of 19.5%. The individual values can be presented instead of an average value, as suggested by the test method (GHD/TEL method, n. d.). The lower value of the two samples was reported here. The test data are presented in Appendix J. The results for water permeability are summarised in Table *4-12*. Water permeability coefficients for different mixes at the two ages are compared in Figures *4-17* and *4.18.*

Table 4-12: Water permeability test results.

| Mixture | | 28 days | 180 days |
|---|---|---|---|
| **Series** | **Mix ID** | **Water permeability coefficient ($\times 10^{-12}$ m/s)** | **Water permeability coefficient ($\times 10^{-12}$ m/s)** |
| A | A00 | 2.28 | 1.96 |
| | A30 | 0.78 | 0.73 |
| | A40 | 0.79 | 0.62 |
| B | B00 | 1.18 | 1.07 |
| | B30 | 1.10 | 0.98 |
| | B40 | 0.70 | 0.58 |

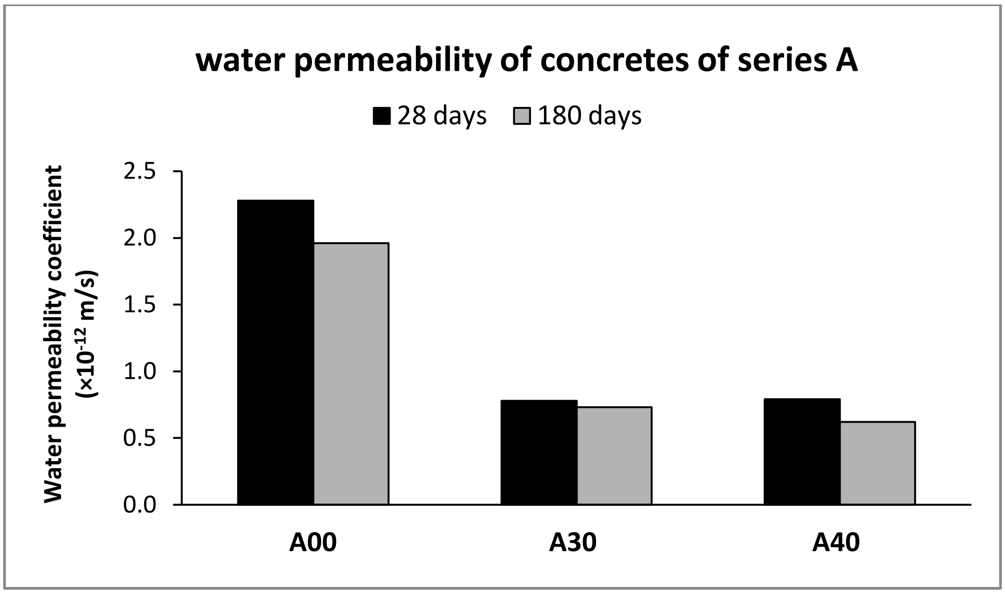


Figure 4-17: Comparison of water permeability of concretes (series A)

In series A, the 28- day water permeability values of the fly ash concrete samples (A30 and A40) were less than that of the control concrete (A00). The values of permeability coefficient of both the fly ash concretes were below $10^{-12}$ m/s which indicate 'very good' performance of concrete (Table *4-10*) according to Papworth and Grace (1985). Permeability coefficients of the fly ash concretes decreased by about 65% of that of the control concrete (A00). Concrete with 40% fly ash (A40) had the similar permeability to that of 30% fly ash concrete (A30) at 28 days. But at 180 days, the permeability of mix A40 was 15% less than that of mix A30 and 68% less than that of mix A00. The low water permeability of the fly ash concretes is mainly because of their lower w/b ratios as compared to that of control concrete mix. Thus, inclusion of fly ash up to 40 % of the total binder has resulted in high strength concrete of lower permeability by allowing reduced w/b ratio.

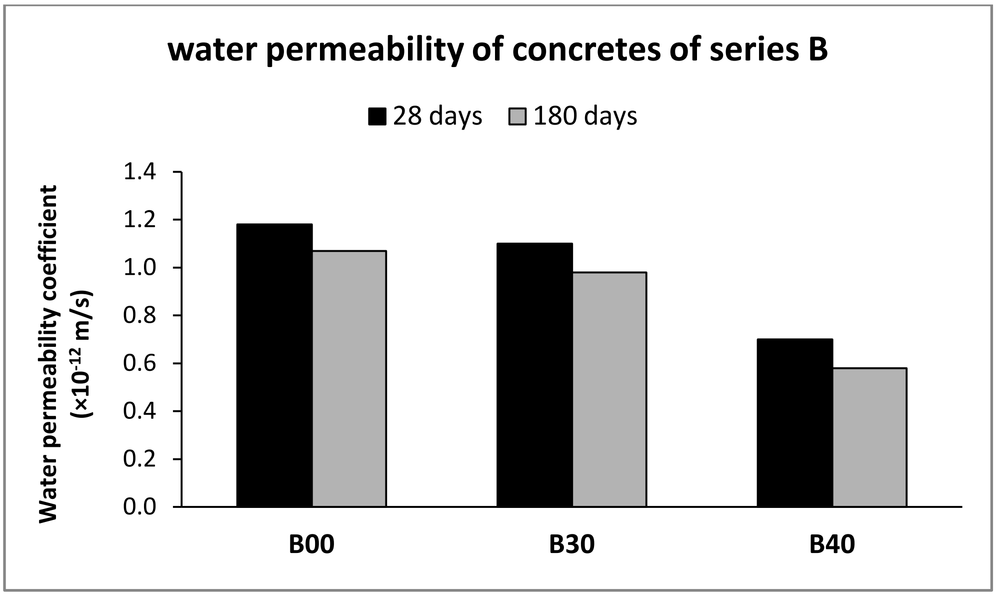


**Figure 4-18: Comparison of water permeability of concretes (series B)**

In series B, cement was replaced by fly ash at the rates of 30% and 40% of the total binder while other constituents were same in the control mix. The cement replacement by fly ash reduced water permeability of the specimens of B30 and B40 as compared to the control concrete. Since the w/b ratio of the concretes of this series was constant, the effect of fly ash on the reduction of water permeability was less than that in series A. While mix B40 (40% fly ash) achieved ‘very good’ performance limit according to Table *4-10*, mix B30 was in the margin of that limit at 28 days. At this age, water permeability coefficient decreased by 7% and 40% of control concrete’s permeability for 30% and 40% fly ash contents respectively. At 180 days, the permeability decreased for every mix. The permeability coefficients reduced by 17%, 11% and 9% for B40, B30 and B00 respectively.

Sorptivity test results of 28 days tests are compared with the results of water permeability at the same age in the Figure *4-19*. The comparison shows similar trends for both series of concretes. This implies the similitude of two different forms of water penetration in concrete; capillary suction and the penetration of water under pressure.

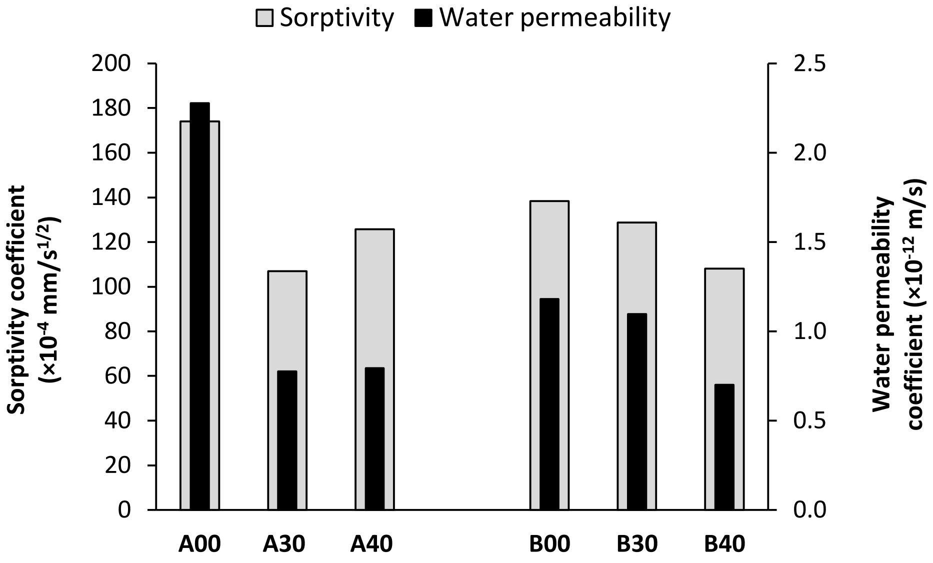


**Figure 4-19: Comparison of sorptivity and water permeability at 28 days.**

The water permeability results generally indicated the positive effects of fly ash incorporation in concrete which varied with the mix proportions. In series A, similar grade of fly ash concretes demonstrated significant resistance to water permeation, while in series B the presence of fly ash also restricted the flow of water. The effect of fly ash on the decrease of permeability of concrete is because of the reduction of the large pores volume by the reaction of fly ash and the pore-blockage effect of fly ash (Marsh et al. 1985).

### 4.4.5. Air Permeability

The ability of the concrete cover to protect the reinforcement is of paramount importance in determining concrete durability. In order to keep the protective ‘passive layer’ on the steel intact, the concrete cover must resist the penetration of carbon dioxide and chloride ions to the depth of the steel. Although the chemistry of the concrete may influence the rate of penetration of these agents, the inherent permeability of the concrete cover can be seen as the key factor in determining the overall durability of reinforced concrete.

**Table 4-13: Protective quality of cementitious materials**
**(samples conditioned to constant weight at 50$^o$C)**

| Quality category | Time (s) | Air exclusion rating (s/ml) | Air permeability ($m^2 \times 10^{-14}$) | Interpretation |
|---|---|---|---|---|
| 0 | < 30 | < 8 | > 170 | Poor |
| 1 | 30-100 | 8-25 | 50-170 | Moderate |
| 2 | 100-300 | 25-75 | 20-50 | Fair |
| 3 | 300-1000 | 75-250 | 5-20 | Good |
| 4 | > 1000 | > 250 | > 5 | Excellent |

**Table 4-14: Air permeability results**

| Mixture | | Curing regime I (28 days water cured) | | | Curing regime II (7 days water cured) | | |
|---|---|---|---|---|---|---|---|
| Series | Mix ID | Time (s) | Air exclusion rating (s/ml) | Air permeability *k* ($m^2 \times 10^{-14}$) | Time (s) | Air exclusion rating (s/ml) | Air permeability *k* ($m^2 \times 10^{-14}$) |
| A | A00 | 432 | 104.6 | 11.9 | 378 | 91.6 | 13.7 |
| | A30 | 530 | 128.7 | 9.7 | 485 | 117.5 | 10.6 |
| | A40 | 481 | 116.2 | 10.7 | 446 | 107.8 | 11.6 |
| B | B00 | 462 | 112.1 | 11.1 | 456 | 110.9 | 11.3 |
| | B30 | 442 | 107.0 | 11.6 | 368 | 88.8 | 14.0 |
| | B40 | 444 | 107.4 | 11.6 | 209 | 50.5 | 24.8 |

The air permeability of concrete was measured using Figg's method as described in section 3.7.11. The time required for the pressure change from 55 kPa to 50 kPa below atmospheric pressure was measured from the standard test holes. Using these test data air exclusion rating (AER) and air permeability (*k*) was calculated. Samples were subjected to both curing regimes I (28 days water cured) and curing regime II

(7 days water cured). The results for each curing regime are given in Table *4-14*. Detail test data are presented in Appendix K.

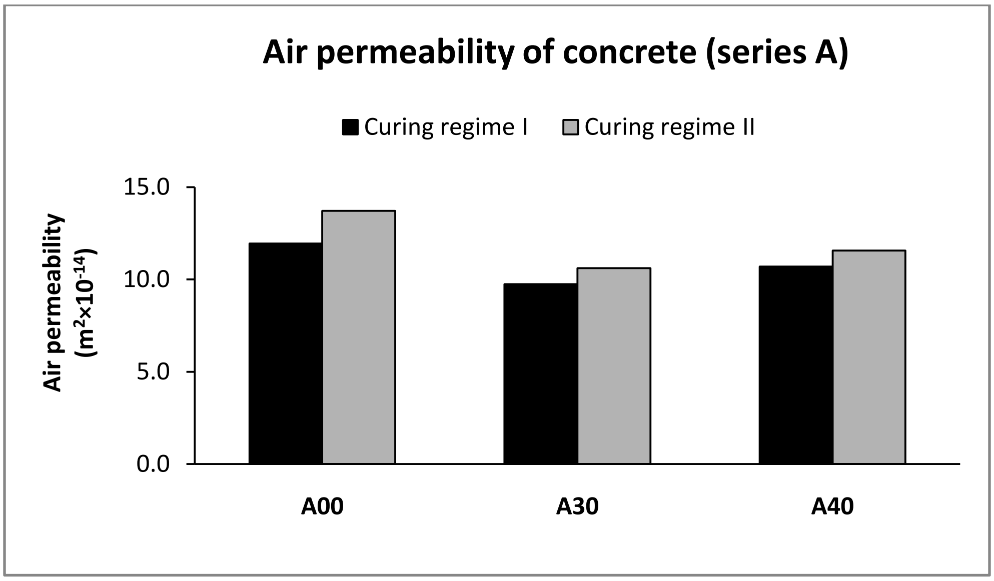


**Figure 4-20: Air permeability of concretes (series A)**

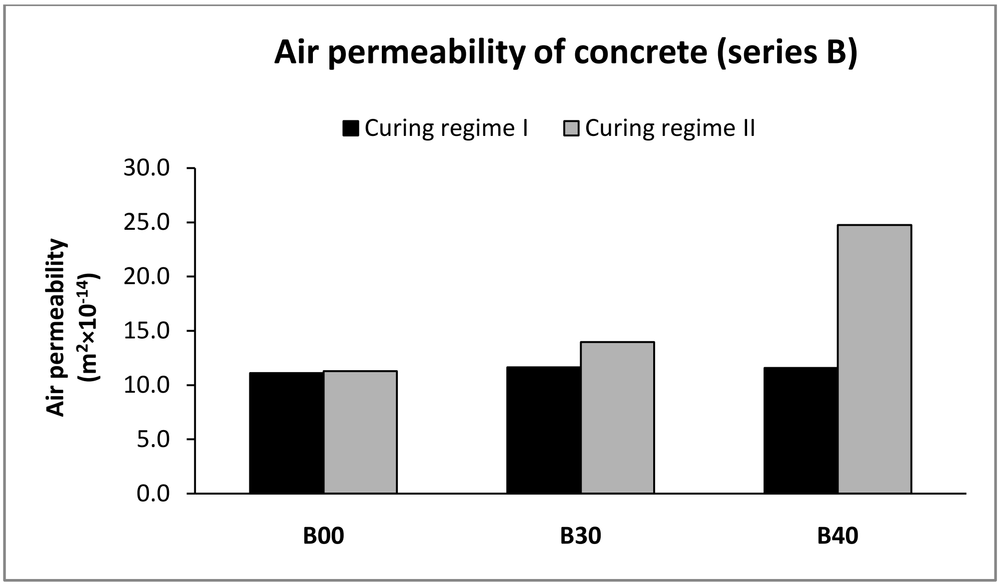


**Figure 4-21: Air permeability of concretes (series B)**

Air permeability results of the concretes of series A are plotted in Figure *4-20.* Fly ash concretes (A30 and A40) have shown less air permeability as compared to control concrete (A00). Concrete with 30% fly ash (A30) achieved the lowest air permeability. The mix A30 attained about 20% less air permeability than the mix A00, while mix A40 attained about 10% reduction than the mix A00. Difference in initial curing condition affected the air permeability values. Permeability of the samples cured for 28 days were less than those cured for 7 days.

The values of air permeability (*k*) of the samples of series B are plotted in the Figure *4-21.* The inclusion of fly ash caused minor increase (about 4%) in air permeability as compared to the control concrete (B00). No difference was observed for the concretes with 30% (B30) and 40% fly ash (B40) cured for 28 days. Samples that were cured for 28 days showed lower air permeability as compared to that cured for 7 days. Air permeability of the sample of B40 was relatively high when cured for only 7 days as compared to that cured for 28 days.

The air permeability parameter is generally expressed as the time required for reducing the vacuum pressure in a sealed standard hole by 5 kPa. This time can be assessed with the aid of Table *4-13*. The table shows concrete quality categories with interpretation depending on the test time as reported by Cather, Figg, Marsden, and O’Brien (1984). The results indicated no significant difference between the values of time for different mixtures to set apart in terms of concrete quality interpretation that is recommended in Table *4-13*. All the mixtures except B40 with water curing for 7 days, required a time in the range of 300-1000 seconds which represent ‘Good’ quality of concrete.

In general, fly ash inclusion as much as 40% of total binder has shown no adverse change in air permeability of concrete provided they were cured adequately.

### 4.4.6. Carbonation

Carbonation can make concrete vulnerable to corrosion whether it is subjected to other aggressive materials or not. Hence, it is desirable to achieve sufficient resistance to carbonation of concrete to protect the reinforcing steel from initiation of corrosion. The rate of carbonation varies with the mix proportions and it can be tested through a direct or indirect method. The method that was followed in this study was an accelerated method as described in section 3.7.12.

Carbonation depth was measured from the edge of split surface of the specimen. In all specimens the top surface was carbonated most. It is because the top surface is finished by trowel during casting which makes the top surface more porous than the rest of the concrete. Hence the readings from the top surface edge were not included in the calculation. Similar approach is recommended by Atis (2003a). The bottom surface edge was also excluded from calculation as the specimen rested on bottom surface, thus was not exposed to carbonation. Four depth measurements were taken from each of the other two sides and the depth of carbonation was calculated as the average of the readings. The results after 28 days of exposure in 2% $CO_2$ concentrated carbonation chamber are given in Table *4-15*. The depth of carbonation readings are given in Appendix L.

**Table 4-15: Average measured depth of carbonation after 28 days of exposure in 2% $CO_2$**

| Mixture | | Average depth of Carbonation (mm) | Standard deviation |
|---|---|---|---|
| Series | Mix ID | | |
| A | A00 | 4.4 | 2.79 |
| | A30 | 4.3 | 1.73 |
| | A40 | 4.7 | 1.28 |
| B | B00 | 1.1 | 0.20 |
| | B30 | 3.7 | 1.51 |
| | B40 | 4.5 | 1.25 |

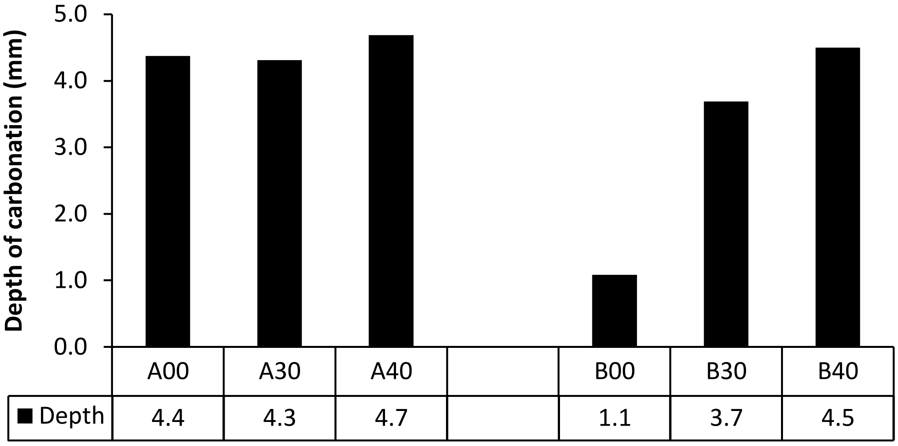


**Figure 4-22: Depth of carbonation of concretes of series A and B**

Average depth of carbonation is plotted in Figure *4-22*. The carbonated split surface of all the samples in series A and B are presented in Figures *4-23* and *4-24* respectively. The bottom line of each picture is the top surface edge of the specimen which was ignored in the measurement. Illustrating all the pictures, some common features can be identified. The depth of carbonation at different location varied with the composition of concrete at the edges. It is relatively higher at the corner of the two edges due to two-dimensional carbonation (Chen et al. 2007) and at the interfacial zones of the coarse aggregates due to poor density of mortar. The presence of air voids at the surface also help $CO_2$ penetrate at the depth beyond normal carbonation depth. The other zones at the edges that contain only mortar indicate relatively uniform depth of carbonation. The aggregates generally remain colourless in the phenolphthalein indicator.

From Figure *4-22,* it can be seen that all the samples of series A suffered almost similar carbonation while concretes of series B have shown variable carbonation depth for different mixes. Fly ash incorporation in concrete influenced the depth of carbonation differently in the two series of concretes.

In case of the concretes of series A, the depth of carbonation for three mixes resulted in very close average values. The standard deviation of the measured depths was relatively less for fly ash concretes (A40 and A30) than the control concrete. Mix A30 had slightly less carbonation than both mix A40 and mix A00. This trend of carbonation results is similar to that of the results of VPV (curing regime II) and air permeability (curing regime II). Since concretes of series A were designed by varying w/b ratio and total binder content, fly ash concretes’ carbonation is similar to that of the control concrete. Thomas et al. (2000) also found similar carbonation trend with concretes of similar grade incorporating up to 30% fly ash.

Fly ash concretes of series B suffered higher carbonation as compared to control concrete (B00). The depth of carbonation increased with the increase of fly ash in the mix. The average carbonated depth of mix B30 and B40 were more than 3 and 4 times of that of mix B00 for similar condition. Carbonation of mix B00 is less than that of mix A00 due to its (B00) significantly less w/b ratio and higher cement content. Carbonation of concretes of series B also followed similar trend of the VPV and air permeability results in curing regime II with fly ash inclusion.

(i) A40

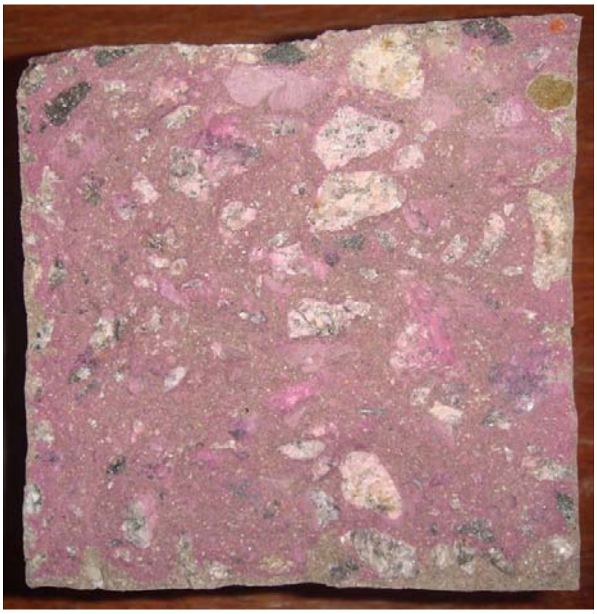
(ii) A30

(iii) A00

**Figure 4-23: Carbonation pattern of concretes of series A (i) A40 (ii) A30 (iii) A00**

(i) B40

(ii) B30



(iii) B00

**Figure 4-24: Carbonation pattern of concretes of series B (i) B40 (ii) B30 (iii) B00**

Hence fly ash replacement without adjusting other mix variables (w/b and total binder content) does not improve the carbonation resistance at 28 days of age. This is because of relatively lower degree of hydration of the fly ash concretes as compared to the control concrete at the test age. Other researchers reported similar results on carbonation due to fly ash incorporation (Chen et al. 2007; Jiang et al. 2000; Khan and Lynsdale, 2002; Sisomphon and Franke, 2007).

Atis (2003a) presented a relationship between compressive strength and carbonation depth that indicated a linearly decreasing trend of carbonation with the increase of compressive strength. A similar trend is also observed in this study when the depths of carbonation are plotted against the 28-day compressive strengths. The trend lines are shown in Figure *4-25*. It shows that the depth of carbonation decreased with the increase of compressive strength. This is expected, since compressive strength indicates the density of the binder paste in the concrete.

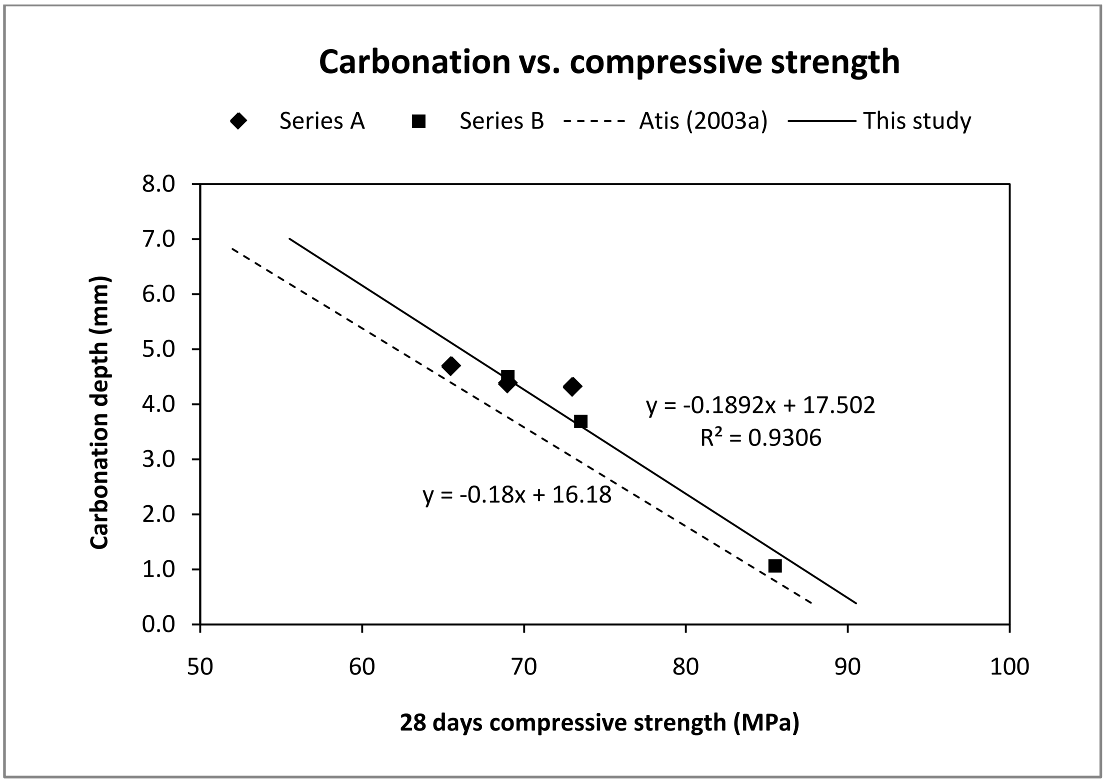


**Figure 4-25: Relationship of depth of carbonation and 28-day compressive strength**

### 4.4.7. Rapid chloride permeability

Chloride ion is believed to be the most dominating agent in initiating concrete's deterioration. Concrete structures in marine environment and those treated with de-icing salt in cold weather are mainly affected by chloride attack. Thus resistance to chloride ion penetration is a much desired property for these types of concrete structures. Among the several methods of chloride resistance tests, the rapid chloride permeability test (RCPT) has been an acceptable method for its quickness, repeatability and precision (Castellote and Andrade, 2006). In this method the likelihood of chloride ion ($Cl^-$) penetration through concrete is measured in terms of the electrical indication within a six-hour test. Total charge passed through the concrete sample is measured and the chloride ion penetrability level can be assessed by following the recommendation of the ASTM C 1202 (ASTM Standards, 2007). The recommendations are given in Table *4-16*.

**Table 4-16: Chloride ion penetrability based on charge passed as per ASTM C 1202 (ASTM Standards, 2007)**

| Charge passed (coulombs) | Chloride ion penetrability |
|---|---|
| >4000 | High |
| 2000-4000 | Moderate |
| 1000-2000 | Low |
| 100-1000 | Very low |
| <100 | Negligible |

In addition, the resistivity of concrete can be determined by using the initial current induced for 60 volt potential. The Ohm's law (Equation 4-4) is used for calculating resistance (R). Then resistivity can be calculated by Equation 4-5.

$$R = \frac{V}{I} \tag{4-4}$$

$$\text{Resistivity} = \frac{RA}{l} \tag{4-5}$$

Where, R = resistance; V = voltage; I = initial current

A = area of the specimen (m); l = thickness of the specimen (m)

The Rapid Chloride Permeability test was performed at 28 days and 180 days. The details of the test results are given in Appendix M. The charge passed and the resistivity values are shown in Table *4-17*. The total charge passed through different mixture of concretes at 28 days and 180 days of age are plotted in Figure*s 4-26*.

**Table 4-17: Rapid chloride permeability test results.**

| Mixture | | 28 days | | 180 days | |
|---|---|---|---|---|---|
| **Series** | **Mix ID** | **Charge passed (Coulomb)** | **Resistivity at 60V (Ω m)** | **Charge passed (Coulomb)** | **Resistivity at 60V (Ω m)** |
| A | A00 | 2722.0 | 83.33 | 1652.5 | 139.57 |
| | A30 | 1757.5 | 146.17 | 573.0 | 354.05 |
| | A40 | 1493.0 | 155.24 | 489.0 | 417.31 |
| B | B00 | 2070.5 | 118.82 | 910.0 | 209.62 |
| | B30 | 1881.0 | 128.77 | 466.0 | 427.55 |
| | B40 | 1574.0 | 150.08 | 566.5 | 387.45 |

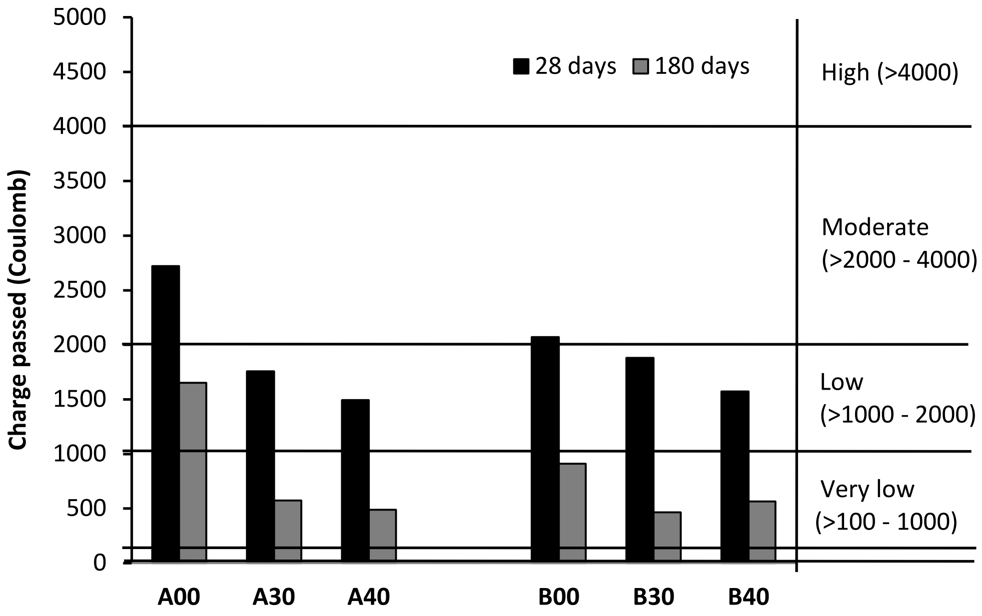


**Figure 4-26: Chloride permeability levels of concretes of series A and B as per ASTM 1202-07 (ASTM Standards, 2007)**

From Figure *4*-26 it can be seen that, the fly ash concretes achieved better resistance than the corresponding control concretes in both series A and B. Chloride penetrability decreased with the increase of fly ash in the mixtures. At 28 days of age, fly ash concretes achieved ‘Low’ level of $Cl^-$ penetration as compared to the ‘Moderate’ level for corresponding control concretes. At 180 days, the level of $Cl^-$ penetration has decreased to ‘Very Low’ for fly ash concretes through attaining lower value of charge passed than that of corresponding control concretes.

In series A, the fly ash concrete samples improved the resistance to chloride ion penetration significantly at early age of 28 days. Concrete with 30% fly ash had 35% less charge passed than the control concrete (A00), while concrete with 40% fly ash had 45% less charge passed than the control concrete. At 180 days of age, the resistance to chloride ion penetration improved in all the mixes, but fly ash concretes improved to a higher degree than the control concrete. At this age, the total charge passed reduced by 68% and 40% of the corresponding 28-day values in the fly ash and the control concrete specimens respectively.

In case of series B, replacing cement partially with fly ash at the same w/b ratio improved the resistance to chloride ion penetration, but to a lesser extent than in series A. At 28 days, the charge passed was 10% and 24% less for 30% and 40% fly ash respectively than for the control concrete (B00). At the later age, the chloride ion penetration level decreased at a faster rate in the fly ash concretes than in the control concrete (B00). While mix B00 achieved 56% reduction of charge passed at 180 days, mix B30 and B40 achieved over 64% reduction. Concrete with 40% fly ash showed slightly higher chloride ion penetrability than the 30% fly ash concrete at 180 days. However, concrete specimens of both 30% and 40% fly ash were in the range of ‘very low’ chloride ion penetration at 180 days.

Similar trend of the effect of fly ash in resisting chloride ion penetration are reported in literature (Malhotra, 1990; Sengul et al. 2005). As discussed in the previous sections, the presence of fly ash in concrete improves the microstructure of the concrete by filling the larger pores with the product of pozzolanic reaction. Fly ash also increases the chloride binding capacity of concrete. The chloride ion penetration depends on the chloride binding capacity of the constituent materials of concrete. While entering into the pores, some chloride ion reacts with the cement compound

$C_3A$ (tricalcium aluminate) and forms stable chloro-complexes. The presence of fly ash leads to an increase of the amount of $C_3A$ in the mix due to higher amount of alumina ($Al_2O_3$) present in the fly ash. This extra $C_3A$ increase the chloride binding capacity of concrete and decrease the total charge passed (Dinakar et al. 2008).

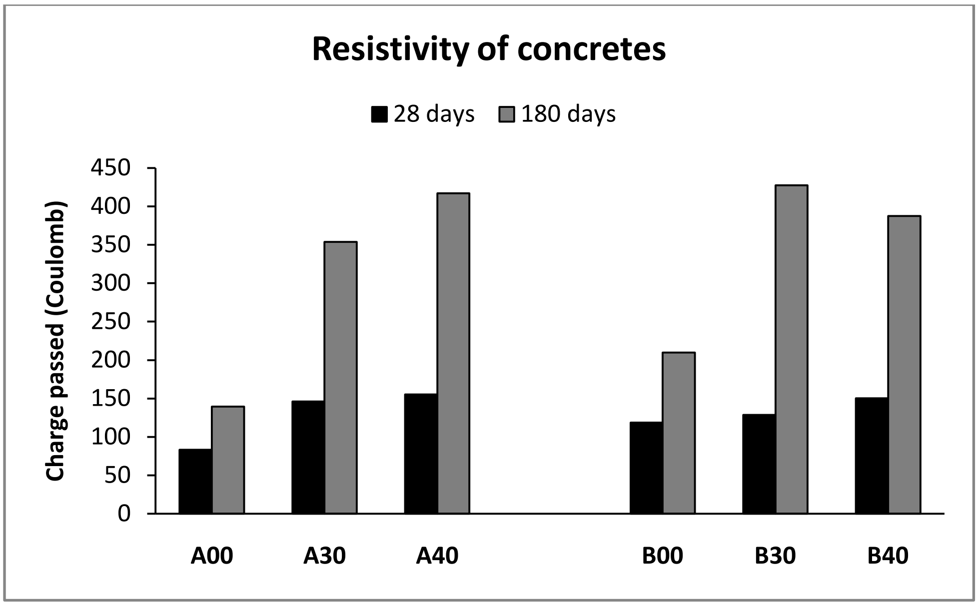


**Figure 4-27: Resistivity results of concretes of series A and B**

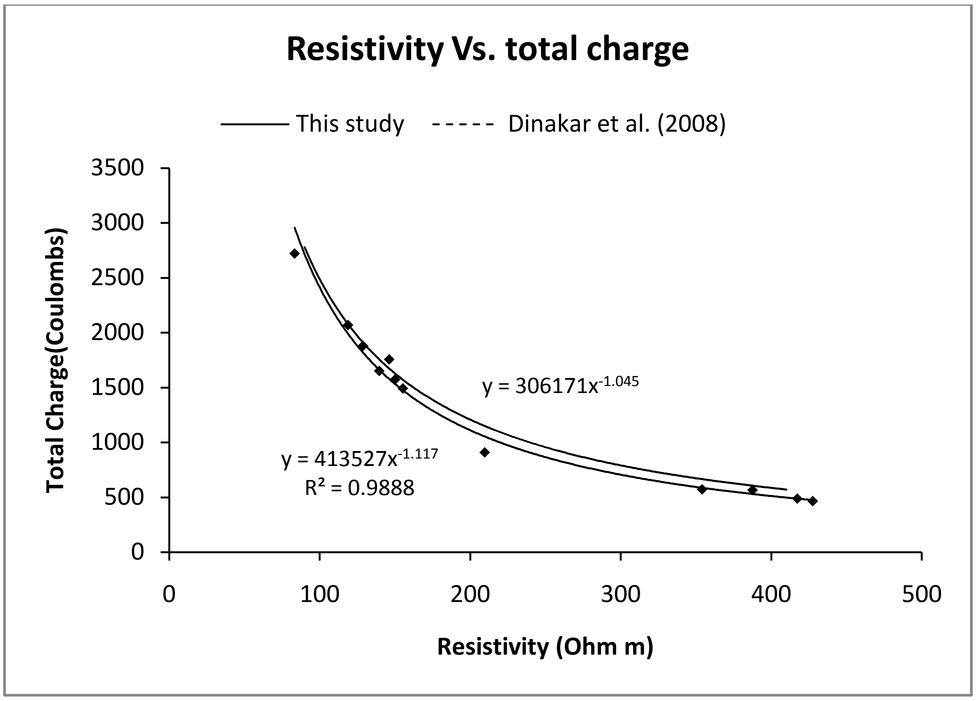


**Figure 4-28: Variation of charge passed with resistivity**

Figure *4-27* presents the resistivity values of different mixture of concretes at 28 days and 180 days of age. It indicates that the fly ash concretes attained higher resistivity as compared to the control OPC concrete. The resistance increased with the increase of fly ash content in concrete. There was significant increase in the resistivity values of the fly ash concrete samples at 180 days as compared to the values at 28 days of age.

Since the resistivity is calculated using the initial reading of current, it is related to the charge passed. The variation of charge passed with the resistivity in all the specimens are shown in the Figure *4-28.* The total charge passed can be expressed as a function of resistivity. For resistivity lower than 200 Ω m, the total charge increased dramatically. With the initial resistivity more than 200 Ω m, 'very low' level of chloride ion penetration (charge passed <1000 coulombs) can be achieved. The results reported by Dinakar et al. (2008) also indicate the similar trend for the results of normally vibrated concrete as well as self compacting concrete (Figure *4-28).*

### 4.4.8. Chloride diffusion

Concrete exposed to chloride environments, such as sea water, is susceptible to chloride attack. Chloride-induced corrosion of reinforcement is one of the major causes of deterioration leading to a reduced service life of reinforced concrete structures. In the presence of chloride ions, the breakdown of the passive oxide layer, even at high pH levels, at the concrete-steel interface is the most common cause that initiates pitting corrosion of steel reinforcement. The subsequent rate of corrosion depends on the availability of oxygen and water near the interface, and is thus a function of the permeability of the concrete protecting the steel. In addition, the environmental regime plays a major role, with alternate wetting and drying being one of the most severe conditions.

Chloride ion moves through concrete with the aid of water permeation. Initially concrete absorbs water slowly by capillary suction (sorption) which leads chloride ion into it. Once in the concrete, chloride ion starts to diffuse in the deeper zone. The diffusion process is assumed to follow Fick's 2nd law of diffusion. The rate of diffusion depends on many factors such as the mix proportions, curing period, maturity, w/b ratio, presence of supplementary cementitious materials etc (Roy, Chye and Northwood, 1993; Page, Short and El-Tarras, 1981; Thomas and Matthews, 2004).

The chloride diffusion test was carried out on three specimens from each mix which were exposed to a sodium chloride solution (165 ± 1 gm/L). The test was conducted at 28 days and 180 days of age. The specimens of 28 days age were exposed to chloride solution for a period of 56 days and the specimens of 180 days age were exposed for about 5 months (147 days). The minimum exposure period as specified in NT Build 443 (Nordtest Method, 1995) is 35 days. However, the exposure period of the specimens were extended considering the presence of fly ash and lower w/b ratio, the curing period and age of the sample. In this regard, the following note as stated in ASTM C 1556-04 (ASTM Standards, 2004a) was followed:

*"The exposure time should be extended for mixtures such as those that are more mature, were made with low w/cm, or high performance mixtures containing supplementary cementitious materials".*

At the end of the exposure period, acid-soluble chloride concentration was measured at different depths up to 16 mm of each specimen. Eight layers from the exposed surface, each having 2 mm thickness, were grinded from each specimen and tested for chloride concentration. The results thus obtained were plotted to produce a best-fit curve indicating the rate of diffusion based on Fick's second law of diffusion (Equation 3-35). A non-linear regression analysis was used to fit the curves with the aid of a computer spreadsheet. The measured chloride concentration value of the topmost layer (0-2 mm) was omitted from the regression analysis as recommended in NT Build 443 (Nordtest Method, 1995). Figure *4-29* shows a typical curve fitted to the measured results. The best-fit curve gives the diffusion coefficient ($D_a$) and the surface chloride concentration ($C_s$). The graphs and complete data set for all the specimens are given in Appendix N.

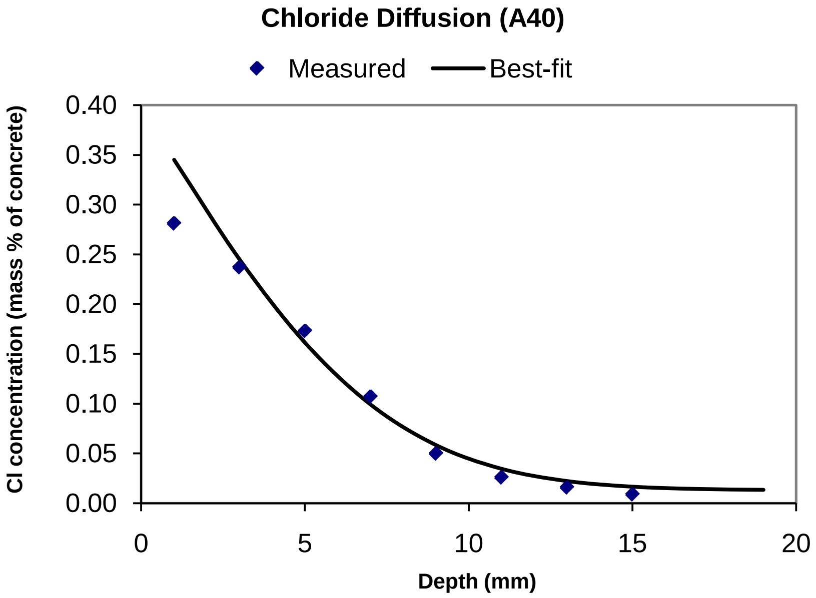


**Figure 4-29: The measured values and the best-fit curve obtained by non-linear regression analysis.**

The penetration parameter $k_{cr}$ was calculated using the Equation 4-6 provided in the NT Build 443 (Nordtest Method, 1995).

$$k_{cr} = 2\sqrt{D_a} \, . erf^{-1}\left(\frac{C_s - C_r}{C_s - C_i}\right) \tag{4-6}$$

Where, $k_{cr}$ = penetration parameter (mm/yr$^{½}$)

$D_a$ = apparent diffusion coefficient (mm$^2$/yr)

$C_s$ = chloride concentration at the exposed surface (mass %)

$C_i$ = initial chloride concentration in the concrete slice (mass %)

$C_r$ = the reference chloride concentration, taken as 0.05 (mass %)

$erf$ = error function

Chloride diffusion coefficients and penetration parameters of the concretes for different exposure periods are shown in Table *4-18*. The variation of the diffusion coefficients of all the samples of series A and B are plotted in Figures *4-30* and *4-31* respectively. Figure *4-32* is shows the penetration parameter ($k_{cr}$) values for both series of concrete.

**Table 4-18: Chloride diffusion test results.**

| Mixture | | 28 days test (Exposure period 56 days) | | | 180 days test (Exposure period 147 days) | | |
|---|---|---|---|---|---|---|---|
| Series | Mix ID | Diffusion coefficient, $D_a$ ($\times 10^{-12}$ m$^2$/s) | Surface chloride (mass % of concrete) | Penetration parameter, $k_{cr}$ (mm/yr$^{1/2}$) | Diffusion coefficient, $D_a$ ($\times 10^{-12}$ m$^2$/s) | Surface chloride (mass % of concrete) | Penetration parameter, $k_{cr}$ (mm/yr$^{1/2}$) |
| A | A00 | 4.68 | 0.57 | 29.7 | 3.41 | 0.62 | 25.3 |
| | A30 | 3.51 | 0.37 | 26.6 | 0.70 | 1.38 | 11.3 |
| | A40 | 3.42 | 0.40 | 26.0 | 0.90 | 1.05 | 12.9 |
| B | B00 | 1.97 | 0.55 | 19.5 | 1.40 | 0.69 | 16.3 |
| | B30 | 2.52 | 0.42 | 22.3 | 0.59 | 1.37 | 10.4 |
| | B40 | 2.37 | 0.47 | 21.3 | 0.65 | 1.32 | 10.9 |

It can be seen from Table *4-18* that, fly ash concretes of series A (A30 and A40) have shown better resistance to chloride penetration in comparison to the control concrete (A00). The diffusion of the fly ash concretes reduced by about 25% of the control concrete’s diffusion at 56 day exposure. The diffusion coefficient did not vary significantly with the increase of fly ash from 30% to 40%. Nevertheless, mix A40 has shown slightly lower diffusion coefficient than mix A30 during 56 days of exposure. Similar trend is also observed for the penetration parameter ($k_{cr}$) values (Figure *4-32*). The fly ash concretes gained enhanced resistance to chloride diffusion during 147 days of exposure as compared to the control concrete.

In series B, the concretes incorporating fly ash (B30 and B40) B have shown higher chloride diffusion than the control concrete (B00) at 56 days of exposure (28 days test). It is usually observed that chloride diffusion is depended on the binder type and w/b ratio in the concrete (Song, Lee and Ann, 2008). Since the concretes of series B had same w/b ratio in each mix, the fly ash concretes had relatively less hydration as compared to the control concrete at 28 days. However at the 180 days test, the chloride diffusion of the fly ash concrete samples decreased by more than 50% of that of the control concrete samples. It indicates continued hydration of fly ash concretes beyond 28 days, which resulted in enhanced resistance to chloride penetration. The penetration parameter ($k_{cr}$) results also indicated the higher resistance to chloride penetration due to fly ash inclusion.

