School of Civil and Mechanical Engineering
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Use of quarry rock dust as a fine aggregate in concrete

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DECLARATION

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

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

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

Publications:

- Wellala, D.P.K., Sarker, P. K. and Rajayogan, V. (2017). Fine crushed aggregate as a partial replacement of natural sand in cement mortar. Paper submitted to the *28th Biennial National Conference of the Concrete Institute of Australia, held in conjunction with the 3rd International Congress on Durability of Concrete (ICDC),* Adelaide Convention Centre, Australia from 22 October to 25 October 2017.

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To whom it may concern

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ABSTRACT

This thesis presents a study on the use of fine crushed aggregates as replacement of natural sand in cement mortar and concrete. Material characterisation of three different types of fine crushed aggregates and their effects on the engineering properties of fresh and hardened mortar and concrete specimens were studied.

Quarry dust is a by-product and is a type of fine crushed aggregate (FCA) that needs to be disposed in a safe and environmentally friendly way. The use of fine crushed aggregates as replacement of natural sand is recognised by the Green Building Council of Australia. However, there is a high variability in the properties of fine crushed aggregates and their usage in concrete production is still limited. This thesis presents a study on the use of FCAs sourced from three different types of rocks, namely Granophyre, Basalt and Granite found in Western Australia.

A set of tests were identified to analyse the physical properties of materials and the New Zealand flow cone test resulted valuable information about the void content and loose packing density providing better estimation on shape, texture and grading. A series of experiments were conducted by increasing the proportion of fine crushed aggregate in steps of 20% replacing natural sand. Flow of fresh mortar increased with the increase of two types of FCAs up to 60% replacement of natural sand and then declined with further increase. Compressive strength of mortar specimens increased with the increase of all three types of quarry dust up to 60% and then declined with further increase. Thus, it was found that up to 40 - 60% replacement of natural sand had positive effect on the performance of mortar mixtures. According to the accelerated mortar bar test (AMBT) results, all the FCAs were found to be non-reactive for sand replacements up to 60%. Basalt above 80% and Granite at 100% were found to be slowly reactive, and Granophyre was non-reactive at 100% sand replacement.

Concrete mixtures were produced using the FCAs and the fresh and hardened properties were evaluated. Workability, bleeding, compressive strength, flexural strength and drying shrinkage properties were determined for concretes containing

the FCAs and natural sand. The FCAs showed higher water demand when compared with natural sand. However, concrete even with the 60% replacement of FCAs showed 80 mm slump which can be considered adequate for many applications. Bleeding of concrete decreased with the increase of FCAs. The compressive strength was improved with the increase of percentage of FCAs. Tensile strength of concrete containing FCAs correlated well with compressive strength in a similar way to the concrete containing natural sand. The 56-day drying shrinkage of the mixtures varied in the range of 402 micro strain to 520 micro strain. These shrinkage values are well below the limiting value recommended by the Australian Standard (AS3600, 2009) for general applications. Therefore, use of the fine crushed aggregates up to 40% to 60% can be considered feasible for concrete mixtures.

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GLOSSARY

The terms defined in this section are throughout the thesis. These might differ from the ones employed in national standards, used by industry experts or used in scientific literature due to their ambiguous perception in various fields.

Aggregate – granular material used in construction as a constituent material of concrete or mortar.

Fine aggregates (FA) – aggregate, most of which passes through a 4.75 mm sieve.

Coarse aggregate (CA) – aggregate, most of which retained on a 4.75 mm sieve.

Filler aggregate – aggregate, most of which passes a 0.075 mm sieve, which can be added to construction materials to provide certain properties.

Fines – Particle size fraction of an aggregate which passes the 0.075mm sieve.

Natural aggregate – aggregate obtained by dredging and screening from seabed, riverbed or won from land based sand and gravel pits and that has not undergone a crushing process.

Crushed aggregate – aggregate produced by crushing and screening of rocks.

Natural sand – natural fine aggregate

Fine crushed aggregate (FCA) – rock particles that are created as by-product in creshed coarse aggregate production.

Manufactured fine aggregate (MFA) – aggregate material passing the 4.75 mm sieve, processed from crushed rocks or gravel with intention to be used in concrete or mortar.

Rock filler – rock particles, most of which passes 0.075 mm sieve and that were created by crushing or milling or aggregates.