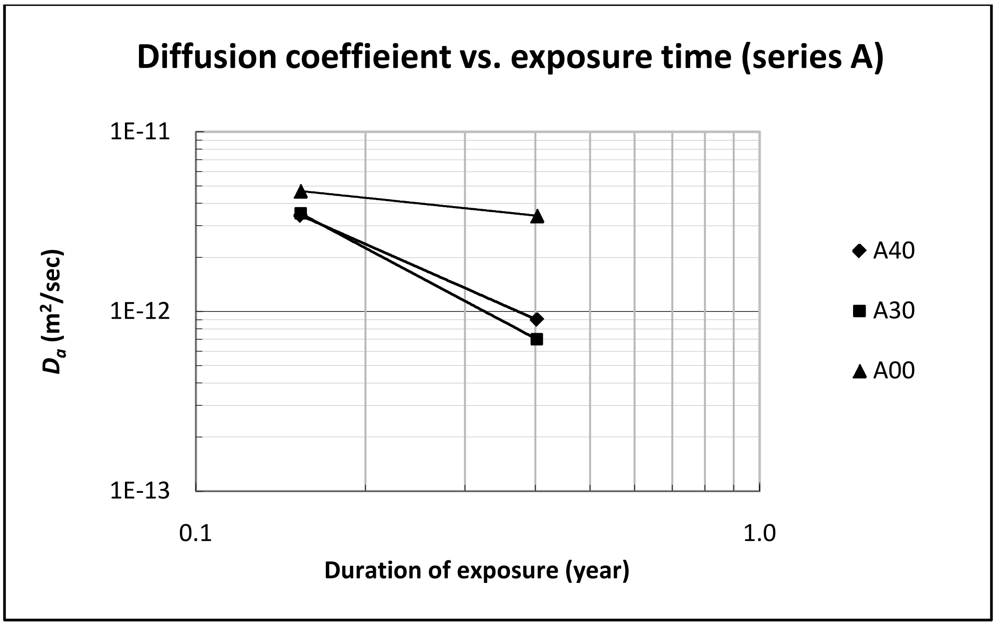


**Figure 4-30: Variation of diffusion coefficient with time of exposure (series A).**

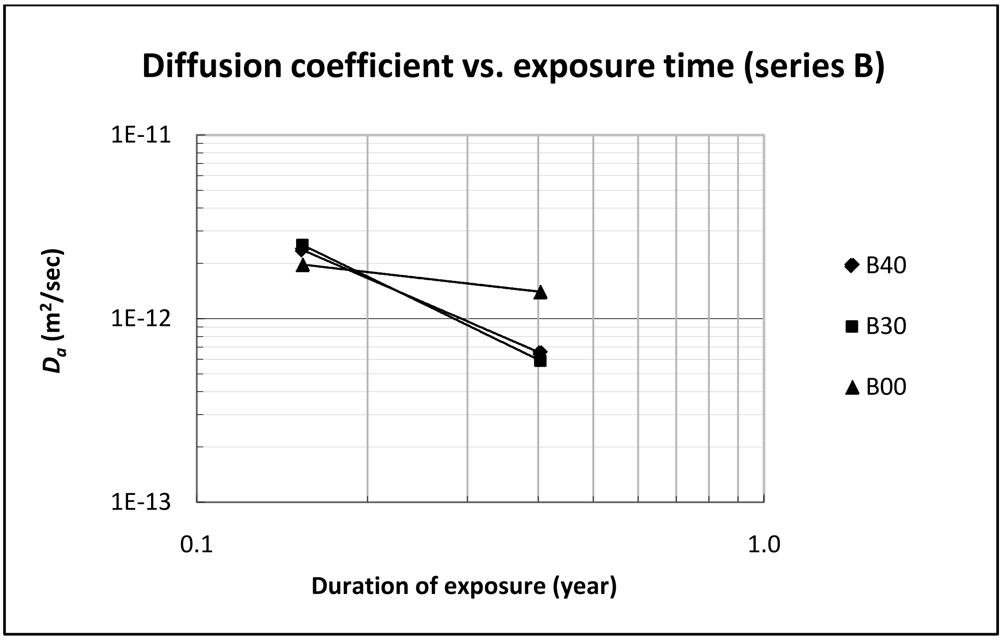


**Figure 4-31: Variation of diffusion coefficient with time of exposure (series B).**

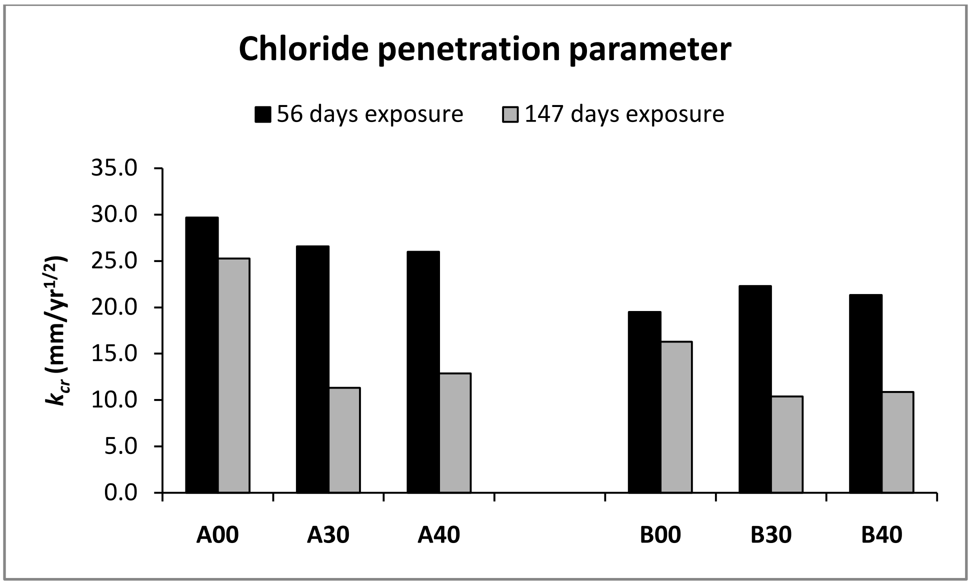


**Figure 4-32: Comparison of chloride penetration parameters.**

From the Figures *4-30* and *4-31,* it can be seen that the diffusion coefficients ($D_a$) decreased with the increase of the exposure period of concrete. Similar trend was reported by other researchers (Costa and Appleton, 1999; Thomas and Matthews, 2004). Chloride diffusion decreased at a higher rate in fly ash concrete samples than the corresponding control concrete samples. As the hydration proceeds in the fly ash concrete, it increases the chloride binding capacity of the pastes in addition to clogging the pore network (Dinakar et al. 2008). In normal cement concrete, chloride ions can move deeper in the paste which is facilitated by interconnected capillary pores. Fly ash, due to its pozzolanic reaction, gradually diminishes the interconnectivity of pores. Hence fly ash concretes achieve greater resistance to chloride ion penetration.

The surface chloride concentration ($C_s$) over the period of exposure is important in explaining chloride diffusion. From Table *4-18* it can be seen that, fly ash concretes have shown less amount of surface chloride at 56 days exposure in comparison to control concrete. The concentration has increased with the increase of exposure period. This supports the observation of Thomas and Matthews (2004). While control concrete have shown very small increase in surface chloride concentration with 147 days of exposure, fly ash concrete have shown significant rise. This could be due to increased resistance to chloride penetration in fly ash concrete. However it can be varied for exposure other than submersed condition (Costa and Appleton, 1999).

# 5. SERVICE LIFE ESTIMATION

## 5.1. Introduction

Service life of concrete structure is a primary consideration in design phases. Being a non-homogeneous porous material, concrete is vulnerable to various forms of deterioration such as corrosion due to carbonation or chloride ingress, disintegration of soundness due to sulphate and acid attack etc. The service life may be affected by both internal and external mechanisms that infringe the normal setting within concrete. Generally it happens due to mixed mode of attack accelerating the deterioration process. Hence, all forms of attack that could happen during the service life should be taken into account in service life estimation and subsequent durability planning.

The service life of concrete structure is stochastic in nature (Cliflotn, 1993). It depends on many random variables such as material characteristics, mixture proportions, curing variation, protective cover on reinforcement, exposure environment etc. The service life estimation with respect to all these variables leads to random results. Hence simple deterministic or probabilistic approach can be applied to assess service life for any particular mixture, considering some of these variables as constant.

In this study, simplistic service life estimation technique was applied to assess the concrete mixes against the corrosion due to carbonation and chloride diffusion. It was assumed that, concrete was subjected to only one form of predominant attack.

## 5.2. Corrosion due to carbonation

### 5.2.1. Procedure

A full probabilistic design method for carbonation induced corrosion of uncracked concrete was followed to estimate service life of the concrete mixes. The model code provided by International Federation for Structural Concrete (*fib* CEB-FIP, 2006) was applied. It is based on the limit state equation (Equation 5-1) in which the concrete cover (a) is compared to the carbonation depth $x_c(t)$ at a certain point of time:

$$\mathbf{g}\left(\mathbf{a}, \mathbf{x_c(t)}\right) = \mathbf{a} - \mathbf{x_c(t)} \ \geq \mathbf{0} \tag{5-1}$$

Where, a = concrete cover [mm]

$x_c(t)$ = carbonation depth at the time t [mm] (given by Equation 5-2)

$$\mathbf{x_c(t)} = \sqrt{\mathbf{2 \,.\, k_e \,.\, k_c \,.\, R_{NAC.0}}^{-1} \,.\, \mathbf{C_s}} \,.\, \sqrt{\mathbf{t}} \,.\, \mathbf{W(t)} \tag{5-2}$$

Where, $k_e$ = environmental function

$k_c$ = execution transfer parameter

$R_{NAC.0}^{-1}$ = Inverse effective carbonation resistance of dry concrete (65% RH) determined at a certain point of time $t_0$ on specimens with the normal carbonation test NAC [(mm$^2$/years)/(kg/m$^3$)]

$C_s$ = $CO_2$ concentration [kg/m$^3$]

W(t) = weather function

Equation 5-*2* is based on diffusion as the prevailing transport mechanism within the concrete (Fick's 1st law of diffusion). It is assumed that the diffusion coefficient for $CO_2$ through the material is a constant material property, although the $CO_2$-diffusion coefficient for a concrete during service life may be a function of numerous variables.

Environmental function $k_e$ can be determined by the Equation 5-3.

$$\mathbf{k_e} = \left\{\frac{\mathbf{1} - \left(\frac{\mathbf{RH_{real}}}{\mathbf{100}}\right)^{\mathbf{f_e}}}{\mathbf{1} - \left(\frac{\mathbf{RH_{ref}}}{\mathbf{100}}\right)^{\mathbf{f_e}}}\right\}^{\mathbf{g_e}} \tag{5-3}$$

Where, $RH_{real}$ = relative humidity of the carbonated layer [%]

$RH_{ref}$ = reference relative humidity [65%]

$f_e$ = constant exponent parameter = 5.0

$g_e$ = constant exponent parameter = 2.5

The execution transfer parameter $k_c$ takes the influence of curing on the effective carbonation resistance into account. Equation 5-*4* is determined to calculate $k_c$.

$$\mathbf{k_c} = \left(\frac{\mathbf{t_c}}{\mathbf{7}}\right)^{\mathbf{b_c}} \tag{5-4}$$

Where, $t_c$ = period of curing [days]

$b_c$ = exponent of regression (mean = -0.567, st. deviation = 0.024)

Inverse carbonation resistance $R_{NAC.0}^{-1}$ can be estimated using Equation *5-5*. The factors $k_t$ and $\varepsilon_t$ have been introduced in order to transform the result gained under “accelerated carbonation” conditions (ACC) into “natural carbonation” condition (NAC).

$$\mathbf{R_{NAC.0}^{-1} = k_t \,.\, R_{ACC.0}^{-1} + \varepsilon_t} \tag{5-5}$$

Where, $R_{ACC.0}^{-1}$ = Inverse effective carbonation resistance of dry concrete determined at a certain point of time $t_0$ on specimens with the accelerated carbonation test ACC [(mm$^2$/years)/(kg/m$^3$)]

$k_t$ = regression parameter which considers the influence of test method on the accelerated test (mean = 1.25, st. deviation = 0.35)

$\varepsilon_t$ = error term considering inaccuracies which occur conditionally when using the accelerated test [(mm$^2$/years)/(kg/m$^3$)] (mean = 315.5, st. deviation = 48)

For measuring $R_{ACC.0}^{-1}$ an accelerated carbonation test (ACC) was suggested in the model code. The test method is described in section 3.7.12. The results of this accelerated test have been presented in section 4.4.6. Using these results, $R_{ACC.0}^{-1}$ can be calculated by Equation 5-*6*.

$$\mathbf{R_{ACC.o}}^{-\mathbf{1}} = \left(\frac{\mathbf{x_c}}{\boldsymbol{\tau}}\right)^{\mathbf{2}} \tag{5-6}$$

Where, $x_c$ = measured carbonation depth in the accelerated test [mm]

$\tau$ = time constant in [(s/kg/m$^3$)$^{0.5}$],

for the described test condition $\tau = 420$.

$CO_2$ concentration $C_s$ (kg/m$^3$) is the sum of that of the atmosphere ($C_{s.atm}$) and additional $CO_2$ concentration due to emission ($C_{s.emi}$). For normal structure only the atmospheric $CO_2$ concentration can be considered. The model code provides mean $C_{s.atm}$ value as 0.00082 kg/m$^3$ with standard deviation of 0.0001.

Weather function (W) takes the meso-climatic conditions due to wetting events of the surface into account.

$$\mathbf{W} = \left(\frac{\mathbf{t_0}}{\mathbf{t}}\right)^{\frac{(\mathbf{p_{sr}}\,.\mathbf{ToW})^{\mathbf{b_w}}}{2}} \tag{5-7}$$

Where, $t_0$ = time of reference [years] = accelerated test duration (0.0767 yr)

$p_{sr}$ = probability of driving rain

ToW = time of wetness = $\frac{(\textbf{days with rainfall} \geq \textbf{2.5 mm/day per year})}{\textbf{365}}$

$b_w$ = exponent of regression (mean = 0.446, st. deviation = 0.163)

The value of $p_{sr}$ is the average distribution of the wind direction during rain events. The quantification of this variable can be given as:

$p_{sr}$ = 0, if interior structural elements are treated,

$p_{sr}$ = 1, if horizontal structural elements are treated and

if vertical structural elements are treated $p_{sr}$ has to be evaluated from weather station data.

### 5.2.2. Assumptions

Some assumptions were made according to the given standard values for the service life estimation using the method described above. The model suggested mean values and standard deviation of the required parameters; hence mean values were mostly selected. Weather related values were assumed. Table *5-1* summarises the values used for calculation.

Carbonation is greatly dependent on the moisture condition. Carbonation in concrete pores occurs only at a relative humidity (RH) between 40% and 90%. When the RH in the pores is higher than 90%, carbon dioxide is not able to enter the pore, and when RH is less than 40%, the carbon dioxide cannot dissolve in the water. Hence, exposure to rain and wet environment influence the rate of carbonation. As mentioned earlier, for the interior elements the probability of driving rain ($p_{sr}$) is 0, which indicates the most susceptible condition to carbonation due to fairly consistent relative humidity of the concrete as compared to other parts of the structure where $p_{sr}$ varies from 0.0 - 1.0. Hence this two boundary limits were applied to predict the highest and the lowest probable level of carbonation for each mix. The actual condition may vary within these limits, knowing the fact that, other variables remain constant, as used in this estimation.

**Table 5-1: Variables quantified for service life assessment for carbonation according to the *fib* Model Code (*fib* CEB-FIP, 2006).**

| Variable | Unit | Value used | Note |
|---|---|---|---|
| $RH_{real}$ | % | 52 | Average RH of Perth (*Perth Climate*, 2010) |
| $RH_{ref}$ | % | 65 | RH of reference test |
| $f_e$ | - | 5.0 | Constant parameter |
| $g_e$ | - | 2.5 | Constant parameter |
| $b_c$ | - | -0.567 | Mean value |
| $t_c$ | days | 7 | Reference test curing period |
| $x_c$ | mm | Test result | Reference test result (section 4.4.6) |
| $\tau$ | $(s/kg/m^3)^{0.5}$ | 420 | Time constant for referred test condition |
| $k_t$ | - | 1.25 | Mean value |
| $\varepsilon_t$ | $[(mm^2/years)/(kg/m^3)]$ | 315.5 | Mean value |
| $C_s$ | $kg/m^3$ | 0.00082 | Mean value |
| t | years | 100 | Expected service life |
| $t_0$ | years | 0.0767 | Time of reference test (28 days) |
| Days with rainfall ≥ 2.5 mm/day | days | 100 | Assumed from the data (*Perth Climate*, 2010) |
| $b_w$ | - | 0.446 | Mean value |
| $p_{sr}$ | - | 0 and 1 | Lowest and highest probability of driving rain |
| a | mm | 20 | Minimum cover requirement |

The service life calculation with *fib* Model Code is based on a reference test, in which concrete samples of 28 days age are tested under accelerated carbonation. It is well known that, the hydration of fly ash in concrete continues beyond 28 days and improves the concrete quality significantly at later age. This property of fly ash concrete is also observed in this study and is presented in chapter 4. However, no distinct consideration of this fact of fly ash incorporated concrete was made in the Model Code. Therefore, it would be conservative to predict service life on the basis of carbonation of fly ash concrete of 28 days age. This is because the carbonation of fly ash concrete is generally high as compared to that of normal cement concrete at 28 days of age. The carbonation of fly ash concrete usually decreases with time. The study of Atis (2003a) shows that, fly ash concrete (50% replacement) suffered less carbonation when it is tested after 3 months. The carbonation of the samples tested at 28 days was higher than that at 3 months. Thus, it is expected that, the efficiency of fly ash concrete to prevent carbonation will be higher at later ages as compared to the control cement concrete.

Considering this fact, the service life estimation has been conducted only for the series A concretes. Fly ash concretes of series A were designed to achieve similar 28-day strength of the corresponding control concrete by varying w/b ratio and binder content. Hence it is assumed that, the fly ash concretes of series A will replicate the carbonation behaviour of control concrete at 28 days.

### 5.2.3. Results

The maximum and minimum probable depths of carbonation for concretes of series A over the age were calculated based on the assumed parameters. The results are plotted in Figure *5-1*. The curves show the variation of carbonation progress with the time. Considering the highest probable rate of carbonation, the time required to carbonate up to minimum cover depth 20 mm is estimated. This time represents the time of initiation of deterioration. Once deterioration process initiates, service life is considered to be over unless any repair or maintenance steps are taken to increase life.

**Table 5-2: Results of carbonation based service life assessment**

| Mixture | | Depth of carbonation in accelerated test (mm) | Time to reach cover depth a = 20 mm (year) | Depth of carbonation after 100 years (mm) |
|---|---|---|---|---|
| Series | Mix ID | | | |
| A | A00 | 4.4 | 42 | 31 |
| | A30 | 4.3 | 44 | 30 |
| | A40 | 4.7 | 37 | 33 |

The carbonation depths are also calculated at the expected service life of 100 years. It is the maximum design service life, in general, for the special types of structures such as monumental buildings and bridges. Table 5-2 gives the measured carbonation depths during reference accelerated test and that after 100 years of life.

Concretes of series A were similar in strength grade at 28 days. Fly ash concretes did not show considerable variation in carbonation in comparison to normal cement concrete during the reference test. So were the trends of predicted carbonation, as any other parameters related to materials behaviour were not considered in the model code except carbonation depth. From Figure *5-1* it can be seen that, carbonation will reach the level of reinforcement at the depth of 20 mm in the concretes of series A at about 40 years. The carbonation depth after 100 years exceeds 30 mm for all the concretes of series A, with the maximum depth of 33 mm for mix A40. Hence to achieve 100 years design service life, depth of reinforcement cover needs to exceed these predicted depths. As an estimation based on the values shown in Table *5-1*, 50-65% increase in cover depth over 20 mm could enhance the service life by about 2.5 times. However, due to continued hydration of the fly ash concrete over the age after 28 days, its service life can be expected to be more than the estimated value.

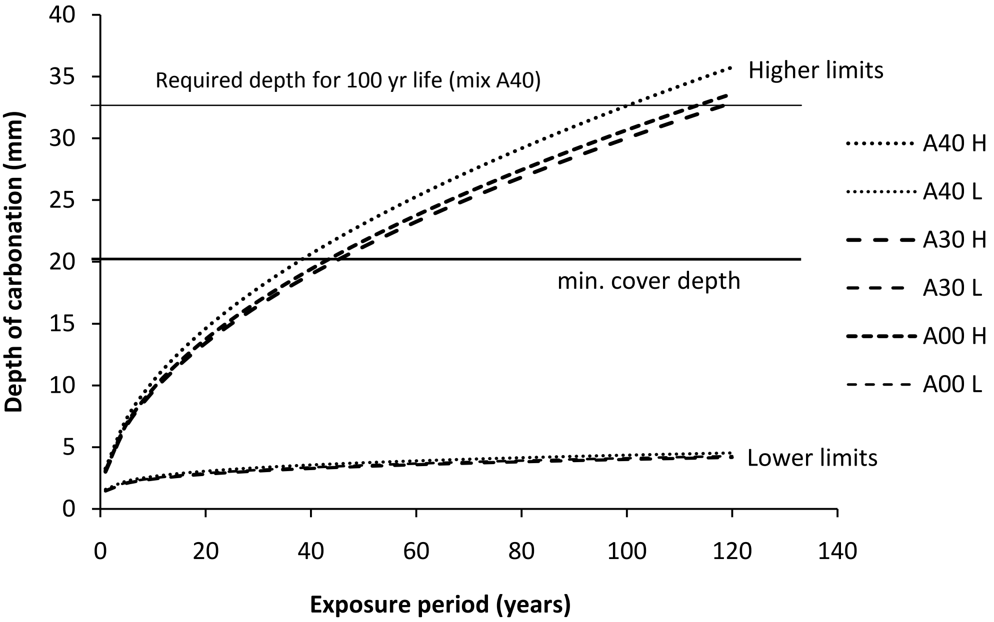


**Figure 5-1: Estimated carbonation limits for concretes of series A**

## 5.3. Corrosion due to chloride diffusion

### 5.3.1. Procedure

Chloride diffusion through concrete is assumed as the only cause of corrosion to estimate the service life in this section. The service life is considered to be the period of initiation of corrosion or the time required for the chloride concentration at the reinforcement surface to reach the critical chloride level ($C_{cr}$). The practical procedure proposed in CSIRO Research Report BRE No. 062 (Cao and Bucea, 2000) for service life estimation of marine structures was followed as the guideline. Similar approach of service life prediction was also published in other reports (Khatri and Sirivivatnanon, 2003) and ConcreteWorks (software) manual (Riding, 2007).

A deterministic approach based on Fick's 2nd law of diffusion was used for calculation of service life. The Equation 5-8 is a solution of Fick's second law. This law is valid only for non-ionic diffusion through inert homogeneous medium. Though concrete does not perfectly meet these criteria, it is commonly used for calculating chloride diffusion through concrete.

$$C(x,t) = C_i + (C_s - C_i).erfc\left(\frac{x}{\sqrt{4.D_a.t}}\right) \tag{5-8}$$

Where, $C(x, t)$ = chloride concentration measured at depth $x$ and exposure time $t$ (mass %)

$C_s$ = projected chloride concentration at the interface between the exposure liquid and test specimen that is determined by the regression analysis, (mass %),

$C_i$ = initial chloride-ion concentration of the cementitious mixture prior to submersion in the exposure solution (mass %)

$x$ = depth below the exposed surface (to the middle of a layer) (m)

$D_a$ = apparent chloride diffusion coefficient (m2/s)

$t$ = the exposure time (s)

*erfc* = complementary error function as shown in Equation 5-9

$$erfc(z) = \frac{2}{\sqrt{\pi}}.\int_z^{\infty} e^{-u^2} du \tag{5-9}$$

The following procedure was used for estimating the service life of the concrete mixes.

- The diffusion coefficient, $D_a(t)$ was calculated for an expected time $t$.
- A surface chloride concentration at time $t$ was assumed.
- Then the chloride concentration at time $t$ was calculated at any specified cover depth $x$ using Equation 5-8.
- The calculation was repeated with different set of $D_a(t)$ and $t$ until the concentration at cover depth equals to the critical chloride level ($C(cover, t) = C_{cr}$). The time at this point is the estimated service life of the concrete member.

### 5.3.2. Assumptions

The variation in service life due to the variation of reinforcement cover depth ($x$) is calculated for different mixes. The exposure condition is assumed constant and all the concrete mixes were subjected to submersed condition. The material characteristics considered in the calculation are chloride diffusion coefficient ($D_a$), surface chloride concentration ($C_s$) and critical (threshold) chloride concentration for initiating corrosion ($C_{cr}$). Hence the service life is considered a function of these four variables: $D_a$, $C_s$, $C_{cr}$, $x$.

The chloride diffusion coefficient ($D_a$) decreases with the decreasing water/binder ratio (Roy et al. 1993) and also by the addition of supplementary cementitious materials (Page et al. 1981). It has been found to decrease with time (Thomas and Matthews, 2004). Thus for the prediction of chloride level at the cover depth at a time $t$, an appropriate value of $D_a$ for that time needs to be used in the calculation. It has been noted that a linear variation can be obtained when $D_a$ is plotted against time in log-log scale (Cao et al. 1998; Maage et al. 1996). By plotting such a relationship with short to medium term results, long term diffusion coefficient can be predicted at any time $t$. However, model equations can be found in literature (Maage et al. 1997; Riding, 2007) to predict $D_a$ at any time $t$ considering single value at earlier stage of life. The Equation 5-10 is used in ConcreteWorks (Riding 2007):

$$D_a(t) = D_{28} \cdot \left(\frac{28}{t}\right)^m + D_{ult} \cdot \left(1 - \left(\frac{28}{t}\right)^m\right) \quad (5\text{-}10)$$

Where, $D_a\ (t)$ = diffusion coefficient ($m^2/s$) at time $t$ (days)

$D_{28}$ = diffusion coefficient at 28 days ($m^2/s$)

$$D_{28} = 2.17 \times 10^{-12} \times e^{\frac{w/cm}{0.279}} \quad (5\text{-}11)$$

$D_{ult}$ = ultimate diffusion coefficient ($m^2/s$) (Equation 5-12)

$$D_{ult} = D_{28} \cdot \left(\frac{28}{36500}\right)^m \quad (5\text{-}12)$$

$m$ = diffusion decay constant

In Equation 5.10, the diffusion coefficient at any time $t$ will decrease with the increase of the diffusion decay constant ($m$). Riding (2007) suggests using variable values of $m$ in the range of 0.26 - 0.6 depending on the presence of supplementary cementitious materials in the mix. In this study, an average value of $m$ equal to 0.40 and the measured values of $D_{28}$ were used in Equation 5.10 to calculate the diffusion coefficient at any specified time.

The surface concentration of chloride in concrete ($C_s$) usually changes with time. It generally increases with the time of exposure. Similar approach of predicting $D_a$ at any time can also be applied to predict $C_s$ using log-log plot. However, the field data indicates that $C_s$ tends to reach a 'maximum' value. The value of $C_s$ used in ConcreteWorks (Riding 2007) follows a maximum value ($C_{s.max}$) for different conditions with a different build up rate. The values of $C_s$ given in Table *5-3* were suggested by Cao and Bucea (2000) for the concretes wet-cured for 7 days prior to exposure to a marine environment.

Surface chloride concentration ($C_s$) can be influenced by the addition of fly ash. It is usually higher for blended cement than that of OPC concrete (Song et al. 2008). The available literature regarding the maximum surface chloride concentration is insufficient to predict $C_s$ for the concretes incorporating fly ash. Thus, in this study, the value of $C_s$ was assumed as 0.8% for both fly ash concrete and control concrete (Table *5-3*).

**Table 5-3: Maximum surface chloride concentration as per CSIRO Research Report BRE No. 062 (Cao and Bucea, 2000)**

| Grade | Cl / Concrete (w/w) |
|---|---|
| 32 MPa | $C_s$ = 1.5% |
| 40 MPa | $C_s$ = 1.2% |
| 50 MPa | $C_s$ = 1.0% |
| 60 MPa | $C_s$ = 0.8% |

The critical chloride concentration ($C_{cr}$) at the level of reinforcement governs the initiation of corrosion. Due to the difficulties of the measurement of [$Cl^-/OH^-$] ratio and the dependency of corrosion initiation on numerous factors, there is no single value of threshold which is accepted universally (Hussain et al. 1995). A value of $C_{cr}$ equal to 0.2% w/w concrete was suggested in the CSIRO Research Report BRE No. 062 (Cao and Bucea, 2000). At this value, the steel corrosion rate is normally less than 2µA.cm$^2$ which indicates the imminent cracking of concrete.

The cover depth of reinforcement ($x$) may vary at different parts of the structure. It was assumed constant for any particular member. Service life was calculated for different cover depth of 10-80 mm. Initial chloride concentration ($C_i$) was obtained from the experiments. Table *5-4* summarises the values used for the service life estimation for each mix.

The service life calculation presented here is limited to the concretes of series A. The concretes of series B had similar w/b ratio. Hence, the chloride diffusion results obtained at 28 days may not represent the actual behaviour at that age due to the incomplete hydration of fly ash concrete. On the other hand, fly ash concretes of series A were designed with lower w/b ratio and higher binder content than those of control concrete to achieve similar 28-day strength. Despite the fact that, the hydration of fly ash incorporated concrete would continue beyond 28 days, it is assumed that fly ash concretes of series A reached the similar maturity of the corresponding control concrete at 28 days.

**Table 5-4: Variables used for service life estimation with the chloride diffusion results.**

| Mix ID | A00 | A30 | A40 |
|---|---|---|---|
| Diffusion coefficient, $D_{28}$ ($\times 10^{-12}$ $m^2/s$) | 4.68 | 3.51 | 3.42 |
| Concrete diffusion decay constant, $m$ | 0.40 | 0.40 | 0.40 |
| Initial chloride level, $C_i$ (% mass of concrete) | 0.020 | 0.010 | 0.013 |
| Surface chloride level, $C_s$ (% mass of concrete) | 0.80 | 0.80 | 0.80 |
| Critical Chloride level, $C_{cr}$ (% mass of concrete) | 0.20 | 0.20 | 0.20 |
| Cover depth (mm) | 10-80 | 10-80 | 10-80 |

### 5.3.3. Results

The service life for various cover depths are estimated and plotted in Figure *5-2*. It represents the variation of service life of similar grade of concretes having different mixture proportions. It can be seen from the figure that, fly ash concretes required less cover depth to reach similar service life of control (OPC) concrete. Incorporation of fly ash increased the service life at a higher rate than that of control concrete. There is no significant difference between the results of the concretes with 30% and 40% fly ash (A30 and A40). This is because of the similarity of the 28-day diffusion coefficient.

The cover depth requirement for fly ash concretes to achieve expected service life of 50 years and 100 years were estimated and shown in Table *5-5* and Figure *5-3*. The Australian Standard AS 3600-2009 (Standards Australia, 2009) specifies the required cover of concrete for various exposure classifications in sea environment for a design life of 50 ± 20 years. The values are shown in Table *5-6*.

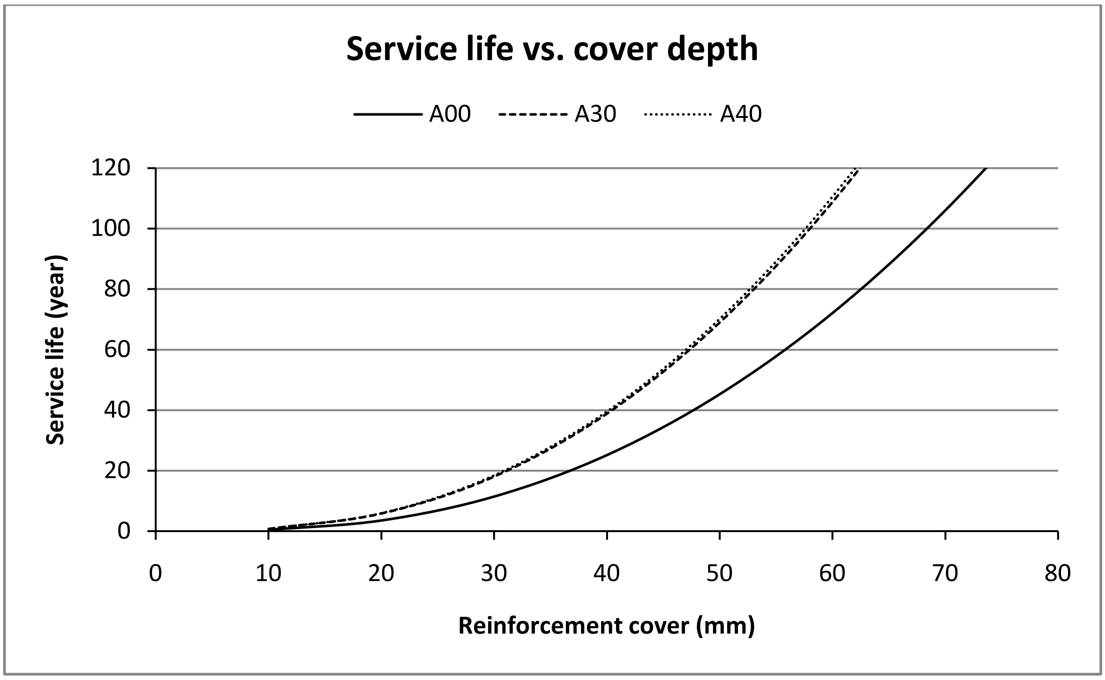


**Figure 5-2: Variation of service life with cover depth**

**Table 5-5: Cover depth requirement for the service life of 50 and 100 years**

| Mixture | | Fly ash (%) | Cover depth required (mm) | |
|---|---|---|---|---|
| Series | Mix ID | | 50 years | 100 years |
| A | A00 | 0 | 53 | 69 |
| | A30 | 30 | 44 | 58 |
| | A40 | 40 | 44 | 58 |

**Table 5-6: Required cover where standard formwork and compaction are used (Table 4.10.3.2, AS 3600-2009)**

| Surfaces of maritime structures in sea water | Exposure classification | Required cover (mm) for concretes with characteristic strength $\geq 50$ MPa |
|---|---|---|
| (a) Permanently submerged | B2 | 35 |
| (b) In spray zone | C1 | 50 |
| (c) In tidal/splash zone | C2 | 65 |

All the concrete mixes in this study were tested under permanently submerged condition (exposure classification B2). For this condition, the required cover depth is 35 mm for a design life of 50 ± 20 years in accordance with the AS 3600-2009. This value is less than that estimated for 50 years service life of both fly ash concretes and the control concrete. The estimated cover depths for fly ash concretes (A40 and A30) are 17% lower than that of control concrete for 50 years service life. This indicates that, fly ash concretes having similar strength grade of control concrete required less cover depth to achieve similar service life.

For 50 years of service life, fly ash concretes required 9 mm less cover than the control concrete. For 100 years of service life, the requirement dropped by at least 11 mm for fly ash concretes as compared to the control concrete. All concretes required about 31% more cover to increase the service life from 50 to 100 years (100% increase).

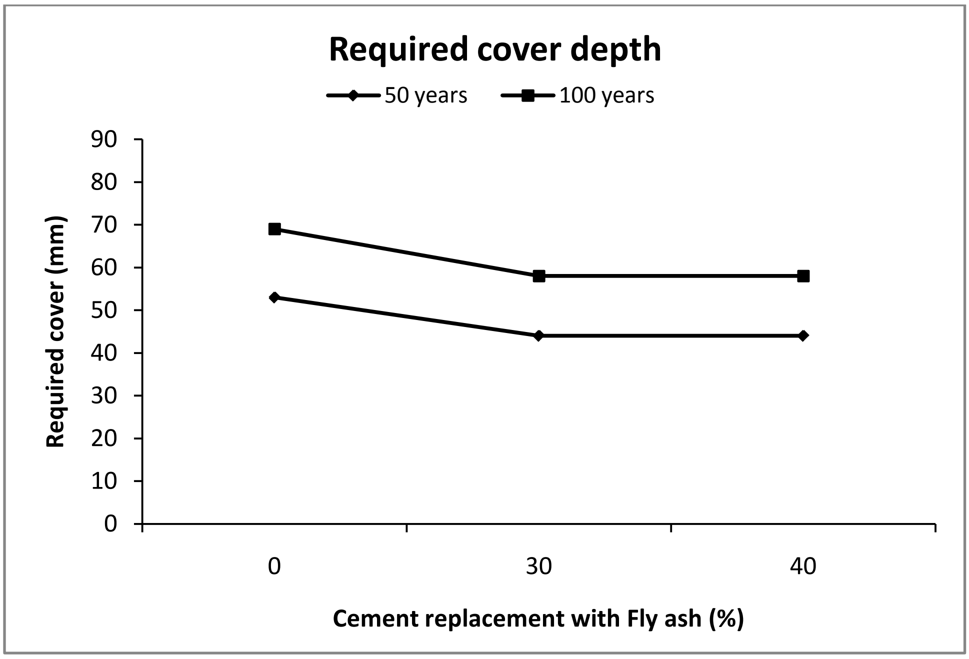


**Figure 5-3: Required cover depth for different fly ash contents in concrete**

It should be noted that the variation of service life due to the deviation of other variables such as $D_a$, $C_s$, $C_{cr}$ and cover depth (Khatri and Sirivivatnanon, 2003) was not considered in this estimation. The variation of diffusion coefficient for the presence of fly ash in concrete is considered only in terms of diffusion coefficient at 28 days which can be varied significantly at later ages. The rate at which fly ash concrete reduce the diffusion of chloride is assumed as similar to that of control concrete. Moreover, the critical chloride content is assumed constant (0.2% w/w concrete) for all the concretes, which can be varied for fly ash concretes (Thomas, 1996).

By adjusting the above mentioned variables, service life could be estimated more accurately. However, the estimate presented here incorporated the effects of fly ash based on the 28-days diffusion while other factors are assumed constant.

# 6. CONCLUSIONS AND RECOMMENDATIONS

## 6.1. Conclusions

Increase in the utilisation of fly ash in concrete can help reduce the green house gas emission associated with cement production. Due to the variation in composition, properties of fly ash vary widely and affect the properties of concrete. In this study a local fly ash of Western Australia was utilized. The results will provide with knowledge on the properties of concrete using the locally available fly ash. This study aimed at determination of the mechanical and durability properties of high strength concrete containing the local fly ash so that the beneficial effects of fly ash in concrete could be utilised in appropriate applications. The concrete mixtures were designed by following the guidelines of the ACI 211.4R-08 (ACI Committee 211, 2008). Fly ash was used as 30% and 40% replacement of cement in two series of concretes. In series A, the incorporation of fly ash was associated with adjustment of the water to binder ratio (w/b) and the total binder content to achieve the same 28-day compressive strength of concrete in all the three mixtures. In series B, fly ash was used in partial replacement of cement while w/b ratio and total binder content were kept constant in all the three mixtures. The mechanical properties of the concretes were investigated by compressive strength, tensile strength and flexural strength test. The investigated durability properties included the drying shrinkage, volume of permeable void, water and air permeability, carbonation and resistance to chloride penetration. The service lives of the concrete mixtures of series A were estimated for carbonation and chloride diffusion by using the well-known Fick’s diffusion laws. The following conclusions are drawn regarding the effect of the local fly ash on the properties of high strength concrete:

***Workability of fresh concrete***

- The workability of concrete containing fly ash was better than that of the control concrete. Fly ash concretes produced higher slump with less amount of superplasticiser as compared to the control concrete.

***Mechanical properties***

- The 28-day compressive strengths of fly ash concretes were similar to that of the control concrete when designed with adjusted w/b ratio and total binder content (series A). The 28-day strength dropped when cement was partially replaced with fly ash without adjustment in the w/b ratio and total binder content (series B). However, fly ash concretes achieved same strength as control concrete at 335 days. Significant strength development of the fly ash concretes occurred during the period between 28 days and 56 days of age. The ultimate compressive strength of the fly ash concretes reached 100 MPa. Using 40% fly ash with a w/b ratio of 0.31, high strength concrete with 28-day compressive strength of 60 MPa could be obtained which reached more than 80 MPa at 56 days.

- Indirect tensile strength and flexural strength results indicated similar trend as that of compressive strength. Strength at 28 days decreased for the replacement of cement by fly ash in concretes that were designed with constant w/b ratio and constant binder content.

***Durability properties***

- The values of drying shrinkage in all the specimens at 56 days were well below the $1000\times10^{-6}$ as specified by the AS 1379-2007 Standard (Standards Australia, 2007). Concrete incorporating fly ash have shown less drying shrinkage than the control concrete when they were designed with adjusted w/b ratio and total binder content (series A). For the concrete having constant w/b ratio and constant total binder content (series B), the shrinkage values of the fly ash concretes were within 4% to that of control concrete up to 180 days.
- The volume of permeable voids of fly ash concrete at 28 days was similar to that of similar strength grade control concrete. However, at 180 days both 30% and 40% fly ash concretes achieved lower volume of permeable voids than that of control concrete. The fly ash concretes that had constant w/b ratio (series B) have shown higher volume of permeable voids as compared to the

control concrete. Volume of permeable voids of the concrete samples cured in water for 28 days were less than that of the samples cured for 7 days.

- The incorporation of fly ash has resulted in less sorption in comparison to the control concrete at 28 days. Significant reduction of sorption was observed for the inclusion of fly ash in concretes of similar 28-day strength (series A). Inclusion of fly ash with constant w/b and constant total binder content in the mix has decreased sorptivity slightly. Rate of sorption decreased for all concretes after 180 days. Fly ash concretes that were cured for 7 days also have shown less sorptivity than the corresponding control concrete. Generally, 28 days water cured samples resulted in less sorption than the 7 days cured samples.
- The water permeability of fly ash concrete was less than that of the equal grade control concrete (series A). The presence of fly ash also reduced water permeability in the concretes that had similar w/b ratio and total binder content (series B). Generally, water permeability decreased with the increase of fly ash content from 30% to 40% of binder and with the increase of the age of concrete.
- Fly ash concretes having similar 28-day compressive strength have shown less air permeability as compared to the control concrete. In concretes with constant w/b and total binder (series B), the inclusion of fly ash slightly increased the air permeability as compared to the control concrete (B00). Air permeability of the samples cured for 28 days were less than those cured for 7 days. The results represented ‘Good’ quality of concrete for all the mixtures with water curing for 28 days.
- In the accelerated carbonation test, the depths of carbonation of the fly ash concretes having similar 28-day compressive strength were very close to that of the control concrete (series A). The depths of carbonation of fly ash concretes were higher than control concrete, when w/b ratio and binder content were not adjusted (series B).
- The fly ash concrete samples improved the resistance to chloride ion penetration significantly at early age of 28 days. At 180 days of age, the resistance to chloride ion penetration improved in all the mixes, but fly ash concretes improved to a higher degree than the control concrete. Replacing

cement partially with fly ash at the same w/b ratio (series B) improved the resistance to chloride ion penetration, but to a lesser extent than in series A.

- Fly ash concretes have shown better resistance in chloride diffusion test at 28 days in comparison to the control concrete when designed with adjusted w/b ratio and total binder content (series A). On the other hand, chloride diffusion at 28 days was higher for fly ash concrete with constant w/b ratio and total binder content. However, the diffusion decreased further at 180 days and surpassed the corresponding control concrete by substantial margin.

***Estimated service life:***

- The service lives of the concretes of series A were estimated for some assumed design parameters using the properties of concrete at the age of 28 days. When corrosion due to the carbonation was considered, the service lives of fly ash concretes were similar to that of control concrete. Fly ash concretes resulted in relatively higher service life than the control concrete, when corrosion due to chloride diffusion was considered as the only dominant form of attack. In other words, the required minimum depth of the concrete cover is less for the fly ash concrete than the control concrete for a specified service life. Since the experimental results showed more decay of the chloride diffusion with age in the fly ash concretes than the control concrete, the estimations are considered to be conservative for the fly ash concretes. At the age of 28 days fly ash concretes of series B, having same w/b ratio and total binder content as that of control concrete, continue to enhance strength and durability properties significantly. Hence service life was not assessed for series B concretes.

## 6.2. Recommendations for further works

This study identified the following scopes for the further research:

1) This study included fly ash as 30% and 40% of the binder in concrete. Some results were close to each other for these two replacement levels. Thus, more study can be done using fly ash with other replacement levels, such as 20%,

50%, 60%. These results will be useful for determining the optimum content of fly ash that can be used beneficially in different applications. The concretes with higher replacement level could be suitable for lower grade concretes.

2) Tests can be done on the samples of various curing conditions to determine the performance of fly ash concretes.
3) The development of microstructure of concrete is important to relate the permeability properties of fly ash concrete with those of the control concrete. Hence, studies of the microstructures of concretes at different ages after casting will be useful.

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# APPENDICES

## APPENDIX A: Trial Mixture Proportions

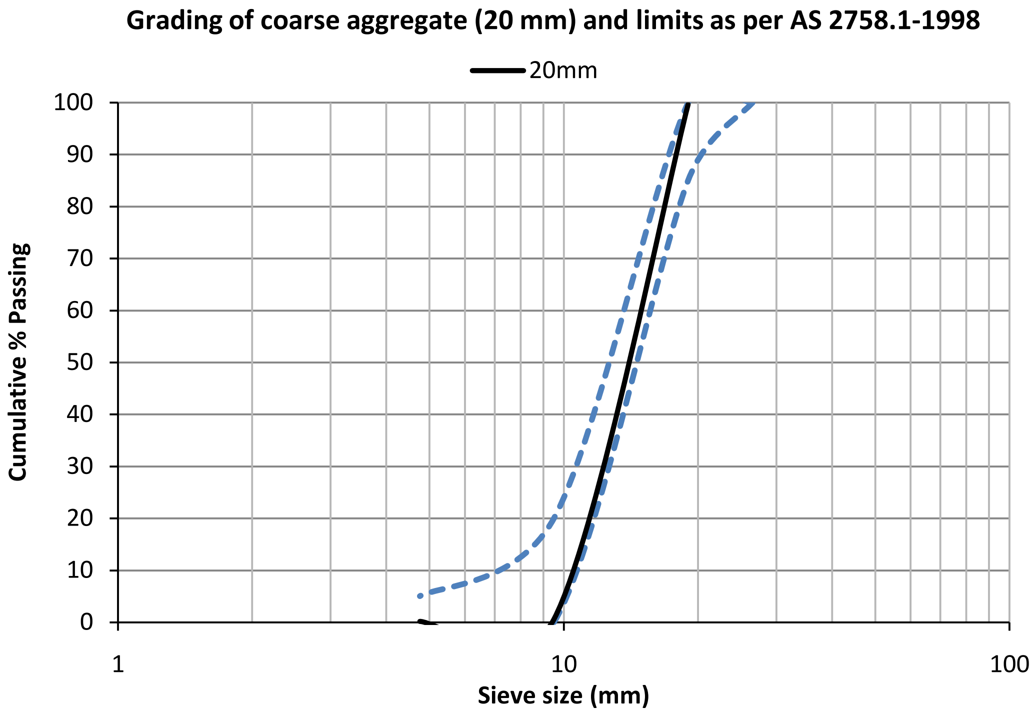
| Trial mix proportions (kg/m$^3$) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Mix no** | **Mix ID** | **Casting date** | **Fly ash (%)** | **Cement** | **Fly ash** | **Coarse aggregate** | | | **Sand** | **Water** | **w/b** |
| | | | | | | **20 mm** | **10 mm** | **7 mm** | | | |
| 1 | T1-40 | 4/06/09 | 40 | 340 | 225 | 535 | 535 | 0 | 585 | 170 | 0.30 |
| 2 | T2-40 | 5/06/09 | 40 | 292 | 194 | 547 | 384 | 233 | 557 | 170 | 0.35 |
| 3 | T3-0 | 12/06/09 | 0 | 567 | 0 | 547 | 384 | 233 | 521 | 170 | 0.30 |
| 4 | T4-40 | 17/06/09 | 40 | 389 | 259 | 547 | 384 | 233 | 417 | 168.5 | 0.26 |
| 5 | T5-40 | 25/06/09 | 40 | 264 | 176 | 557 | 391 | 237 | 665 | 136.5 | 0.31 |
| 6 | T6-0 | 26/06/09 | 0 | 355 | 0 | 557 | 391 | 237 | 722 | 152.5 | 0.43 |
| 7 | T7-0 | 15/07/09 | 0 | 517 | 0 | 557 | 391 | 237 | 594 | 150 | 0.29 |
| 8 | T7-30 | 15/07/09 | 30 | 362 | 155 | 557 | 391 | 237 | 570 | 150 | 0.29 |
| 9 | T7-40 | 15/07/09 | 40 | 310 | 207 | 557 | 391 | 237 | 561 | 150 | 0.29 |

| Observations | | | | | |
|---|---|---|---|---|---|
| **Mix no** | **Mix ID** | **Superplasticiser (ml/100 kg)** | **Slump (mm)** | **Compressive strength (MPa)** | |
| | | | | **7 days** | **28 days** |
| 1 | T1-40 | 1000 | 235 | 38.52 | 53.02 |
| 2 | T2-40 | 685 | 235 | 32.70 | 47.13 |
| 3 | T3-0 | 540 | 35 | 59.52 | 69.04 |
| 4 | T4-40 | 790 | 74 | 56.45 | 72.01 |
| 5 | T5-40 | 800 | 44 | 46.25 | 62.98 |
| 6 | T6-0 | 940 | 73 | 50.91 | 60.78 |
| 7 | T7-0 | 1000 | 50 | 72.93 | 80.24 |
| 8 | T7-30 | 800 | 171 | 59.00 | 72.39 |
| 9 | T7-40 | 800 | 157 | 50.87 | 63.85 |

# APPENDIX B: Sieve Analysis of Aggregates

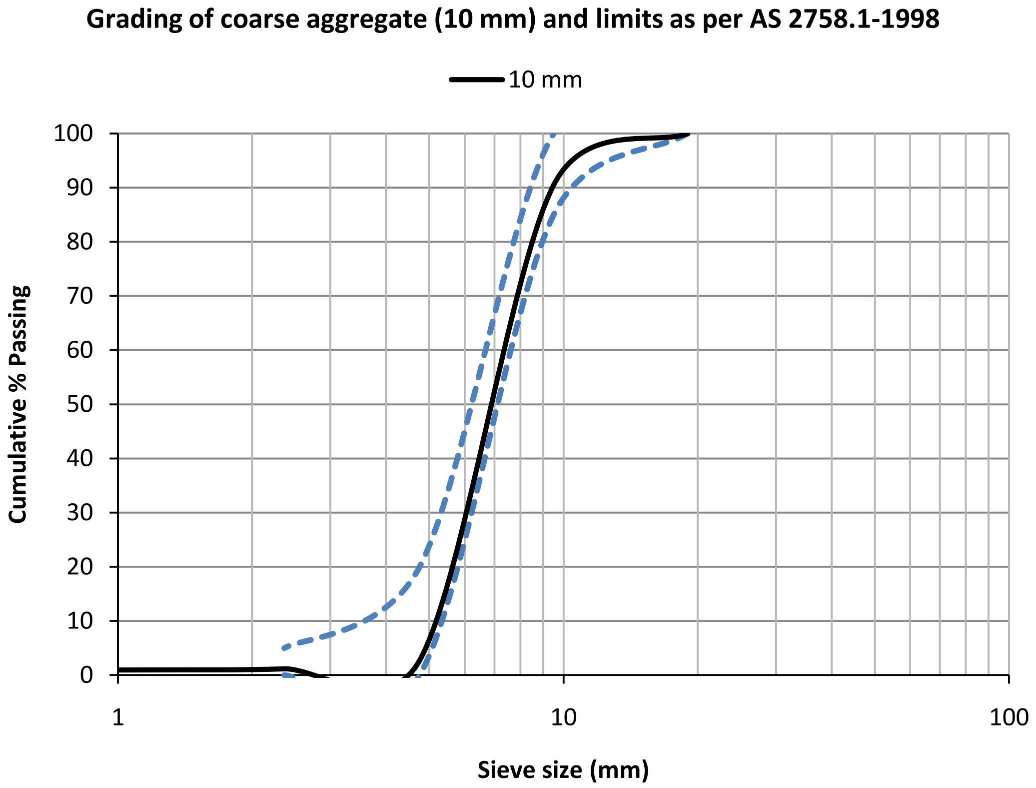
| | | | |
|---|---|---|---|
| Sample: | **Coarse aggregate** | Condition: | Dry |
| Nominal size: | **20 mm** | Total weight: | 5005 gm |

| **Sieve size (mm)** | **Retained weight (gm)** | **Retained weight (%)** | **Cumulative retained weight (%)** | **Cumulative passing (%)** | **Fineness Modulus (FM)** |
|---|---|---|---|---|---|
| 19 | 17.40 | 0.35 | 0.35 | 99.65 | 6.99 |
| 9.5 | 4957.80 | 99.07 | 99.42 | 0.58 | |
| 4.75 | 21.80 | 0.44 | 99.85 | 0.15 | |
| 2.36 | 0.00 | 0.00 | 99.85 | 0.15 | |
| 1.18 | 0.00 | 0.00 | 99.85 | 0.15 | |
| 0.6 | 0.00 | 0.00 | 99.85 | 0.15 | |
| 0.3 | 0.00 | 0.00 | 99.85 | 0.15 | |
| 0.15 | 0.00 | 0.00 | 99.85 | 0.15 | |
| Pan | 7.40 | 0.15 | 100.00 | | |
| Total | 5004.40 | 100.00 | | | |



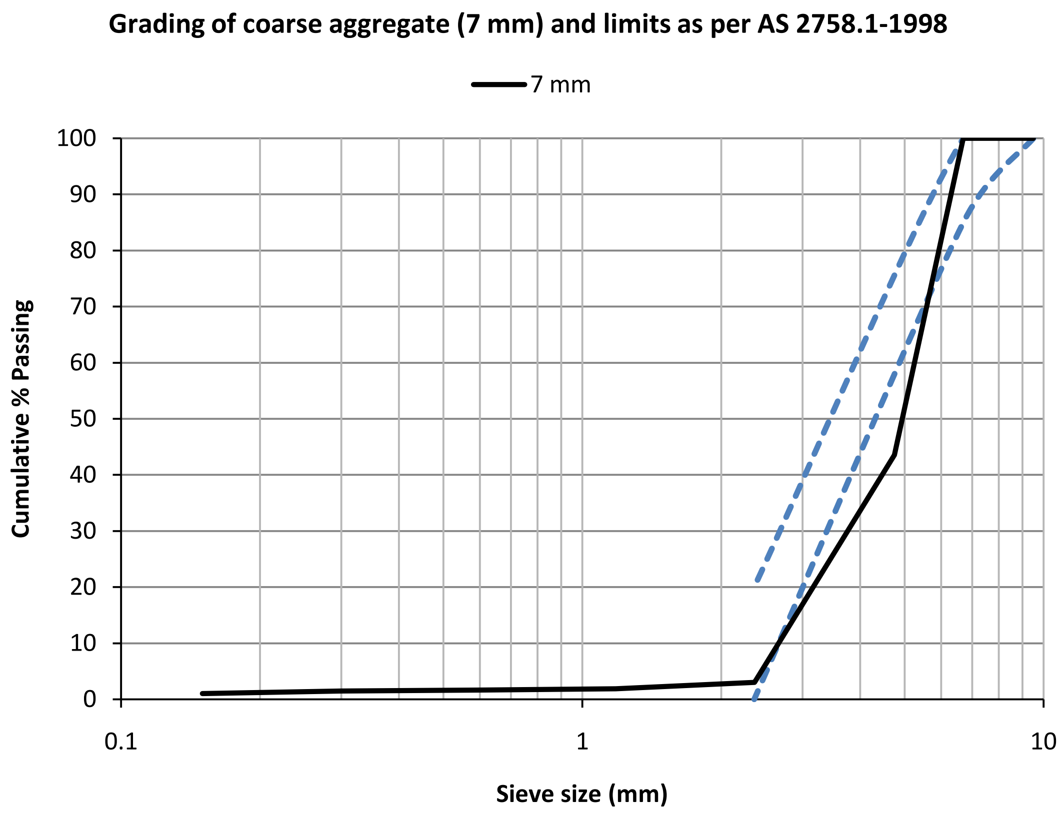
| | | | |
|---|---|---|---|
| Sample: | **Coarse aggregate** | Condition: | Dry |
| Nominal size: | **10 mm** | Total weight: | 2025 gm |

| Sieve size (mm) | Retained weight (gm) | Retained weight (%) | Cumulative retained weight (%) | Cumulative passing (%) | Fineness Modulus (FM) |
|---|---|---|---|---|---|
| 19 | 0.00 | 0.00 | 0.00 | 100.00 | 6.02 |
| 9.5 | 192.30 | 9.52 | 9.52 | 90.48 | |
| 4.75 | 1774.70 | 87.83 | 97.34 | 2.66 | |
| 2.36 | 30.70 | 1.52 | 98.86 | 1.14 | |
| 1.18 | 4.10 | 0.20 | 99.06 | 0.94 | |
| 0.6 | 0.60 | 0.03 | 99.09 | 0.91 | |
| 0.3 | 0.70 | 0.03 | 99.13 | 0.87 | |
| 0.15 | 3.00 | 0.15 | 99.28 | 0.72 | |
| Pan | 14.60 | 0.72 | 100.00 | | |
| Total | 2020.70 | 100.00 | | | |



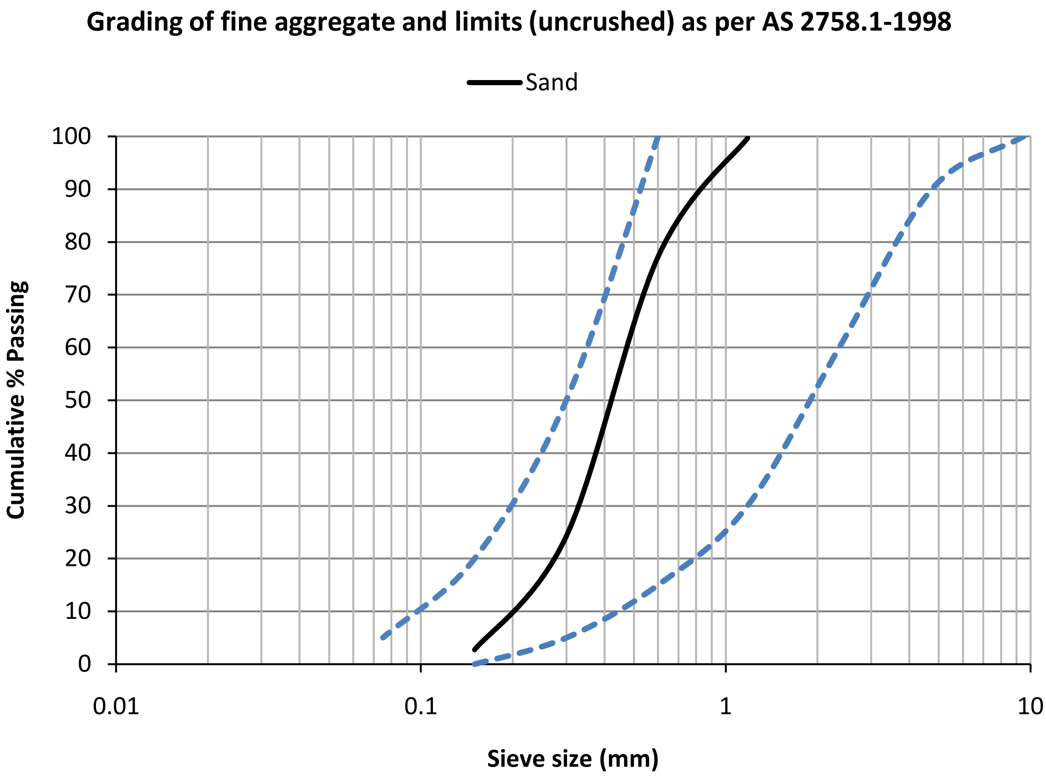
| | | | |
|---|---|---|---|
| Sample: | **Coarse aggregate** | Condition: | Dry |
| Nominal size: | **7 mm** | Total weight: | 2020 gm |

| **Sieve size (mm)** | **Retained weight (gm)** | **Retained weight (%)** | **Cumulative retained weight (%)** | **Cumulative passing (%)** | **Fineness Modulus (FM)** |
|---|---|---|---|---|---|
| 19 | 0.00 | 0.00 | 0.00 | 100.00 | 5.47 |
| 9.5 | 0.00 | 0.00 | 0.00 | 100.00 | |
| 4.75 | 1136.50 | 56.44 | 56.44 | 43.56 | |
| 2.36 | 816.20 | 40.53 | 96.97 | 3.03 | |
| 1.18 | 22.60 | 1.12 | 98.09 | 1.91 | |
| 0.6 | 4.70 | 0.23 | 98.33 | 1.67 | |
| 0.3 | 3.90 | 0.19 | 98.52 | 1.48 | |
| 0.15 | 9.00 | 0.45 | 98.97 | 1.03 | |
| Pan | 20.80 | 1.03 | 100.00 | | |
| Total | 2013.70 | 100.00 | | | |



| Sample: | **Fine aggregate** | Condition:<br>Total weight: | Dry<br>500 gm |
|---|---|---|---|

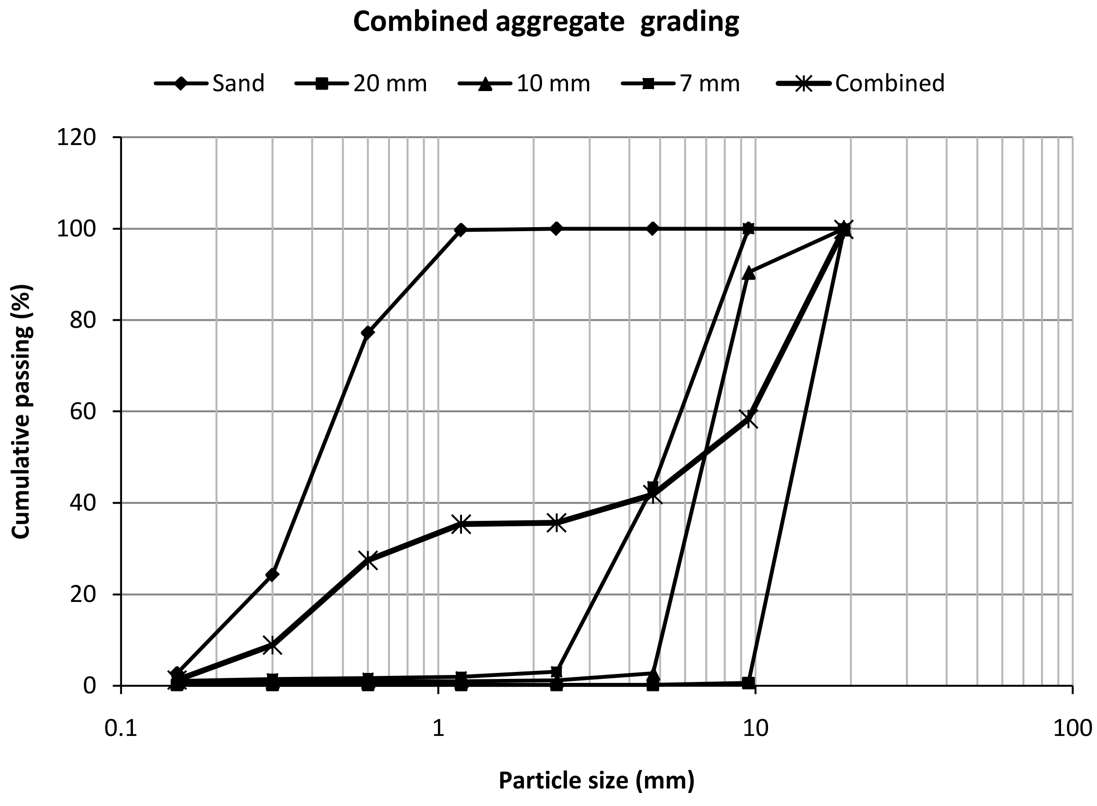
| Sieve size (mm) | Retained weight (gm) | Retained weight (%) | Cumulative retained weight (%) | Cumulative passing (%) | Fineness Modulus (FM) |
|---|---|---|---|---|---|
| 19 | 0.00 | 0.00 | 0.00 | 100.00 | 1.96 |
| 9.5 | 0.00 | 0.00 | 0.00 | 100.00 | |
| 4.75 | 0.00 | 0.00 | 0.00 | 100.00 | |
| 2.36 | 0.00 | 0.00 | 0.00 | 100.00 | |
| 1.18 | 1.50 | 0.30 | 0.30 | 99.70 | |
| 0.6 | 111.80 | 22.49 | 22.80 | 77.20 | |
| 0.3 | 263.30 | 52.98 | 75.77 | 24.23 | |
| 0.15 | 107.00 | 21.53 | 97.30 | 2.70 | |
| Pan | 13.40 | 2.70 | 100.00 | | |
| Total | 497.00 | 100.00 | | | |



Sample: **Combined aggregate with following fraction**
Condition: Dry

| | 20 mm | 10 mm | 7 mm | Sand |
|---|---|---|---|---|
| Fraction (%) | 41 | 9 | 15 | 35 |

| Sieve size (mm) | Retained weight (%) | Cumulative retained weight (%) | Cumulative passing (%) | Fineness Modulus (FM) |
|---|---|---|---|---|
| 19 | 0.14 | 0.14 | 99.86 | 4.92 |
| 9.5 | 41.47 | 41.62 | 58.38 | |
| 4.75 | 16.55 | 58.17 | 41.83 | |
| 2.36 | 6.22 | 64.38 | 35.62 | |
| 1.18 | 0.29 | 64.67 | 35.33 | |
| 0.6 | 7.91 | 72.59 | 27.41 | |
| 0.3 | 18.57 | 91.16 | 8.84 | |
| 0.15 | 7.62 | 98.78 | 1.22 | |
| Pan | 1.22 | 100.00 | 0.00 | |
| Total | 100 | | | |



# APPENDIX C: Concrete Mix Design

Concrete Mix Design (ACI 211.4R-08) Mix ID: **A00**

Given Information

Specified Compr. strength at 28 days f'c = 7250 psi 50 MPa

Fine Aggregate Properties

Fine ness Modulus = 1.96

Relative density (Oven dry) = 2.60

Absorption = 0.99 %

Bulk density 105.4 lb/ft$^3$ 1686.8 kg/m$^3$

Coarse Aggregate Properties

Relative density (Oven dry) = 2.69

Bulk density = 102.8 lb/ft$^3$ 1645.2 kg/m$^3$

Relative Density (Sp. Gr.) of cement = 3.15

Relative Density (Sp. Gr.) of fly ash = 2.64

Step 1: Select Slump and Required Stength

Slump = 1 - 2 inch 25 - 50 mm

Required Avg. Strength f'cr = 8675 psi 59.83 MPa

Step 2: Select Maximum size of aggregate = 0.75 inch 20 mm

Step 3: Select Optimum Coarse Aggregate Content

Fractional Volm of OD CA VCA = 0.72

Mass of Dry CA $CA_{OD}$ = 1998.4 lb/ft$^3$ 1184.5 kg/m$^3$

Step 4: Estimate Mixing Water and Air Content

Required Water = 246.3 lb/ft$^3$ 146.0 kg/m$^3$

Air Content = 1.5 %

Void content of Fine aggregate = 34.909 %

Mixing water adjustment = -0.725 lb/ft$^3$

Water after adjustment = 245.6 lb/ft$^3$ 145.6 kg/m$^3$

Step 5: Water to Cementitous Material ratio, w/cm = 0.41

Step 6: Content of Cementitious Materials (CM) = 599.0 lb/ft$^3$ 355.0 kg/m$^3$

Step 7: Proportion Basic Mixture with Cement

| | Cement | Fly Ash | CA | FA | Water |
|---|---|---|---|---|---|
| kg/m$^3$ | 355.01 | 0 | 1184.47 | 739.64 | 145.55 |

Step 8: Proportion Mixture with Cement and Fly Ash (0%)

| | Cement | Fly Ash | CA | FA | Water |
|---|---|---|---|---|---|
| kg/m$^3$ | 355.01 | 0 | 1184.47 | 739.64 | 145.55 |

Step 9: Final Mixture Proportion with water adjustment due to aggregate moisture

| Aggr. | 20 mm | 10 mm | 7 mm | Sand |
|---|---|---|---|---|
| Abs(%) | 0.348 | 0.415 | 0.911 | 0.988 |
| MC (%) | 0.590 | 0.441 | 0.986 | 1.380 |

| **Mix** | **Fly ash** | **Cement** | **Fly ash** | **20 mm (63%)** | **10 mm (14%)** | **7 mm (23%)** | **Sand** | **Water** | **w/b** |
|---|---|---|---|---|---|---|---|---|---|
| | % | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | |
| OD | 0 | 355.01 | 0 | 746.27 | 165.83 | 272.43 | 739.64 | 145.55 | 0.41 |
| Wet | 0 | 355.01 | 0 | 750.62 | 166.56 | 275.11 | 746.95 | 140.56 | 0.41 |

Concrete Mix Design (ACI 211.4R-08) Mix ID: **A30**

Given Information

Specified Compr. strength at 28 days f'c = 7250 psi 50 MPa

Fine Aggregate Properties

Fine ness Modulus = 1.96

Relative density (Oven dry) = 2.60

Absorption = 0.99 %

Bulk density 105.4 lb/ft$^3$ 1686.8 kg/m$^3$

Coarse Aggregate Properties

Relative density (Oven dry) = 2.69

Bulk density = 102.8 lb/ft$^3$ 1645.2 kg/m$^3$

Relative Density (Sp. Gr.) of cement = 3.15

Relative Density (Sp. Gr.) of fly ash = 2.64

Step 1: Select Slump and Required Stength

Slump = 1 - 2 inch 25 - 50 mm

Required Avg. Strength f'cr = 8675 psi 59.83 MPa

Step 2: Select Maximum size of aggregate = 0.75 inch 20 mm

Step 3: Select Optimum Coarse Aggregate Content

Fractional Volm of OD CA VCA = 0.72

Mass of Dry CA CA$_{OD}$ = 1998.4 lb/ft$^3$ 1184.5 kg/m$^3$

Step 4: Estimate Mixing Water and Air Content

Required Water = 238.3 lb/ft$^3$ 141.24 kg/m$^3$

Air Content = 1.5 %

Void content of Fine aggregate = 34.909 %

Mixing water adjustment = -0.725 lb/ft$^3$

Water after adjustment = 237.57 lb/ft$^3$ 140.81 kg/m$^3$

Step 5: Water to Cementitous Material ratio, w/cm = 0.32

Step 6: Content of Cementitious Materials (CM) = 742.4 lb/ft$^3$ 440.0 kg/m$^3$

Step 7: Proportion Basic Mixture with Cement

| | Cement | Fly Ash | CA | FA | Water |
|---|---|---|---|---|---|
| kg/m$^3$ | 440.03 | 0.00 | 1184.47 | 681.9 | 140.81 |

Step 8: Proportion Mixture with Cement and Fly Ash (30%)

| | Cement | Fly Ash | CA | FA | Water |
|---|---|---|---|---|---|
| kg/m$^3$ | 308.02 | 132.01 | 1184.47 | 660.89 | 140.81 |

Step 9: Final Mixture Proportion with water adjustment due to aggregate moisture

| Aggr. | 20 mm | 10 mm | 7 mm | Sand |
|---|---|---|---|---|
| Abs(%) | 0.348 | 0.415 | 0.911 | 0.988 |
| MC (%) | 0.441 | 0.712 | 0.911 | 1.295 |

| **Mix** | **Fly ash** | **Cement** | **Fly ash** | **20 mm (63%)** | **10 mm (14%)** | **7 mm (23%)** | **Sand** | **Water** | **w/b** |
|---|---|---|---|---|---|---|---|---|---|
| | % | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | |
| OD | 30 | 308.02 | 132.01 | 746.22 | 165.83 | 272.43 | 660.89 | 140.81 | 0.32 |
| Wet | 30 | 308.02 | 132.01 | 749.08 | 166.67 | 274.89 | 667.42 | 136.20 | 0.32 |

Concrete Mix Design (ACI 211.4R-08) Mix ID: **A40**

Given Information

Specified Compr. strength at 28 days f'c = 7250 psi 50 MPa

Fine Aggregate Properties

Fine ness Modulus = 1.96

Relative density (Oven dry) = 2.595

Absorption = 0.99 %

Bulk density 105.4 lb/ft$^3$ 1686.8 kg/m$^3$

Coarse Aggregate Properties

Relative density (Oven dry) = 2.69

Bulk density = 102.8 lb/ft$^3$ 1645.2 kg/m$^3$

Relative Density (Sp. Gr.) of cement = 3.15

Relative Density (Sp. Gr.) of fly ash = 2.64

Step 1: Select Slump and Required Stength

Slump = 1 - 2 inch 25 - 50 mm

Required Avg. Strength f'cr = 8675 psi 59.828 MPa

Step 2: Select Maximum size of aggregate = 0.75 inch 20 mm

Step 3: Select Optimum Coarse Aggregate Content

Fractional Volm of OD CA VCA = 0.72

Mass of Dry CA $CA_{OD}$ = 1998.4 lb/ft$^3$ 1184.5 kg/m$^3$

Step 4: Estimate Mixing Water and Air Content

Required Water = 231 lb/ft$^3$ 136.91 kg/m$^3$

Air Content = 1.5 %

Void content of Fine aggregate = 34.909 %

Mixing water adjustment = -0.725 lb/ft$^3$

Water after adjustment = 230.27 lb/ft$^3$ 136.48 kg/m$^3$

Step 5: Water to Cementitous Material ratio, w/cm = 0.31

Step 6: Content of Cementitious Materials (CM) = 742.82 lb/ft$^3$ 440.27 kg/m$^3$

Step 7: Proportion Basic Mixture with Cement

| | Cement | Fly Ash | CA | FA | Water |
|---|---|---|---|---|---|
| kg/m$^3$ | 440.27 | 0.00 | 1184.4 | 692.9 | 136.5 |

Step 8: Proportion Mixture with Cement and Fly Ash (40%)

| | Cement | Fly Ash | CA | FA | Water |
|---|---|---|---|---|---|
| kg/m$^3$ | 264.16 | 176.11 | 1184.5 | 664.9 | 136.48 |

Step 9: Final Mixture Proportion with water adjustment due to aggregate moisture

| Aggr. | 20 mm | 10 mm | 7 mm | Sand |
|---|---|---|---|---|
| Abs(%) | 0.348 | 0.415 | 0.911 | 0.988 |
| MC (%) | 0.441 | 0.712 | 0.911 | 1.295 |

| **Mix** | **Fly ash** | **Cement** | **Fly ash** | **20 mm (63%)** | **10 mm (14%)** | **7 mm (23%)** | **Sand** | **Water** | **w/b** |
|---|---|---|---|---|---|---|---|---|---|
| | % | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | |
| OD | 40 | 264.16 | 176.11 | 746.22 | 165.83 | 272.43 | 664.91 | 136.48 | 0.31 |
| Wet | 40 | 264.16 | 176.11 | 749.51 | 167.01 | 274.91 | 671.48 | 133.22 | 0.31 |

Concrete Mix Design (ACI 211.4R-08) Mix ID: **B00**

Given Information

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Specified Compr. strength at 28 days | f'c = | 7250 | psi | 50 | MPa |
| | Fine Aggregate Properties | | | | | |
| | Fine ness Modulus | = | 1.96 | | | |
| | Relative density (Oven dry) | = | 2.60 | | | |
| | Absorption | = | 0.99 | % | | |
| | Bulk density | | 105.4 | lb/ft$^3$ | 1686.8 | kg/m$^3$ |
| | Coarse Aggregate Properties | | | | | |
| | Relative density (Oven dry) | = | 2.69 | | | |
| | Bulk density | = | 102.8 | lb/ft$^3$ | 1645.2 | kg/m$^3$ |
| | Relative Density (Sp. Gr.) of cement | = | 3.15 | | | |
| | Relative Density (Sp. Gr.) of fly ash | = | 2.64 | | | |
| Step 1: | Select Slump and Required Stength | | | | | |
| | Slump | = | 1 - 2 | inch | 25 - 50 | mm |
| | Required Avg. Strength | f'cr = | 8675 | psi | 59.828 | MPa |
| Step 2: | Select Maximum size of aggregate | = | 0.75 | inch | 20 | mm |
| Step 3: | Select Optimum Coarse Aggregate Content | | | | | |
| | Fractional Volm of OD CA | VCA = | 0.72 | | | |
| | Mass of Dry CA | $CA_{OD}$ = | 1998.4 | lb/ft$^3$ | 1184.5 | kg/m$^3$ |
| Step 4: | Estimate Mixing Water and Air Content | | | | | |
| | Required Water | = | 253.8 | lb/ft$^3$ | 150.4 | kg/m$^3$ |
| | Air Content | = | 1.5 | % | | |
| | Void content of Fine aggregate | = | 34.909 | % | | |
| | Mixing water adjustment | = | -0.725 | lb/ft$^3$ | | |
| | Water after adjustment | = | 253.1 | lb/ft$^3$ | 150 | kg/m$^3$ |
| Step 5: | Water to Cementitous Material ratio, w/cm | = | 0.29 | | | |
| Step 6: | Content of Cementitious Materials (CM) | = | 872.7 | lb/ft$^3$ | 517.23 | kg/m$^3$ |

Step 7: Proportion Basic Mixture with Cement

| | Cement | Fly Ash | CA | FA | Water |
|---|---|---|---|---|---|
| kg/m$^3$ | 517.23 | 0 | 1184.47 | 594.46 | 150 |

Step 8: Proportion Mixture with Cement and Fly Ash (0%)

| | Cement | Fly Ash | CA | FA | Water |
|---|---|---|---|---|---|
| kg/m$^3$ | 517.23 | 0 | 1184.47 | 594.46 | 150 |

Step 9: Final Mixture Proportion with water adjustment due to aggregate moisture

| Aggr. | 20 mm | 10 mm | 7 mm | Sand |
|---|---|---|---|---|
| Abs(%) | 0.348 | 0.415 | 0.911 | 0.988 |
| MC (%) | 0.575 | 0.562 | 1.020 | 1.518 |

| **Mix** | **Fly ash** | **Cement** | **Fly ash** | **20 mm (63%)** | **10 mm (14%)** | **7 mm (23%)** | **Sand** | **Water** | **w/b** |
|---|---|---|---|---|---|---|---|---|---|
| | % | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | |
| OD | 0 | 517 | 0 | 746.22 | 165.83 | 272.43 | 594.46 | 150 | 0.29 |
| Wet | 0 | 517 | 0 | 750.51 | 166.78 | 275.21 | 600.34 | 144.57 | 0.29 |

Concrete Mix Design (ACI 211.4R-08) Mix ID: **B30**

Given Information

Specified Compr. strength at 28 days f'c = 7250 psi 50 MPa

Fine Aggregate Properties

Fine ness Modulus = 1.96

Relative density (Oven dry) = 2.60

Absorption = 0.99 %

Bulk density 105.4 lb/ft$^3$ 1686.8 kg/m$^3$

Coarse Aggregate Properties

Relative density (Oven dry) = 2.69

Bulk density = 102.8 lb/ft$^3$ 1645.2 kg/m$^3$

Relative Density (Sp. Gr.) of cement = 3.15

Relative Density (Sp. Gr.) of fly ash = 2.64

Step 1: Select Slump and Required Stength

Slump = 1 - 2 inch 25 - 50 mm

Required Avg. Strength f'cr = 8675 psi 59.828 MPa

Step 2: Select Maximum size of aggregate = 0.75 inch 20 mm

Step 3: Select Optimum Coarse Aggregate Content

Fractional Volm of OD CA VCA = 0.72

Mass of Dry CA $CA_{OD}$ = 1998.4 lb/ft$^3$ 1184.5 kg/m$^3$

Step 4: Estimate Mixing Water and Air Content

Required Water = 253.8 lb/ft$^3$ 150.4 kg/m$^3$

Air Content = 1.5 %

Void content of Fine aggregate = 34.909 %

Mixing water adjustment = -0.725 lb/ft$^3$

Water after adjustment = 253.1 lb/ft$^3$ 150 kg/m$^3$

Step 5: Water to Cementitous Material ratio, w/cm = 0.29

Step 6: Content of Cementitious Materials (CM) = 872.7 lb/ft$^3$ 517.23 kg/m$^3$

Step 7: Proportion Basic Mixture with Cement

|  | Cement | Fly Ash | CA | FA | Water |
|---|---|---|---|---|---|
| kg/m$^3$ | 517.23 | 0 | 1184.47 | 594.46 | 150 |

Step 8: Proportion Mixture with Cement and Fly Ash (30%)

|  | Cement | Fly Ash | CA | FA | Water |
|---|---|---|---|---|---|
| kg/m$^3$ | 362.06 | 155.17 | 1184.47 | 569.77 | 150 |

Step 9: Final Mixture Proportion with water adjustment due to aggregate moisture

| Aggr. | 20 mm | 10 mm | 7 mm | Sand |
|---|---|---|---|---|
| Abs(%) | 0.348 | 0.415 | 0.911 | 0.988 |
| MC (%) | 0.437 | 0.484 | 1.280 | 1.985 |

| **Mix** | **Fly ash** | **Cement** | **Fly ash** | **20 mm (63%)** | **10 mm (14%)** | **7 mm (23%)** | **Sand** | **Water** | **w/b** |
|---|---|---|---|---|---|---|---|---|---|
|  | % | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ |  |
| OD | 30 | 362.06 | 155.17 | 746.22 | 165.83 | 272.43 | 569.77 | 150 | 0.29 |
| Wet | 30 | 362.06 | 155.17 | 749.48 | 166.63 | 275.92 | 575.4 | 142.46 | 0.29 |

Concrete Mix Design (ACI 211.4R-08) Mix ID: **B40**

Given Information

| | | | | | | |
|---|---|---|---|---|---|---|
| Specified Compr. strength at 28 days | f'c = | 7250 | psi | 50 | MPa |
| Fine Aggregate Properties | | | | | |
| Fine ness Modulus | = | 1.96 | | | |
| Relative density (Oven dry) | = | 2.60 | | | |
| Absorption | = | 0.99 | % | | |
| Bulk density | | 105.4 | $lb/ft^3$ | 1686.8 | $kg/m^3$ |
| Coarse Aggregate Properties | | | | | |
| Relative density (Oven dry) | = | 2.69 | | | |
| Bulk density | = | 102.8 | $lb/ft^3$ | 1645.2 | $kg/m^3$ |
| Relative Density (Sp. Gr.) of cement | = | 3.15 | | | |
| Relative Density (Sp. Gr.) of fly ash | = | 2.64 | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Step 1: | Select Slump and Required Stength | | | | | | |
| | Slump | = | 1 - 2 | inch | 25 - 50 | mm |
| | Required Avg. Strength | f'cr = | 8675 | psi | 59.828 | MPa |
| Step 2: | Select Maximum size of aggregate | = | 0.75 | inch | 20 | mm |
| Step 3: | Select Optimum Coarse Aggregate Content | | | | | |
| | Fractional Volm of OD CA | VCA = | 0.72 | | | |
| | Mass of Dry CA | $CA_{OD}$ = | 1998.4 | $lb/ft^3$ | 1184.5 | $kg/m^3$ |
| Step 4: | Estimate Mixing Water and Air Content | | | | | |
| | Required Water | = | 253.8 | $lb/ft^3$ | 150.4 | $kg/m^3$ |
| | Air Content | = | 1.5 | % | | |
| | Void content of Fine aggregate | = | 34.909 | % | | |
| | Mixing water adjustment | = | -0.725 | $lb/ft^3$ | | |
| | Water after adjustment | = | 253.1 | $lb/ft^3$ | 150 | $kg/m^3$ |
| Step 5: | Water to Cementitous Material ratio, w/cm | = | 0.29 | | | |
| Step 6: | Content of Cementitious Materials (CM) | = | 872.7 | $lb/ft^3$ | 517.23 | $kg/m^3$ |

Step 7: Proportion Basic Mixture with Cement

| | Cement | Fly Ash | CA | FA | Water |
|---|---|---|---|---|---|
| $kg/m^3$ | 517.23 | 0 | 1184.47 | 594.46 | 150 |

Step 8: Proportion Mixture with Cement and Fly Ash (40%)

| | Cement | Fly Ash | CA | FA | Water |
|---|---|---|---|---|---|
| $kg/m^3$ | 310.34 | 206.89 | 1184.47 | 561.54 | 150 |

Step 9: Final Mixture Proportion with water adjustment due to aggregate moisture

| Aggr. | 20 mm | 10 mm | 7 mm | Sand |
|---|---|---|---|---|
| Abs(%) | 0.348 | 0.415 | 0.911 | 0.988 |
| MC (%) | 0.441 | 0.712 | 0.911 | 1.295 |

| **Mix** | **Fly ash** | **Cement** | **Fly ash** | **20 mm (63%)** | **10 mm (14%)** | **7 mm (23%)** | **Sand** | **Water** | **w/b** |
|---|---|---|---|---|---|---|---|---|---|
| | % | $kg/m^3$ | $kg/m^3$ | $kg/m^3$ | $kg/m^3$ | $kg/m^3$ | $kg/m^3$ | $kg/m^3$ | |
| OD | 40 | 310.34 | 206.89 | 746.22 | 165.83 | 272.43 | 561.54 | 150 | 0.29 |
| Wet | 40 | 310.34 | 206.89 | 749.37 | 166.66 | 274.77 | 567.09 | 146.65 | 0.29 |

# APPENDIX D: Compressive Strength test

## Compressive strength test : SERIES – A

| Mix ID (Casting date) | | A00 (24/08/09) | | | A30 (10/08/09) | | | A40 (07/08/09) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Days** | **No** | **Load (KN)** | **Strength (MPa)** | **Avg. Strength (st. dev.) (MPa)** | **Load (KN)** | **Strength (MPa)** | **Avg. Strength (st. dev.) (MPa)** | **Load (KN)** | **Strength (MPa)** | **Avg. Strength (st. dev.) (MPa))** |
| **3** | 1 | 379.6 | 48.53 | 46.79 (1.56) | 358.3 | 45.80 | 46.12 (0.36) | 325.3 | 41.42 | 40.76 (0.60) |
| | 2 | 355.2 | 45.50 | | 361.7 | 46.05 | | 316.2 | 40.26 | |
| | 3 | 361.2 | 46.36 | | 365.3 | 46.51 | | 318.9 | 40.60 | |
| **7** | 1 | 467.5 | 59.64 | 57.21 (2.68) | 456.1 | 58.42 | 57.87 (0.48) | 404.4 | 51.59 | 50.56 (1.58) |
| | 2 | 453.7 | 57.65 | | 451.3 | 57.58 | | 381.3 | 48.74 | |
| | 3 | 423.3 | 54.33 | | 451.5 | 57.60 | | 404.8 | 51.34 | |
| **28** | 1 | 554.2 | 70.70 | 68.89 (2.27) | 588.5 | 75.08 | 72.99 (2.02) | 512.6 | 65.53 | 65.60 (1.86) |
| | 2 | 517.9 | 66.34 | | 569.8 | 72.84 | | 497.9 | 63.78 | |
| | 3 | 542.6 | 69.64 | | 555.7 | 71.04 | | 529.1 | 67.50 | |
| **56** | 1 | 605.5 | 77.25 | 77.32 (1.21) | 704 | 90.54 | 90.71 (0.72) | 659.5 | 84.99 | 87.88 (2.54) |
| | 2 | 615.8 | 78.56 | | 700.5 | 90.09 | | 701.9 | 89.73 | |
| | 3 | 594.4 | 76.14 | | 711.5 | 91.50 | | 692.8 | 88.92 | |
| **91** | 1 | 612 | 78.39 | 78.01 (1.39) | 722.1 | 92.87 | 92.25 (0.58) | 708 | 90.33 | 88.53 (1.84) |
| | 2 | 621.7 | 79.16 | | 714.7 | 91.73 | | 687.6 | 88.61 | |
| | 3 | 599.4 | 76.47 | | 720.8 | 92.14 | | 676.5 | 86.65 | |
| **210** | 1 | 606.3 | 77.82 | 78.32 (0.64) | 726.1 | 93.01 | 95.76 (3.90) | 698 | 89.41 | 89.93 (0.76) |
| | 2 | 610.9 | 78.09 | | 772.2 | 98.52 | | 698 | 89.59 | |
| | 3 | 618.3 | 79.04 | | Outlier | - | | 710.3 | 90.80 | |
| **335** | 1 | 625.4 | 80.11 | 79.46 (1.54) | 800.8 | 102.58 | 99.38 (3.32) | 752.6 | 96.79 | 97.13 (0.53) |
| | 2 | 606.7 | 77.71 | | 753.7 | 95.96 | | 766.1 | 97.74 | |
| | 3 | 631.5 | 80.57 | | 769.7 | 99.59 | | 759.3 | 96.87 | |

## Compressive strength test : SERIES – B

| **Mix ID (Casting date)** | | **B00 (20/08/09)** | | | **B30 (17/08/09)** | | | **B40 (13/08/09)** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Days** | **No** | **Load (KN)** | **Strength (MPa)** | **Avg. Strength (st. dev.) (MPa)** | **Load (KN)** | **Strength (MPa)** | **Avg. Strength (st. dev.) (MPa)** | **Load (KN)** | **Strength (MPa)** | **Avg. Strength (st. dev.) (MPa)** |
| 3 | 1 | 516.5 | 66.03 | 67.36 (1.39) | 374.1 | 47.71 | 44.62 (2.99) | 320.4 | 40.71 | 40.96 (0.32) |
| | 2 | 520.8 | 67.25 | | 325.8 | 41.73 | | 320.8 | 40.85 | |
| | 3 | 537.1 | 68.80 | | 348.9 | 44.42 | | 321.3 | 41.32 | |
| 7 | 1 | 525.8 | 67.62 | 70.48 (2.70) | 470.9 | 60.20 | 59.28 (0.79) | 421.2 | 53.84 | 51.76 (2.02) |
| | 2 | 568.7 | 72.99 | | 463.5 | 58.78 | | 387.3 | 49.81 | |
| | 3 | 557.4 | 70.83 | | 461.5 | 58.88 | | 402.3 | 51.63 | |
| 28 | 1 | 641.1 | 81.95 | 85.49 (3.36) | 570.2 | 72.89 | 73.59 (0.86) | 550.4 | 70.08 | 69.03 (1.03) |
| | 2 | 675.7 | 85.86 | | 571.3 | 73.33 | | 541.8 | 68.98 | |
| | 3 | 693.5 | 88.65 | | 584.4 | 74.56 | | 534.2 | 68.02 | |
| 56 | 1 | 748 | 95.81 | 96.24 (0.37) | 720 | 92.78 | 92.93 (1.61) | 693.6 | 88.31 | 89.16 (1.69) |
| | 2 | 755.8 | 96.42 | | 714.9 | 91.39 | | 711.3 | 91.11 | |
| | 3 | 756.2 | 96.48 | | 737.1 | 94.61 | | 690.3 | 88.07 | |
| 91 | 1 | 780.3 | 99.95 | 101.05 (1.33) | 756.5 | 96.32 | 96.58 (0.71) | 699.2 | 89.92 | 89.31 (0.58) |
| | 2 | 798.8 | 102.52 | | 752.7 | 96.03 | | 698.1 | 89.24 | |
| | 3 | 790.8 | 100.69 | | 763.3 | 97.38 | | 695.8 | 88.77 | |
| 210 | 1 | outlier | - | 101.33 (0.08) | 768.2 | 98.40 | 98.26 (0.98) | 712.5 | 91.45 | 92.26 (3.35) |
| | 2 | 790.6 | 101.27 | | 757.5 | 97.22 | | 753.5 | 95.94 | |
| | 3 | 796.3 | 101.39 | | 774.2 | 99.17 | | 699.2 | 89.38 | |
| 335 | 1 | 830.6 | 105.97 | 102.36 (3.63) | 765.5 | 97.86 | 99.65 (2.67) | 780.6 | 99.79 | 100.52 (1.54) |
| | 2 | 775.3 | 98.71 | | 798.7 | 102.72 | | 798.5 | 102.28 | |
| | 3 | 801 | 102.40 | | 768 | 98.37 | | 778.2 | 99.48 | |

# APPENDIX E: Indirect Tensile Strength test

## Indirect tensile strength test : SERIES – A

**Mix ID : A00** Casting date: 24/08/2009

| Days | Sample No | Diameter (mm) | Height (mm) | Load (KN) | Strength (MPa) | Avg. strength (MPa) |
|---|---|---|---|---|---|---|
| 7 | 1 | 148.1 | 300 | 242.6 | 3.48 | 3.4 |
| | 2 | 148.2 | 300.3 | 236.2 | 3.38 | |
| 28 | 1 | 149.8 | 300 | 272.3 | 3.86 | 3.8 |
| | 2 | 150.1 | 299.8 | 262.2 | 3.71 | |
| 335 | 1 | 149.8 | 297.5 | 348.6 | 4.98 | 5.1 |
| | 2 | 149.9 | 298.5 | 360.2 | 5.12 | |

**Mix ID : A30** Casting date: 10/08/2009

| Days | Sample No | Diameter (mm) | Height (mm) | Load (KN) | Strength (MPa) | Avg. strength (MPa) |
|---|---|---|---|---|---|---|
| 7 | 1 | 147.9 | 300.5 | 300.5 | 4.30 | 4.2 |
| | 2 | 148.1 | 299 | 289.7 | 4.16 | |
| 28 | 1 | 149.9 | 299 | 304.7 | 4.33 | 4.4 |
| | 2 | 149.9 | 300.8 | 322.6 | 4.55 | |
| 335 | 1 | 149.8 | 300 | 425.7 | 6.03 | 5.7 |
| | 2 | 149.9 | 300 | 382.9 | 5.42 | |

**Mix ID : A40** Casting date: 7/08/2009

| Days | Sample No | Diameter (mm) | Height (mm) | Load (KN) | Strength (MPa) | Avg. strength (MPa) |
|---|---|---|---|---|---|---|
| 7 | 1 | 148.1 | 298 | 238 | 3.43 | 3.5 |
| | 2 | 148.1 | 298.3 | 249.8 | 3.60 | |
| 28 | 1 | 148.07 | 301.7 | 262.9 | 3.75 | 3.8 |
| | 2 | 147.8 | 302 | 271 | 3.87 | |
| 335 | 1 | 149.9 | 300 | 422.5 | 5.98 | 5.9 |
| | 2 | 149.8 | 301 | 404.4 | 5.71 | |

## Indirect tensile strength test : SERIES - B

**Mix ID : B00** Casting date: 20/08/2009

| Days | Sample No | Diameter (mm) | Height (mm) | Load (KN) | Strength (MPa) | Avg. strength (MPa) |
|---|---|---|---|---|---|---|
| 7 | 1 | 150 | 299.5 | 302.1 | 4.28 | 4.3 |
| | 2 | 150 | 299.5 | 310.2 | 4.40 | |
| 28 | 1 | 150 | 300 | 317 | 4.48 | 4.4 |
| | 2 | 149.9 | 300.5 | 303 | 4.28 | |
| 335 | 1 | 149.9 | 299 | 442.6 | 6.29 | 6.3 |
| | 2 | 149.9 | 300.5 | 448.5 | 6.34 | |

**Mix ID : B30** Casting date: 17/08/2009

| Days | Sample No | Diameter (mm) | Height (mm) | Load (KN) | Strength (MPa) | Avg. strength (MPa) |
|---|---|---|---|---|---|---|
| 7 | 1 | 148.1 | 300.5 | 272.8 | 3.90 | 3.9 |
| | 2 | 147.6 | 300.5 | 277 | 3.98 | |
| 28 | 1 | 150 | 301.5 | 295.4 | 4.16 | 4.2 |
| | 2 | 150 | 300.5 | 302.6 | 4.27 | |
| 335 | 1 | 149.8 | 300.5 | 343.2 | 4.85 | 5.0 |
| | 2 | 149.9 | 300 | 366.1 | 5.18 | |