NOMENCLATURE

L	Principal dimension of a particle long axis	(m)
I	Principal dimension of a particle intermediate axis	(m)
S	Principal dimension of a particle short axis	(m)
ρ_a	Apparent particle density	(t / m^3)
ρ_{bd}	Particle density on dry basis	(t / m^3)
ρ_{bs}	Particle density (SSD)	(t / m^3)
W_a	Water absorption	(%)
ρ_w	Density of water at the test temperature	g/cm^3
m_1	Weight of oven dried test sample in air	gm
m_2	Weight of SSD sample	gm
m_3	Weight of pycnometer and its content	gm
m_4	Weight of pycnometer filled only with water	gm
γ_{mix}	Dry density of mixture	kg/m^3
γ_n	Dry density of natural sand	kg/m^3
γ_{mfs}	Dry density of FCA	kg/m^3
n	Percentage of natural sand	%
$(1- n)$	Percentage of FCA	%
V_c	Void content	%
A	Mass of water required to fill the receiving can	g
B	Average mass of aggregates in three runs in receiving can	g
D	Density of aggregates in dry basis	g/cm^3
D_{25}	Average diameter of mortar spread after dropping	mm
D_0	Base diameter	mm
f_{cm}	Compressive strength	MPa

P	Maximum load at failure	N
A	Area of the loaded surface	mm^2
E_n	Expansion after n-day	%
l_n	Length of the specimen after n-day	mm
l_z	Length of the specimen at the zero reading	mm
l_g	Lffective gauge length of the specimen	mm
V	Total volume of water collected	ml
A	Internal cross sectional area of the bleeding pot	mm^2
t	Selected time interval	min
V_1	Total quantity of bleed water collected during the test	ml
M	Batch mass of concrete from which the sample was taken	kg
V_2	Volume of free mixing water	l
S	Mass of concrete in test specimen	kg
f_c	Compressive strength	MPa
P	Maximum force applied	kN
A	Cross sectional area	mm^2
f_{ct}	Indirect tensile strength	MPa
L	Average length of the sample	mm
D	Average diameter of the sample	mm

CHAPTER 1

1. INTRODUCTION

1.1 Background

Concrete is a mixture of water, cement or binder and aggregates. Significant development in concrete technology has occurred during the past few decades. Today, highly complex mixtures which may contain several chemical admixtures and aggregates of different types and sizes are being used in modern concrete construction work. Researchers have found how aggregates crucially influence the properties of composite materials. It changes from the outdated view of aggregates as being simply inert filler material which can be used as a bulk constituent required for mass and economy.

1.1.1 Aggregates

According to Alexander et al. (2005), aggregates are defined as mineral constituents of concrete in granular or particulate form, usually containing both coarse and fine fractions. ASTM C125 defines aggregates as “a granular material such as sand, gravel, crushed stone or iron blast-furnace slag, used with a cementing medium to form hydraulic cement concrete or mortar”. Australian Standard AS 2758.0 (2009) defines aggregates as “Granular material produced from crushed rock, gravel, sand, metallurgical slag, or reclaimed material, used to make concrete, and more generally in construction work”. The Standard defines the coarse aggregates as aggregates which majority of particles retained on a 4.75 mm AS sieve and fine aggregates as the majority of particles which may have formed naturally in sand deposits or purpose-made manufactured sand, pass the same sieve. Australian Standard AS 2758.1 (2014) defines manufactured fine aggregate as a purpose-made crushed fine aggregate produced from a suitable source material. Further information about the source material has been provided in the same standard. Strength, durability and shape characteristics should be taken into account when manufactured fine aggregates are used. The production procedure of manufactured fine aggregate generally comprises crushing, screening and possibly washing or otherwise dry extraction of fine fraction. Crusher dust with appropriate strength, durability and shape characteristics which meets the specified requirements is allowed to be used as manufactured fine aggregates according to AS 2758.1 (2014).

1.1.2 Consumption of aggregates

Aggregate has become the most abundantly used material beside water and soil in worldwide. Between 70% and 80% of the volume of concrete is consisted of aggregates: both the coarse and fine fractions. Percentage of fine aggregate in concrete usually varies between 35% and 45% of total volume of aggregates. Aggregate consumption basically depends on the development of a country or region, its economic activities and the nature of the construction activities carried out. Alexander and Mindess (2005) estimated the worldwide consumption of aggregates only for concrete construction as 4.5 billion tons per year. The global demand of aggregates can be expected to increase in the near future in order to meet the increasing demand of infrastructures and residential structures. The implications of these figures for the responsible and proper use of such immense amounts of natural resources are clear. Sources for fine aggregates and their limitations shall be discussed separately in the following paragraphs.