**Mix ID : B40** Casting date: 13/08/2009

| Days | Sample No | Diameter (mm) | Height (mm) | Load (KN) | Strength (MPa) | Avg. strength (MPa) |
|---|---|---|---|---|---|---|
| 7 | 1 | 148 | 300.5 | 260.9 | 3.73 | 3.6 |
| | 2 | 148 | 299.5 | 236.1 | 3.39 | |
| 28 | 1 | 150 | 300 | 296.5 | 4.19 | 4.1 |
| | 2 | 150 | 301 | 289.7 | 4.08 | |
| 335 | 1 | 149.9 | 300 | 409.2 | 5.79 | 5.7 |
| | 2 | 149.9 | 300 | 389 | 5.51 | |

# APPENDIX F: Flexural Strength test (Modulus of Rupture)

## SERIES - A

| Mix ID (Casting date) | Test days | No. | Avg. B (mm) | Avg. D (mm) | Span, L (mm) | Load (KN) | Strength (MPa) | Avg. Strength (MPa) |
|---|---|---|---|---|---|---|---|---|
| **A00** (24/08/09) | 28 | 1 | 100.3 | 100.3 | 300 | 23.02 | 6.85 | 7.2 |
| | | 2 | 100.6 | 100.9 | 300 | 26.01 | 7.61 | |
| **A30** (10/08/09) | 28 | 1 | 100.5 | 99.3 | 300 | 26.94 | 8.16 | 8.0 |
| | | 2 | 99.85 | 99.8 | 300 | 25.74 | 7.76 | |
| **A40** (07/08/09) | 28 | 1 | 100.6 | 98.8 | 300 | 20.2 | 6.17 | 6.1 |
| | | 2 | 101.05 | 101.5 | 300 | 20.81 | 6.00 | |

## SERIES - B

| Mix ID (Casting date) | Test days | No. | Avg. B (mm) | Avg. D (mm) | Span, L (mm) | Load (KN) | Strength (MPa) | Avg. Strength (MPa) |
|---|---|---|---|---|---|---|---|---|
| **B00** (20/08/09) | 28 | 1 | 100.0 | 100.5 | 300 | 31.35 | 9.32 | 9.9 |
| | | 2 | 100.2 | 100.2 | 300 | 35.18 | 10.50 | |
| **B30** (17/08/09) | 28 | 1 | 100.2 | 100.5 | 300 | 25.01 | 7.42 | 7.3 |
| | | 2 | 100.5 | 99.8 | 300 | 23.69 | 7.10 | |
| **B40** (13/08/09) | 28 | 1 | 99.8 | 100.5 | 300 | 21.65 | 6.45 | 6.7 |
| | | 2 | 98.0 | 99.5 | 300 | 22.23 | 6.87 | |

# APPENDIX G: Drying Shrinkage test

## Drying shrinkage test : SERIES – A

**Mix ID : A00** Casting date: 24/08/2009

| Days | Ref.bar (inch) | Sample 1 (inch) | Sample 2 (inch) | Sample 3 (inch) | Sample 1 (micro-strain) | Sample 2 (micro-strain) | Sample 3 (micro-strain) | Avg. (st. dev.) (micro-strain) |
|---|---|---|---|---|---|---|---|---|
| 7 | 0.2026 | 0.3198 | 0.3202 | 0.3270 | - | - | - | - |
| 14 | 0.2026 | 0.3175 | 0.3183 | 0.3250 | 229.6 | 198.1 | 199.1 | 209.0 (17.9) |
| 21 | 0.2023 | 0.3165 | 0.3171 | 0.3240 | 305.8 | 289.6 | 267.2 | 287.5 (19.4) |
| 28 | 0.2026 | 0.3165 | 0.3170 | 0.3240 | 338.3 | 330.2 | 305.8 | 324.8 (16.9) |
| 56 | 0.2025 | 0.3156 | 0.3161 | 0.3232 | 419.6 | 403.4 | 374.9 | 399.3 (22.6) |
| 120 | 0.2026 | 0.3155 | 0.3161 | 0.3231 | 432.8 | 418.6 | 389.1 | 413.5 (22.3) |
| 180 | 0.2015 | 0.3145 | 0.3149 | - | 426.7 | 426.7 | - | 426.7 (0.0) |

**Mix ID : A30** Casting date: 10/08/2009

| Days | Ref.bar (inch) | Sample 1 (inch) | Sample 2 (inch) | Sample 3 (inch) | Sample 1 (micro-strain) | Sample 2 (micro-strain) | Sample 3 (micro-strain) | Avg. (st. dev.) (micro-strain) |
|---|---|---|---|---|---|---|---|---|
| 7 | 0.2026 | 0.3255 | 0.3198 | 0.3159 | - | - | - | - |
| 14 | 0.2025 | 0.3234 | 0.3177 | 0.3137 | 200.7 | 209.0 | 212.9 | 207.5 (6.2) |
| 21 | 0.2026 | 0.3229 | 0.3171 | 0.3132 | 267.5 | 273.0 | 273.0 | 271.2 (3.1) |
| 28 | 0.2027 | 0.3227 | 0.3170 | 0.3131 | 291.6 | 296.7 | 296.7 | 295.0 (2.9) |
| 56 | 0.2025 | 0.3221 | 0.3162 | 0.3122 | 338.3 | 360.7 | 365.8 | 354.9 (14.6) |
| 120 | 0.2026 | 0.3220 | 0.3161 | 0.3122 | 358.6 | 378.0 | 380.0 | 372.2 (11.8) |
| 180 | 0.2026 | 0.3219 | 0.3161 | 0.3122 | 365.8 | 378.0 | 378.0 | 373.9 (7.0) |

**Mix ID : A40** Casting date: 7/08/2009

| Days | Ref.bar (inch) | Sample 1 (inch) | Sample 2 (inch) | Sample 3 (inch) | Sample 1 (micro-strain) | Sample 2 (micro-strain) | Sample 3 (micro-strain) | Avg. (st. dev.) (micro-strain) |
|---|---|---|---|---|---|---|---|---|
| 7 | 0.2026 | 0.3276 | 0.3085 | 0.3084 | - | - | - | - |
| 14 | 0.2026 | 0.3255 | 0.3065 | 0.3066 | 211.3 | 207.3 | 186.9 | 201.8 (13.1) |
| 21 | 0.2026 | 0.3248 | 0.3058 | 0.3058 | 282.4 | 278.4 | 273.3 | 278.0 (4.6) |
| 28 | 0.2023 | 0.3244 | 0.3053 | 0.3053 | 294.6 | 295.7 | 290.6 | 293.6 (2.7) |
| 56 | 0.2023 | 0.3236 | 0.3047 | 0.3049 | 376.9 | 356.6 | 334.3 | 355.9 (21.3) |
| 120 | 0.2025 | 0.3239 | 0.3048 | 0.3048 | 363.7 | 366.8 | 356.6 | 362.4 (5.2) |
| 180 | 0.2024 | 0.3237 | 0.3047 | 0.3047 | 377.3 | 369.8 | 359.7 | 368.9 (8.8) |

## Drying shrinkage test : SERIES – B

**Mix ID : B00** Casting date: 20/08/2009

| Days | Ref.bar (inch) | Sample 1 (inch) | Sample 2 (inch) | Sample 3 (inch) | Sample 1 (micro-strain) | Sample 2 (micro-strain) | Sample 3 (micro-strain) | Avg. (st. dev.) (micro-strain) |
|---|---|---|---|---|---|---|---|---|
| 7 | 0.2026 | 0.3285 | 0.3191 | 0.3215 | | | | |
| 14 | 0.2025 | 0.3266 | 0.3172 | 0.3197 | 172.7 | 174.8 | 170.7 | 172.7 (2.0) |
| 21 | 0.2026 | 0.3264 | 0.3170 | 0.3194 | 205.2 | 203.2 | 206.2 | 204.9 (1.6) |
| 28 | 0.2025 | 0.3261 | 0.3166 | 0.3190 | 243.8 | 257.0 | 260.1 | 253.7 (8.6) |
| 56 | 0.2026 | 0.3249 | 0.3157 | 0.3179 | 349.5 | 333.2 | 355.6 | 346.1 (11.6) |
| 120 | 0.2023 | 0.3247 | 0.3154 | 0.3177 | 354.6 | 348.5 | 358.6 | 353.9 (5.1) |
| 180 | 0.1371 | 0.25935 | 0.2500 | 0.2524 | 367.8 | 364.1 | 367.1 | 366.3 (2.0) |

**Mix ID : B30** Casting date: 17/08/2009

| Days | Ref.bar (inch) | Sample 1 (inch) | Sample 2 (inch) | Sample 3 (inch) | Sample 1 (micro-strain) | Sample 2 (micro-strain) | Sample 3 (micro-strain) | Avg. (st. dev.) (micro-strain) |
|---|---|---|---|---|---|---|---|---|
| 7 | 0.2025 | 0.3288 | 0.3342 | 0.3117 | - | - | - | - |
| 14 | 0.2026 | 0.3270 | 0.3322 | 0.3100 | 193.0 | 220.5 | 180.8 | 198.1 (20.3) |
| 21 | 0.2027 | 0.3267 | 0.3319 | 0.3097 | 236.7 | 258.1 | 223.5 | 239.4 (17.4) |
| 28 | 0.2023 | 0.3258 | 0.3311 | 0.3089 | 281.4 | 298.7 | 264.2 | 281.4 (17.3) |
| 56 | 0.2023 | 0.3255 | 0.3306 | 0.3083 | 318.0 | 347.5 | 325.1 | 330.2 (15.4) |
| 120 | 0.2024 | 0.3254 | 0.3306 | 0.3084 | 333.2 | 359.7 | 323.1 | 338.7 (18.9) |
| 180 | 0.2026 | 0.3255 | 0.3307 | 0.3083 | 342.1 | 364.4 | 358.6 | 355.0 (11.6) |

**Mix ID : B40** Casting date: 13/08/2009

| Days | Ref.bar (inch) | Sample 1 (inch) | Sample 2 (inch) | Sample 3 (inch) | Sample 1 (micro-strain) | Sample 2 (micro-strain) | Sample 3 (micro-strain) | Avg. (st. dev.) (micro-strain) |
|---|---|---|---|---|---|---|---|---|
| 7 | 0.2026 | 0.3152 | 0.3220 | 0.3290 | - | - | - | - |
| 14 | 0.2026 | 0.3129 | 0.3198 | 0.3267 | 237.7 | 225.6 | 229.6 | 231.0 (6.2) |
| 21 | 0.2024 | 0.3123 | 0.3190 | 0.3260 | 280.4 | 288.5 | 279.4 | 282.8 (5.0) |
| 28 | 0.2024 | 0.3121 | 0.3190 | 0.3259 | 296.7 | 289.6 | 294.6 | 293.6 (3.7) |
| 56 | 0.2024 | 0.3115 | 0.3183 | 0.3253 | 359.7 | 354.6 | 350.5 | 354.9 (4.6) |
| 120 | 0.2020 | 0.3109 | 0.3177 | 0.3247 | 380.0 | 374.9 | 373.9 | 376.3 (3.3) |
| 180 | 0.2022 | 0.3111 | 0.3179 | - | 383.4 | 374.6 | - | 379.0 (6.2) |

# APPENDIX H: Volume of Permeable Void (VPV) test results

## VPV test at 28 days: SERIES – A (28 days cured)

| Mix ID | No. | Oven dry wt $M_1$ (gm) | SSD wt $M_{2i}$ (gm) | Boiled wt $M_{3b}$ (gm) | Submerged wt $M_{4ib}$ (gm) | Immersed Absorption (%) | Boiled Absorption (%) | AVPV (%) |
|---|---|---|---|---|---|---|---|---|
| **A00** | 1 | 896.44 | 934.51 | 934.85 | 553.39 | 4.25 | 4.28 | 10.07 |
| | 2 | 860.69 | 900.42 | 900.65 | 528.71 | 4.62 | 4.64 | 10.74 |
| | 3 | 872.82 | 912.08 | 912.56 | 537.43 | 4.50 | 4.55 | 10.59 |
| | 4 | 842.89 | 879.11 | 879.31 | 518.6 | 4.30 | 4.32 | 10.10 |
| | Average (nearest 0.1) | | | | | **4.4** | **4.5** | **10.4** |
| | Standard deviation | | | | | | | **0.34** |
| **A30** | 1 | 839.07 | 877.24 | 877.46 | 518.6 | 4.55 | 4.58 | 10.70 |
| | 2 | 879.66 | 918.16 | 918.38 | 544.14 | 4.38 | 4.40 | 10.35 |
| | 3 | 839.92 | 875.73 | 876.1 | 519.08 | 4.26 | 4.31 | 10.13 |
| | 4 | 917.88 | 956.16 | 956.49 | 568.59 | 4.17 | 4.21 | 9.95 |
| | Average (nearest 0.1) | | | | | **4.3** | **4.4** | **10.3** |
| | Standard deviation | | | | | | | **0.32** |
| **A40** | 1 | 865.89 | 905.46 | 905.72 | 534.58 | 4.57 | 4.60 | 10.73 |
| | 2 | 863.41 | 903.64 | 903.87 | 532.92 | 4.66 | 4.69 | 10.91 |
| | 3 | 915.12 | 952.22 | 952.5 | 566.02 | 4.05 | 4.08 | 9.67 |
| | 4 | - | - | - | - | - | - | - |
| | Average (nearest 0.1) | | | | | **4.4** | **4.5** | **10.4** |
| | Standard deviation | | | | | | | **0.67** |

## VPV test at 28 days: SERIES – B (28 days cured)

| Mix ID | No. | Oven dry wt $M_1$ (gm) | SSD wt $M_{2i}$ (gm) | Boiled wt $M_{3b}$ (gm) | Submerged wt $M_{4ib}$ (gm) | Immersed Absorption (%) | Boiled Absorption (%) | AVPV (%) |
|---|---|---|---|---|---|---|---|---|
| **B00** | 1 | 856.88 | 894.9 | 895.16 | 531.06 | 4.44 | 4.47 | 10.51 |
| | 2 | 864.68 | 904.66 | 904.93 | 535.9 | 4.62 | 4.65 | 10.91 |
| | 3 | 864.13 | 899.79 | 900.18 | 536.13 | 4.13 | 4.17 | 9.90 |
| | 4 | 904.78 | 941.52 | 941.78 | 562.32 | 4.06 | 4.09 | 9.75 |
| | Average (nearest 0.1) | | | | | **4.3** | **4.4** | **10.3** |
| | Standard deviation | | | | | | | **0.54** |
| **B30** | 1 | 917.15 | 957.05 | 957.3 | 569.64 | 4.35 | 4.38 | 10.36 |
| | 2 | 850.34 | 889.28 | 889.53 | 528.48 | 4.58 | 4.61 | 10.85 |
| | 3 | 860.25 | 902.23 | 902.45 | 532.92 | 4.88 | 4.91 | 11.42 |
| | 4 | 869.41 | 913.65 | 913.85 | 539.16 | 5.09 | 5.11 | 11.86 |
| | Average (nearest 0.1) | | | | | **4.7** | **4.8** | **11.1** |
| | Standard deviation | | | | | | | **0.66** |
| **B40** | 1 | 933.23 | 973.94 | 974.09 | 580.5 | 4.36 | 4.38 | 10.38 |
| | 2 | 842.17 | 884.49 | 884.72 | 521.32 | 5.03 | 5.05 | 11.71 |
| | 3 | 871.83 | 912.84 | 913.1 | 540.94 | 4.70 | 4.73 | 11.09 |
| | 4 | 863.4 | 905.7 | 905.91 | 535.27 | 4.90 | 4.92 | 11.47 |
| | Average (nearest 0.1) | | | | | **4.8** | **4.8** | **11.2** |
| | Standard deviation | | | | | | | **0.58** |

## VPV test at 28 days: SERIES – A (7 days cured)

| Mix ID | No. | Oven dry wt $M_1$ (gm) | SSD wt $M_{2i}$ (gm) | Boiled wt $M_{3b}$ (gm) | Submerged wt $M_{4ib}$ (gm) | Immersed Absorption (%) | Boiled Absorption (%) | AVPV (%) |
|---|---|---|---|---|---|---|---|---|
| **A00** | 1 | 903.36 | 942.19 | 942.57 | 557.85 | 4.30 | 4.34 | 10.19 |
| | 2 | 847.04 | 883.61 | 884.01 | 521.78 | 4.32 | 4.36 | 10.21 |
| | 3 | 820.56 | 859.08 | 859.39 | 504.77 | 4.69 | 4.73 | 10.95 |
| | 4 | 875.22 | 916 | 916.22 | 538.85 | 4.66 | 4.68 | 10.86 |
| | Average (nearest 0.1) | | | | | **4.5** | **4.5** | **10.6** |
| | Standard deviation | | | | | | | **0.41** |
| **A30** | 1 | 782.15 | 818.07 | 818.29 | 482.22 | 4.59 | 4.62 | 10.75 |
| | 2 | 891.6 | 932.68 | 932.75 | 549.3 | 4.61 | 4.62 | 10.73 |
| | 3 | 871.04 | 907.94 | 908 | 538.14 | 4.24 | 4.24 | 9.99 |
| | 4 | 929.02 | 966.72 | 966.96 | 575.77 | 4.06 | 4.08 | 9.70 |
| | Average (nearest 0.1) | | | | | **4.4** | **4.4** | **10.3** |
| | Standard deviation | | | | | | | **0.53** |
| **A40** | 1 | 849.32 | 886.47 | 886.9 | 525.05 | 4.37 | 4.42 | 10.39 |
| | 2 | 833.63 | 870.71 | 871.15 | 515.9 | 4.45 | 4.50 | 10.56 |
| | 3 | 892.79 | 930.35 | 930.91 | 552.64 | 4.21 | 4.27 | 10.08 |
| | 4 | - | - | - | - | - | - | - |
| | Average (nearest 0.1) | | | | | **4.3** | **4.4** | **10.3** |
| | Standard deviation | | | | | | | **0.25** |

## VPV test at 28 days: SERIES – B (7 days cured)

| Mix ID | No. | Oven dry wt $M_1$ (gm) | SSD wt $M_{2i}$ (gm) | Boiled wt $M_{3b}$ (gm) | Submerged wt $M_{4ib}$ (gm) | Immersed Absorption (%) | Boiled Absorption (%) | AVPV (%) |
|---|---|---|---|---|---|---|---|---|
| **B00** | 1 | 905.85 | 942.92 | 943.02 | 561.84 | 4.09 | 4.10 | 9.75 |
| | 2 | 878.91 | 916.01 | 916.11 | 546.22 | 4.22 | 4.23 | 10.06 |
| | 3 | 843.81 | 883.66 | 883.88 | 522.33 | 4.72 | 4.75 | 11.08 |
| | 4 | 862.53 | 901.31 | 901.57 | 534.81 | 4.50 | 4.53 | 10.64 |
| | Average (nearest 0.1) | | | | | **4.4** | **4.4** | **10.4** |
| | Standard deviation | | | | | | | **0.60** |
| **B30** | 1 | 899.58 | 942.89 | 943.28 | 557.13 | 4.81 | 4.86 | 11.32 |
| | 2 | 825.34 | 865.15 | 865.66 | 510.74 | 4.82 | 4.89 | 11.36 |
| | 3 | 850.73 | 893.55 | 894.1 | 526.84 | 5.03 | 5.10 | 11.81 |
| | 4 | - | - | - | - | - | - | - |
| | Average (nearest 0.1) | | | | | **4.9** | **5.0** | **11.5** |
| | Standard deviation | | | | | | | **0.27** |
| **B40** | 1 | 902.26 | 946.14 | 946.64 | 559.54 | 4.86 | 4.92 | 11.46 |
| | 2 | 831.8 | 873.14 | 873.55 | 516.2 | 4.97 | 5.02 | 11.68 |
| | 3 | 871.06 | 911.37 | 911.78 | 540.48 | 4.63 | 4.67 | 10.97 |
| | 4 | 882 | 922.33 | 922.63 | 548.25 | 4.57 | 4.61 | 10.85 |
| | Average (nearest 0.1) | | | | | **4.8** | **4.8** | **11.2** |
| | Standard deviation | | | | | | | **0.40** |

## VPV test at 180 days: SERIES – A (28 days cured)

| Mix ID | No. | Oven dry wt $M_1$ (gm) | SSD wt $M_{2i}$ (gm) | Boiled wt $M_{3b}$ (gm) | Submerged wt $M_{4ib}$ (gm) | Immersed Absorption (%) | Boiled Absorption (%) | AVPV (%) |
|---|---|---|---|---|---|---|---|---|
| **A00** | 1 | 860.03 | 895.94 | 896.22 | 529.85 | 4.18 | 4.21 | 9.88 |
| | 2 | 891.69 | 929.6 | 929.72 | 550.56 | 4.25 | 4.26 | 10.03 |
| | 3 | 812.67 | 850.09 | 850.44 | 498.59 | 4.60 | 4.65 | 10.73 |
| | 4 | - | - | - | - | - | - | - |
| | Average (nearest 0.1) | | | | | **4.3** | **4.4** | **10.2** |
| | Standard deviation | | | | | | | **0.46** |
| **A30** | 1 | 856.36 | 894.42 | 895.73 | 528.74 | 4.44 | 4.60 | 10.73 |
| | 2 | 875.22 | 909.04 | 910.35 | 541.07 | 3.86 | 4.01 | 9.51 |
| | 3 | 869.55 | 903.23 | 904.47 | 537.85 | 3.87 | 4.02 | 9.52 |
| | 4 | 922.17 | 957.35 | 958.75 | 570.62 | 3.81 | 3.97 | 9.42 |
| | Average (nearest 0.1) | | | | | **4.0** | **4.2** | **9.8** |
| | Standard deviation | | | | | | | **0.62** |
| **A40** | 1 | 904.35 | 941.11 | 941.82 | 561.17 | 4.06 | 4.14 | 9.84 |
| | 2 | 860.6 | 896.22 | 896.98 | 533.24 | 4.14 | 4.23 | 10.00 |
| | 3 | 830.85 | 867.66 | 868.37 | 514.78 | 4.43 | 4.52 | 10.61 |
| | 4 | 932.36 | 970.47 | 971.13 | 576.64 | 4.09 | 4.16 | 9.83 |
| | Average (nearest 0.1) | | | | | **4.2** | **4.3** | **10.1** |
| | Standard deviation | | | | | | | **0.37** |

## VPV test at 180 days: SERIES – B (28 days cured)

| Mix ID | No. | Oven dry wt $M_1$ (gm) | SSD wt $M_{2i}$ (gm) | Boiled wt $M_{3b}$ (gm) | Submerged wt $M_{4ib}$ (gm) | Immersed Absorption (%) | Boiled Absorption (%) | AVPV (%) |
|---|---|---|---|---|---|---|---|---|
| **B00** | 1 | 899.61 | 936.76 | 937.1 | 556.03 | 4.13 | 4.17 | 9.84 |
| | 2 | 869.17 | 904.77 | 905.06 | 538.95 | 4.10 | 4.13 | 9.80 |
| | 3 | 872.9 | 907.81 | 908.13 | 540.93 | 4.00 | 4.04 | 9.59 |
| | 4 | 912.29 | 948.48 | 948.82 | 564.98 | 3.97 | 4.00 | 9.52 |
| | Average (nearest 0.1) | | | | | **4.1** | **4.1** | **9.7** |
| | Standard deviation | | | | | | | **0.16** |
| **B30** | 1 | 898.07 | 936.72 | 937.77 | 557.92 | 4.30 | 4.42 | 10.45 |
| | 2 | 875.14 | 916.12 | 917.03 | 543.3 | 4.68 | 4.79 | 11.21 |
| | 3 | 923.36 | 963.23 | 964.28 | 573.95 | 4.32 | 4.43 | 10.48 |
| | 4 | 781 | 813.23 | 813.99 | 486.97 | 4.13 | 4.22 | 10.09 |
| | Average (nearest 0.1) | | | | | **4.4** | **4.5** | **10.6** |
| | Standard deviation | | | | | | | **0.47** |
| **B40** | 1 | 904.71 | 946.91 | 947.28 | 561.09 | 4.66 | 4.71 | 11.02 |
| | 2 | 848.78 | 888.5 | 888.97 | 526.34 | 4.68 | 4.74 | 11.08 |
| | 3 | 847.8 | 886 | 886.67 | 526.94 | 4.51 | 4.58 | 10.81 |
| | 4 | 881.32 | 917.93 | 918.77 | 548.23 | 4.15 | 4.25 | 10.11 |
| | Average (nearest 0.1) | | | | | **4.5** | **4.6** | **10.8** |
| | Standard deviation | | | | | | | **0.45** |

## VPV test at 180 days: SERIES – A (7 days cured)

| Mix ID | No. | Oven dry wt $M_1$ (gm) | SSD wt $M_{2i}$ (gm) | Boiled wt $M_{3b}$ (gm) | Submerged wt $M_{4ib}$ (gm) | Immersed Absorption (%) | Boiled Absorption (%) | AVPV (%) |
|---|---|---|---|---|---|---|---|---|
| **A00** | 1 | 874.26 | 914.38 | 914.44 | 536.17 | 4.59 | 4.60 | 10.62 |
| | 2 | 923.18 | 962.69 | 962.96 | 568.47 | 4.28 | 4.31 | 10.08 |
| | 3 | 891.35 | 933.02 | 933.23 | 547.69 | 4.67 | 4.70 | 10.86 |
| | 4 | 892.13 | 929.14 | 929.45 | 551.96 | 4.15 | 4.18 | 9.89 |
| | Average (nearest 0.1) | | | | | **4.4** | **4.5** | **10.4** |
| | Standard deviation | | | | | | | **0.46** |
| **A30** | 1 | - | - | - | - | - | - | - |
| | 2 | 904.28 | 942.17 | 942.99 | 559.32 | 4.19 | 4.28 | 10.09 |
| | 3 | 925.93 | 966.56 | 967.54 | 572.05 | 4.39 | 4.49 | 10.52 |
| | 4 | 934.68 | 974.32 | 975.23 | 577.9 | 4.24 | 4.34 | 10.21 |
| | Average (nearest 0.1) | | | | | **4.3** | **4.4** | **10.3** |
| | Standard deviation | | | | | | | **0.22** |
| **A40** | 1 | 917.98 | 957.53 | 958.18 | 568.08 | 4.31 | 4.38 | 10.31 |
| | 2 | 892.58 | 933.41 | 933.57 | 550.71 | 4.57 | 4.59 | 10.71 |
| | 3 | 899.58 | 938.67 | 939.32 | 556.36 | 4.35 | 4.42 | 10.38 |
| | 4 | 926.76 | 964.85 | 965.49 | 574.47 | 4.11 | 4.18 | 9.90 |
| | Average (nearest 0.1) | | | | | **4.3** | **4.4** | **10.3** |
| | Standard deviation | | | | | | | **0.33** |

## VPV test at 180 days: SERIES – B (7 days cured)

| Mix ID | No. | Oven dry wt $M_1$ (gm) | SSD wt $M_{2i}$ (gm) | Boiled wt $M_{3b}$ (gm) | Submerged wt $M_{4ib}$ (gm) | Immersed Absorption (%) | Boiled Absorption (%) | AVPV (%) |
|---|---|---|---|---|---|---|---|---|
| **B00** | 1 | 910.84 | 947.1 | 947.34 | 567.44 | 3.98 | 4.01 | 9.61 |
| | 2 | 927.49 | 968.43 | 968.53 | 574.72 | 4.41 | 4.42 | 10.42 |
| | 3 | 916.64 | 953.65 | 953.87 | 569.19 | 4.04 | 4.06 | 9.68 |
| | 4 | 901.03 | 942.4 | 942.46 | 560.45 | 4.59 | 4.60 | 10.85 |
| | Average (nearest 0.1) | | | | | **4.3** | **4.3** | **10.1** |
| | Standard deviation | | | | | | | **0.60** |
| **B30** | 1 | 923.71 | 964.4 | 964.96 | 573.75 | 4.41 | 4.47 | 10.54 |
| | 2 | 892.4 | 934.8 | 935.1 | 553.32 | 4.75 | 4.78 | 11.18 |
| | 3 | 913.69 | 955 | 955.52 | 567.07 | 4.52 | 4.58 | 10.77 |
| | 4 | - | - | - | - | - | - | - |
| | Average (nearest 0.1) | | | | | **4.6** | **4.6** | **10.8** |
| | Standard deviation | | | | | | | **0.32** |
| **B40** | 1 | 891.41 | 931.43 | 931.74 | 553.14 | 4.49 | 4.52 | 10.65 |
| | 2 | 911.53 | 955.28 | 955.46 | 564.76 | 4.80 | 4.82 | 11.24 |
| | 3 | 920.02 | 960.06 | 960.31 | 570.97 | 4.35 | 4.38 | 10.35 |
| | 4 | 907.51 | 950.65 | 950.85 | 562.14 | 4.75 | 4.78 | 11.15 |
| | Average (nearest 0.1) | | | | | **4.6** | **4.6** | **10.9** |
| | Standard deviation | | | | | | | **0.42** |

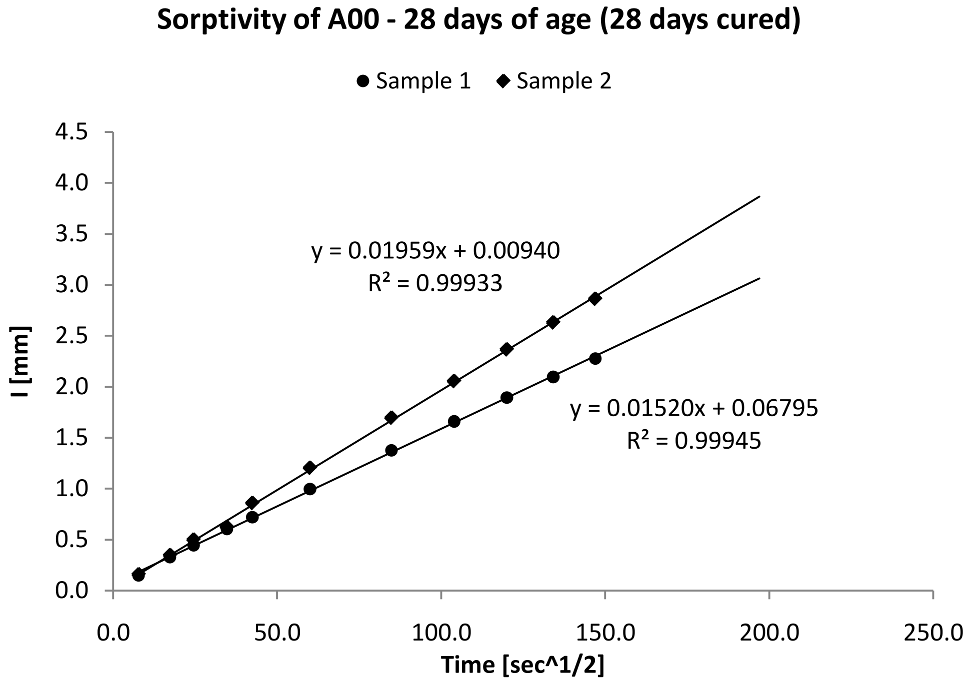
# APPENDIX I: Sorptivity test results

## Sorptivity test at 28 days: SERIES – A

| | | | |
|---|---|---|---|
| Mix ID: | **A00** | Test age: | **28 days** |
| Casting date: | 24/08/2009 | Curing period: | 28 days |

| | Unit | Sample 1 | Sample 2 |
|---|---|---|---|
| Average diameter | mm | 99.775 | 99.85 |
| Average thickness | mm | 49.27 | 49.33 |
| Mass of conditioned specimen | gm | 888.92 | 886.86 |
| Mass after sealing specimen | gm | 891.37 | 889.24 |
| Exposed area | $mm^2$ | 7818.7 | 7830.46 |

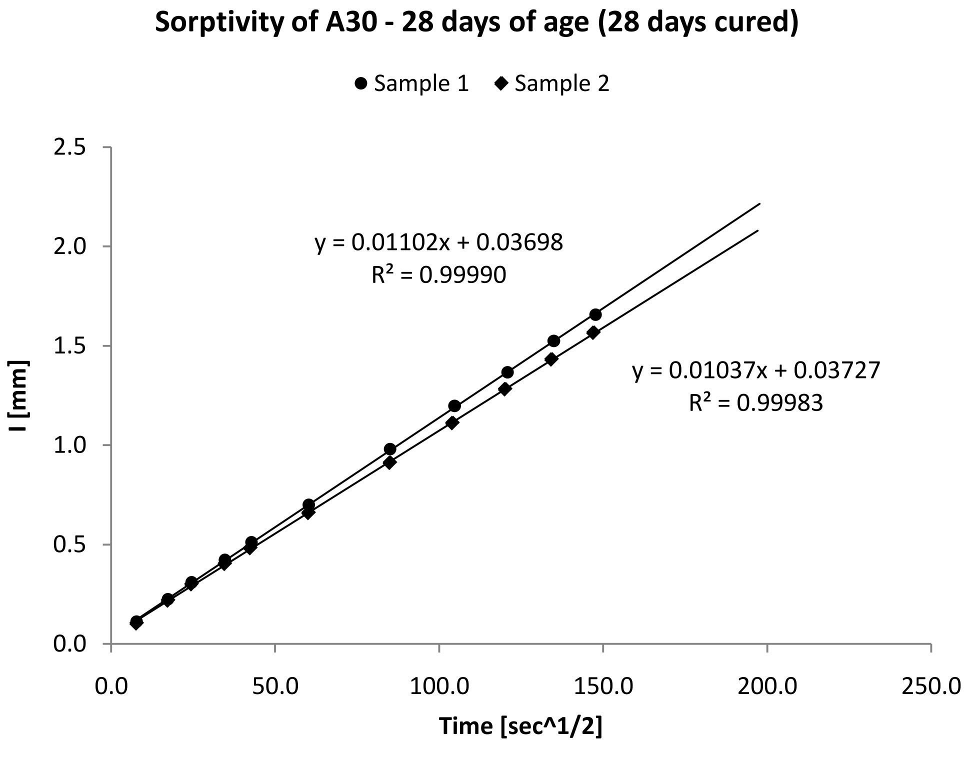
| | Sample 1 | | | | | Sample 2 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Time after initial contact | | $(sec)^{1/2}$ | Mass (gm) | Mass diff. (gm) | Absorp-tion, I | Time (sec) | $(sec)^{1/2}$ | Mass (gm) | Mass diff. (gm) | Absorp-tion, I |
| Interval | (sec) | | | | | | | | | |
| 0 | 0 | 0.0 | 891.37 | 0 | 0 | 0 | 0.0 | 889.24 | 0 | 0 |
| 1 min | 60 | 7.7 | 892.53 | 1.16 | 0.1484 | 60 | 7.7 | 890.49 | 1.25 | 0.1600 |
| 5 min | 300 | 17.3 | 893.92 | 2.55 | 0.3263 | 300 | 17.3 | 891.96 | 2.72 | 0.3481 |
| 10 min | 600 | 24.5 | 894.85 | 3.48 | 0.4453 | 600 | 24.5 | 893.15 | 3.91 | 0.5003 |
| 20 min | 1200 | 34.6 | 896.1 | 4.73 | 0.6053 | 1200 | 34.6 | 894.12 | 4.88 | 0.6245 |
| 30 min | 1800 | 42.4 | 897 | 5.63 | 0.7204 | 1800 | 42.4 | 895.96 | 6.72 | 0.8599 |
| 1 hr | 3600 | 60.0 | 899.16 | 7.79 | 0.9968 | 3600 | 60.0 | 898.66 | 9.42 | 1.2054 |
| 2 hr | 7200 | 84.9 | 902.13 | 10.76 | 1.3769 | 7200 | 84.9 | 902.5 | 13.26 | 1.6968 |
| 3 hr | 10800 | 103.9 | 904.35 | 12.98 | 1.6610 | 10800 | 103.9 | 905.31 | 16.07 | 2.0564 |
| 4 hr | 14400 | 120.0 | 906.18 | 14.81 | 1.8951 | 14400 | 120.0 | 907.74 | 18.5 | 2.3673 |
| 5 hr | 18000 | 134.2 | 907.76 | 16.39 | 2.0973 | 18000 | 134.2 | 909.81 | 20.57 | 2.6322 |
| 6 hr | 21600 | 147.0 | 909.17 | 17.8 | 2.2777 | 21600 | 147.0 | 911.62 | 22.38 | 2.8638 |



| | | | |
|---|---|---|---|
| Mix ID: | **A30** | Test age: | **28 days** |
| Casting date: | 10/08/2009 | Curing period: | 28 days |

| | **Unit** | **Sample 1** | **Sample 2** |
|---|---|---|---|
| Average diameter | mm | 99.63 | 99.475 |
| Average thickness | mm | 50.9 | 49.9 |
| Mass of conditioned specimen | gm | 921.63 | 907.22 |
| Mass after sealing specimen | gm | 924.33 | 909.77 |
| Exposed area | $mm^2$ | 7795.21 | 7771.75 |

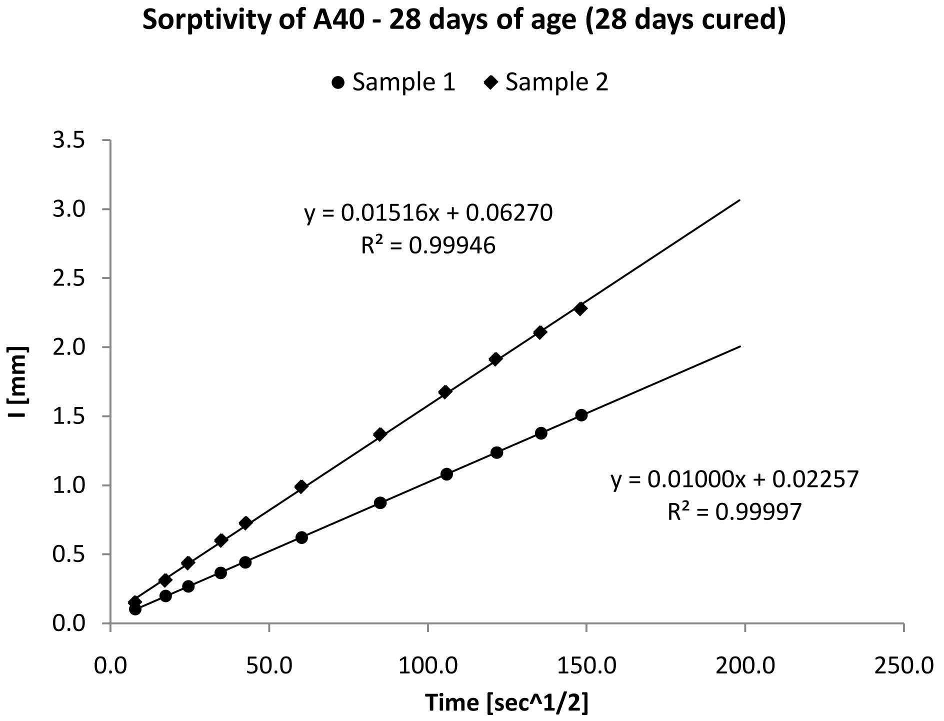
| | **Sample 1** | | | | | **Sample 2** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time after initial contact** | | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** | **Time (sec)** | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** |
| **Interval** | **(sec)** | | | | | | | | | |
| 0 | 0 | 0.0 | 924.33 | 0 | 0 | 0 | 0.0 | 909.77 | 0 | 0 |
| 1 min | 60 | 7.7 | 925.21 | 0.88 | 0.1126 | 60 | 7.7 | 910.58 | 0.81 | 0.1036 |
| 5 min | 300 | 17.3 | 926.09 | 1.76 | 0.2252 | 300 | 17.3 | 911.48 | 1.71 | 0.2188 |
| 10 min | 600 | 24.5 | 926.75 | 2.42 | 0.3097 | 600 | 24.5 | 912.12 | 2.35 | 0.3007 |
| 20 min | 1200 | 34.6 | 927.63 | 3.3 | 0.4223 | 1200 | 34.6 | 912.92 | 3.15 | 0.4031 |
| 30 min | 1830 | 42.8 | 928.33 | 4 | 0.5119 | 1800 | 42.4 | 913.54 | 3.77 | 0.4824 |
| 1 hr | 3630 | 60.2 | 929.8 | 5.47 | 0.7000 | 3620 | 60.2 | 914.92 | 5.15 | 0.6590 |
| 2 hr | 7230 | 85.0 | 931.99 | 7.66 | 0.9802 | 7220 | 85.0 | 916.89 | 7.12 | 0.9111 |
| 3 hr | 10960 | 104.7 | 933.69 | 9.36 | 1.1977 | 10825 | 104.0 | 918.45 | 8.68 | 1.1107 |
| 4 hr | 14610 | 120.9 | 935.01 | 10.68 | 1.3666 | 14425 | 120.1 | 919.78 | 10.01 | 1.2809 |
| 5 hr | 18210 | 134.9 | 936.24 | 11.91 | 1.5240 | 18025 | 134.3 | 920.95 | 11.18 | 1.4306 |
| 6 hr | 21810 | 147.7 | 937.27 | 12.94 | 1.6558 | 21625 | 147.1 | 922 | 12.23 | 1.5650 |



| | | | |
|---|---|---|---|
| Mix ID: | **A40** | Test age: | **28 days** |
| Casting date: | 07/08/2009 | Curing period: | 28 days |

| | **Unit** | **Sample 1** | **Sample 2** |
|---|---|---|---|
| Average diameter | mm | 99.75 | 99.925 |
| Average thickness | mm | 51.15 | 51.15 |
| Mass of conditioned specimen | gm | 919.91 | 942.09 |
| Mass after sealing specimen | gm | 922.47 | 944.68 |
| Exposed area | $mm^2$ | 7814.78 | 7842.22 |

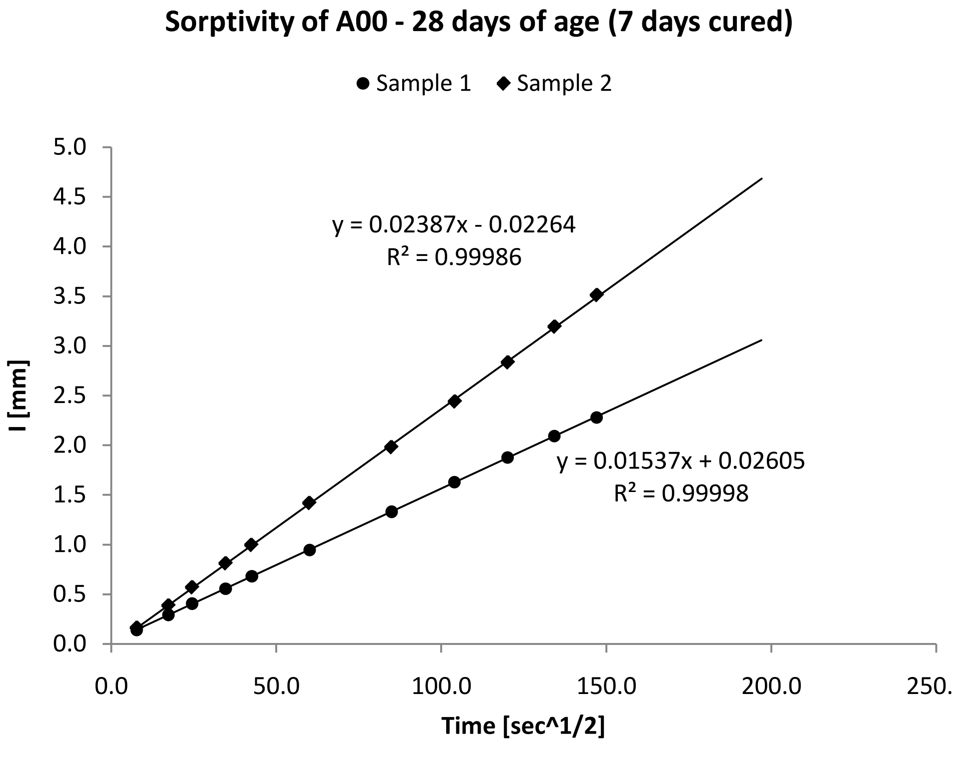
| | **Sample 1** | | | | | **Sample 2** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time after initial contact** | | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** | **Time (sec)** | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** |
| **Interval** | **(sec)** | | | | | | | | | |
| 0 | 0 | 0.0 | 922.47 | 0 | 0 | 0 | 0.0 | 944.68 | 0 | 0 |
| 1 min | 60 | 7.7 | 923.28 | 0.81 | 0.1036 | 60 | 7.7 | 945.86 | 1.18 | 0.1510 |
| 5 min | 300 | 17.3 | 924.02 | 1.55 | 0.1983 | 300 | 17.3 | 947.11 | 2.43 | 0.3109 |
| 10 min | 600 | 24.5 | 924.57 | 2.1 | 0.2687 | 600 | 24.5 | 948.09 | 3.41 | 0.4364 |
| 20 min | 1200 | 34.6 | 925.33 | 2.86 | 0.3660 | 1220 | 34.9 | 949.37 | 4.69 | 0.6001 |
| 30 min | 1800 | 42.4 | 925.92 | 3.45 | 0.4415 | 1820 | 42.7 | 950.35 | 5.67 | 0.7255 |
| 1 hr | 3620 | 60.2 | 927.33 | 4.86 | 0.6219 | 3620 | 60.2 | 952.41 | 7.73 | 0.9892 |
| 2 hr | 7220 | 85.0 | 929.29 | 6.82 | 0.8727 | 7220 | 85.0 | 955.37 | 10.69 | 1.3679 |
| 3 hr | 11210 | 105.9 | 930.92 | 8.45 | 1.0813 | 11125 | 105.5 | 957.77 | 13.09 | 1.6750 |
| 4 hr | 14810 | 121.7 | 932.14 | 9.67 | 1.2374 | 14725 | 121.3 | 959.63 | 14.95 | 1.9130 |
| 5 hr | 18410 | 135.7 | 933.24 | 10.77 | 1.3782 | 18325 | 135.4 | 961.14 | 16.46 | 2.1063 |
| 6 hr | 22010 | 148.4 | 934.26 | 11.79 | 1.5087 | 21925 | 148.1 | 962.48 | 17.8 | 2.2777 |



| | | | |
|---|---|---|---|
| Mix ID: | **A00** | Test age: | **28 days** |
| Casting date: | 24/08/2009 | Curing period: | 7 days |

| | **Unit** | **Sample 1** | **Sample 2** |
|---|---|---|---|
| Average diameter | mm | 99.73 | 99.525 |
| Average thickness | mm | 51.1 | 49.67 |
| Mass of conditioned specimen | gm | 922.22 | 885 |
| Mass after sealing specimen | gm | 924.69 | 889.07 |
| Exposed area | $mm^2$ | 7810.86 | 7779.6 |

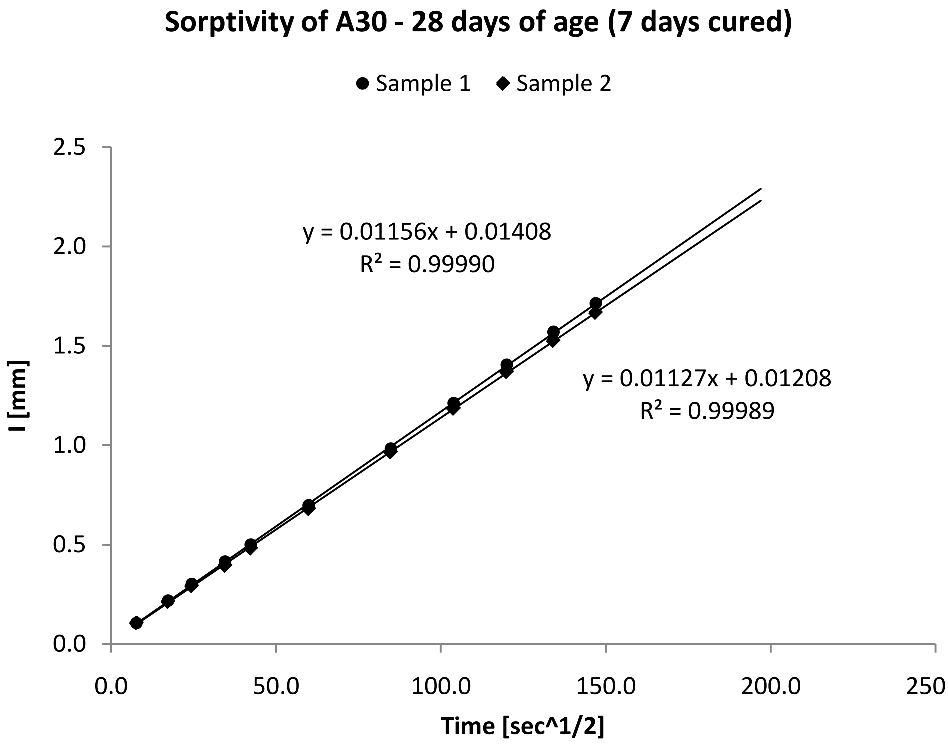
| | **Sample 1** | | | | | **Sample 2** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time after initial contact** | | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** | **Time (sec)** | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** |
| **Interval** | **(sec)** | | | | | | | | | |
| 0 | 0 | 0.0 | 924.69 | 0 | 0 | 0 | 0.0 | 889.07 | 0 | 0 |
| 1 min | 60 | 7.7 | 925.79 | 1.1 | 0.1412 | 60 | 7.7 | 890.34 | 1.27 | 0.1630 |
| 5 min | 300 | 17.3 | 926.98 | 2.29 | 0.2939 | 300 | 17.3 | 892.08 | 3.01 | 0.3863 |
| 10 min | 600 | 24.5 | 927.86 | 3.17 | 0.4069 | 600 | 24.5 | 893.51 | 4.44 | 0.5699 |
| 20 min | 1200 | 34.6 | 929.03 | 4.34 | 0.5570 | 1200 | 34.6 | 895.39 | 6.32 | 0.8112 |
| 30 min | 1815 | 42.6 | 930 | 5.31 | 0.6815 | 1800 | 42.4 | 896.83 | 7.76 | 0.9960 |
| 1 hr | 3615 | 60.1 | 932.07 | 7.38 | 0.9472 | 3600 | 60.0 | 900.12 | 11.05 | 1.4182 |
| 2 hr | 7215 | 84.9 | 935.06 | 10.37 | 1.3310 | 7200 | 84.9 | 904.5 | 15.43 | 1.9804 |
| 3 hr | 10815 | 104.0 | 937.38 | 12.69 | 1.6287 | 10835 | 104.1 | 908.08 | 19.01 | 2.4399 |
| 4 hr | 14415 | 120.1 | 939.31 | 14.62 | 1.8765 | 14435 | 120.1 | 911.15 | 22.08 | 2.8339 |
| 5 hr | 18015 | 134.2 | 940.99 | 16.3 | 2.0921 | 18040 | 134.3 | 913.95 | 24.88 | 3.1933 |
| 6 hr | 21615 | 147.0 | 942.45 | 17.76 | 2.2795 | 21640 | 147.1 | 916.43 | 27.36 | 3.5116 |



| Mix ID: | **A30** | Test age: | **28 days** |
|---|---|---|---|
| Casting date: | 10/08/2009 | Curing period: | 7 days |

| | **Unit** | **Sample 1** | **Sample 2** |
|---|---|---|---|
| Average diameter | mm | 100.15 | 100.025 |
| Average thickness | mm | 51.6 | 50.6 |
| Mass of conditioned specimen | gm | 939.89 | 911.63 |
| Mass after sealing specimen | gm | 942.52 | 914.26 |
| Exposed area | $mm^2$ | 7877.58 | 7857.93 |

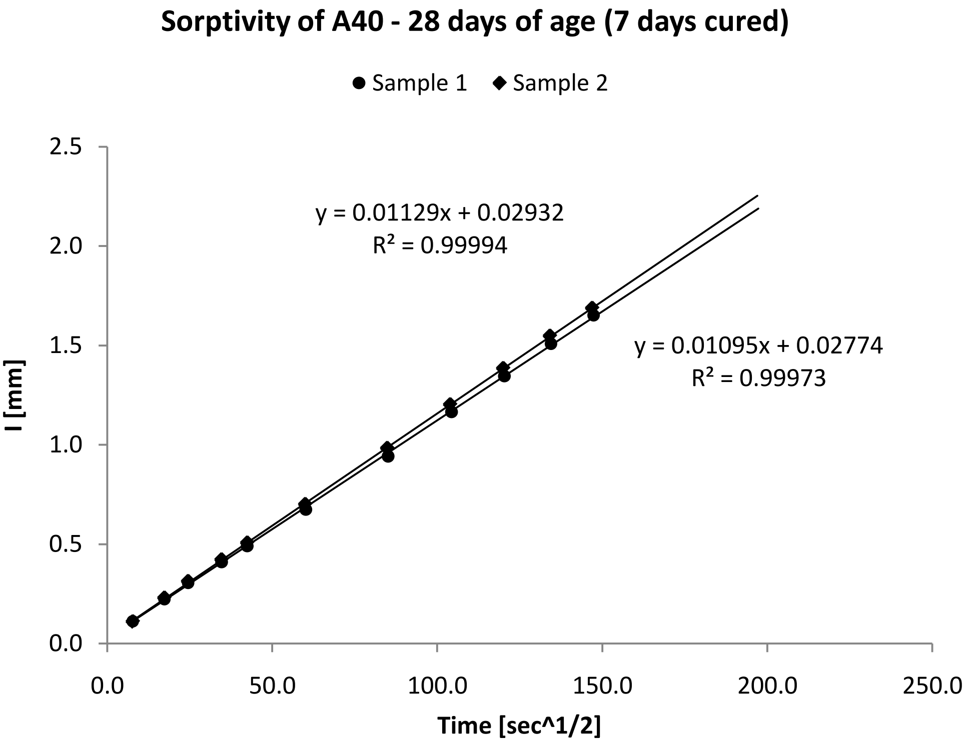
| | **Sample 1** | | | | | **Sample 2** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time after initial contact** | | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorption, I** | **Time (sec)** | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorption, I** |
| **Interval** | **(sec)** | | | | | | | | | |
| 0 | 0 | 0.0 | 942.52 | 0 | 0 | 0 | 0.0 | 914.26 | 0 | 0 |
| 1 min | 60 | 7.7 | 943.35 | 0.83 | 0.1065 | 60 | 7.7 | 915.09 | 0.83 | 0.1065 |
| 5 min | 300 | 17.3 | 944.23 | 1.71 | 0.2195 | 300 | 17.3 | 915.92 | 1.66 | 0.2131 |
| 10 min | 600 | 24.5 | 944.88 | 2.36 | 0.3029 | 600 | 24.5 | 916.54 | 2.28 | 0.2926 |
| 20 min | 1200 | 34.6 | 945.75 | 3.23 | 0.4146 | 1200 | 34.6 | 917.34 | 3.08 | 0.3953 |
| 30 min | 1800 | 42.4 | 946.42 | 3.9 | 0.5006 | 1800 | 42.4 | 918.01 | 3.75 | 0.4813 |
| 1 hr | 3600 | 60.0 | 947.96 | 5.44 | 0.6982 | 3600 | 60.0 | 919.56 | 5.3 | 0.6802 |
| 2 hr | 7200 | 84.9 | 950.19 | 7.67 | 0.9844 | 7200 | 84.9 | 921.78 | 7.52 | 0.9652 |
| 3 hr | 10800 | 103.9 | 951.97 | 9.45 | 1.2129 | 10800 | 103.9 | 923.49 | 9.23 | 1.1847 |
| 4 hr | 14400 | 120.0 | 953.47 | 10.95 | 1.4054 | 14400 | 120.0 | 924.93 | 10.67 | 1.3695 |
| 5 hr | 18000 | 134.2 | 954.76 | 12.24 | 1.5710 | 18000 | 134.2 | 926.15 | 11.89 | 1.5261 |
| 6 hr | 21600 | 147.0 | 955.88 | 13.36 | 1.7147 | 21600 | 147.0 | 927.25 | 12.99 | 1.6672 |



| | | | |
|---|---|---|---|
| Mix ID: | **A40** | Test age: | **28 days** |
| Casting date: | 07/08/2009 | Curing period: | 7 days |

| | **Unit** | **Sample 1** | **Sample 2** |
|---|---|---|---|
| Average diameter | mm | 99.60 | 99.3 |
| Average thickness | mm | 50.4 | 51.7 |
| Mass of conditioned specimen | gm | 910.74 | 915.33 |
| Mass after sealing specimen | gm | 913.35 | 917.82 |
| Exposed area | $mm^2$ | 7791.29 | 7744.43 |

| | **Sample 1** | | | | | **Sample 2** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time after initial contact** | | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** | **Time (sec)** | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** |
| **Interval** | **(sec)** | | | | | | | | | |
| 0 | 0 | 0.0 | 913.35 | 0 | 0 | 0 | 0.0 | 917.82 | 0 | 0 |
| 1 min | 60 | 7.7 | 914.23 | 0.88 | 0.1129 | 60 | 7.7 | 918.68 | 0.86 | 0.1104 |
| 5 min | 300 | 17.3 | 915.1 | 1.75 | 0.2246 | 300 | 17.3 | 919.61 | 1.79 | 0.2297 |
| 10 min | 600 | 24.5 | 915.73 | 2.38 | 0.3055 | 600 | 24.5 | 920.26 | 2.44 | 0.3132 |
| 20 min | 1200 | 34.6 | 916.55 | 3.2 | 0.4107 | 1200 | 34.6 | 921.11 | 3.29 | 0.4223 |
| 30 min | 1800 | 42.4 | 917.17 | 3.82 | 0.4903 | 1800 | 42.4 | 921.77 | 3.95 | 0.5070 |
| 1 hr | 3620 | 60.2 | 918.6 | 5.25 | 0.6738 | 3600 | 60.0 | 923.28 | 5.46 | 0.7008 |
| 2 hr | 7245 | 85.1 | 920.69 | 7.34 | 0.9421 | 7200 | 84.9 | 925.48 | 7.66 | 0.9831 |
| 3 hr | 10880 | 104.3 | 922.43 | 9.08 | 1.1654 | 10800 | 103.9 | 927.19 | 9.37 | 1.2026 |
| 4 hr | 14480 | 120.3 | 923.83 | 10.48 | 1.3451 | 14400 | 120.0 | 928.61 | 10.79 | 1.3849 |
| 5 hr | 18080 | 134.5 | 925.1 | 11.75 | 1.5081 | 18000 | 134.2 | 929.88 | 12.06 | 1.5479 |
| 6 hr | 21705 | 147.3 | 926.21 | 12.86 | 1.6506 | 21600 | 147.0 | 930.97 | 13.15 | 1.6878 |

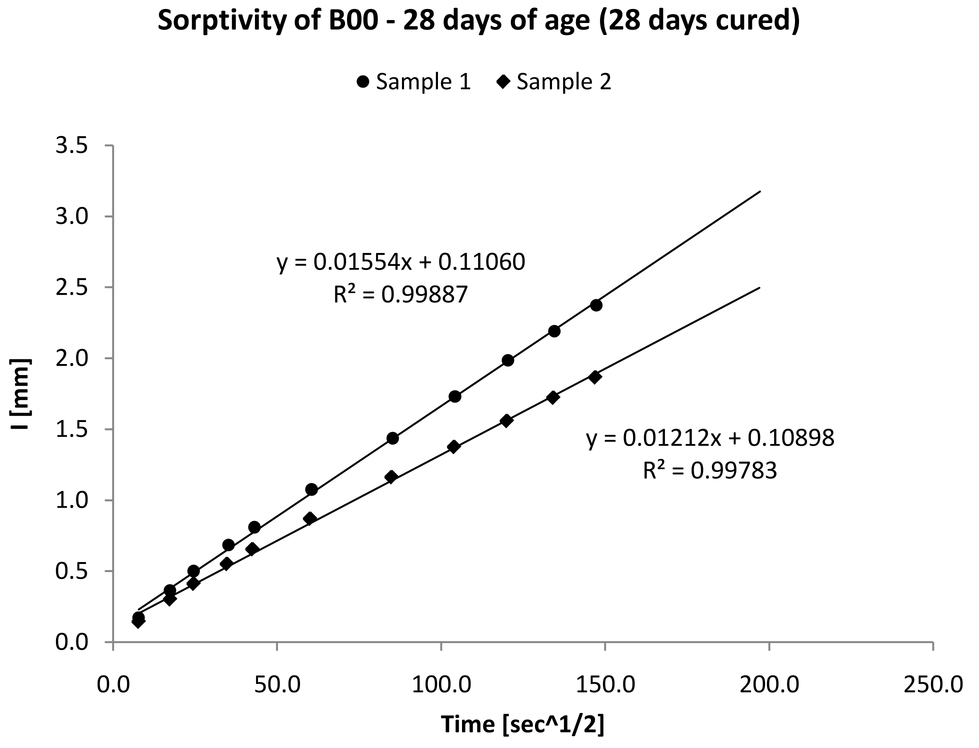


## Sorptivity test at 28 days: SERIES – B

| | | | |
|---|---|---|---|
| Mix ID: | **B00** | Test age: | **28 days** |
| Casting date: | 20/08/2009 | Curing period: | 28 days |

| | Unit | Sample 1 | Sample 2 |
|---|---|---|---|
| Average diameter | mm | 99.8 | 99.55 |
| Average thickness | mm | 49.2 | 49.3 |
| Mass of conditioned specimen | gm | 910.73 | 898.91 |
| Mass after sealing specimen | gm | 913.16 | 901.30 |
| Exposed area | $mm^2$ | 7822.6 | 7783.47 |

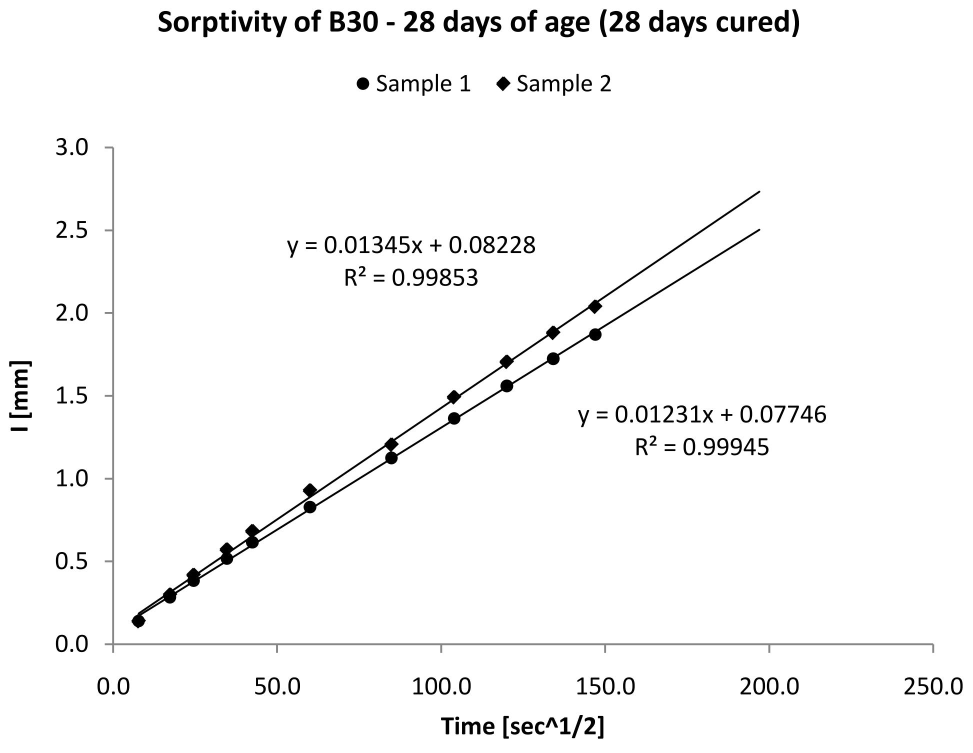
| | Sample 1 | | | | | Sample 2 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Time after initial contact | | $(sec)^{1/2}$ | Mass (gm) | Mass diff. (gm) | Absorption, I | Time (sec) | $(sec)^{1/2}$ | Mass (gm) | Mass diff. (gm) | Absorption, I |
| Interval | (sec) | | | | | | | | | |
| 0 | 0 | 0.0 | 913.16 | 0 | 0 | 0 | 0.0 | 901.3 | 0 | 0 |
| 1 min | 60 | 7.7 | 914.51 | 1.35 | 0.1727 | 60 | 7.7 | 902.42 | 1.12 | 0.1433 |
| 5 min | 300 | 17.3 | 916.01 | 2.85 | 0.3647 | 300 | 17.3 | 903.65 | 2.35 | 0.3007 |
| 10 min | 600 | 24.5 | 917.07 | 3.91 | 0.5003 | 600 | 24.5 | 904.51 | 3.21 | 0.4108 |
| 20 min | 1235 | 35.1 | 918.51 | 5.35 | 0.6846 | 1200 | 34.6 | 905.6 | 4.3 | 0.5502 |
| 30 min | 1855 | 43.1 | 919.49 | 6.33 | 0.8100 | 1800 | 42.4 | 906.41 | 5.11 | 0.6539 |
| 1 hr | 3655 | 60.5 | 921.57 | 8.41 | 1.0762 | 3600 | 60.0 | 908.09 | 6.79 | 0.8689 |
| 2 hr | 7255 | 85.2 | 924.39 | 11.23 | 1.4370 | 7200 | 84.9 | 910.38 | 9.08 | 1.1619 |
| 3 hr | 10855 | 104.2 | 926.69 | 13.53 | 1.7313 | 10800 | 103.9 | 912.04 | 10.74 | 1.3743 |
| 4 hr | 14480 | 120.3 | 928.68 | 15.52 | 1.9860 | 14400 | 120.0 | 913.47 | 12.17 | 1.5573 |
| 5 hr | 18080 | 134.5 | 930.29 | 17.13 | 2.1920 | 18000 | 134.2 | 914.75 | 13.45 | 1.7211 |
| 6 hr | 21680 | 147.2 | 931.71 | 18.55 | 2.3737 | 21600 | 147.0 | 915.87 | 14.57 | 1.8644 |



| | | | |
|---|---|---|---|
| Mix ID: | **B30** | Test age: | **28 days** |
| Casting date: | 17/08/2009 | Curing period: | 28 days |

| | Unit | Sample 1 | Sample 2 |
|---|---|---|---|
| Average diameter | mm | 99.725 | 99.775 |
| Average thickness | mm | 50.23 | 50.67 |
| Mass of conditioned specimen | gm | 911.36 | 918.53 |
| Mass after sealing specimen | gm | 913.95 | 921.01 |
| Exposed area | $mm^2$ | 7810.9 | 7818.70 |

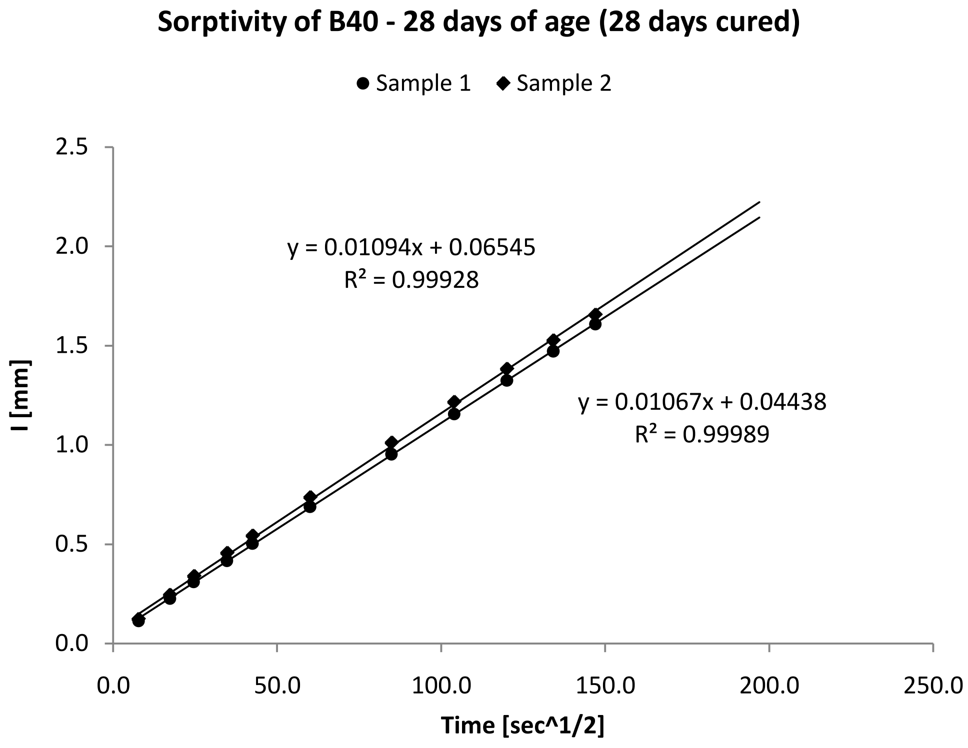
| | **Sample 1** | | | | | **Sample 2** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time after initial contact** | | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorption, I** | **Time (sec)** | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorption, I** |
| **Interval** | **(sec)** | | | | | | | | | |
| 0 | 0 | 0.0 | 913.95 | 0 | 0 | 0 | 0.0 | 921.01 | 0 | 0 |
| 1 min | 60 | 7.7 | 915.05 | 1.1 | 0.1408 | 60 | 7.7 | 922.09 | 1.08 | 0.1382 |
| 5 min | 300 | 17.3 | 916.17 | 2.22 | 0.2841 | 300 | 17.3 | 923.34 | 2.33 | 0.2982 |
| 10 min | 600 | 24.5 | 916.95 | 3 | 0.3839 | 600 | 24.5 | 924.27 | 3.26 | 0.4172 |
| 20 min | 1200 | 34.6 | 917.99 | 4.04 | 0.5170 | 1200 | 34.6 | 925.47 | 4.46 | 0.5707 |
| 30 min | 1800 | 42.4 | 918.76 | 4.81 | 0.6155 | 1800 | 42.4 | 926.34 | 5.33 | 0.6820 |
| 1 hr | 3600 | 60.0 | 920.42 | 6.47 | 0.8279 | 3600 | 60.0 | 928.26 | 7.25 | 0.9277 |
| 2 hr | 7200 | 84.9 | 922.74 | 8.79 | 1.1248 | 7200 | 84.9 | 930.42 | 9.41 | 1.2041 |
| 3 hr | 10800 | 103.9 | 924.61 | 10.66 | 1.3641 | 10800 | 103.9 | 932.66 | 11.65 | 1.4908 |
| 4 hr | 14400 | 120.0 | 926.14 | 12.19 | 1.5599 | 14400 | 120.0 | 934.33 | 13.32 | 1.7045 |
| 5 hr | 18000 | 134.2 | 927.42 | 13.47 | 1.7237 | 18000 | 134.2 | 935.7 | 14.69 | 1.8798 |
| 6 hr | 21600 | 147.0 | 928.56 | 14.61 | 1.8695 | 21600 | 147.0 | 936.93 | 15.92 | 2.0372 |



| | | | |
|---|---|---|---|
| Mix ID: | **B40** | Test age: | **28 days** |
| Casting date: | 13/08/2009 | Curing period: | 28 days |

| | **Unit** | **Sample 1** | **Sample 2** |
|---|---|---|---|
| Average diameter | mm | 99.63 | 99.625 |
| Average thickness | mm | 49.9 | 48.95 |
| Mass of conditioned specimen | gm | 908.26 | 890.07 |
| Mass after sealing specimen | gm | 910.77 | 892.58 |
| Exposed area | $mm^2$ | 7795.21 | 7795.21 |

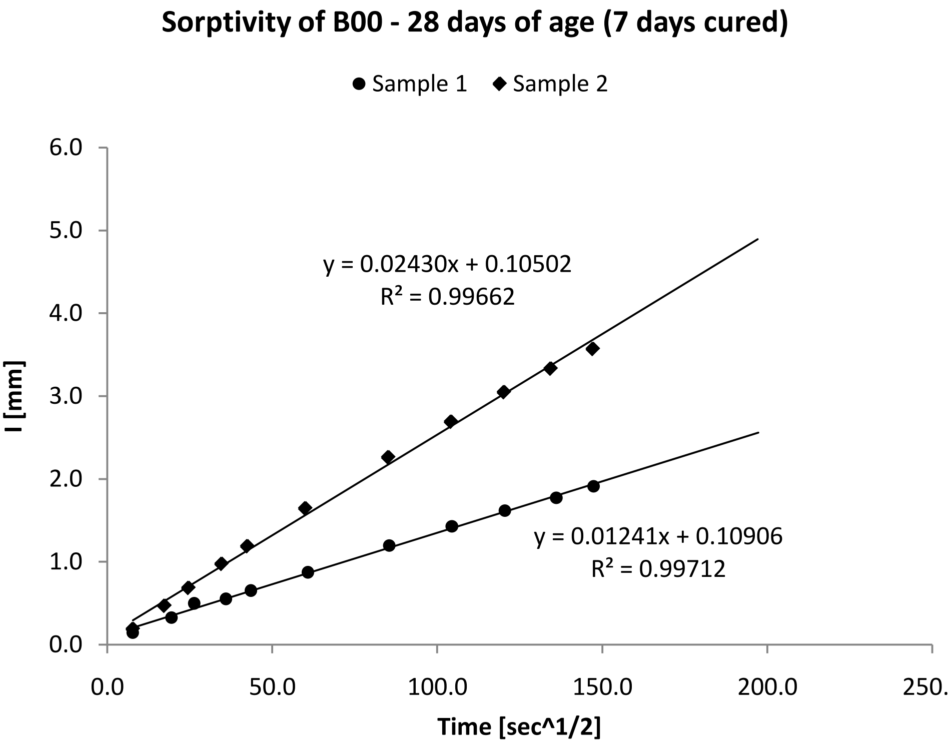
| | **Sample 1** | | | | | **Sample 2** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time after initial contact** | | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** | **Time (sec)** | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** |
| **Interval** | **(sec)** | | | | | | | | | |
| 0 | 0 | 0.0 | 910.77 | 0 | 0 | 0 | 0.0 | 892.58 | 0 | 0 |
| 1 min | 60 | 7.7 | 911.66 | 0.89 | 0.1139 | 60 | 7.7 | 893.54 | 0.96 | 0.1228 |
| 5 min | 300 | 17.3 | 912.54 | 1.77 | 0.2265 | 300 | 17.3 | 894.49 | 1.91 | 0.2444 |
| 10 min | 600 | 24.5 | 913.19 | 2.42 | 0.3097 | 610 | 24.7 | 895.23 | 2.65 | 0.3391 |
| 20 min | 1200 | 34.6 | 914.03 | 3.26 | 0.4172 | 1210 | 34.8 | 896.14 | 3.56 | 0.4555 |
| 30 min | 1800 | 42.4 | 914.7 | 3.93 | 0.5029 | 1810 | 42.5 | 896.82 | 4.24 | 0.5426 |
| 1 hr | 3600 | 60.0 | 916.15 | 5.38 | 0.6884 | 3615 | 60.1 | 898.33 | 5.75 | 0.7358 |
| 2 hr | 7200 | 84.9 | 918.22 | 7.45 | 0.9533 | 7215 | 84.9 | 900.48 | 7.9 | 1.0109 |
| 3 hr | 10800 | 103.9 | 919.8 | 9.03 | 1.1555 | 10815 | 104.0 | 902.08 | 9.5 | 1.2156 |
| 4 hr | 14400 | 120.0 | 921.12 | 10.35 | 1.3244 | 14415 | 120.1 | 903.38 | 10.8 | 1.3820 |
| 5 hr | 18000 | 134.2 | 922.27 | 11.5 | 1.4716 | 18015 | 134.2 | 904.5 | 11.92 | 1.5253 |
| 6 hr | 21600 | 147.0 | 923.33 | 12.56 | 1.6072 | 21615 | 147.0 | 905.51 | 12.93 | 1.6546 |



| | | | |
|---|---|---|---|
| Mix ID: | **B00** | Test age: | **28 days** |
| Casting date: | 20/08/2009 | Curing period: | 7 days |

| | **Unit** | **Sample 1** | **Sample 2** |
|---|---|---|---|
| Average diameter | mm | 99.85 | 99.6 |
| Average thickness | mm | 49.77 | 51.43 |
| Mass of conditioned specimen | gm | 910.27 | 938.08 |
| Mass after sealing specimen | gm | 912.66 | 942.22 |
| Exposed area | $mm^2$ | 7830.46 | 7791.3 |

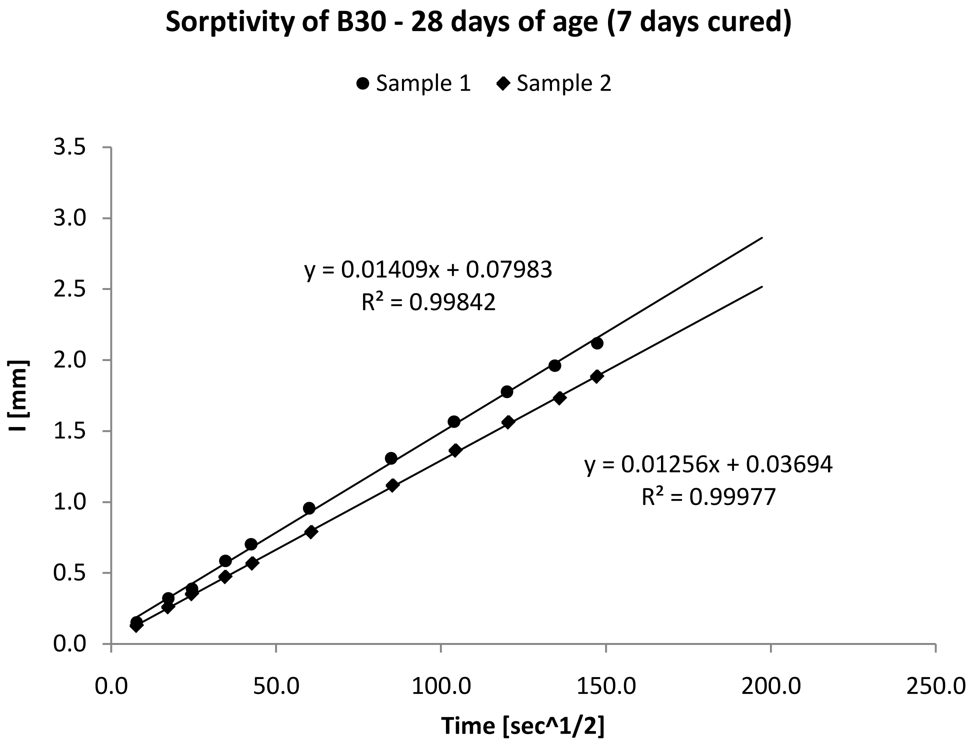
| | **Sample 1** | | | | | **Sample 2** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time after initial contact** | | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorption, I** | **Time (sec)** | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorption, I** |
| **Interval** | **(sec)** | | | | | | | | | |
| 0 | 0 | 0.0 | 912.66 | 0 | 0 | 0 | 0.0 | 942.22 | 0 | 0 |
| 1 min | 60 | 7.7 | 913.8 | 1.14 | 0.1463 | 60 | 7.7 | 943.7 | 1.48 | 0.1900 |
| 5 min | 380 | 19.5 | 915.21 | 2.55 | 0.3273 | 300 | 17.3 | 945.88 | 3.66 | 0.4698 |
| 10 min | 695 | 26.4 | 916.55 | 3.89 | 0.4993 | 605 | 24.6 | 947.56 | 5.34 | 0.6854 |
| 20 min | 1295 | 36.0 | 916.97 | 4.31 | 0.5532 | 1200 | 34.6 | 949.82 | 7.6 | 0.9754 |
| 30 min | 1895 | 43.5 | 917.75 | 5.09 | 0.6533 | 1800 | 42.4 | 951.48 | 9.26 | 1.1885 |
| 1 hr | 3695 | 60.8 | 919.47 | 6.81 | 0.8741 | 3600 | 60.0 | 955.04 | 12.82 | 1.6454 |
| 2 hr | 7305 | 85.5 | 921.98 | 9.32 | 1.1962 | 7250 | 85.1 | 959.84 | 17.62 | 2.2615 |
| 3 hr | 10905 | 104.4 | 923.79 | 11.13 | 1.4285 | 10850 | 104.2 | 963.18 | 20.96 | 2.6902 |
| 4 hr | 14505 | 120.4 | 925.26 | 12.6 | 1.6172 | 14450 | 120.2 | 965.96 | 23.74 | 3.0470 |
| 5 hr | 18505 | 136.0 | 926.47 | 13.81 | 1.7725 | 18050 | 134.4 | 968.17 | 25.95 | 3.3306 |
| 6 hr | 21705 | 147.3 | 927.54 | 14.88 | 1.9098 | 21650 | 147.1 | 970.02 | 27.8 | 3.5681 |



| | | | |
|---|---|---|---|
| Mix ID: | **B30** | Test age: | **28 days** |
| Casting date: | 17/08/2009 | Curing period: | 7 days |

| | **Unit** | **Sample 1** | **Sample 2** |
|---|---|---|---|
| Average diameter | mm | 99.55 | 99.875 |
| Average thickness | mm | 48.83 | 50 |
| Mass of conditioned specimen | gm | 881.06 | 911.93 |
| Mass after sealing specimen | gm | 883.54 | 914.42 |
| Exposed area | $mm^2$ | 7783.47 | 7834.4 |

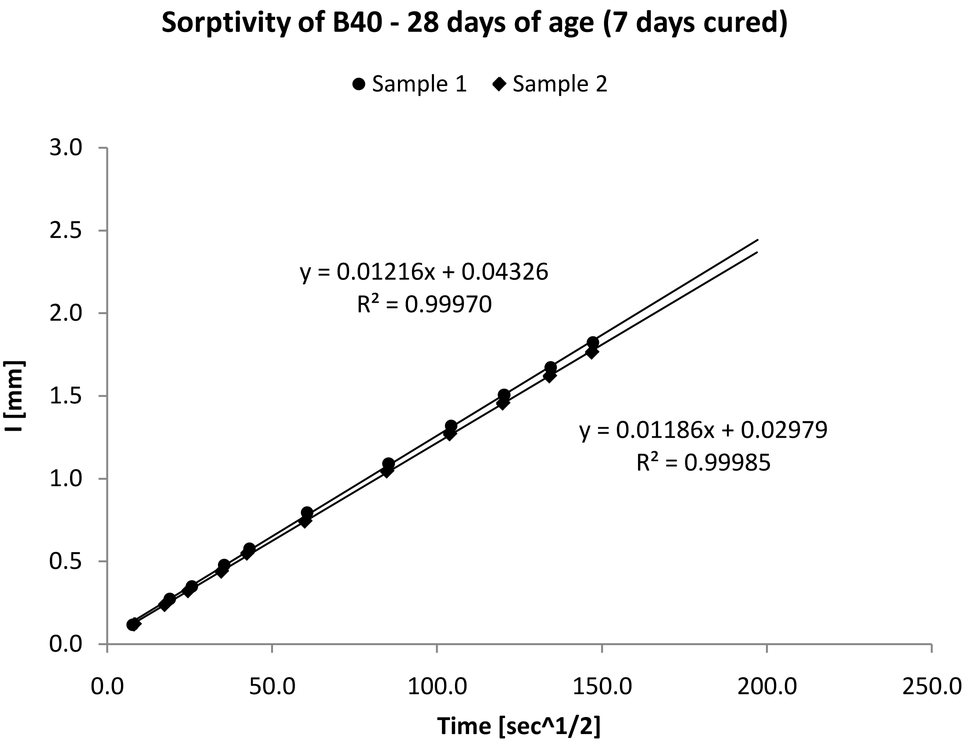
| | **Sample 1** | | | | | **Sample 2** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time after initial contact** | | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorption, I** | **Time (sec)** | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorption, I** |
| **Interval** | **(sec)** | | | | | | | | | |
| 0 | 0 | 0.0 | 883.54 | 0 | 0 | 0 | 0.0 | 914.42 | 0 | 0 |
| 1 min | 60 | 7.7 | 884.73 | 1.19 | 0.1527 | 60 | 7.7 | 915.42 | 1 | 0.1283 |
| 5 min | 300 | 17.3 | 886.04 | 2.5 | 0.3209 | 300 | 17.3 | 916.44 | 2.02 | 0.2593 |
| 10 min | 600 | 24.5 | 886.56 | 3.02 | 0.3876 | 600 | 24.5 | 917.16 | 2.74 | 0.3517 |
| 20 min | 1200 | 34.6 | 888.1 | 4.56 | 0.5853 | 1200 | 34.6 | 918.1 | 3.68 | 0.4723 |
| 30 min | 1800 | 42.4 | 889.01 | 5.47 | 0.7021 | 1835 | 42.8 | 918.84 | 4.42 | 0.5673 |
| 1 hr | 3600 | 60.0 | 890.99 | 7.45 | 0.9562 | 3685 | 60.7 | 920.56 | 6.14 | 0.7881 |
| 2 hr | 7200 | 84.9 | 893.73 | 10.19 | 1.3079 | 7295 | 85.4 | 923.12 | 8.7 | 1.1166 |
| 3 hr | 10800 | 103.9 | 895.74 | 12.2 | 1.5659 | 10910 | 104.5 | 925.04 | 10.62 | 1.3631 |
| 4 hr | 14400 | 120.0 | 897.38 | 13.84 | 1.7763 | 14510 | 120.5 | 926.59 | 12.17 | 1.5620 |
| 5 hr | 18095 | 134.5 | 898.81 | 15.27 | 1.9599 | 18510 | 136.1 | 927.91 | 13.49 | 1.7314 |
| 6 hr | 21710 | 147.3 | 900.04 | 16.5 | 2.1177 | 21710 | 147.3 | 929.1 | 14.68 | 1.8842 |



| | | | |
|---|---|---|---|
| Mix ID: | **B40** | Test age: | **28 days** |
| Casting date: | 13/08/2009 | Curing period: | 7 days |

| | **Unit** | **Sample 1** | **Sample 2** |
|---|---|---|---|
| Average diameter | mm | 99.43 | 99.45 |
| Average thickness | mm | 48.4 | 51.16 |
| Mass of conditioned specimen | gm | 883.35 | 922.67 |
| Mass after sealing specimen | gm | 885.98 | 925.29 |
| Exposed area | $mm^2$ | 7763.94 | 7767.84 |

| | **Sample 1** | | | | | **Sample 2** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time after initial contact** | | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** | **Time (sec)** | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** |
| **Interval** | **(sec)** | | | | | | | | | |
| 0 | 0 | 0.0 | 885.98 | 0 | 0 | 0 | 0.0 | 925.29 | 0 | 0 |
| 1 min | 60 | 7.7 | 886.9 | 0.92 | 0.1181 | 70 | 8.4 | 926.22 | 0.93 | 0.1194 |
| 5 min | 360 | 19.0 | 888.12 | 2.14 | 0.2747 | 310 | 17.6 | 927.14 | 1.85 | 0.2374 |
| 10 min | 660 | 25.7 | 888.7 | 2.72 | 0.3491 | 610 | 24.7 | 927.79 | 2.5 | 0.3209 |
| 20 min | 1260 | 35.5 | 889.71 | 3.73 | 0.4787 | 1210 | 34.8 | 928.71 | 3.42 | 0.4390 |
| 30 min | 1860 | 43.1 | 890.47 | 4.49 | 0.5763 | 1810 | 42.5 | 929.56 | 4.27 | 0.5480 |
| 1 hr | 3675 | 60.6 | 892.18 | 6.2 | 0.7958 | 3610 | 60.1 | 931.07 | 5.78 | 0.7419 |
| 2 hr | 7275 | 85.3 | 894.48 | 8.5 | 1.0910 | 7210 | 84.9 | 933.43 | 8.14 | 1.0448 |
| 3 hr | 10875 | 104.3 | 896.26 | 10.28 | 1.3194 | 10810 | 104.0 | 935.18 | 9.89 | 1.2694 |
| 4 hr | 14475 | 120.3 | 897.72 | 11.74 | 1.5068 | 14410 | 120.0 | 936.63 | 11.34 | 1.4555 |
| 5 hr | 18075 | 134.4 | 899 | 13.02 | 1.6711 | 18010 | 134.2 | 937.91 | 12.62 | 1.6198 |
| 6 hr | 21675 | 147.2 | 900.18 | 14.2 | 1.8225 | 21610 | 147.0 | 939.03 | 13.74 | 1.7635 |

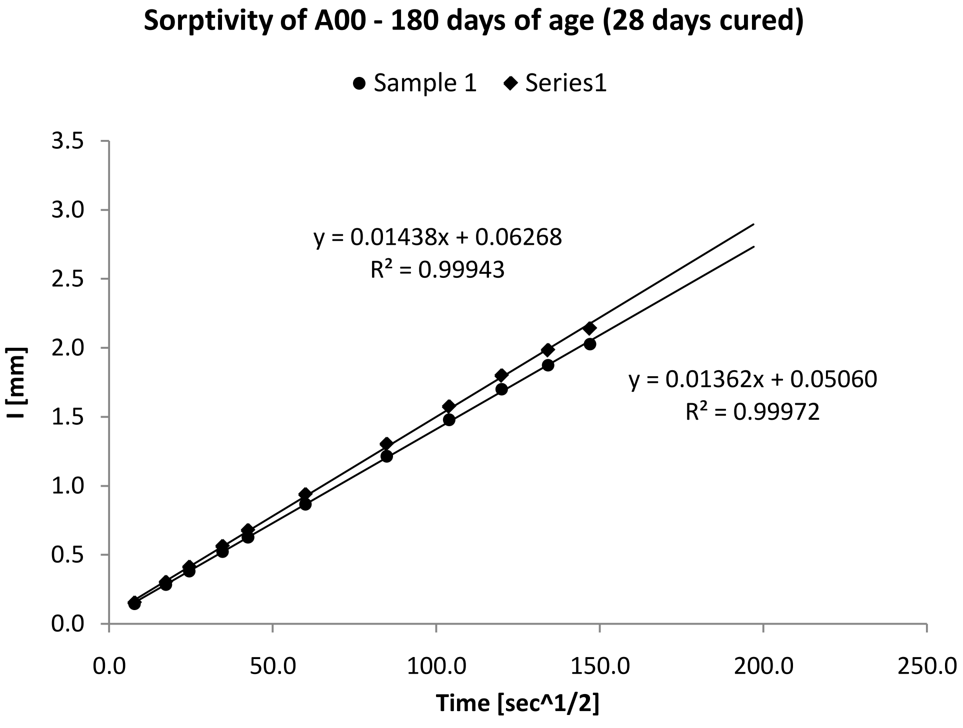


## Sorptivity test at 180 days: SERIES – A

| | | | |
|---|---|---|---|
| Mix ID: | **A00** | Test age: | **180 days** |
| Casting date: | 10/08/2009 | Curing period: | 28 days |

| | **Unit** | **Sample 1** | **Sample 2** |
|---|---|---|---|
| Average diameter | mm | 99.75 | 99.875 |
| Average thickness | mm | 50.6 | 51 |
| Mass of conditioned specimen | gm | 900.64 | 916.11 |
| Mass after sealing specimen | gm | 903.96 | 918.72 |
| Exposed area | $mm^2$ | 7814.78 | 7834.38 |

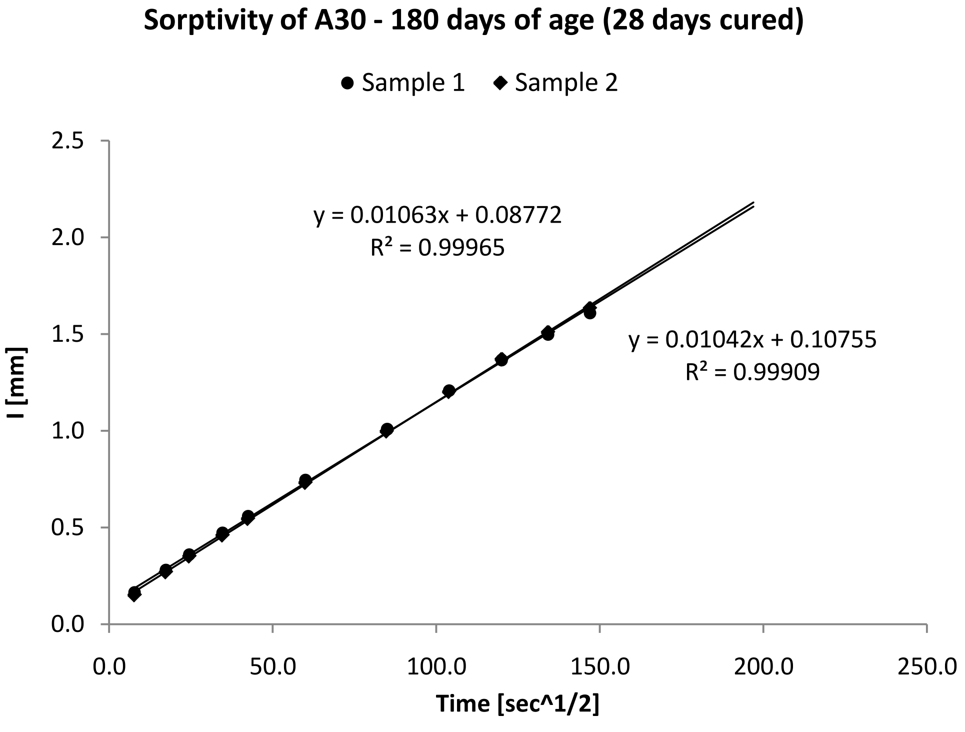
| | **Sample 1** | | | | | **Sample 2** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time after initial contact** | | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorption, I** | **Time (sec)** | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorption, I** |
| **Interval** | **(sec)** | | | | | | | | | |
| 0 | 0 | 0.0 | 903.96 | 0 | 0 | 0 | 0.0 | 918.72 | 0 | 0 |
| 1 min | 60 | 7.7 | 905.11 | 1.15 | 0.1469 | 60 | 7.7 | 919.92 | 1.2 | 0.1532 |
| 5 min | 300 | 17.3 | 906.19 | 2.23 | 0.2848 | 300 | 17.3 | 921.09 | 2.37 | 0.3027 |
| 10 min | 600 | 24.5 | 906.96 | 3 | 0.3831 | 600 | 24.5 | 921.95 | 3.23 | 0.4125 |
| 20 min | 1200 | 34.6 | 908.06 | 4.1 | 0.5236 | 1200 | 34.6 | 923.13 | 4.41 | 0.5632 |
| 30 min | 1800 | 42.4 | 908.88 | 4.92 | 0.6283 | 1800 | 42.4 | 924.03 | 5.31 | 0.6781 |
| 1 hr | 3600 | 60.0 | 910.76 | 6.8 | 0.8684 | 3600 | 60.0 | 926.07 | 7.35 | 0.9386 |
| 2 hr | 7200 | 84.9 | 913.48 | 9.52 | 1.2158 | 7200 | 84.9 | 928.93 | 10.21 | 1.3039 |
| 3 hr | 10800 | 103.9 | 915.55 | 11.59 | 1.4801 | 10800 | 103.9 | 931.06 | 12.34 | 1.5759 |
| 4 hr | 14400 | 120.0 | 917.29 | 13.33 | 1.7023 | 14400 | 120.0 | 932.82 | 14.1 | 1.8007 |
| 5 hr | 18000 | 134.2 | 918.65 | 14.69 | 1.8760 | 18000 | 134.2 | 934.26 | 15.54 | 1.9846 |
| 6 hr | 21610 | 147.0 | 919.84 | 15.88 | 2.0280 | 21600 | 147.0 | 935.49 | 16.77 | 2.1416 |



| | | | |
|---|---|---|---|
| Mix ID: | **A30** | Test age: | **180 days** |
| Casting date: | 10/08/2009 | Curing period: | 28 days |

| | **Unit** | **Sample 1** | **Sample 2** |
|---|---|---|---|
| Average diameter | mm | 99.9 | 99.8 |
| Average thickness | mm | 46.2 | 47.5 |
| Mass of conditioned specimen | gm | 835.29 | 859.00 |
| Mass after sealing specimen | gm | 837.72 | 861.40 |
| Exposed area | $mm^2$ | 7838.30 | 7822.62 |

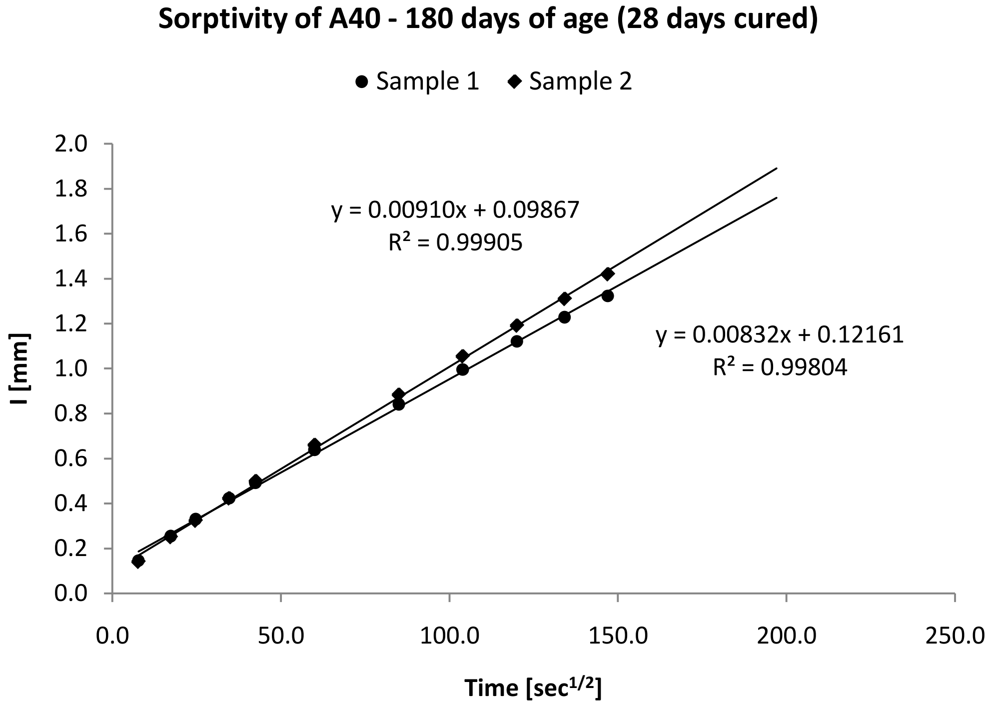
| | **Sample 1** | | | | | **Sample 2** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time after initial contact** | | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** | **Time (sec)** | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** |
| **Interval** | **(sec)** | | | | | | | | | |
| 0 | 0 | 0.0 | 837.72 | 0 | 0 | 0 | 0.0 | 861.4 | 0 | 0 |
| 1 min | 60 | 7.7 | 839.01 | 1.29 | 0.1647 | 60 | 7.7 | 862.58 | 1.18 | 0.1507 |
| 5 min | 300 | 17.3 | 839.92 | 2.2 | 0.2810 | 300 | 17.3 | 863.51 | 2.11 | 0.2695 |
| 10 min | 600 | 24.5 | 840.54 | 2.82 | 0.3601 | 600 | 24.5 | 864.15 | 2.75 | 0.3512 |
| 20 min | 1200 | 34.6 | 841.42 | 3.7 | 0.4725 | 1200 | 34.6 | 865 | 3.6 | 0.4597 |
| 30 min | 1805 | 42.5 | 842.1 | 4.38 | 0.5594 | 1800 | 42.4 | 865.67 | 4.27 | 0.5453 |
| 1 hr | 3600 | 60.0 | 843.56 | 5.84 | 0.7458 | 3600 | 60.0 | 867.13 | 5.73 | 0.7318 |
| 2 hr | 7225 | 85.0 | 845.62 | 7.9 | 1.0089 | 7200 | 84.9 | 869.21 | 7.81 | 0.9974 |
| 3 hr | 10800 | 103.9 | 847.18 | 9.46 | 1.2081 | 10800 | 103.9 | 870.81 | 9.41 | 1.2017 |
| 4 hr | 14400 | 120.0 | 848.42 | 10.7 | 1.3665 | 14400 | 120.0 | 872.13 | 10.73 | 1.3703 |
| 5 hr | 18000 | 134.2 | 849.45 | 11.73 | 1.4980 | 18000 | 134.2 | 873.22 | 11.82 | 1.5095 |
| 6 hr | 21600 | 147.0 | 850.32 | 12.6 | 1.6091 | 21600 | 147.0 | 874.19 | 12.79 | 1.6334 |



| | | | |
|---|---|---|---|
| Mix ID: | **A40** | Test age: | **180 days** |
| Casting date: | 7/08/2009 | Curing period: | 28 days |

| | **Unit** | **Sample 1** | **Sample 2** |
|---|---|---|---|
| Average diameter | mm | 99.85 | 99.7 |
| Average thickness | mm | 46.5 | 46.9 |
| Mass of conditioned specimen | gm | 871.03 | 852.52 |
| Mass after sealing specimen | gm | 873.78 | 855.04 |
| Exposed area | $mm^2$ | 7830.456 | 7806.9 |

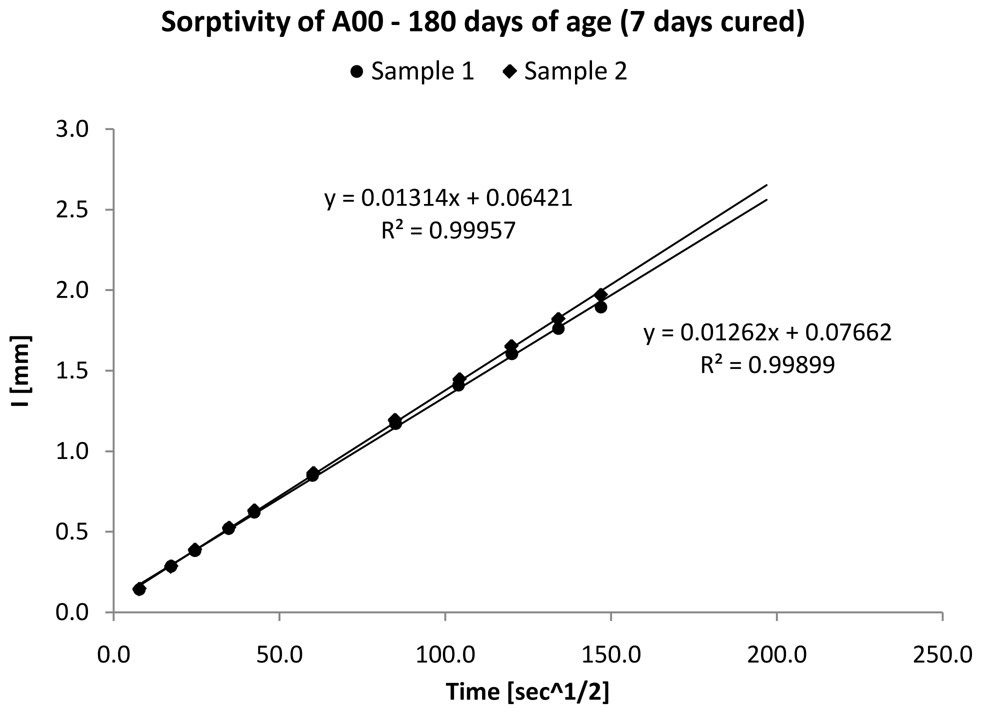
| | **Sample 1** | | | | | **Sample 2** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time after initial contact** | | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** | **Time (sec)** | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** |
| **Interval** | **(sec)** | | | | | | | | | |
| 0 | 0 | 0.0 | 873.78 | 0 | 0 | 0 | 0.0 | 855.04 | 0 | 0 |
| 1 min | 60 | 7.7 | 874.93 | 1.15 | 0.1469 | 60 | 7.7 | 856.14 | 1.1 | 0.1405 |
| 5 min | 300 | 17.3 | 875.78 | 2.00 | 0.2554 | 300 | 17.3 | 857.00 | 1.96 | 0.2503 |
| 10 min | 610 | 24.7 | 876.37 | 2.59 | 0.3308 | 610 | 24.7 | 857.57 | 2.53 | 0.3231 |
| 20 min | 1200 | 34.6 | 877.10 | 3.32 | 0.4240 | 1200 | 34.6 | 858.35 | 3.31 | 0.4227 |
| 30 min | 1800 | 42.4 | 877.64 | 3.86 | 0.4929 | 1810 | 42.5 | 858.95 | 3.91 | 0.4993 |
| 1 hr | 3600 | 60.0 | 878.79 | 5.01 | 0.6398 | 3600 | 60.0 | 860.21 | 5.17 | 0.6602 |
| 2 hr | 7220 | 85.0 | 880.37 | 6.59 | 0.8416 | 7220 | 85.0 | 861.96 | 6.92 | 0.8837 |
| 3 hr | 10800 | 103.9 | 881.58 | 7.80 | 0.9961 | 10800 | 103.9 | 863.30 | 8.26 | 1.0549 |
| 4 hr | 14400 | 120.0 | 882.56 | 8.78 | 1.1213 | 14400 | 120.0 | 864.37 | 9.33 | 1.1915 |
| 5 hr | 18000 | 134.2 | 883.40 | 9.62 | 1.2285 | 18000 | 134.2 | 865.30 | 10.26 | 1.3103 |
| 6 hr | 21600 | 147.0 | 884.14 | 10.36 | 1.3230 | 21600 | 147.0 | 866.16 | 11.12 | 1.4201 |



| | | | |
|---|---|---|---|
| Mix ID: | **A00** | Test age: | **180 days** |
| Casting date: | 24/08/2009 | Curing period: | 7 days |

| | **Unit** | **Sample 1** | **Sample 2** |
|---|---|---|---|
| Average diameter | mm | 99.93 | 99.925 |
| Average thickness | mm | 49.3 | 46.7 |
| Mass of conditioned specimen | gm | 894.14 | 847.06 |
| Mass after sealing specimen | gm | 896.9 | 849.66 |
| Exposed area | $mm^2$ | 7842.22 | 7842.22 |

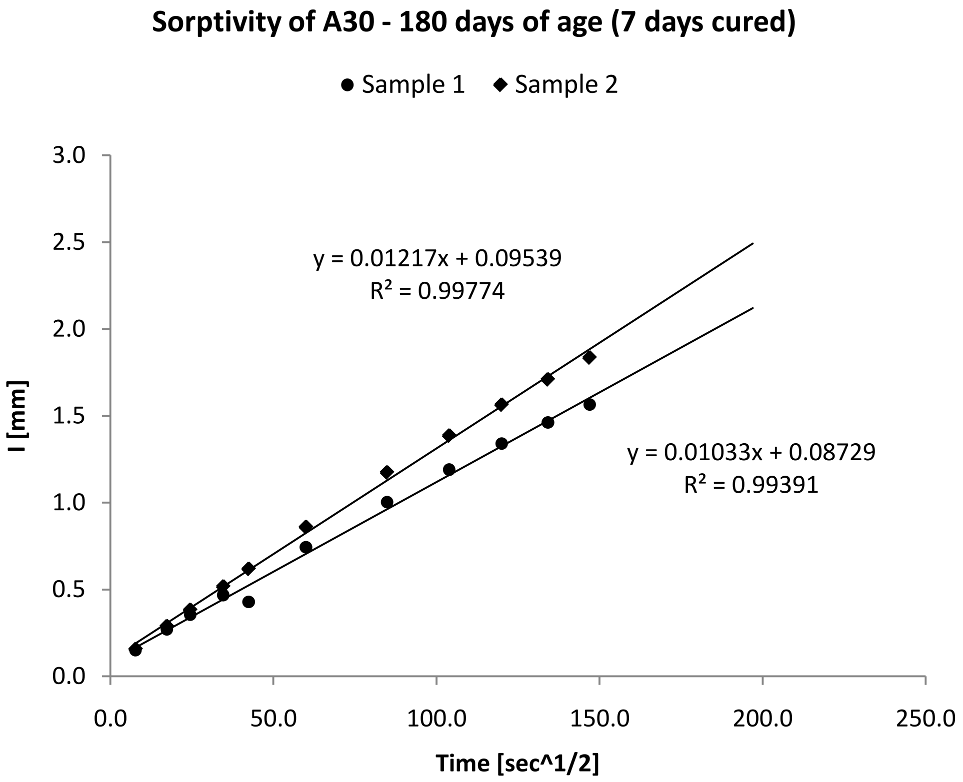
| | **Sample 1** | | | | | **Sample 2** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time after initial contact** | | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorption, I** | **Time (sec)** | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorption, I** |
| **Interval** | **(sec)** | | | | | | | | | |
| 0 | 0 | 0.0 | 896.9 | 0 | 0 | 0 | 0.0 | 849.66 | 0 | 0 |
| 1 min | 60 | 7.7 | 898.03 | 1.13 | 0.1434 | 60 | 7.7 | 850.8 | 1.14 | 0.1446 |
| 5 min | 300 | 17.3 | 899.16 | 2.26 | 0.2867 | 300 | 17.3 | 851.9 | 2.24 | 0.2842 |
| 10 min | 600 | 24.5 | 899.92 | 3.02 | 0.3832 | 600 | 24.5 | 852.72 | 3.06 | 0.3883 |
| 20 min | 1200 | 34.6 | 901.01 | 4.11 | 0.5215 | 1210 | 34.8 | 853.79 | 4.13 | 0.5240 |
| 30 min | 1800 | 42.4 | 901.8 | 4.9 | 0.6217 | 1800 | 42.4 | 854.64 | 4.98 | 0.6319 |
| 1 hr | 3600 | 60.0 | 903.6 | 6.7 | 0.8501 | 3630 | 60.2 | 856.47 | 6.81 | 0.8640 |
| 2 hr | 7230 | 85.0 | 906.14 | 9.24 | 1.1724 | 7200 | 84.9 | 859.07 | 9.41 | 1.1939 |
| 3 hr | 10825 | 104.0 | 908.01 | 11.11 | 1.4096 | 10890 | 104.4 | 861.06 | 11.4 | 1.4464 |
| 4 hr | 14425 | 120.1 | 909.55 | 12.65 | 1.6050 | 14400 | 120.0 | 862.68 | 13.02 | 1.6520 |
| 5 hr | 18000 | 134.2 | 910.78 | 13.88 | 1.7611 | 18000 | 134.2 | 864.01 | 14.35 | 1.8207 |
| 6 hr | 21600 | 147.0 | 911.83 | 14.93 | 1.8943 | 21600 | 147.0 | 865.19 | 15.53 | 1.9704 |



| | | | |
|---|---|---|---|
| Mix ID: | **A30** | Test age: | **180 days** |
| Casting date: | 10/08/2009 | Curing period: | 7 days |

| | **Unit** | **Sample 1** | **Sample 2** |
|---|---|---|---|
| Average diameter | mm | 99.93 | 99.85 |
| Average thickness | mm | 44.9 | 49 |
| Mass of conditioned specimen | gm | 825.59 | 895.13 |
| Mass after sealing specimen | gm | 828.01 | 897.57 |
| Exposed area | $mm^2$ | 7842.22 | 7830.46 |

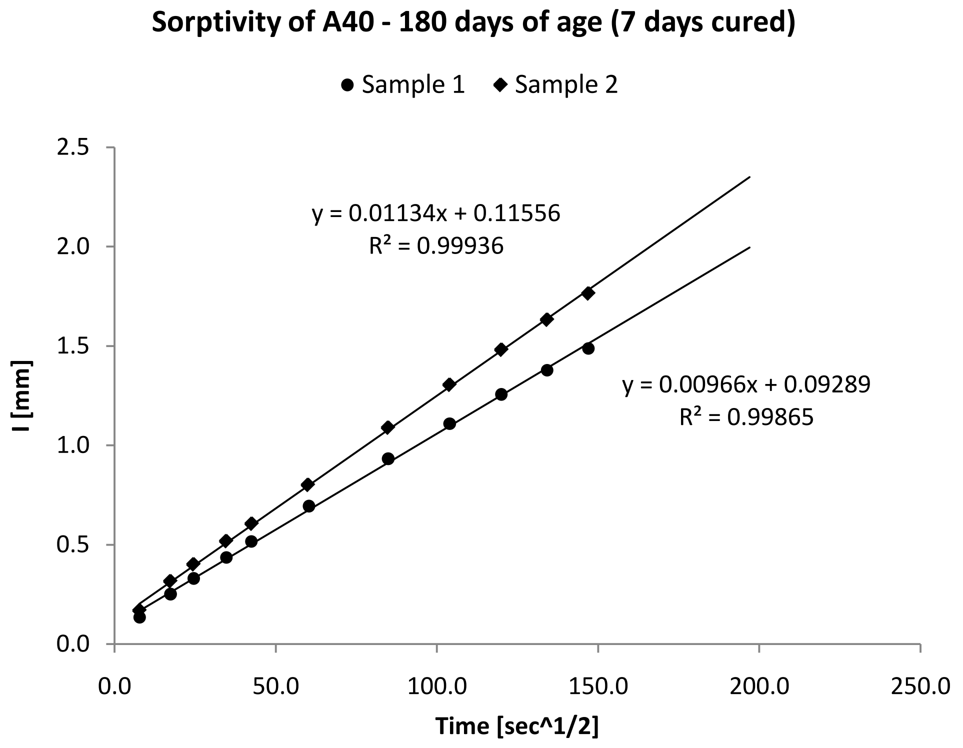
| | **Sample 1** | | | | | **Sample 2** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time after initial contact** | | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** | **Time (sec)** | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** |
| **Interval** | **(sec)** | | | | | | | | | |
| 0 | 0 | 0.0 | 828.01 | 0 | 0 | 0 | 0.0 | 897.57 | 0 | 0 |
| 1 min | 60 | 7.7 | 829.2 | 1.19 | 0.1510 | 60 | 7.7 | 898.81 | 1.24 | 0.1573 |
| 5 min | 300 | 17.3 | 830.15 | 2.14 | 0.2715 | 300 | 17.3 | 899.85 | 2.28 | 0.2893 |
| 10 min | 600 | 24.5 | 830.81 | 2.8 | 0.3553 | 600 | 24.5 | 900.59 | 3.02 | 0.3832 |
| 20 min | 1200 | 34.6 | 831.7 | 3.69 | 0.4682 | 1200 | 34.6 | 901.65 | 4.08 | 0.5177 |
| 30 min | 1800 | 42.4 | 831.39 | 3.38 | 0.4289 | 1800 | 42.4 | 902.45 | 4.88 | 0.6192 |
| 1 hr | 3600 | 60.0 | 833.87 | 5.86 | 0.7435 | 3600 | 60.0 | 904.35 | 6.78 | 0.8602 |
| 2 hr | 7200 | 84.9 | 835.92 | 7.91 | 1.0036 | 7200 | 84.9 | 906.83 | 9.26 | 1.1749 |
| 3 hr | 10800 | 103.9 | 837.39 | 9.38 | 1.1901 | 10800 | 103.9 | 908.5 | 10.93 | 1.3868 |
| 4 hr | 14400 | 120.0 | 838.57 | 10.56 | 1.3398 | 14400 | 120.0 | 909.9 | 12.33 | 1.5644 |
| 5 hr | 18000 | 134.2 | 839.53 | 11.52 | 1.4616 | 18000 | 134.2 | 911.05 | 13.48 | 1.7103 |
| 6 hr | 21600 | 147.0 | 840.34 | 12.33 | 1.5644 | 21600 | 147.0 | 912.04 | 14.47 | 1.8359 |



| | | | |
|---|---|---|---|
| Mix ID: | **A40** | Test age: | **180 days** |
| Casting date: | 07/08/2009 | Curing period: | 7 days |

| | **Unit** | **Sample 1** | **Sample 2** |
|---|---|---|---|
| Average diameter | mm | 100.18 | 100.125 |
| Average thickness | mm | 45.3 | 49.3 |
| Mass of conditioned specimen | gm | 827.86 | 904.12 |
| Mass after sealing specimen | gm | 830.47 | 906.68 |
| Exposed area | $mm^2$ | 7881.51 | 7873.65 |

| | **Sample 1** | | | | | **Sample 2** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time after initial contact** | | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** | **Time (sec)** | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** |
| **Interval** | **(sec)** | | | | | | | | | |
| 0 | 0 | 0.0 | 830.47 | 0 | 0 | 0 | 0.0 | 906.68 | 0 | 0 |
| 1 min | 60 | 7.7 | 831.53 | 1.06 | 0.1345 | 60 | 7.7 | 908.01 | 1.33 | 0.1687 |
| 5 min | 300 | 17.3 | 832.45 | 1.98 | 0.2512 | 300 | 17.3 | 909.17 | 2.49 | 0.3159 |
| 10 min | 600 | 24.5 | 833.07 | 2.6 | 0.3299 | 600 | 24.5 | 909.84 | 3.16 | 0.4009 |
| 20 min | 1200 | 34.6 | 833.9 | 3.43 | 0.4352 | 1200 | 34.6 | 910.76 | 4.08 | 0.5177 |
| 30 min | 1800 | 42.4 | 834.54 | 4.07 | 0.5164 | 1810 | 42.5 | 911.45 | 4.77 | 0.6052 |
| 1 hr | 3635 | 60.3 | 835.94 | 5.47 | 0.6940 | 3600 | 60.0 | 912.99 | 6.31 | 0.8006 |
| 2 hr | 7200 | 84.9 | 837.82 | 7.35 | 0.9326 | 7200 | 84.9 | 915.26 | 8.58 | 1.0886 |
| 3 hr | 10800 | 103.9 | 839.21 | 8.74 | 1.1089 | 10800 | 103.9 | 916.96 | 10.28 | 1.3043 |
| 4 hr | 14400 | 120.0 | 840.37 | 9.9 | 1.2561 | 14400 | 120.0 | 918.35 | 11.67 | 1.4807 |
| 5 hr | 18000 | 134.2 | 841.33 | 10.86 | 1.3779 | 18000 | 134.2 | 919.54 | 12.86 | 1.6317 |
| 6 hr | 21600 | 147.0 | 842.19 | 11.72 | 1.4870 | 21600 | 147.0 | 920.58 | 13.9 | 1.7636 |

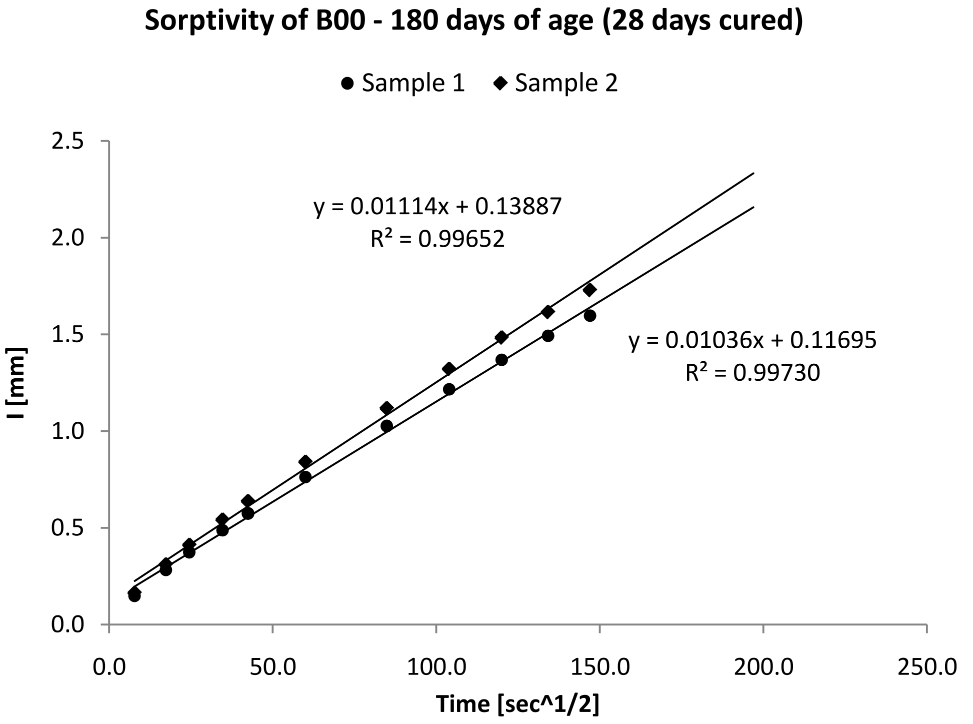


## Sorptivity test at 180 days: SERIES – B

| | | | |
|---|---|---|---|
| Mix ID: | **B00** | Test age: | **180 days** |
| Casting date: | 20/08/2009 | Curing period: | 28 days |

| | **Unit** | **Sample 1** | **Sample 2** |
|---|---|---|---|
| Average diameter | mm | 99.50 | 99.45 |
| Average thickness | mm | 50.1 | 48.1 |
| Mass of conditioned specimen | gm | 908.27 | 875.43 |
| Mass after sealing specimen | gm | 911.07 | 877.90 |
| Exposed area | $mm^2$ | 7775.66 | 7767.84 |

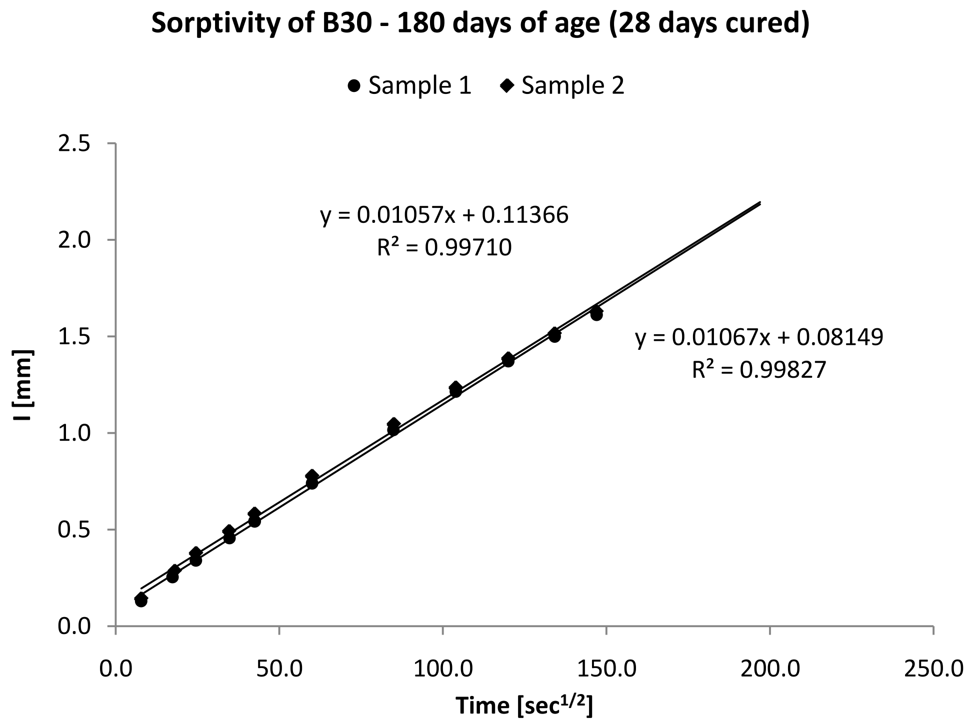
| | **Sample 1** | | | | | **Sample 2** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time after initial contact** | | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** | **Time (sec)** | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** |
| **Interval** | **(sec)** | | | | | | | | | |
| 0 | 0 | 0.0 | 911.07 | 0 | 0 | 0 | 0.0 | 877.9 | 0 | 0 |
| 1 min | 60 | 7.7 | 912.23 | 1.16 | 0.1481 | 60 | 7.7 | 879.19 | 1.29 | 0.1647 |
| 5 min | 300 | 17.3 | 913.28 | 2.21 | 0.2822 | 300 | 17.3 | 880.34 | 2.44 | 0.3116 |
| 10 min | 600 | 24.5 | 914 | 2.93 | 0.3742 | 600 | 24.5 | 881.13 | 3.23 | 0.4125 |
| 20 min | 1200 | 34.6 | 914.89 | 3.82 | 0.4878 | 1200 | 34.6 | 882.15 | 4.25 | 0.5428 |
| 30 min | 1800 | 42.4 | 915.57 | 4.5 | 0.5747 | 1800 | 42.4 | 882.9 | 5 | 0.6385 |
| 1 hr | 3600 | 60.0 | 917.04 | 5.97 | 0.7624 | 3600 | 60.0 | 884.49 | 6.59 | 0.8416 |
| 2 hr | 7200 | 84.9 | 919.11 | 8.04 | 1.0268 | 7200 | 84.9 | 886.66 | 8.76 | 1.1187 |
| 3 hr | 10800 | 103.9 | 920.6 | 9.53 | 1.2170 | 10800 | 103.9 | 888.25 | 10.35 | 1.3218 |
| 4 hr | 14400 | 120.0 | 921.79 | 10.72 | 1.3690 | 14400 | 120.0 | 889.52 | 11.62 | 1.4839 |
| 5 hr | 18000 | 134.2 | 922.76 | 11.69 | 1.4929 | 18000 | 134.2 | 890.55 | 12.65 | 1.6155 |
| 6 hr | 21600 | 147.0 | 923.58 | 12.51 | 1.5976 | 21600 | 147.0 | 891.44 | 13.54 | 1.7291 |



| | | | |
|---|---|---|---|
| Mix ID: | **B30** | Test age: | **180 days** |
| Casting date: | 17/08/2009 | Curing period: | 28 days |

| | **Unit** | **Sample 1** | **Sample 2** |
|---|---|---|---|
| Average diameter | mm | 99.75 | 99.775 |
| Average thickness | mm | 47.4 | 47.2 |
| Mass of conditioned specimen | gm | 859.08 | 856.33 |
| Mass after sealing specimen | gm | 861.76 | 858.85 |
| Exposed area | $mm^2$ | 7814.78 | 7818.70 |

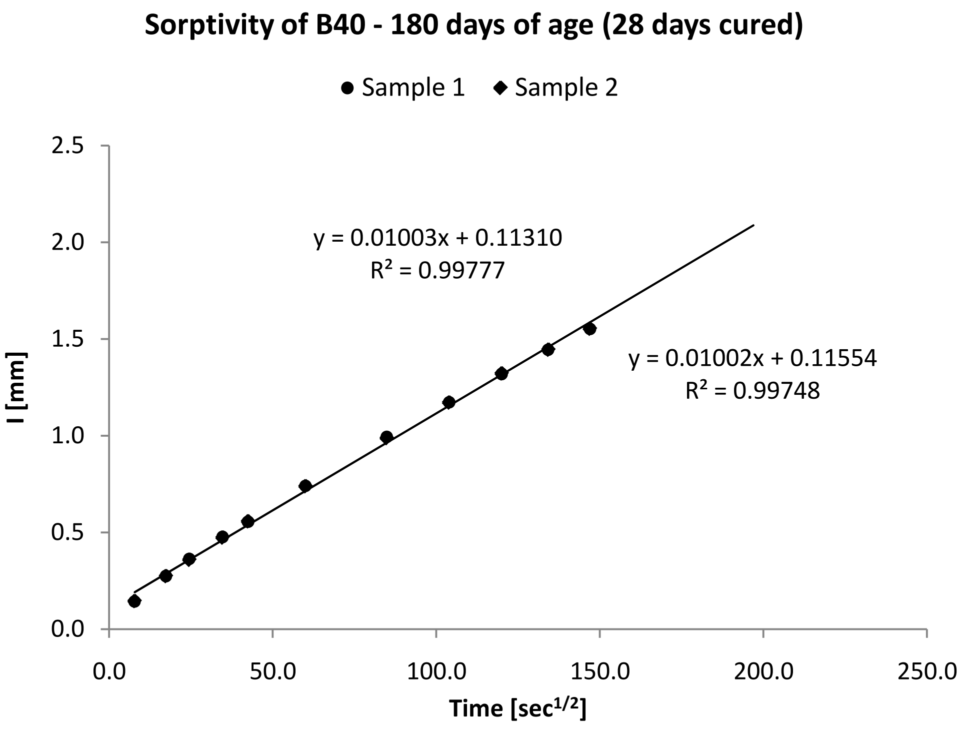
| | **Sample 1** | | | | | **Sample 2** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time after initial contact** | | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** | **Time (sec)** | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** |
| **Interval** | **(sec)** | | | | | | | | | |
| 0 | 0 | 0.0 | 861.76 | 0 | 0 | 0 | 0.0 | 858.85 | 0 | 0 |
| 1 min | 60 | 7.7 | 862.79 | 1.03 | 0.1315 | 60 | 7.7 | 859.97 | 1.12 | 0.1430 |
| 5 min | 300 | 17.3 | 863.76 | 2 | 0.2554 | 324 | 18.0 | 861.09 | 2.24 | 0.2861 |
| 10 min | 600 | 24.5 | 864.43 | 2.67 | 0.3410 | 600 | 24.5 | 861.81 | 2.96 | 0.3780 |
| 20 min | 1205 | 34.7 | 865.34 | 3.58 | 0.4572 | 1200 | 34.6 | 862.7 | 3.85 | 0.4917 |
| 30 min | 1800 | 42.4 | 866.02 | 4.26 | 0.5440 | 1800 | 42.4 | 863.41 | 4.56 | 0.5823 |
| 1 hr | 3600 | 60.0 | 867.56 | 5.8 | 0.7407 | 3600 | 60.0 | 864.94 | 6.09 | 0.7777 |
| 2 hr | 7200 | 84.9 | 869.72 | 7.96 | 1.0165 | 7225 | 85.0 | 867.04 | 8.19 | 1.0459 |
| 3 hr | 10800 | 103.9 | 871.28 | 9.52 | 1.2158 | 10800 | 103.9 | 868.52 | 9.67 | 1.2349 |
| 4 hr | 14400 | 120.0 | 872.5 | 10.74 | 1.3716 | 14400 | 120.0 | 869.7 | 10.85 | 1.3856 |
| 5 hr | 18000 | 134.2 | 873.51 | 11.75 | 1.5006 | 18000 | 134.2 | 870.71 | 11.86 | 1.5146 |
| 6 hr | 21600 | 147.0 | 874.38 | 12.62 | 1.6117 | 21600 | 147.0 | 871.6 | 12.75 | 1.6283 |



| Mix ID: | **B40** | Test age: | **180 days** |
|---|---|---|---|
| Casting date: | 13/08/2009 | Curing period: | 28 days |

| | **Unit** | **Sample 1** | **Sample 2** |
|---|---|---|---|
| Average diameter | mm | 99.98 | 99.95 |
| Average thickness | mm | 48.5 | 46.4 |
| Mass of conditioned specimen | gm | 866.08 | 852.41 |
| Mass after sealing specimen | gm | 868.49 | 854.86 |
| Exposed area | $mm^2$ | 7850.07 | 7846.15 |

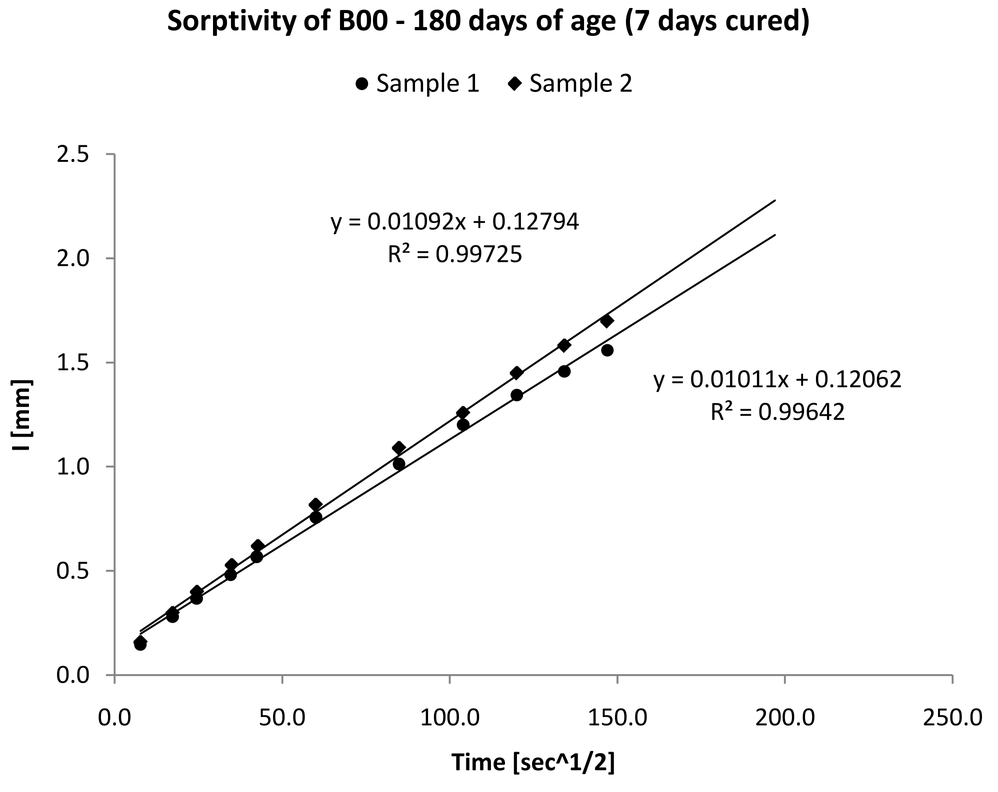
| | **Sample 1** | | | | | **Sample 2** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time after initial contact** | | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** | **Time (sec)** | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** |
| **Interval** | **(sec)** | | | | | | | | | |
| 0 | 0 | 0.0 | 868.49 | 0 | 0 | 0 | 0.0 | 854.86 | 0 | 0 |
| 1 min | 60 | 7.7 | 869.62 | 1.13 | 0.1443 | 60 | 7.7 | 856 | 1.14 | 0.1456 |
| 5 min | 300 | 17.3 | 870.65 | 2.16 | 0.2758 | 300 | 17.3 | 857.01 | 2.15 | 0.2746 |
| 10 min | 600 | 24.5 | 871.34 | 2.85 | 0.3640 | 600 | 24.5 | 857.67 | 2.81 | 0.3589 |
| 20 min | 1200 | 34.6 | 872.23 | 3.74 | 0.4776 | 1200 | 34.6 | 858.57 | 3.71 | 0.4738 |
| 30 min | 1800 | 42.4 | 872.85 | 4.36 | 0.5568 | 1800 | 42.4 | 859.23 | 4.37 | 0.5581 |
| 1 hr | 3600 | 60.0 | 874.3 | 5.81 | 0.7420 | 3600 | 60.0 | 860.65 | 5.79 | 0.7394 |
| 2 hr | 7200 | 84.9 | 876.28 | 7.79 | 0.9948 | 7200 | 84.9 | 862.6 | 7.74 | 0.9884 |
| 3 hr | 10800 | 103.9 | 877.68 | 9.19 | 1.1736 | 10800 | 103.9 | 864.04 | 9.18 | 1.1723 |
| 4 hr | 14400 | 120.0 | 878.83 | 10.34 | 1.3205 | 14400 | 120.0 | 865.22 | 10.36 | 1.3230 |
| 5 hr | 18000 | 134.2 | 879.81 | 11.32 | 1.4456 | 18030 | 134.3 | 866.18 | 11.32 | 1.4456 |
| 6 hr | 21600 | 147.0 | 880.65 | 12.16 | 1.5529 | 21600 | 147.0 | 867.03 | 12.17 | 1.5542 |



| | | | |
|---|---|---|---|
| Mix ID: | **B00** | Test age: | **180 days** |
| Casting date: | 20/08/2009 | Curing period: | 7 days |

| | **Unit** | **Sample 1** | **Sample 2** |
|---|---|---|---|
| Average diameter | mm | 99.80 | 99.8 |
| Average thickness | mm | 48.4 | 49.2 |
| Mass of conditioned specimen | gm | 885.71 | 901.18 |
| Mass after sealing specimen | gm | 888.25 | 903.76 |
| Exposed area | $mm^2$ | 7822.62 | 7822.62 |

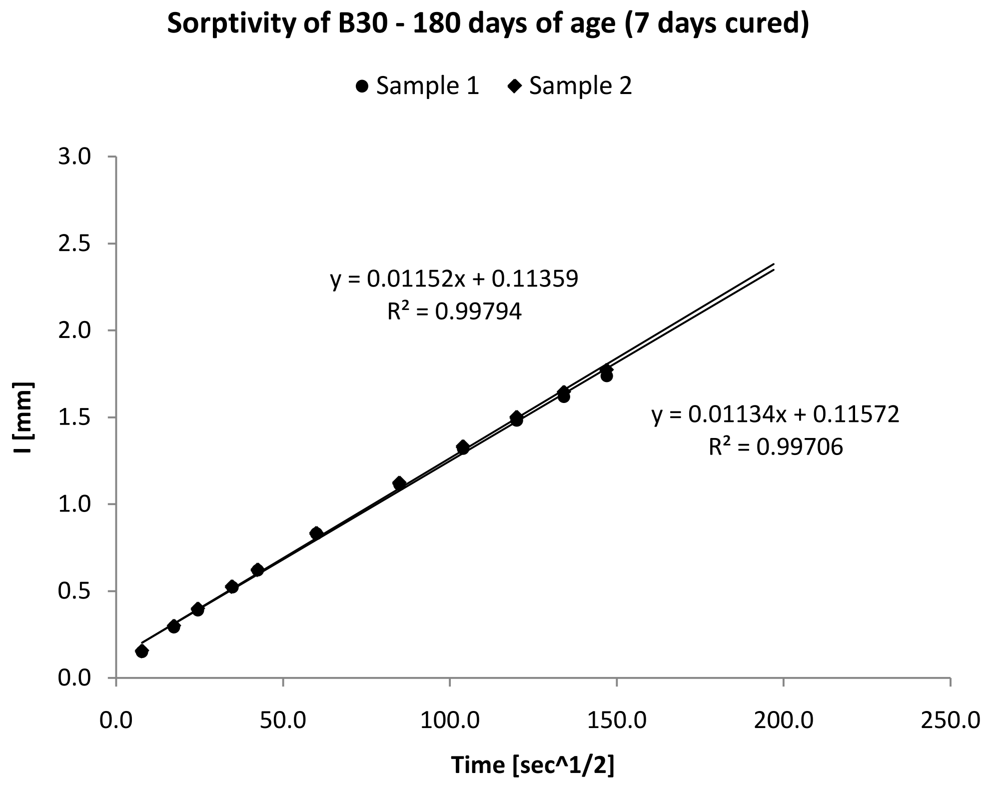
| | **Sample 1** | | | | | **Sample 2** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time after initial contact** | | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** | **Time (sec)** | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** |
| **Interval** | **(sec)** | | | | | | | | | |
| 0 | 0 | 0.0 | 888.25 | 0 | 0 | 0 | 0.0 | 903.76 | 0 | 0 |
| 1 min | 60 | 7.7 | 889.41 | 1.16 | 0.1472 | 60 | 7.7 | 905.01 | 1.25 | 0.1586 |
| 5 min | 300 | 17.3 | 890.46 | 2.21 | 0.2804 | 300 | 17.3 | 906.11 | 2.35 | 0.2982 |
| 10 min | 600 | 24.5 | 891.15 | 2.9 | 0.3679 | 605 | 24.6 | 906.91 | 3.15 | 0.3997 |
| 20 min | 1200 | 34.6 | 892.05 | 3.8 | 0.4821 | 1225 | 35.0 | 907.92 | 4.16 | 0.5278 |
| 30 min | 1800 | 42.4 | 892.73 | 4.48 | 0.5684 | 1830 | 42.8 | 908.64 | 4.88 | 0.6192 |
| 1 hr | 3610 | 60.1 | 894.22 | 5.97 | 0.7575 | 3600 | 60.0 | 910.2 | 6.44 | 0.8171 |
| 2 hr | 7200 | 84.9 | 896.24 | 7.99 | 1.0138 | 7200 | 84.9 | 912.35 | 8.59 | 1.0899 |
| 3 hr | 10815 | 104.0 | 897.72 | 9.47 | 1.2015 | 10810 | 104.0 | 913.67 | 9.91 | 1.2574 |
| 4 hr | 14400 | 120.0 | 898.85 | 10.6 | 1.3449 | 14400 | 120.0 | 915.18 | 11.42 | 1.4490 |
| 5 hr | 18000 | 134.2 | 899.74 | 11.49 | 1.4578 | 18005 | 134.2 | 916.22 | 12.46 | 1.5809 |
| 6 hr | 21600 | 147.0 | 900.54 | 12.29 | 1.5593 | 21600 | 147.0 | 917.14 | 13.38 | 1.6976 |



| | | | |
|---|---|---|---|
| Mix ID: | **B30** | Test age: | **180 days** |
| Casting date: | 17/08/2009 | Curing period: | 7 days |

| | **Unit** | **Sample 1** | **Sample 2** |
|---|---|---|---|
| Average diameter | mm | 99.75 | 99.775 |
| Average thickness | mm | 47.6 | 48 |
| Mass of conditioned specimen | gm | 859.27 | 869.06 |
| Mass after sealing specimen | gm | 861.88 | 871.71 |
| Exposed area | $mm^2$ | 7814.78 | 7818.70 |

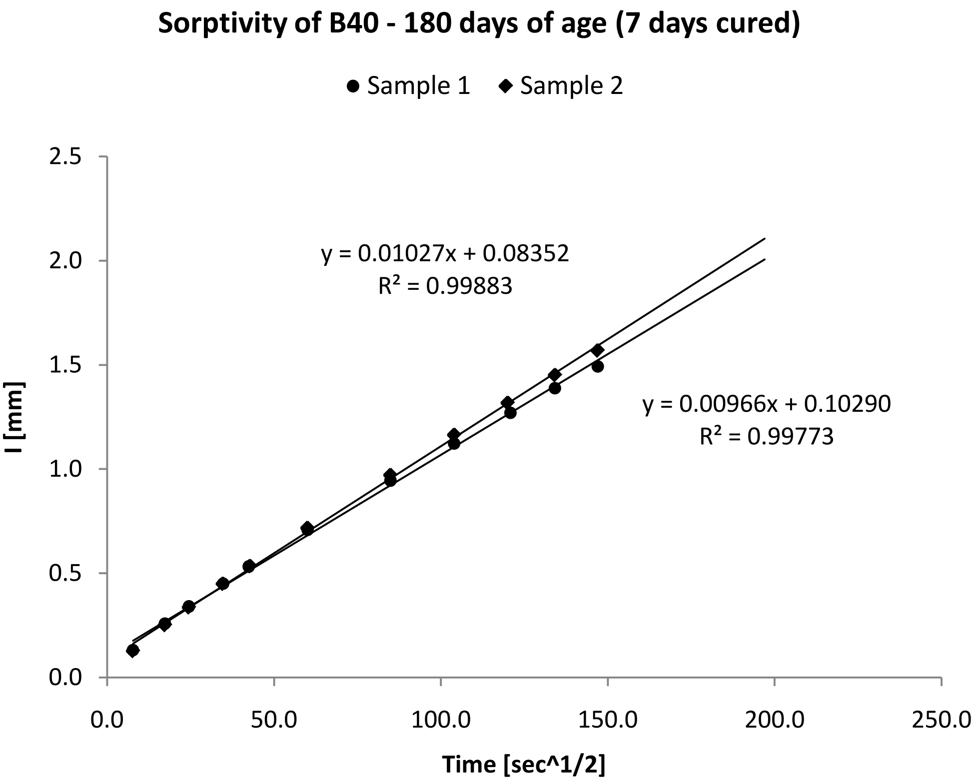
| | **Sample 1** | | | | | **Sample 2** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time after initial contact** | | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** | **Time (sec)** | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** |
| **Interval** | **(sec)** | | | | | | | | | |
| 0 | 0 | 0.0 | 861.88 | 0 | 0 | 0 | 0.0 | 871.71 | 0 | 0 |
| 1 min | 60 | 7.7 | 863.07 | 1.19 | 0.1510 | 60 | 7.7 | 872.93 | 1.22 | 0.1548 |
| 5 min | 300 | 17.3 | 864.19 | 2.31 | 0.2931 | 300 | 17.3 | 874.06 | 2.35 | 0.2982 |
| 10 min | 600 | 24.5 | 864.96 | 3.08 | 0.3908 | 600 | 24.5 | 874.84 | 3.13 | 0.3971 |
| 20 min | 1215 | 34.9 | 866 | 4.12 | 0.5227 | 1205 | 34.7 | 875.85 | 4.14 | 0.5253 |
| 30 min | 1800 | 42.4 | 866.77 | 4.89 | 0.6204 | 1800 | 42.4 | 876.61 | 4.9 | 0.6217 |
| 1 hr | 3600 | 60.0 | 868.43 | 6.55 | 0.8311 | 3600 | 60.0 | 878.27 | 6.56 | 0.8323 |
| 2 hr | 7200 | 84.9 | 870.65 | 8.77 | 1.1127 | 7200 | 84.9 | 880.55 | 8.84 | 1.1216 |
| 3 hr | 10800 | 103.9 | 872.28 | 10.4 | 1.3195 | 10800 | 103.9 | 882.2 | 10.49 | 1.3310 |
| 4 hr | 14400 | 120.0 | 873.56 | 11.68 | 1.4819 | 14400 | 120.0 | 883.53 | 11.82 | 1.4997 |
| 5 hr | 18000 | 134.2 | 874.63 | 12.75 | 1.6177 | 18000 | 134.2 | 884.66 | 12.95 | 1.6431 |
| 6 hr | 21600 | 147.0 | 875.57 | 13.69 | 1.7370 | 21600 | 147.0 | 885.66 | 13.95 | 1.7700 |



| | | | |
|---|---|---|---|
| Mix ID: | **B40** | Test age: | **180 days** |
| Casting date: | 13/08/2009 | Curing period: | 7 days |

| | **Unit** | **Sample 1** | **Sample 2** |
|---|---|---|---|
| Average diameter | mm | 99.55 | 99.7 |
| Average thickness | mm | 48.3 | 46.8 |
| Mass of conditioned specimen | gm | 870.66 | 841.76 |
| Mass after sealing specimen | gm | 873.07 | 844.24 |
| Exposed area | $mm^2$ | 7783.47 | 7806.95 |

| | **Sample 1** | | | | | **Sample 2** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time after initial contact** | | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** | **Time (sec)** | **$(sec)^{1/2}$** | **Mass (gm)** | **Mass diff. (gm)** | **Absorp-tion, I** |
| **Interval** | **(sec)** | | | | | | | | | |
| 0 | 0 | 0.0 | 873.07 | 0 | 0 | 0 | 0.0 | 844.24 | 0 | 0 |
| 1 min | 60 | 7.7 | 874.11 | 1.04 | 0.1320 | 60 | 7.7 | 845.25 | 1.01 | 0.1281 |
| 5 min | 300 | 17.3 | 875.11 | 2.04 | 0.2588 | 300 | 17.3 | 846.23 | 1.99 | 0.2525 |
| 10 min | 600 | 24.5 | 875.76 | 2.69 | 0.3413 | 600 | 24.5 | 846.9 | 2.66 | 0.3375 |
| 20 min | 1210 | 34.8 | 876.62 | 3.55 | 0.4504 | 1200 | 34.6 | 847.79 | 3.55 | 0.4504 |
| 30 min | 1800 | 42.4 | 877.27 | 4.2 | 0.5329 | 1830 | 42.8 | 848.46 | 4.22 | 0.5354 |
| 1 hr | 3610 | 60.1 | 878.66 | 5.59 | 0.7093 | 3600 | 60.0 | 849.9 | 5.66 | 0.7181 |
| 2 hr | 7200 | 84.9 | 880.52 | 7.45 | 0.9452 | 7200 | 84.9 | 851.9 | 7.66 | 0.9719 |
| 3 hr | 10800 | 103.9 | 881.92 | 8.85 | 1.1229 | 10810 | 104.0 | 853.42 | 9.18 | 1.1648 |
| 4 hr | 14595 | 120.8 | 883.08 | 10.01 | 1.2701 | 14400 | 120.0 | 854.63 | 10.39 | 1.3183 |
| 5 hr | 18000 | 134.2 | 884.01 | 10.94 | 1.3881 | 18000 | 134.2 | 855.68 | 11.44 | 1.4515 |
| 6 hr | 21600 | 147.0 | 884.83 | 11.76 | 1.4921 | 21600 | 147.0 | 856.61 | 12.37 | 1.5695 |



# APPENDIX J: Water Permeability test results

## Water permeability test : SERIES – A

Mix ID: **A00** Casting Date: 24/08/2009
Test age: **28 days**

| | Avg. thickness (mm) | Avg. diameter (mm) | Area ($m^2$) | Pressure head (m) | Dry wt (gm) | Coated dry wt. (gm) | Coated wet wt. (gm) |
|---|---|---|---|---|---|---|---|
| **Sample 1** | 50.575 | 100 | 0.0079 | 97 | 919.56 | 1062.76 | 1108.2 |
| **Sample 2** | 49.675 | 99.95 | 0.0078 | 97 | 902.49 | 1040.3 | 1082.35 |

| | Day after pressurisation | Start time | Finish time | Start volume (ml) | Finish volume (ml) | Time (sec) | Flow ($m^3/s$) | Perm coeff. (m/s) | Avg. 7th day perm. coeff. k (m/s) |
|---|---|---|---|---|---|---|---|---|---|
| **Sample 1** | 1 | 10:06:15 | 12:06:30 | 1.71 | 0 | 7215 | 2.37E-10 | 1.57E-11 | 2.28E-12 |
| | 2 | 9:48:10 | 13:04:30 | 1.73 | 0.01 | 11780 | 1.46E-10 | 9.69E-12 | |
| | 6 | 10:02:55 | 15:00:00 | 0.86 | 0.15 | 17825 | 3.98E-11 | 2.64E-12 | |
| | 7 | 8:58:20 | 14:34:00 | 0.87 | 0.15 | 20140 | 3.57E-11 | 2.37E-12 | |
| **Sample 2** | 1 | 12:13:05 | 14:02:20 | 1.68 | 0.74 | 6555 | 1.43E-10 | 9.36E-12 | |
| | 2 | 8:29:15 | 12:56:10 | 0.32 | 1.78 | 16015 | 9.12E-11 | 5.95E-12 | |
| | 6 | 8:59:30 | 14:39:10 | 0.86 | 0.12 | 20380 | 3.63E-11 | 2.37E-12 | |
| | 7 | 9:03:00 | 14:02:00 | 0.87 | 0.27 | 17940 | 3.34E-11 | 2.18E-12 | |

Mix ID: **A00** Casting Date: 24/08/2009
Test age: **180 days**

| | Avg. thickness (mm) | Avg. diameter (mm) | Area ($m^2$) | Pressure head (m) | Dry wt (gm) | Coated dry wt. (gm) | Coated wet wt. (gm) |
|---|---|---|---|---|---|---|---|
| **Sample 1** | 50.875 | 100 | 0.0079 | 97 | 928.91 | 1073.38 | 1116.8 |
| **Sample 2** | 50.625 | 99.7 | 0.0078 | 97 | 917.55 | 1067.51 | 1111.25 |

| | Day after pressurisation | Start time | Finish time | Start volume (ml) | Finish volume (ml) | Time (sec) | Flow ($m^3/s$) | Perm coeff. (m/s) | Avg. 7th day perm. coeff. k (m/s) |
|---|---|---|---|---|---|---|---|---|---|
| **Sample 1** | 1 | 9:27:35 | 10:59:40 | 1.83 | 0 | 5525 | 3.31E-10 | 2.21E-11 | 1.96E-12 |
| | 5 | 8:48:50 | 11:06:55 | 1.81 | 0 | 8285 | 2.18E-10 | 1.46E-11 | |
| | 6 | 9:26:00 | 13:18:40 | 0.86 | 0.31 | 13960 | 3.94E-11 | 2.63E-12 | |
| | 7 | 10:11:00 | 14:47:45 | 0.87 | 0.4 | 16605 | 2.83E-11 | 1.89E-12 | |
| **Sample 2** | 1 | 9:28:50 | 11:05:30 | 1.9 | 0 | 5800 | 3.28E-10 | 2.19E-11 | |
| | 5 | 8:47:50 | 11:37:05 | 1.88 | 0.11 | 10155 | 1.74E-10 | 1.17E-11 | |
| | 6 | 9:29:15 | 13:18:00 | 0.88 | 0.4 | 13725 | 3.50E-11 | 2.34E-12 | |
| | 7 | 10:11:15 | 15:08:10 | 0.88 | 0.34 | 17815 | 3.03E-11 | 2.03E-12 | |

Mix ID: **A30** Casting Date: 10/08/2009
Test age: **28 days**

| | Avg. thickness (mm) | Avg. diameter (mm) | Area ($m^2$) | Pressure head (m) | Dry wt (gm) | Coated dry wt. (gm) | Coated wet wt. (gm) |
|---|---|---|---|---|---|---|---|
| **Sample 1** | 48.35 | 99.6 | 0.0078 | 97 | 892.48 | 1030.73 | 1069.62 |
| **Sample 2** | 48.925 | 99.75 | 0.0078 | 97 | 897.04 | 1033.35 | 1073.23 |

| | Day after pressurisation | Start time | Finish time | Start volume (ml) | Finish volume (ml) | Time (sec) | Flow ($m^3$/s) | Perm coeff. (m/s) | Avg. 7th day perm. coeff. k (m/s) |
|---|---|---|---|---|---|---|---|---|---|
| **Sample 1** | 1 | 12:14:51 | 14:00:35 | 0.81 | 0.03 | 6344 | 1.23E-10 | 7.87E-12 | 0.78E-12 |
| | 2 | 8:28:35 | 12:54:55 | 0.79 | 0.09 | 15980 | 4.38E-11 | 2.80E-12 | |
| | 6 | 10:36:30 | 14:28:20 | 0.82 | 0.69 | 13910 | 9.35E-12 | 5.98E-13 | |
| | 7 | 9:14:00 | 14:03:00 | 0.84 | 0.63 | 17340 | 1.21E-11 | 7.75E-13 | |
| **Sample 2** | 1 | 12:13:05 | 14:02:20 | 1.68 | 0.74 | 6555 | 1.43E-10 | 9.26E-12 | |
| | 2 | 8:29:15 | 12:56:10 | 0.32 | 1.78 | 16015 | 9.12E-11 | 5.88E-12 | |
| | 6 | 10:34:00 | 14:25:50 | 0.2 | 0.36 | 13910 | 1.15E-11 | 7.42E-13 | |
| | 7 | 9:01:00 | 14:19:36 | 0.74 | 0.51 | 19116 | 1.20E-11 | 7.77E-13 | |

Mix ID: **A30** Casting Date: 10/08/2009
Test age: **180 days**

| | Avg. thickness (mm) | Avg. diameter (mm) | Area ($m^2$) | Pressure head (m) | Dry wt (gm) | Coated dry wt. (gm) | Coated wet wt. (gm) |
|---|---|---|---|---|---|---|---|
| **Sample 1** | 50.175 | 99.75 | 0.0078 | 97 | 925 | 1074.72 | 1115.74 |
| **Sample 2** | 49.275 | 99.85 | 0.0078 | 97 | 911.37 | 1055.14 | 1096.15 |

| | Day after pressurisation | Start time | Finish time | Start volume (ml) | Finish volume (ml) | Time (sec) | Flow ($m^3$/s) | Perm coeff. (m/s) | Avg. 7th day perm. coeff. k (m/s) |
|---|---|---|---|---|---|---|---|---|---|
| **Sample 1** | 1 | 10:26:20 | 14:38:50 | 1.87 | 0 | 15150 | 1.23E-10 | 8.17E-12 | 0.73E-12 |
| | 5 | 10:45:40 | 14:53:30 | 1.88 | 1.52 | 14870 | 2.42E-11 | 1.60E-12 | |
| | 6 | 8:14:00 | 15:08:00 | 1.875 | 1.55 | 24840 | 1.31E-11 | 8.66E-13 | |
| | 7 | 8:14:00 | 13:34:00 | 0.88 | 0.69 | 19200 | 9.90E-12 | 6.55E-13 | |
| **Sample 2** | 1 | 10:27:15 | 13:54:50 | 1.84 | 0 | 12455 | 1.48E-10 | 9.58E-12 | |
| | 5 | 10:45:00 | 14:52:10 | 1.87 | 1.52 | 14830 | 2.36E-11 | 1.53E-12 | |
| | 6 | 8:13:00 | 15:07:00 | 1.83 | 1.42 | 24840 | 1.65E-11 | 1.07E-12 | |
| | 7 | 8:16:00 | 13:28:00 | 0.86 | 0.63 | 18720 | 1.23E-11 | 7.97E-13 | |

Mix ID: **A40** Casting Date: 07/08/2009
Test age: **28 days**

| | Avg. thickness (mm) | Avg. diameter (mm) | Area (m$^2$) | Pressure head (m) | Dry wt (gm) | Coated dry wt. (gm) | Coated wet wt. (gm) |
|---|---|---|---|---|---|---|---|
| **Sample 1** | 49.8 | 100 | 0.0079 | 97 | 917.28 | 1059.59 | 1102.03 |
| **Sample 2** | 48.975 | 99.85 | 0.0078 | 97 | 898.83 | 1039.03 | 1080.49 |

| | Day after pressurisation | Start time | Finish time | Start volume (ml) | Finish volume (ml) | Time (sec) | Flow (m$^3$/s) | Perm coeff. (m/s) | Avg. 7th day perm. coeff. k (m/s) |
|---|---|---|---|---|---|---|---|---|---|
| **Sample 1** | 1 | 12:14:51 | 14:00:35 | 0.81 | 0.03 | 6344 | 1.23E-10 | 8.04E-12 | 0.79E-12 |
| | 2 | 8:28:35 | 12:54:55 | 0.79 | 0.09 | 15980 | 4.38E-11 | 2.86E-12 | |
| | 6 | 10:36:30 | 14:28:20 | 0.82 | 0.69 | 13910 | 9.35E-12 | 6.11E-13 | |
| | 7 | 9:05:00 | 14:05:00 | 0.79 | 0.6 | 18000 | 1.06E-11 | 6.90E-13 | |
| **Sample 2** | 1 | 12:13:05 | 14:02:20 | 1.68 | 0.74 | 6555 | 1.43E-10 | 9.25E-12 | |
| | 2 | 8:29:15 | 12:56:10 | 0.32 | 1.78 | 16015 | 9.12E-11 | 5.88E-12 | |
| | 6 | 10:34:00 | 14:25:50 | 0.2 | 0.36 | 13910 | 1.15E-11 | 7.42E-13 | |
| | 7 | 9:03:00 | 14:02:00 | 0.87 | 0.62 | 17940 | 1.39E-11 | 8.99E-13 | |

Mix ID: **A40** Casting Date: 07/08/2009
Test age: **180 days**

| | Avg. thickness (mm) | Avg. diameter (mm) | Area (m$^2$) | Pressure head (m) | Dry wt (gm) | Coated dry wt. (gm) | Coated wet wt. (gm) |
|---|---|---|---|---|---|---|---|
| **Sample 1** | 49.6 | 99.7 | 0.0078 | 97 | 912.48 | 1064.67 | 1106.65 |
| **Sample 2** | 49.9 | 99.6 | 0.0078 | 97 | 910.04 | 1057.84 | 1101.21 |

| | Day after pressurisation | Start time | Finish time | Start volume (ml) | Finish volume (ml) | Time (sec) | Flow (m$^3$/s) | Perm coeff. (m/s) | Avg. 7th day perm. coeff. k (m/s) |
|---|---|---|---|---|---|---|---|---|---|
| **Sample 1** | 1 | 10:29:00 | 13:33:40 | 1.8 | 0 | 11080 | 1.62E-10 | 1.06E-11 | 0.62E-12 |
| | 5 | 10:50:50 | 14:59:10 | 0.22 | 0.64 | 14900 | 2.82E-11 | 1.85E-12 | |
| | 6 | 8:14:50 | 15:18:00 | 0.23 | 0.58 | 25390 | 1.38E-11 | 9.03E-13 | |
| | 7 | 8:17:40 | 13:27:00 | 0.88 | 0.68 | 18560 | 1.08E-11 | 7.06E-13 | |
| **Sample 2** | 1 | 10:46:00 | 15:00:10 | 1.78 | 0 | 15250 | 1.17E-10 | 7.71E-12 | |
| | 5 | 10:46:20 | 14:56:30 | 1.87 | 1.7 | 15010 | 1.13E-11 | 7.48E-13 | |
| | 6 | 8:12:50 | 15:06:00 | 1.86 | 1.71 | 24790 | 6.05E-12 | 4.00E-13 | |
| | 7 | 8:16:00 | 13:23:00 | 0.86 | 0.71 | 18420 | 8.14E-12 | 5.38E-13 | |

## Water permeability test : SERIES – B

Mix ID: **B00** Casting Date: 20/08/2009
Test age: **28 days**

| | **Avg. thickness (mm)** | **Avg. diameter (mm)** | **Area ($m^2$)** | **Pressure head (m)** | **Dry wt (gm)** | **Coated dry wt. (gm)** | **Coated wet wt. (gm)** |
|---|---|---|---|---|---|---|---|
| **Sample 1** | 52.05 | 99.6 | 0.0078 | 97 | 958.31 | 1105.72 | 1145.36 |
| **Sample 2** | 49.8 | 99.6 | 0.0078 | 97 | 896.88 | 1042.99 | 1089.98 |

| | **Day after pressurisation** | **Start time** | **Finish time** | **Start volume (ml)** | **Finish volume (ml)** | **Time (sec)** | **Flow ($m^3$/s)** | **Perm coeff. (m/s)** | **Avg. 7th day perm. coeff. k (m/s)** |
|---|---|---|---|---|---|---|---|---|---|
| **Sample 1** | 1 | 12:14:51 | 14:00:35 | 0.81 | 0.03 | 6344 | 1.23E-10 | 8.47E-12 | 1.18E-12 |
| | 2 | 8:28:35 | 12:54:55 | 0.79 | 0.09 | 15980 | 4.38E-11 | 3.02E-12 | |
| | 6 | 10:36:30 | 14:28:20 | 0.82 | 0.69 | 13910 | 9.35E-12 | 6.44E-13 | |
| | 7 | 9:52:50 | 12:54:10 | 0.82 | 0.6 | 10880 | 2.02E-11 | 1.39E-12 | |
| **Sample 2** | 1 | 12:13:05 | 14:02:20 | 1.68 | 0.74 | 6555 | 1.43E-10 | 9.45E-12 | |
| | 2 | 8:29:15 | 12:56:10 | 0.32 | 1.78 | 16015 | 9.12E-11 | 6.01E-12 | |
| | 6 | 10:34:00 | 14:25:50 | 0.2 | 0.36 | 13910 | 1.15E-11 | 7.58E-13 | |
| | 7 | 9:48:20 | 13:02:20 | 0.83 | 0.66 | 11640 | 1.46E-11 | 9.62E-13 | |

Mix ID: **B00** Casting Date: 20/08/2009
Test age: **180 days**

| | **Avg. thickness (mm)** | **Avg. diameter (mm)** | **Area ($m^2$)** | **Pressure head (m)** | **Dry wt (gm)** | **Coated dry wt. (gm)** | **Coated wet wt. (gm)** |
|---|---|---|---|---|---|---|---|
| **Sample 1** | 50 | 99.8 | 0.0078 | 97 | 923.85 | 1074.74 | 1109.01 |
| **Sample 2** | 49.95 | 99.6 | 0.0078 | 97 | 922.65 | 1069.85 | 1108.3 |

| | **Day after pressurisation** | **Start time** | **Finish time** | **Start volume (ml)** | **Finish volume (ml)** | **Time (sec)** | **Flow ($m^3$/s)** | **Perm coeff. (m/s)** | **Avg. 7th day perm. coeff. k (m/s)** |
|---|---|---|---|---|---|---|---|---|---|
| **Sample 1** | 1 | 9:31:40 | 11:48:30 | 1.88 | 0 | 8210 | 2.29E-10 | 1.51E-11 | 1.07E-12 |
| | 2 | 9:26:45 | 13:28:30 | 1.84 | 0 | 14505 | 1.27E-10 | 8.36E-12 | |
| | 6 | 9:22:00 | 15:45:15 | 0.88 | 0.33 | 22995 | 2.39E-11 | 1.58E-12 | |
| | 7 | 9:20:20 | 15:26:10 | 0.88 | 0.53 | 21950 | 1.59E-11 | 1.05E-12 | |
| **Sample 2** | 1 | 9:33:55 | 12:04:20 | 1.88 | 0.1 | 9025 | 1.97E-10 | 1.30E-11 | |
| | 2 | 9:25:50 | 13:29:20 | 1.83 | 0.35 | 14610 | 1.01E-10 | 6.70E-12 | |
| | 6 | 9:17:20 | 15:40:40 | 0.88 | 0.38 | 23000 | 2.17E-11 | 1.44E-12 | |
| | 7 | 9:25:40 | 15:31:00 | 0.85 | 0.49 | 21920 | 1.64E-11 | 1.09E-12 | |

Mix ID: **B30** Casting Date: 17/08/2009
Test age: **28 days**

| | Avg. thickness (mm) | Avg. diameter (mm) | Area ($m^2$) | Pressure head (m) | Dry wt (gm) | Coated dry wt. (gm) | Coated wet wt. (gm) |
|---|---|---|---|---|---|---|---|
| **Sample 1** | 49.75 | 99.7 | 0.0078 | 97 | 920.6 | 1058.2 | 1099.78 |
| **Sample 2** | 51.775 | 99.75 | 0.0078 | 97 | 942.55 | 1089.02 | 1134.23 |

| | Day after pressurisation | Start time | Finish time | Start volume (ml) | Finish volume (ml) | Time (sec) | Flow ($m^3/s$) | Perm coeff. (m/s) | Avg. 7th day perm. coeff. k (m/s) |
|---|---|---|---|---|---|---|---|---|---|
| **Sample 1** | 1 | 12:14:51 | 14:00:35 | 0.81 | 0.03 | 6344 | 1.23E-10 | 8.08E-12 | 1.10E-12 |
| | 2 | 8:28:35 | 12:54:55 | 0.79 | 0.09 | 15980 | 4.38E-11 | 2.88E-12 | |
| | 6 | 10:36:30 | 14:28:20 | 0.82 | 0.69 | 13910 | 9.35E-12 | 6.14E-13 | |
| | 7 | 8:59:00 | 14:28:00 | 0.87 | 0.49 | 19740 | 1.93E-11 | 1.26E-12 | |
| **Sample 2** | 1 | 22:08:10 | 12:39:20 | 1.8 | 0 | 52270 | 3.44E-11 | 2.35E-12 | |
| | 2 | 9:49:40 | 13:46:33 | 1.8 | 0.29 | 14213 | 1.06E-10 | 7.26E-12 | |
| | 6 | 10:04:10 | 15:01:00 | 0.87 | 0.53 | 17810 | 1.91E-11 | 1.30E-12 | |
| | 7 | 15:05:30 | 16:09:10 | 0.85 | 0.799 | 3820 | 1.34E-11 | 9.12E-13 | |

Mix ID: **B30** Casting Date: 17/08/2009
Test age: **180 days**

| | Avg. thickness (mm) | Avg. diameter (mm) | Area ($m^2$) | Pressure head (m) | Dry wt (gm) | Coated dry wt. (gm) | Coated wet wt. (gm) |
|---|---|---|---|---|---|---|---|
| **Sample 1** | 49.425 | 100 | 0.0079 | 97 | 909.16 | 1052.89 | 1095.84 |
| **Sample 2** | 49.4 | 99.8 | 0.0078 | 97 | 903.52 | 1049.29 | 1093.08 |

| | Day after pressurisation | Start time | Finish time | Start volume (ml) | Finish volume (ml) | Time (sec) | Flow ($m^3/s$) | Perm coeff. (m/s) | Avg. 7th day perm. coeff. k (m/s) |
|---|---|---|---|---|---|---|---|---|---|
| **Sample 1** | 1 | 9:26:20 | 11:15:10 | 1.84 | 0 | 6530 | 2.82E-10 | 1.83E-11 | 1.28E-12 |
| | 2 | 8:48:45 | 11:56:50 | 1.86 | 0 | 11285 | 1.65E-10 | 1.07E-11 | |
| | 6 | 10:56:35 | 15:57:00 | 0.89 | 0.4 | 18025 | 2.72E-11 | 1.76E-12 | |
| | 7 | 8:47:45 | 14:43:00 | 0.87 | 0.35 | 21315 | 2.44E-11 | 1.58E-12 | |
| **Sample 2** | 1 | 9:27:30 | 11:32:02 | 1.74 | 0 | 7472 | 2.33E-10 | 1.52E-11 | |
| | 2 | 8:49:25 | 12:46:50 | 1.86 | 0.26 | 14245 | 1.12E-10 | 7.31E-12 | |
| | 6 | 10:57:00 | 15:58:00 | 0.87 | 0.575 | 18060 | 1.63E-11 | 1.06E-12 | |
| | 7 | 8:47:45 | 14:42:30 | 0.83 | 0.51 | 21285 | 1.50E-11 | 9.79E-13 | |

Mix ID: **B40** Casting Date: 13/08/2009
Test age: **28 days**

| | Avg. thickness (mm) | Avg. diameter (mm) | Area ($m^2$) | Pressure head (m) | Dry wt (gm) | Coated dry wt. (gm) | Coated wet wt. (gm) |
|---|---|---|---|---|---|---|---|
| **Sample 1** | 49.65 | 99.9 | 0.0078 | 97 | 896.07 | 1034.16 | 1079.23 |
| **Sample 2** | 47.9 | 100.05 | 0.0079 | 97 | 869.24 | 1001.67 | 1047.9 |

| | Day after pressurisation | Start time | Finish time | Start volume (ml) | Finish volume (ml) | Time (sec) | Flow ($m^3$/s) | Perm coeff. (m/s) | Avg. 7th day perm. coeff. k (m/s) |
|---|---|---|---|---|---|---|---|---|---|
| **Sample 1** | 1 | 9:36:20 | 11:11:15 | 1.6 | 0.45 | 5695 | 2.02E-10 | 1.32E-11 | 0.70E-12 |
| | 2 | 8:28:35 | 12:54:55 | 0.79 | 0.09 | 15980 | 4.38E-11 | 2.86E-12 | |
| | 6 | 10:36:30 | 14:28:20 | 0.82 | 0.69 | 13910 | 9.35E-12 | 6.10E-13 | |
| | 7 | 9:49:00 | 13:07:00 | 0.9 | 0.77 | 11880 | 1.09E-11 | 7.15E-13 | |
| **Sample 2** | 1 | 12:13:05 | 14:02:20 | 1.68 | 0.74 | 6555 | 1.43E-10 | 9.01E-12 | |
| | 2 | 8:29:15 | 12:56:10 | 0.32 | 1.78 | 16015 | 9.12E-11 | 5.73E-12 | |
| | 6 | 10:34:00 | 14:25:50 | 0.2 | 0.36 | 13910 | 1.15E-11 | 7.22E-13 | |
| | 7 | 9:51:00 | 13:09:00 | 0.82 | 0.69 | 11880 | 1.09E-11 | 6.87E-13 | |

Mix ID: **B40** Casting Date: 13/08/2009
Test age: **180 days**

| | Avg. thickness (mm) | Avg. diameter (mm) | Area ($m^2$) | Pressure head (m) | Dry wt (gm) | Coated dry wt. (gm) | Coated wet wt. (gm) |
|---|---|---|---|---|---|---|---|
| **Sample 1** | 50.28 | 99.95 | 0.0078 | 97 | 920.08 | 1070.05 | 1115.62 |
| **Sample 2** | 50.58 | 99.35 | 0.0078 | 97 | 921.93 | 1074.36 | 1117.8 |

| | Day after pressurisation | Start time | Finish time | Start volume (ml) | Finish volume (ml) | Time (sec) | Flow ($m^3$/s) | Perm coeff. (m/s) | Avg. 7th day perm. coeff. k (m/s) |
|---|---|---|---|---|---|---|---|---|---|
| **Sample 1** | 1 | 9:50:30 | 12:49:00 | 1.86 | 0.09 | 10710 | 1.65E-10 | 1.09E-11 | 0.90E-12 |
| | 2 | 9:41:30 | 14:47:45 | 1.91 | 0 | 18375 | 1.04E-10 | 6.87E-12 | |
| | 6 | 10:20:00 | 15:40:00 | 0.86 | 0.58 | 19200 | 1.46E-11 | 9.63E-13 | |
| | 7 | 8:44:30 | 14:48:00 | 0.87 | 0.68 | 21810 | 8.71E-12 | 5.75E-13 | |
| **Sample 2** | 1 | 9:52:30 | 12:24:10 | 1.84 | 0 | 9100 | 2.02E-10 | 1.36E-11 | |
| | 2 | 8:18:30 | 12:15:00 | 1.84 | 0 | 14190 | 1.30E-10 | 8.72E-12 | |
| | 6 | 10:21:30 | 15:47:00 | 0.84 | 0.33 | 19530 | 2.61E-11 | 1.76E-12 | |
| | 7 | 8:44:00 | 14:30:00 | 0.85 | 0.47 | 20760 | 1.83E-11 | 1.23E-12 | |

# APPENDIX K: Air Permeability test results

## Air permeability test : SERIES – A

| Curing regime | Mix ID | Hole no. | Depth of hole (mm) | Time measurements (sec) | | | Avg. (st. dev.) | Air Exclusion Rating, AER (s/ml) | | Air permeability, $k$ $(m^2 \times 10^{-14})$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | i | ii | iii | (sec) | AER | Avg. | $k$ | Avg. $k$ |
| 28 days water curing (I) | **A00** | 1 | 38 | 369 | 433 | 414 | 432 (35) | 97.3 | 104.6 | 12.8 | 11.9 |
| | | 2 | 44 | 390 | 480 | 438 | | 104.9 | | 11.8 | |
| | | 3 | 36 | 453 | 464 | 446 | | 111.5 | | 11.2 | |
| | **A30** | 1 | 37 | 526 | 564 | 578 | 530 (47) | 135.0 | 128.7 | 9.2 | 9.7 |
| | | 2 | 38 | 533 | 549 | 583 | | 134.7 | | 9.3 | |
| | | 3 | 38 | 487 | 514 | 437 | | 116.3 | | 10.7 | |
| | **A40** | 1 | 39 | 475 | 497 | - | 481 (27) | 117.8 | 116.2 | 10.6 | 10.7 |
| | | 2 | 42 | 436 | 480 | 483 | | 112.7 | | 11.0 | |
| | | 3 | 44 | 449 | 509 | 510 | | 118.0 | | 10.5 | |
| 7 days water curing (II) | **A00** | 1 | 39 | 322 | 388 | 414 | 378 (49) | 90.8 | 91.6 | 13.7 | 13.7 |
| | | 2 | 40 | 315 | 361 | | | 81.8 | | 15.2 | |
| | | 3 | 37 | 380 | 431 | 451 | | 102.2 | | 12.2 | |
| | **A30** | 1 | 40 | 408 | 497 | 519 | 485 (37) | 114.9 | 117.5 | 10.8 | 10.6 |
| | | 2 | 38 | 453 | 491 | 516 | | 118.1 | | 10.6 | |
| | | 3 | 39 | 460 | 503 | 514 | | 119.3 | | 10.4 | |
| | **A40** | 1 | 40 | 436 | 481 | 493 | 446 (33) | 113.8 | 107.8 | 10.9 | 11.6 |
| | | 2 | 40 | 421 | 451 | 463 | | 107.8 | | 11.6 | |
| | | 3 | 44 | 386 | 425 | 454 | | 101.7 | | 12.2 | |

## Air permeability test : SERIES – B

| Curing regime | Mix ID | Hole no. | Depth of hole (mm) | Time measurements (sec) | | | Avg. (st. dev.) | Air Exclusion Rating, AER (s/ml) | | Air permeability, $k$ $(m^2 \times 10^{-14})$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | i | ii | iii | (sec) | AER | Avg. | $k$ | Avg. $k$ |
| 28 days water curing (I) | **B00** | 1 | 41 | 434 | 471 | 497 | 462 (32) | 113.0 | 112.1 | 11.0 | 11.1 |
| | | 2 | 36 | 445 | 481 | - | | 112.6 | | 11.1 | |
| | | 3 | 38 | 402 | 484 | 484 | | 110.8 | | 11.3 | |
| | **B30** | 1 | 40 | 402 | 493 | 491 | 442 (51) | 111.9 | 107.0 | 11.1 | 11.6 |
| | | 2 | 44 | 393 | 466 | 491 | | 108.5 | | 11.4 | |
| | | 3 | 40 | 349 | 442 | 455 | | 100.6 | | 12.4 | |
| | **B40** | 1 | 43 | 343 | 466 | 487 | 444 (53) | 104.3 | 107.4 | 11.9 | 11.6 |
| | | 2 | 42 | 383 | 490 | 481 | | 109.1 | | 11.4 | |
| | | 3 | 40 | 410 | 455 | 482 | | 108.7 | | 11.4 | |
| 7 days water curing (II) | **B00** | 1 | 35 | 444 | 492 | 516 | 456 (36) | 117.8 | 110.9 | 10.6 | 11.3 |
| | | 2 | 35 | 426 | 469 | 480 | | 111.5 | | 11.2 | |
| | | 3 | 37 | 404 | 425 | 449 | | 103.5 | | 12.1 | |
| | **B30** | 1 | 42 | 330 | 363 | 370 | 368 (33) | 85.6 | 88.8 | 14.5 | 14.0 |
| | | 2 | 44 | 326 | 383 | 391 | | 88.4 | | 14.0 | |
| | | 3 | 46 | 331 | 403 | 416 | | 92.3 | | 13.4 | |
| | **B40** | 1 | 43 | 247 | 229 | 224 | 209 (20) | 56.3 | 50.5 | 22.0 | 24.8 |
| | | 2 | 44 | 198 | 200 | 196 | | 47.8 | | 26.0 | |
| | | 3 | 37 | 196 | 195 | | | 47.5 | | 26.3 | |

# APPENDIX L: Carbonation test results

| Mix ID | Carbonated edge | Depth of carbonation (mm) | | | | | |
|---|---|---|---|---|---|---|---|
| | | i | ii | iii | iv | Average | St. dev. |
| **A00** | Right edge | 4.5 | 2 | 1 | 3 | 4.4 | 2.79 |
| | Left edge | 9 | 4 | 3.5 | 8 | | |
| | | | | | | | |
| **A30** | Right edge | 3 | 7 | 3 | 5 | 4.3 | 1.73 |
| | Left edge | 2.5 | 3 | 4.5 | 6.5 | | |
| | | | | | | | |
| **A40** | Right edge | 4 | 3.5 | 6 | 6.5 | 4.7 | 1.28 |
| | Left edge | 6 | 4.5 | 3.5 | 3.5 | | |
| | | | | | | | |
| **B00** | Right edge | 1.5 | 1 | 1 | 1 | 1.1 | 0.20 |
| | Left edge | 1 | 1 | 1 | 1 | | |
| | | | | | | | |
| **B30** | Right edge | 5.5 | 5 | 5 | 1 | 3.7 | 1.51 |
| | Left edge | 4 | 3.5 | 2.5 | 3 | | |
| | | | | | | | |
| **B40** | Right edge | 5 | 4.5 | 5 | 3 | 4.5 | 1.25 |
| | Left edge | 7 | 3.5 | 3.5 | 4.5 | | |

# APPENDIX M: Rapid Chloride Permeability test results

## Rapid chloride permeability test : SERIES – A

Mix ID: **A00** Casting date: 24/08/2009

| **Test age:** | **28 days** | | **180 days** | |
|---|---|---|---|---|
| **Samples** | **Sample 1** | **Sample 2** | **Sample 1** | **Sample 2** |
| Avg. thickness (mm) | 49.9 | 49.7 | 50 | 51 |
| Avg. diameter (mm) | 99.9 | 99.6 | 100.2 | 100 |
| Area (mm$^2$) | 7838.3 | 7791.3 | 7885.4 | 7854.0 |

| **Elapsed time (hours)** | **28 days** | | **180 days** | |
|---|---|---|---|---|
| | **Current (amperes)** | | | |
| | **Sample 1** | **Sample 2** | **Sample 1** | **Sample 2** |
| 0.0 | 0.114 | 0.112 | 0.067 | 0.067 |
| 0.5 | 0.124 | 0.121 | 0.072 | 0.072 |
| 1.0 | 0.133 | 0.129 | 0.074 | 0.078 |
| 1.5 | 0.142 | 0.130 | 0.079 | 0.083 |
| 2.0 | 0.148 | 0.130 | 0.082 | 0.084 |
| 2.5 | 0.149 | 0.134 | 0.083 | 0.085 |
| 3.0 | 0.150 | 0.139 | 0.085 | 0.087 |
| 3.5 | 0.150 | 0.139 | 0.086 | 0.089 |
| 4.0 | 0.150 | 0.139 | 0.087 | 0.091 |
| 4.5 | 0.150 | 0.139 | 0.09 | 0.093 |
| 5.0 | 0.150 | 0.139 | 0.09 | 0.094 |
| 5.5 | 0.151 | 0.140 | 0.092 | 0.098 |
| 6.0 | 0.152 | 0.140 | 0.096 | 0.101 |
| **Calculations:** | | | | |
| Total charge passed (coulomb) | 3114 | 2889 | 1803 | 1868 |
| Equivalent charge of standard sample (coulomb) | 2816 | 2628 | 1619 | 1686 |
| **Average charge passed (coulomb)** | **2722** | | **1652.5** | |
| **Chloride permeability** | **Moderate** | | **Low** | |
| Voltage (V) | 60 | 60 | 60 | 60 |
| Initial current (mA) | 114 | 112 | 67 | 67 |
| Resistance (Ohm) | 0.526 | 0.536 | 0.896 | 0.896 |
| Resistivity (Ohm m) | 82.67 | 83.98 | 141.23 | 137.91 |
| **Avg. Resistivity (Ohm m)** | **83.33** | | **139.57** | |

Mix ID: **A30** Casting date: 10/08/2009

| **Test age:** | **28 days** | | **180 days** | |
|---|---|---|---|---|
| **Samples** | **Sample 1** | **Sample 2** | **Sample 1** | **Sample 2** |
| Avg. thickness (mm) | 46.8 | 47 | 49.5 | 48.9 |
| Avg. diameter (mm) | 99.5 | 99.4 | 99.6 | 100.1 |
| Area (mm$^2$) | 7775.7 | 7760.0 | 7791.3 | 7869.7 |

| **Elapsed time (hours)** | **28 days** | | **180 days** | |
|---|---|---|---|---|
| | **Current (amperes)** | | | |
| | **Sample 1** | **Sample 2** | **Sample 1** | **Sample 2** |
| 0.0 | 0.069 | 0.067 | 0.026 | 0.028 |
| 0.5 | 0.074 | 0.073 | 0.026 | 0.028 |
| 1.0 | 0.077 | 0.077 | 0.027 | 0.028 |
| 1.5 | 0.082 | 0.082 | 0.028 | 0.028 |
| 2.0 | 0.085 | 0.085 | 0.028 | 0.028 |
| 2.5 | 0.087 | 0.087 | 0.029 | 0.03 |
| 3.0 | 0.090 | 0.092 | 0.029 | 0.03 |
| 3.5 | 0.093 | 0.095 | 0.029 | 0.03 |
| 4.0 | 0.095 | 0.096 | 0.03 | 0.031 |
| 4.5 | 0.097 | 0.098 | 0.03 | 0.031 |
| 5.0 | 0.098 | 0.100 | 0.03 | 0.031 |
| 5.5 | 0.100 | 0.102 | 0.031 | 0.032 |
| 6.0 | 0.105 | 0.108 | 0.031 | 0.033 |
| **Calculations:** | | | | |
| Total charge passed (coulomb) | 1917 | 1934.1 | 622 | 644 |
| Equivalent charge of standard sample (coulomb) | 1748 | 1767 | 566 | 580 |
| **Average charge passed (coulomb)** | **1757.5** | | **573** | |
| **Chloride permeability** | **Low** | | **Very Low** | |
| Voltage (V) | 60 | 60 | 60 | 60 |
| Initial current (mA) | 69 | 67 | 26 | 28 |
| Resistance (Ohm) | 0.870 | 0.896 | 2.308 | 2.143 |
| Resistivity (Ohm m) | 144.48 | 147.86 | 363.23 | 344.86 |
| **Avg. Resistivity (Ohm m)** | **146.17** | | **354.05** | |

Mix ID: **A40** Casting date: 07/08/2009

| **Test age:** | **28 days** | | **180 days** | |
|---|---|---|---|---|
| **Samples** | **Sample 1** | **Sample 2** | **Sample 1** | **Sample 2** |
| Avg. thickness (mm) | 50 | 48.4 | 49.9 | 49.1 |
| Avg. diameter (mm) | 99.5 | 99.5 | 100.1 | 99.9 |
| Area ($mm^2$) | 7775.7 | 7775.7 | 7869.7 | 7838.3 |

| **Elapsed time (hours)** | **28 days** | | **180 days** | |
|---|---|---|---|---|
| | **Current (amperes)** | | | |
| | **Sample 1** | **Sample 2** | **Sample 1** | **Sample 2** |
| 0.0 | 0.066 | 0.057 | 0.025 | 0.021 |
| 0.5 | 0.069 | 0.059 | 0.026 | 0.021 |
| 1.0 | 0.070 | 0.063 | 0.027 | 0.022 |
| 1.5 | 0.070 | 0.066 | 0.027 | 0.022 |
| 2.0 | 0.074 | 0.069 | 0.027 | 0.022 |
| 2.5 | 0.078 | 0.072 | 0.027 | 0.022 |
| 3.0 | 0.082 | 0.074 | 0.028 | 0.023 |
| 3.5 | 0.084 | 0.076 | 0.028 | 0.023 |
| 4.0 | 0.084 | 0.078 | 0.028 | 0.024 |
| 4.5 | 0.086 | 0.080 | 0.028 | 0.024 |
| 5.0 | 0.087 | 0.082 | 0.028 | 0.024 |
| 5.5 | 0.088 | 0.082 | 0.028 | 0.024 |
| 6.0 | 0.088 | 0.083 | 0.028 | 0.024 |
| **Calculations:** | | | | |
| Total charge passed (coulomb) | 1708 | 1568 | 591 | 492 |
| Equivalent charge of standard sample (coulomb) | 1557 | 1429 | 533 | 445 |
| **Average charge passed (coulomb)** | **1493** | | **489** | |
| **Chloride permeability** | **Low** | | **Very Low** | |
| Voltage (V) | 60 | 60 | 60 | 60 |
| Initial current (mA) | 66 | 57 | 25 | 21 |
| Resistance (Ohm) | 0.909 | 1.053 | 2.400 | 2.857 |
| Resistivity (Ohm m) | 141.38 | 169.11 | 378.50 | 456.11 |
| **Avg. Resistivity (Ohm m)** | **155.24** | | **417.31** | |

## Rapid chloride permeability test : SERIES – B

Mix ID: **B00** Casting date: 13/08/2009

| **Test age:** | **28 days** | | **180 days** | |
|---|---|---|---|---|
| **Samples** | **Sample 1** | **Sample 2** | **Sample 1** | **Sample 2** |
| Avg. thickness (mm) | 48.4 | 49 | 50.9 | 50.2 |
| Avg. diameter (mm) | 99.4 | 99.4 | 99.7 | 100.1 |
| Area (mm$^2$) | 7760.0 | 7760.0 | 7806.9 | 7869.7 |

| **Elapsed time (hours)** | **28 days** | | **180 days** | |
|---|---|---|---|---|
| | **Current (amperes)** | | | |
| | **Sample 1** | **Sample 2** | **Sample 1** | **Sample 2** |
| 0.0 | 0.079 | 0.082 | 0.042 | 0.047 |
| 0.5 | 0.087 | 0.085 | 0.043 | 0.048 |
| 1.0 | 0.089 | 0.088 | 0.043 | 0.049 |
| 1.5 | 0.095 | 0.090 | 0.043 | 0.05 |
| 2.0 | 0.104 | 0.100 | 0.043 | 0.05 |
| 2.5 | 0.105 | 0.105 | 0.043 | 0.051 |
| 3.0 | 0.107 | 0.110 | 0.043 | 0.051 |
| 3.5 | 0.111 | 0.112 | 0.043 | 0.051 |
| 4.0 | 0.113 | 0.113 | 0.043 | 0.051 |
| 4.5 | 0.114 | 0.114 | 0.043 | 0.051 |
| 5.0 | 0.116 | 0.119 | 0.043 | 0.051 |
| 5.5 | 0.117 | 0.121 | 0.043 | 0.051 |
| 6.0 | 0.119 | 0.127 | 0.043 | 0.051 |
| **Calculations:** | | | | |
| Total charge passed (coulomb) | 2263 | 2271 | 928 | 1085 |
| Equivalent charge of standard sample (coulomb) | 2067 | 2074 | 842 | 978 |
| **Average charge passed (coulomb)** | **2070.5** | | **910.0** | |
| **Chloride permeability** | **Moderate** | | **Very Low** | |
| Voltage (V) | 60 | 60 | 60 | 60 |
| Initial current (mA) | 79 | 82 | 42 | 47 |
| Resistance (Ohm) | 0.759 | 0.732 | 1.429 | 1.277 |
| Resistivity (Ohm m) | 121.77 | 115.88 | 219.11 | 200.13 |
| **Avg. Resistivity (Ohm m)** | **118.82** | | **209.62** | |

Mix ID: **B30** Casting date: 17/08/2009

| **Test age:** | **28 days** | | **180 days** | |
|---|---|---|---|---|
| **Samples** | **Sample 1** | **Sample 2** | **Sample 1** | **Sample 2** |
| Avg. thickness (mm) | 49.4 | 49.3 | 50 | 49.7 |
| Avg. diameter (mm) | 99.5 | 99.5 | 99.6 | 99.9 |
| Area ($mm^2$) | 7775.7 | 7775.7 | 7791.3 | 7838.3 |

| **Elapsed time (hours)** | **28 days** | | **180 days** | |
|---|---|---|---|---|
| | **Current (amperes)** | | | |
| | **Sample 1** | **Sample 2** | **Sample 1** | **Sample 2** |
| 0.0 | 0.071 | 0.076 | 0.022 | 0.022 |
| 0.5 | 0.077 | 0.083 | 0.023 | 0.022 |
| 1.0 | 0.080 | 0.087 | 0.023 | 0.022 |
| 1.5 | 0.084 | 0.091 | 0.023 | 0.022 |
| 2.0 | 0.087 | 0.093 | 0.024 | 0.023 |
| 2.5 | 0.090 | 0.094 | 0.024 | 0.023 |
| 3.0 | 0.093 | 0.098 | 0.025 | 0.023 |
| 3.5 | 0.096 | 0.103 | 0.025 | 0.023 |
| 4.0 | 0.097 | 0.105 | 0.025 | 0.024 |
| 4.5 | 0.099 | 0.110 | 0.025 | 0.024 |
| 5.0 | 0.100 | 0.112 | 0.026 | 0.024 |
| 5.5 | 0.106 | 0.120 | 0.026 | 0.024 |
| 6.0 | 0.108 | 0.121 | 0.026 | 0.025 |
| **Calculations:** | | | | |
| Total charge passed (coulomb) | 1977.3 | 2150.1 | 527 | 500 |
| Equivalent charge of standard sample (coulomb) | 1802 | 1960 | 480 | 452 |
| **Average charge passed (coulomb)** | **1881** | | **466** | |
| **Chloride permeability** | **Low** | | **Very Low** | |
| Voltage (V) | 60 | 60 | 60 | 60 |
| Initial current (mA) | 71 | 76 | 22 | 22 |
| Resistance (Ohm) | 0.845 | 0.789 | 2.727 | 2.727 |
| Resistivity (Ohm m) | 133.02 | 124.52 | 424.98 | 430.12 |
| **Avg. Resistivity (Ohm m)** | **128.77** | | **427.55** | |

Mix ID: **B40** Casting date: 13/08/2009

| **Test age:** | **28 days** | | **180 days** | |
|---|---|---|---|---|
| **Samples** | **Sample 1** | **Sample 2** | **Sample 1** | **Sample 2** |
| Avg. thickness (mm) | 49.2 | 47.6 | 49.9 | 49.5 |
| Avg. diameter (mm) | 99.7 | 99.7 | 100.2 | 99.9 |
| Area (mm$^2$) | 7806.9 | 7806.9 | 7881.5 | 7838.3 |

| **Elapsed time (hours)** | **28 days** | | **180 days** | |
|---|---|---|---|---|
| | **Current (amperes)** | | | |
| | **Sample 1** | **Sample 2** | **Sample 1** | **Sample 2** |
| 0.0 | 0.064 | 0.065 | 0.024 | 0.025 |
| 0.5 | 0.066 | 0.072 | 0.025 | 0.027 |
| 1.0 | 0.069 | 0.076 | 0.026 | 0.028 |
| 1.5 | 0.070 | 0.079 | 0.028 | 0.028 |
| 2.0 | 0.072 | 0.081 | 0.029 | 0.029 |
| 2.5 | 0.074 | 0.085 | 0.03 | 0.029 |
| 3.0 | 0.077 | 0.087 | 0.03 | 0.03 |
| 3.5 | 0.078 | 0.089 | 0.03 | 0.03 |
| 4.0 | 0.080 | 0.090 | 0.031 | 0.03 |
| 4.5 | 0.082 | 0.092 | 0.031 | 0.03 |
| 5.0 | 0.083 | 0.093 | 0.031 | 0.03 |
| 5.5 | 0.084 | 0.093 | 0.031 | 0.03 |
| 6.0 | 0.085 | 0.094 | 0.031 | 0.03 |
| **Calculations:** | | | | |
| Total charge passed (coulomb) | 1637 | 1830 | 629 | 627 |
| Equivalent charge of standard sample (coulomb) | 1486 | 1661 | 566 | 567 |
| **Average charge passed (coulomb)** | **1574** | | **566.5** | |
| **Chloride permeability** | **Low** | | **Very Low** | |
| Voltage (V) | 60 | 60 | 60 | 60 |
| Initial current (mA) | 64 | 65 | 24 | 25 |
| Resistance (Ohm) | 0.938 | 0.923 | 2.500 | 2.400 |
| Resistivity (Ohm m) | 148.76 | 151.40 | 394.87 | 380.04 |
| **Avg. Resistivity (Ohm m)** | **150.08** | | **387.45** | |

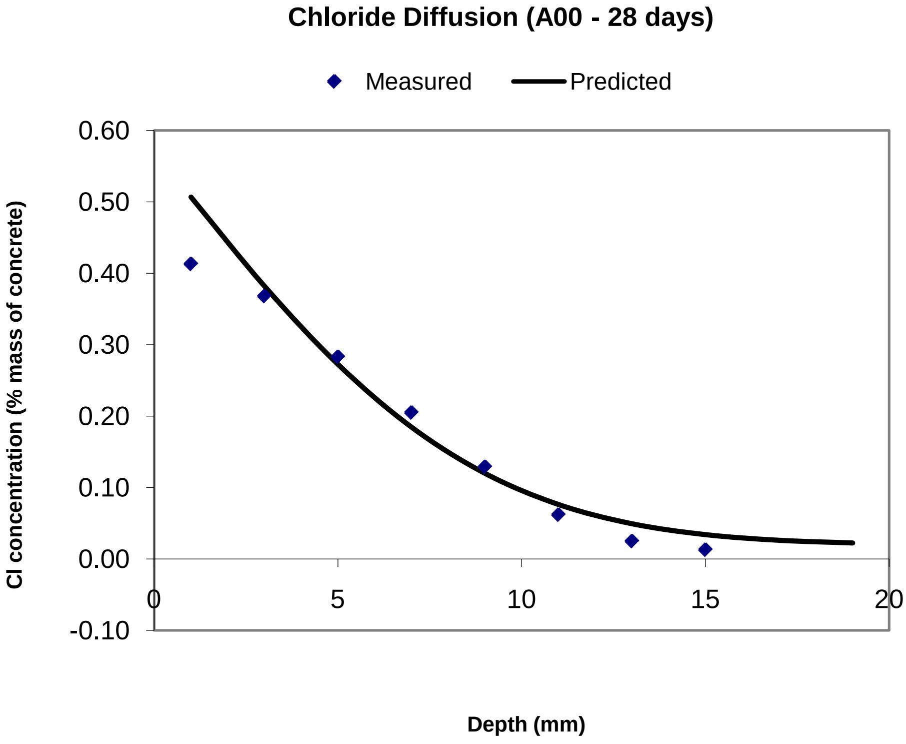
# APPENDIX N: Chloride Diffusion test results

## Chloride diffusion test at 28 days : SERIES – A

Mix ID: **A00** Casting date: 24/08/2009
Test age: **28 days**

| Depth (mm) | $Cl^-$ concentration (mass % of concrete) | | | | | error (measured - predicted) | $(error)^2$ |
|---|---|---|---|---|---|---|---|
| | Sample 1 | Sample 2 | Sample 3 | Average measured | Predicted | | |
| 1 | 0.458 | 0.387 | 0.395 | 0.413 | 0.507 | | |
| 3 | 0.402 | 0.328 | 0.375 | 0.368 | 0.382 | -0.014 | 1.94E-04 |
| 5 | 0.316 | 0.266 | 0.266 | 0.283 | 0.273 | 0.010 | 1.09E-04 |
| 7 | 0.230 | 0.192 | 0.194 | 0.205 | 0.185 | 0.020 | 4.13E-04 |
| 9 | 0.155 | 0.121 | 0.111 | 0.129 | 0.120 | 0.009 | 8.07E-05 |
| 11 | 0.085 | 0.049 | 0.052 | 0.062 | 0.076 | -0.014 | 2.08E-04 |
| 13 | 0.035 | 0.022 | 0.017 | 0.025 | 0.050 | -0.025 | 6.00E-04 |
| 15 | 0.016 | 0.012 | 0.010 | 0.013 | 0.034 | -0.021 | 4.52E-04 |

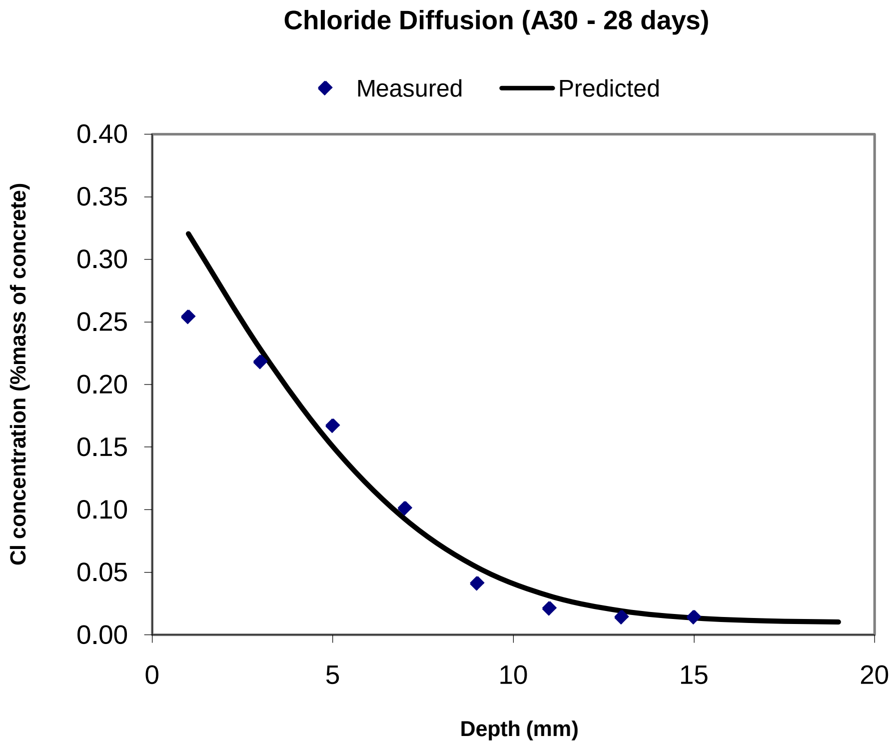
| $C_s$ (%mass of concrete) | $C_i$ (%mass of concrete) | $D_a$ ($m^2/s$) | $t$ (days) | Sum of $(error)^2$ |
|---|---|---|---|---|
| 0.57 | 0.020 | $4.68 \times 10^{-12}$ | 56 | 2.06E-03 |



Mix ID: **A30** Casting date: 10/08/2009
Test age: **28 days**

| **Depth (mm)** | **Cl$^-$ concentration (mass % of concrete)** | | | | | **error (measured - predicted)** | **(error)$^2$** |
|---|---|---|---|---|---|---|---|
| | **Sample 1** | **Sample 2** | **Sample 3** | **Average measured** | **Predicted** | | |
| 1 | 0.272 | 0.232 | 0.259 | 0.254 | 0.320 | | |
| 3 | 0.232 | 0.194 | 0.228 | 0.218 | 0.228 | -0.010 | 1.01E-04 |
| 5 | 0.162 | 0.153 | 0.188 | 0.167 | 0.150 | 0.017 | 2.74E-04 |
| 7 | 0.080 | 0.103 | 0.121 | 0.101 | 0.093 | 0.008 | 7.22E-05 |
| 9 | 0.033 | 0.048 | 0.041 | 0.041 | 0.054 | -0.013 | 1.69E-04 |
| 11 | 0.016 | 0.031 | 0.015 | 0.021 | 0.031 | -0.010 | 1.04E-04 |
| 13 | 0.012 | 0.020 | 0.009 | 0.014 | 0.019 | -0.005 | 2.72E-05 |
| 15 | 0.012 | 0.021 | 0.009 | 0.014 | 0.014 | 0.000 | 1.56E-07 |

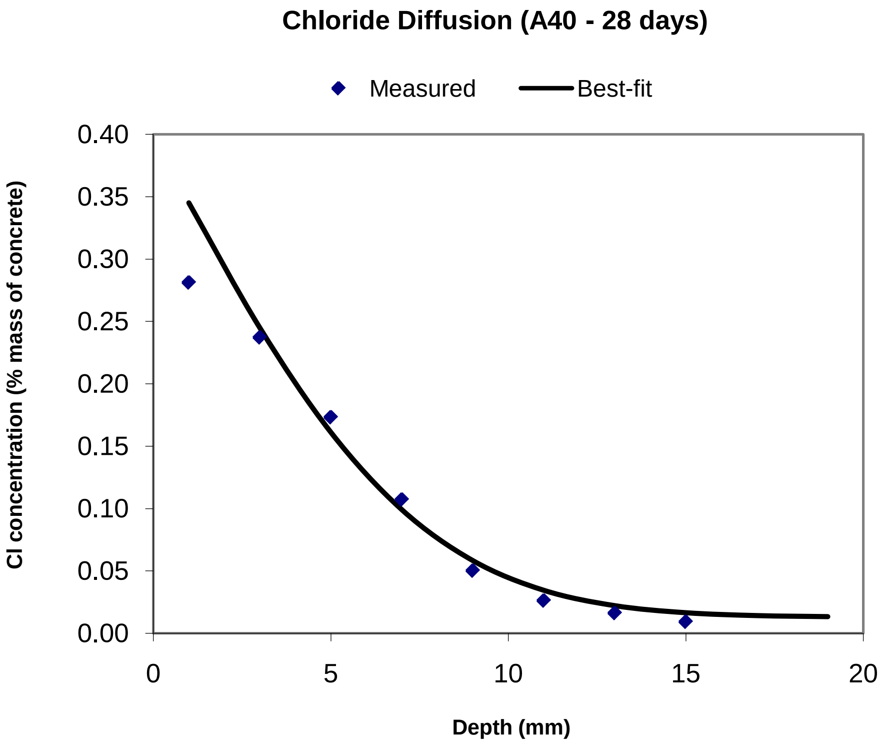
| **$C_s$ (%mass of concrete)** | **$C_i$ (%mass of concrete)** | **$D_a$ (m$^2$/s)** | **$t$ (days)** | **Sum of (error)$^2$** |
|---|---|---|---|---|
| 0.37 | 0.010 | $3.51 \times 10^{-12}$ | 56 | 7.47E-04 |



Mix ID: **A40** Casting date: 07/08/2009
Test age: **28 days**

| **Depth (mm)** | **$Cl^-$ concentration (mass % of concrete)** | | | | | **error (measured - predicted)** | **$(error)^2$** |
|---|---|---|---|---|---|---|---|
| | **Sample 1** | **Sample 2** | **Sample 3** | **Average measured** | **Predicted** | | |
| 1 | 0.308 | 0.269 | 0.267 | 0.281 | 0.345 | | |
| 3 | 0.249 | 0.234 | 0.228 | 0.237 | 0.245 | -0.008 | 6.06E-05 |
| 5 | 0.179 | 0.174 | 0.167 | 0.173 | 0.161 | 0.012 | 1.42E-04 |
| 7 | 0.110 | 0.102 | 0.109 | 0.107 | 0.099 | 0.008 | 6.29E-05 |
| 9 | 0.045 | 0.050 | 0.056 | 0.050 | 0.058 | -0.008 | 6.85E-05 |
| 11 | 0.022 | 0.025 | 0.032 | 0.026 | 0.034 | -0.008 | 7.19E-05 |
| 13 | 0.012 | 0.014 | 0.021 | 0.016 | 0.022 | -0.006 | 3.79E-05 |
| 15 | 0.006 | 0.009 | 0.011 | 0.009 | 0.017 | -0.008 | 5.63E-05 |

| **$C_s$ (%mass of concrete)** | **$C_i$ (%mass of concrete)** | **$D_a$ ($m^2/s$)** | **$t$ (days)** | **Sum of $(error)^2$** |
|---|---|---|---|---|
| 0.40 | 0.013 | $3.42 \times 10^{-12}$ | 56 | 5.00E-04 |

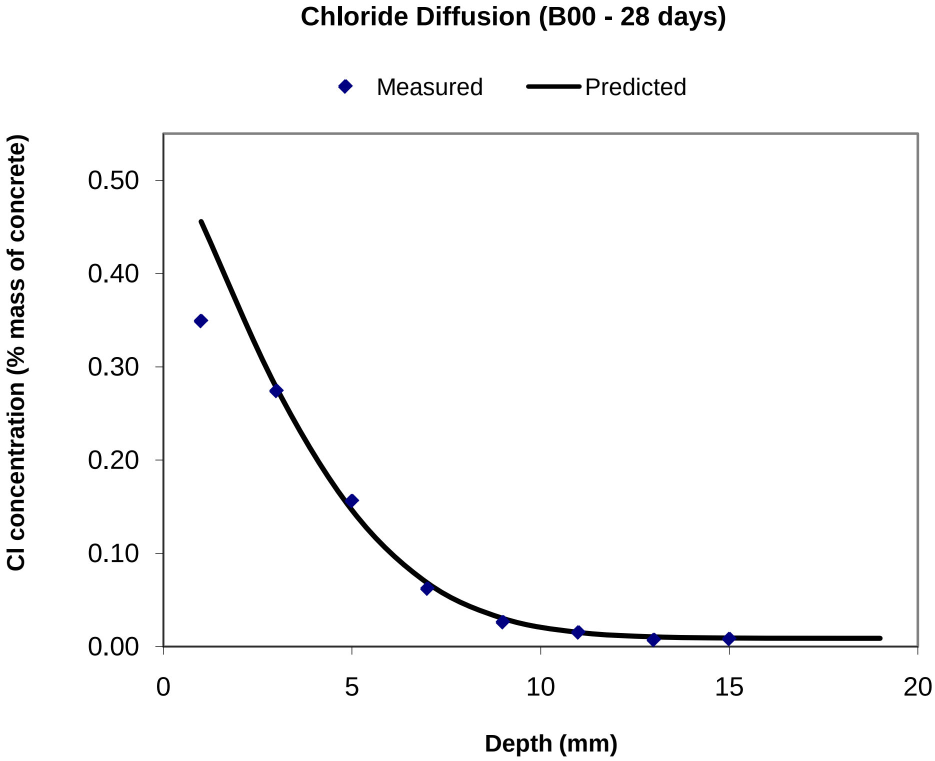


## Chloride diffusion test at 28 days : SERIES – B

Mix ID: **B00** Casting date: 20/08/2009
Test age: **28 days**

| **Depth (mm)** | **$Cl^-$ concentration (mass % of concrete)** | | | | | **error (measured - predicted)** | **$(error)^2$** |
|---|---|---|---|---|---|---|---|
| | **Sample 1** | **Sample 2** | **Sample 3** | **Average measured** | **Predicted** | | |
| 1 | 0.322 | 0.356 | 0.369 | 0.349 | 0.456 | | |
| 3 | 0.242 | 0.283 | 0.298 | 0.274 | 0.277 | -0.003 | 1.02E-05 |
| 5 | 0.126 | 0.164 | 0.178 | 0.156 | 0.146 | 0.010 | 9.35E-05 |
| 7 | 0.037 | 0.041 | 0.087 | 0.055 | 0.068 | -0.006 | 3.89E-05 |
| 9 | 0.019 | 0.016 | 0.041 | 0.026 | 0.030 | -0.004 | 1.88E-05 |
| 11 | 0.014 | 0.011 | 0.021 | 0.015 | 0.015 | 0.000 | 1.42E-07 |
| 13 | 0.010 | 0.005 | 0.006 | 0.007 | 0.011 | -0.004 | 1.28E-05 |
| 15 | 0.009 | 0.007 | 0.007 | 0.008 | 0.009 | -0.001 | 1.74E-06 |

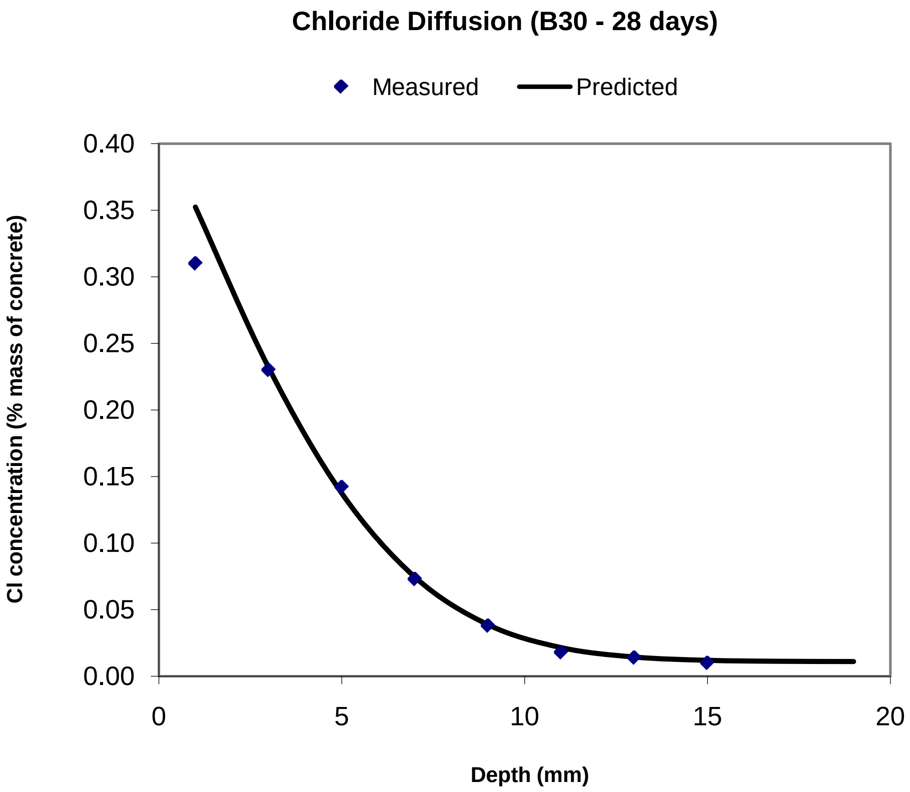
| **$C_s$ (%mass of concrete)** | **$C_i$ (%mass of concrete)** | **$D_a$ ($m^2/s$)** | ***t* (days)** | **Sum of $(error)^2$** |
|---|---|---|---|---|
| 0.55 | 0.009 | $1.97 \times 10^{-12}$ | 56 | 1.76E-04 |



Mix ID: **B30** Casting date: 17/08/2009
Test age: **28 days**

| **Depth (mm)** | **$Cl^-$ concentration (mass % of concrete)** | | | | | **error (measured - predicted)** | **$(error)^2$** |
|---|---|---|---|---|---|---|---|
| | **Sample 1** | **Sample 2** | **Sample 3** | **Average measured** | **Predicted** | | |
| 1 | 0.323 | 0.285 | 0.323 | 0.310 | 0.352 | | |
| 3 | 0.226 | 0.220 | 0.243 | 0.230 | 0.232 | -0.002 | 3.53E-06 |
| 5 | 0.146 | 0.143 | 0.138 | 0.142 | 0.137 | 0.005 | 2.04E-05 |
| 7 | 0.075 | 0.076 | 0.069 | 0.073 | 0.074 | -0.001 | 2.25E-06 |
| 9 | 0.042 | 0.039 | 0.034 | 0.038 | 0.039 | -0.001 | 5.83E-07 |
| 11 | 0.024 | 0.017 | 0.012 | 0.018 | 0.022 | -0.004 | 1.24E-05 |
| 13 | 0.012 | 0.014 | 0.015 | 0.014 | 0.014 | 0.000 | 1.92E-07 |
| 15 | 0.010 | 0.007 | 0.013 | 0.010 | 0.012 | -0.002 | 3.87E-06 |

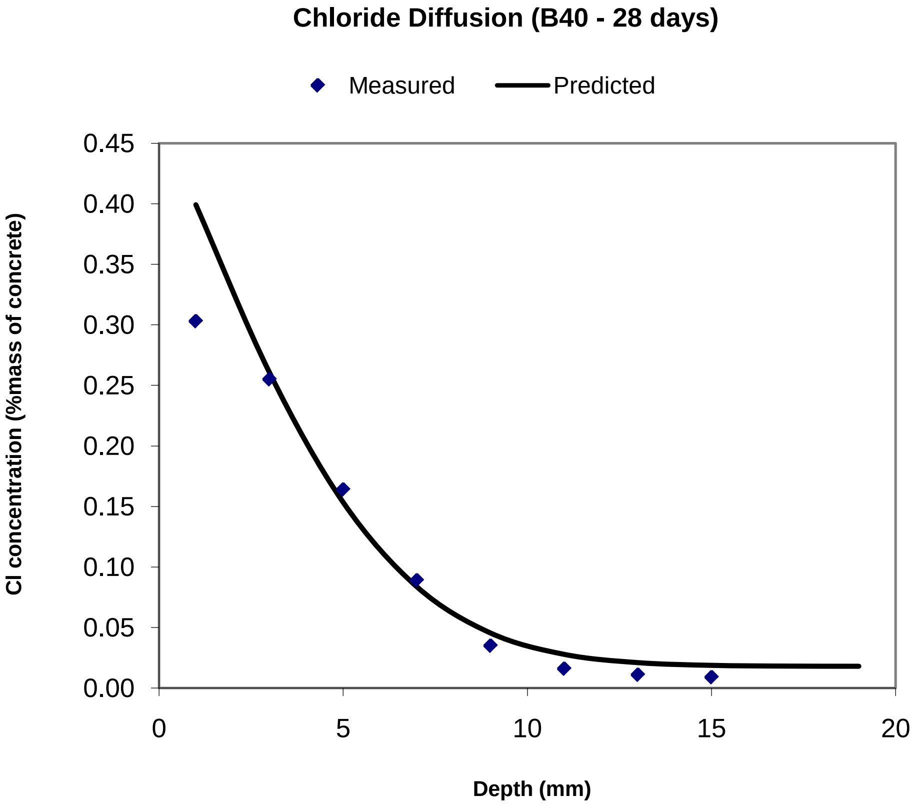
| **$C_s$ (%mass of concrete)** | **$C_i$ (%mass of concrete)** | **$D_a$ ($m^2/s$)** | **$t$ (days)** | **Sum of $(error)^2$** |
|---|---|---|---|---|
| 0.42 | 0.011 | $2.52 \times 10^{-12}$ | 56 | 4.32E-05 |



Mix ID: **B40** Casting date: 13/08/2009
Test age: **28 days**

| **Depth (mm)** | **$Cl^-$ concentration (mass % of concrete)** | | | | | **error (measured - predicted)** | **$(error)^2$** |
|---|---|---|---|---|---|---|---|
| | **Sample 1** | **Sample 2** | **Sample 3** | **Average measured** | **Predicted** | | |
| 1 | 0.308 | 0.315 | 0.285 | 0.303 | 0.399 | - | - |
| 3 | 0.257 | 0.259 | 0.248 | 0.255 | 0.261 | -0.006 | 3.05E-05 |
| 5 | 0.151 | 0.170 | 0.170 | 0.164 | 0.153 | 0.011 | 1.12E-04 |
| 7 | 0.073 | 0.099 | 0.094 | 0.089 | 0.084 | 0.005 | 2.81E-05 |
| 9 | 0.027 | 0.035 | 0.042 | 0.035 | 0.046 | -0.011 | 1.10E-04 |
| 11 | 0.010 | 0.014 | 0.023 | 0.016 | 0.028 | -0.012 | 1.41E-04 |
| 13 | 0.007 | 0.008 | 0.017 | 0.011 | 0.021 | -0.010 | 1.01E-04 |
| 15 | 0.007 | 0.008 | 0.013 | 0.009 | 0.019 | -0.010 | 9.59E-05 |

| **$C_s$ (%mass of concrete)** | **$C_i$ (%mass of concrete)** | **$D_a$ ($m^2/s$)** | **$t$ (days)** | **Sum of $(error)^2$** |
|---|---|---|---|---|
| 0.47 | 0.018 | $2.37 \times 10^{-12}$ | 56 | 0.000619 |

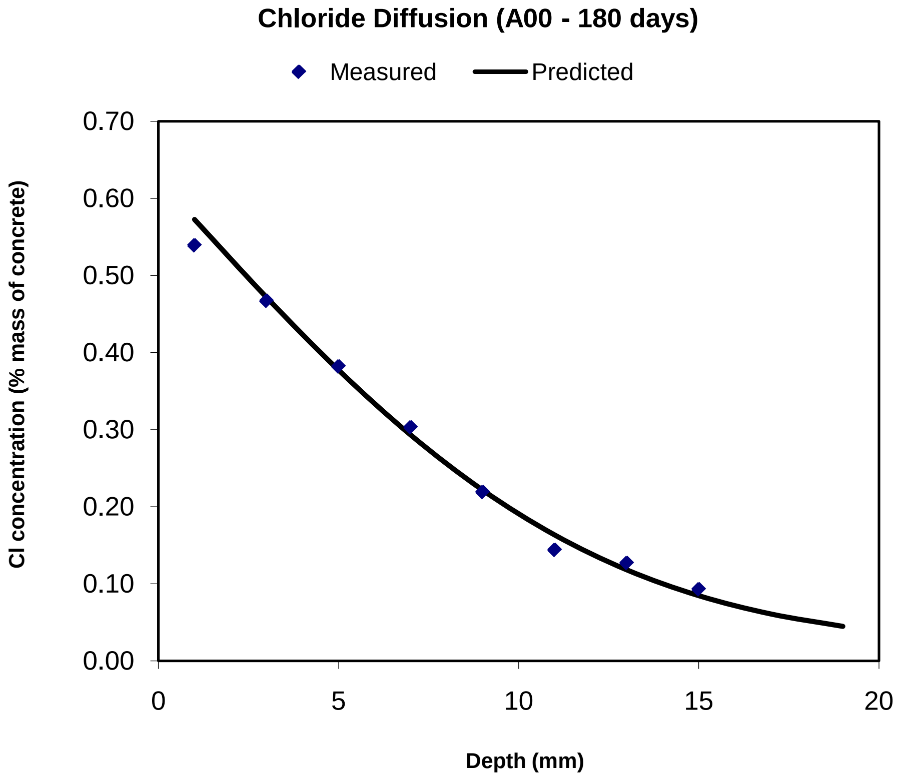


## Chloride diffusion test at 180 days : SERIES – A

Mix ID: **A00** Casting date: 24/08/2009
Test age: **180 days**

| Depth (mm) | $Cl^-$ concentration (mass % of concrete) | | | | | error (measured - predicted) | $(error)^2$ |
|---|---|---|---|---|---|---|---|
| | Sample 1 | Sample 2 | Sample 3 | Average measured | Predicted | | |
| 1 | 0.550 | 0.493 | 0.574 | 0.539 | 0.573 | | |
| 3 | 0.470 | 0.437 | 0.494 | 0.467 | 0.472 | -0.005 | 2.07E-05 |
| 5 | 0.353 | 0.398 | 0.396 | 0.382 | 0.377 | 0.005 | 2.26E-05 |
| 7 | 0.335 | 0.300 | 0.274 | 0.303 | 0.293 | 0.010 | 9.64E-05 |
| 9 | 0.232 | 0.212 | 0.212 | 0.219 | 0.222 | -0.003 | 6.84E-06 |
| 11 | 0.138 | 0.130 | 0.164 | 0.144 | 0.163 | -0.019 | 3.77E-04 |
| 13 | 0.130 | 0.115 | 0.135 | 0.127 | 0.118 | 0.009 | 7.68E-05 |
| 15 | 0.101 | 0.090 | 0.089 | 0.093 | 0.085 | 0.008 | 6.85E-05 |

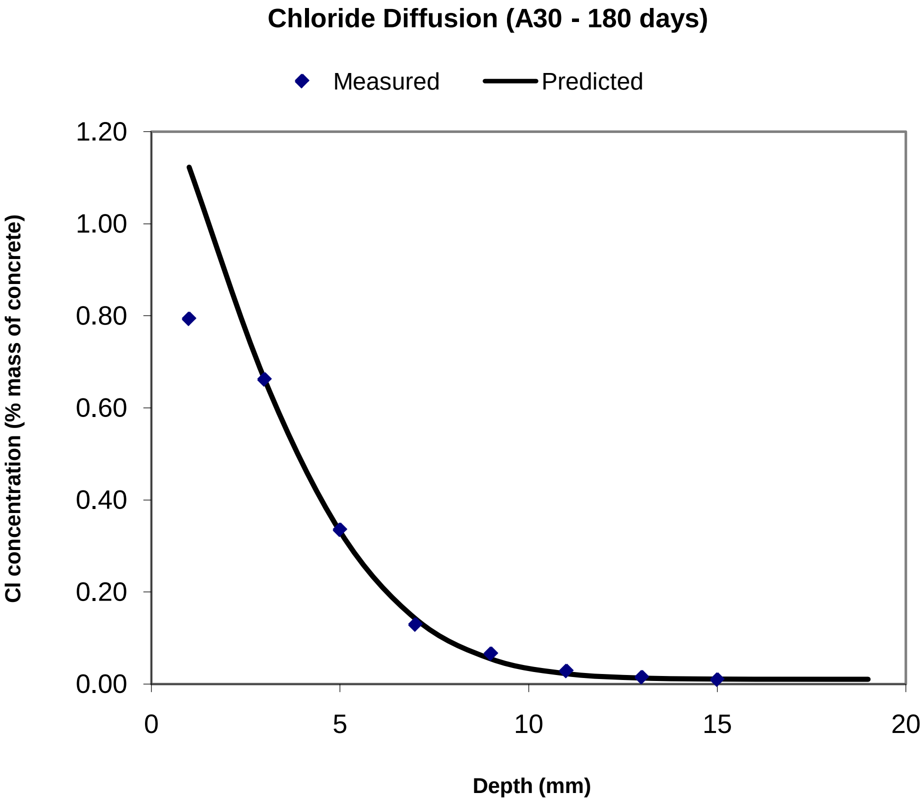
| $C_s$ (%mass of concrete) | $C_i$ (%mass of concrete) | $D_a$ ($m^2/s$) | $t$ (days) | Sum of $(error)^2$ |
|---|---|---|---|---|
| 0.62 | 0.020 | $3.41 \times 10^{-12}$ | 147 | 6.69E-04 |



Mix ID: **A30** Casting date: 10/08/2009
Test age: **180 days**

| **Depth (mm)** | **Cl⁻ concentration (mass % of concrete)** | | | | | **error (measured - predicted)** | **$(\text{error})^2$** |
|---|---|---|---|---|---|---|---|
| | **Sample 1** | **Sample 2** | **Sample 3** | **Average measured** | **Predicted** | | |
| 1 | 0.861 | 0.639 | 0.879 | 0.793 | 1.123 | | |
| 3 | 0.674 | 0.618 | 0.693 | 0.662 | 0.662 | 0.000 | 7.17E-08 |
| 5 | 0.348 | 0.285 | 0.373 | 0.335 | 0.331 | 0.004 | 1.41E-05 |
| 7 | 0.100 | 0.131 | 0.156 | 0.129 | 0.142 | -0.012 | 1.53E-04 |
| 9 | 0.064 | 0.079 | 0.054 | 0.066 | 0.054 | 0.012 | 1.35E-04 |
| 11 | 0.024 | 0.033 | 0.028 | 0.028 | 0.022 | 0.006 | 3.84E-05 |
| 13 | 0.019 | 0.014 | 0.013 | 0.015 | 0.013 | 0.002 | 4.79E-06 |
| 15 | 0.009 | 0.008 | 0.011 | 0.010 | 0.010 | -0.001 | 6.97E-07 |

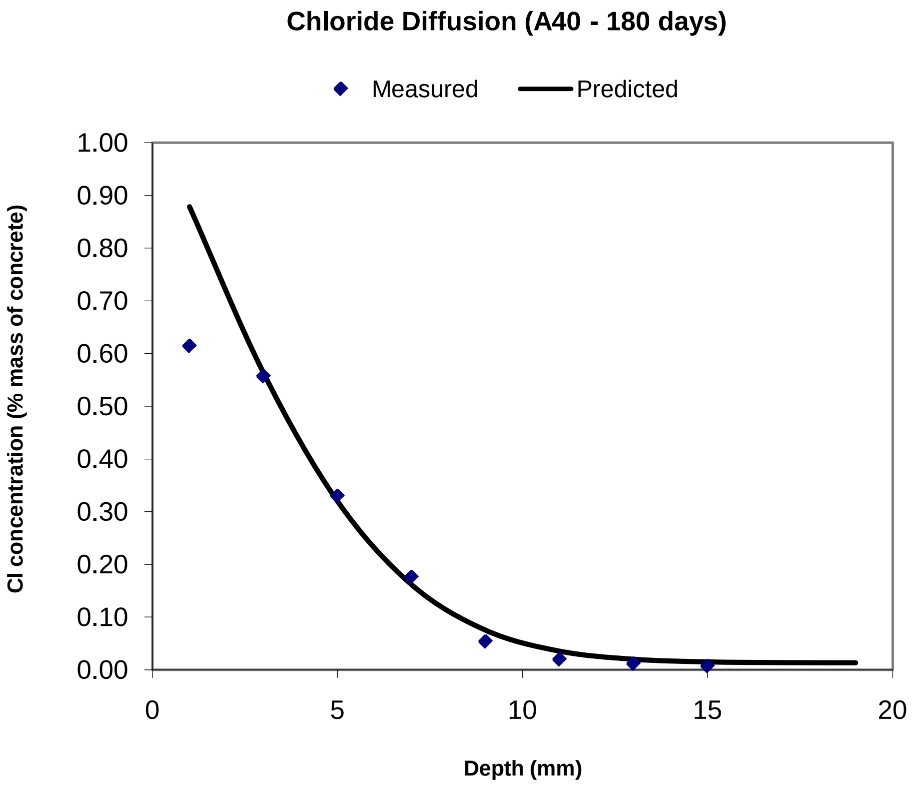
| **$C_s$ (%mass of concrete)** | **$C_i$ (%mass of concrete)** | **$D_a$ ($m^2/s$)** | **$t$ (days)** | **Sum of $(\text{error})^2$** |
|---|---|---|---|---|
| 1.38 | 0.010 | $0.70 \times 10^{-12}$ | 147 | 3.46E-04 |



Mix ID: **A40** Casting date: 07/08/2009
Test age: **180 days**

| **Depth (mm)** | **$Cl^-$ concentration (mass % of concrete)** | | | | | **error (measured - predicted)** | **$(error)^2$** |
|---|---|---|---|---|---|---|---|
| | **Sample 1** | **Sample 2** | **Sample 3** | **Average measured** | **Predicted** | | |
| 1 | 0.517 | 0.717 | 0.609 | 0.614 | 0.879 | | |
| 3 | 0.551 | 0.539 | 0.581 | 0.557 | 0.563 | -0.006 | 4.04E-05 |
| 5 | 0.303 | 0.311 | 0.375 | 0.330 | 0.320 | 0.010 | 1.00E-04 |
| 7 | 0.163 | 0.163 | 0.202 | 0.176 | 0.161 | 0.015 | 2.13E-04 |
| 9 | 0.043 | 0.040 | 0.079 | 0.054 | 0.075 | -0.021 | 4.55E-04 |
| 11 | 0.019 | 0.016 | 0.023 | 0.020 | 0.035 | -0.016 | 2.44E-04 |
| 13 | 0.012 | 0.011 | 0.012 | 0.012 | 0.020 | -0.008 | 6.65E-05 |
| 15 | 0.009 | 0.005 | 0.006 | 0.007 | 0.015 | -0.008 | 5.91E-05 |

| **$C_s$ (%mass of concrete)** | **$C_i$ (%mass of concrete)** | **$D_a$ ($m^2/s$)** | **$t$ (days)** | **Sum of $(error)^2$** |
|---|---|---|---|---|
| 1.05 | 0.013 | $0.90 \times 10^{-12}$ | 147 | 1.18E-03 |

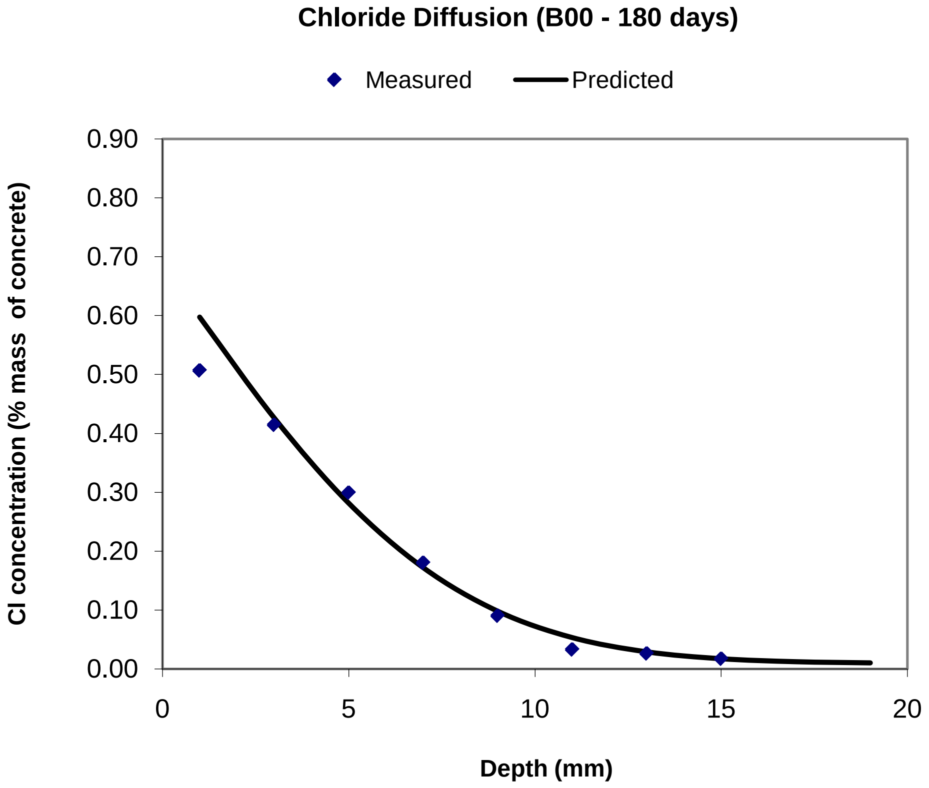


## Chloride diffusion test at 180 days : SERIES – B

Mix ID: **B00** Casting date: 20/08/2009
Test age: **180 days**

| **Depth (mm)** | **$Cl^-$ concentration (mass % of concrete)** | | | | | **error (measured - predicted)** | **$(error)^2$** |
|---|---|---|---|---|---|---|---|
| | **Sample 1** | **Sample 2** | **Sample 3** | **Average measured** | **Predicted** | | |
| 1 | 0.600 | 0.459 | 0.462 | 0.507 | 0.597 | | |
| 3 | 0.476 | 0.389 | 0.379 | 0.415 | 0.426 | -0.011 | 1.30E-04 |
| 5 | 0.327 | 0.278 | 0.293 | 0.299 | 0.281 | 0.018 | 3.27E-04 |
| 7 | 0.164 | 0.189 | 0.188 | 0.180 | 0.172 | 0.009 | 7.37E-05 |
| 9 | 0.077 | 0.092 | 0.102 | 0.090 | 0.098 | -0.007 | 5.40E-05 |
| 11 | 0.036 | 0.029 | 0.034 | 0.033 | 0.053 | -0.020 | 3.96E-04 |
| 13 | 0.027 | 0.024 | 0.028 | 0.026 | 0.029 | -0.002 | 6.14E-06 |
| 15 | 0.012 | 0.014 | 0.026 | 0.017 | 0.017 | 0.000 | 1.09E-07 |

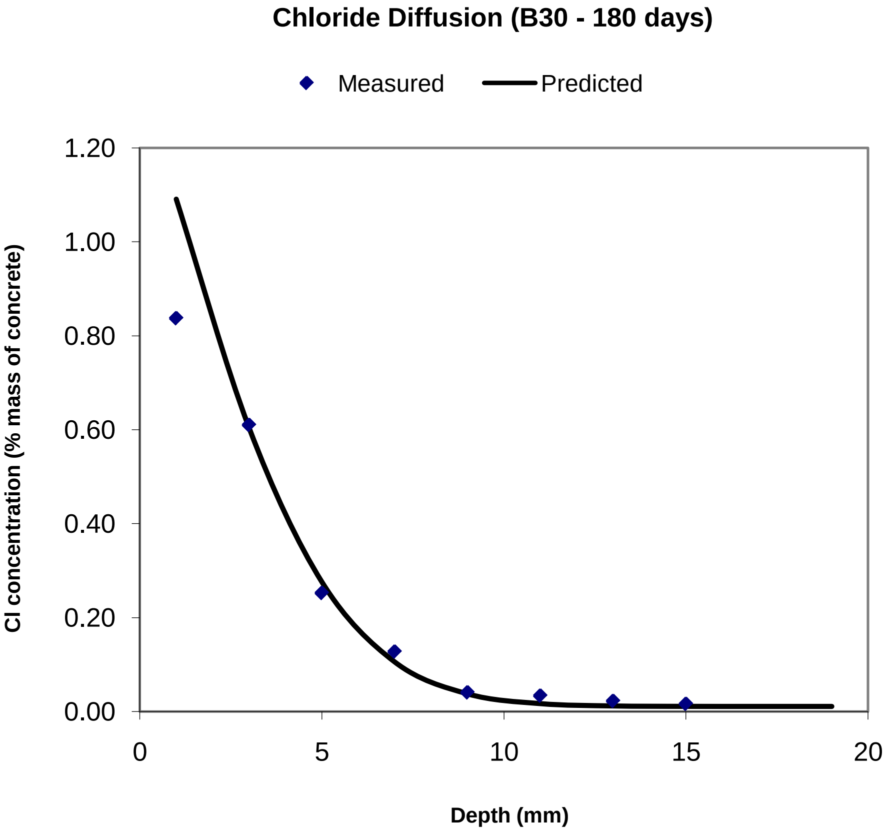
| **$C_s$ (%mass of concrete)** | **$C_i$ (%mass of concrete)** | **$D_a$ ($m^2/s$)** | ***t* (days)** | **Sum of $(error)^2$** |
|---|---|---|---|---|
| 0.69 | 0.009 | $1.40 \times 10^{-12}$ | 147 | 9.87E-04 |



Mix ID: **B30** Casting date: 17/08/2009
Test age: **180 days**

| **Depth (mm)** | **$Cl^-$ concentration (mass % of concrete)** | | | | | **error (measured - predicted)** | **$(error)^2$** |
|---|---|---|---|---|---|---|---|
| | **Sample 1** | **Sample 2** | **Sample 3** | **Average measured** | **Predicted** | | |
| 1 | 0.852 | 0.857 | 0.805 | 0.838 | 1.091 | | |
| 3 | 0.618 | 0.522 | 0.692 | 0.611 | 0.604 | 0.006 | 4.16E-05 |
| 5 | 0.203 | 0.227 | 0.328 | 0.253 | 0.276 | -0.023 | 5.35E-04 |
| 7 | 0.142 | 0.111 | 0.130 | 0.128 | 0.106 | 0.022 | 4.93E-04 |
| 9 | 0.038 | 0.039 | 0.046 | 0.041 | 0.038 | 0.003 | 1.05E-05 |
| 11 | 0.033 | 0.032 | 0.037 | 0.034 | 0.017 | 0.017 | 2.91E-04 |
| 13 | 0.017 | 0.023 | 0.028 | 0.023 | 0.012 | 0.011 | 1.14E-04 |
| 15 | 0.015 | 0.018 | 0.017 | 0.017 | 0.011 | 0.005 | 2.89E-05 |

| **$C_s$ (%mass of concrete)** | **$C_i$ (%mass of concrete)** | **$D_a$ ($m^2/s$)** | **$t$ (days)** | **Sum of $(error)^2$** |
|---|---|---|---|---|
| 1.37 | 0.011 | $0.59 \times 10^{-12}$ | 147 | 1.51E-03 |



Mix ID: **B40** Casting date: 13/08/2009
Test age: **180 days**

| **Depth (mm)** | **Cl⁻ concentration (mass % of concrete)** | | | | | **error (measured - predicted)** | **$(error)^2$** |
|---|---|---|---|---|---|---|---|
| | **Sample 1** | **Sample 2** | **Sample 3** | **Average measured** | **Predicted** | | |
| 1 | 0.842 | 1.086 | 0.803 | 0.910 | 1.066 | | |
| 3 | 0.599 | 0.704 | 0.541 | 0.615 | 0.616 | -0.001 | 9.95E-07 |
| 5 | 0.369 | 0.300 | 0.258 | 0.309 | 0.301 | 0.008 | 6.78E-05 |
| 7 | 0.127 | 0.078 | 0.107 | 0.104 | 0.128 | -0.024 | 5.54E-04 |
| 9 | 0.049 | 0.050 | 0.120 | 0.073 | 0.052 | 0.021 | 4.32E-04 |
| 11 | 0.037 | 0.017 | 0.070 | 0.042 | 0.027 | 0.015 | 2.22E-04 |
| 13 | 0.017 | 0.013 | 0.036 | 0.022 | 0.020 | 0.002 | 5.42E-06 |
| 15 | 0.015 | 0.010 | 0.017 | 0.014 | 0.018 | -0.004 | 1.95E-05 |

| **$C_s$ (%mass of concrete)** | **$C_i$ (%mass of concrete)** | **$D_a$ ($m^2/s$)** | **$t$ (days)** | **Sum of $(error)^2$** |
|---|---|---|---|---|
| 1.32 | 0.018 | $0.65 \times 10^{-12}$ | 147 | 1.30E-03 |