1.1.3 Sources of natural fine aggregates and their limitations

Natural fine aggregates for concrete are obtained from a variety of sources. They are mainly from pits, river banks and beds, the seabed, gravelly or sandy terraces and dunes. The existence of natural sands with required qualities for engineering purpose within the economically favourable distance of major developing areas may be acute due to the high demand for huge construction projects in those areas. Aggregate sources should be as close as possible to the place where they are used in order to minimise the transportation cost. River sand, which is one of the constituents used in the production of conventional concrete, has become highly expensive and also scarce as result of the growing pressure because of the negative environmental impact. Therefore, it is important to consider the environmental impact on extracting natural sand from those existing sources.

Challenging issues and need for finding alternative materials to replace natural fine aggregate or river sand in production of conventional concrete shall be discussed in the following paragraph.

1.1.4 Environmental consideration and requirements of alternate materials

Increasing extraction of natural sand from river beds creates serious environmental concerns such as loosing water retaining sand strata, deepening of river causing bank slides, disturbing of aquatic lives as well as affecting agriculture due to lowering the underground water table etc. are few examples. Marine sources may be utilised increasingly in the future as an alternative to land base deposits. While this could be one way of lightening the local shortage, even this could have negative impact from the environmental grounds. Oceans and coastal environment are important to natural resources such as fish breeding and maintenance of the biological life cycles which are not easily recoverable. For an example, Norway (Manning, 2004) has highlighted the consequences due to the extensive use of natural sand and gravel deposits for aggregates in those areas. Furthermore, marine sand dredging in Japan was banned in 2000 and started importing sand from China in 2006 thus making Western Japan dependant on manufactured sand in concrete construction works (Kaya et al. 2009). When these facts are taken into consideration, alternative sources should be developed, researched and successfully applied. This will include industrial waste products from various industries, marginal materials such as porous and low strength rock materials which had been previously disregarded.

1.1.5 Fine crushed aggregates (FCAs) as replacement of natural sand

As natural sources for fine aggregates depleted, fine crushed aggregate (FCA) also known as quarry dust or manufactured sand is one of the best alternative materials which need to be proved that this satisfies the specific requirements to use as an engineering material. Significant research efforts have been put-in to assess the feasibility of using quarry rock dust (manufactured sand) as a partial replacement of concrete constituents with an additional advantage of safe and environment friendly way of their disposal. The production of crushed coarse aggregate is not only causing environmental hazards such as noise pollution, landslides and most importantly as non-renewable materials are used, also approximately 20-35% of the crushed rock ends up as fine waste or “quarry dust” (Harrison et al. 2000). Mitchell et al. (2008) reported that, about 55 million tons of quarry wastes are produced annually in the UK. This incurred an additional cost for the quarry operations as the stockpiles have to be managed. These negative impacts could be minimised by using this quarry waste in concrete applications appropriately. In summary, utilisation of quarry dust with partial or full replacement of natural sand could provide an opportunity to reuse the quarry waste, reduce the demand for natural sand and increase the productivity of quarries resulting in economic and environmental benefits.

As Alexander and Mindess (2005) described, the properties and quality of the material will depend on several factors such as nature of the parent rock, degree of weathering, method of extraction and importantly the crushing and processing. In fact, crushing of different types of rocks (igneous / gritstone / limestone / granite) produces quarry dust with different properties. Considering these facts, this study aims to examine the strength and durability performance of concrete when quarry dust is used as fine aggregate and to address limitations of use in concrete construction work.

1.2 Scope and objectives

The aim of this research is to use FCAs locally available in Western Australia as fine aggregate in concrete as partial replacement of natural sand. A comprehensive study on the materials, mortar and concrete properties was carried out by increasing the percentage of fine crushed aggregates as replacement of natural sand. To achieve this aim the research objectives are:

- To analyse three types of fine crushed aggregates namely Granophyre, Basalat and Granite including flow characteristics.
- To investigate the fresh and hardened properties of cement mortar incorporating the fine crushed aggregates.

- To assess the performance of fresh and hardened concrete containing the fine crushed aggregates of mixtures selected based on the results of mortar.

1.3 Research significance

The significance of this research are as follows:

- Analysing different sources of quarry rock dust for their physical and chemical properties helps to investigate that the sample of quarry dust which has properties more close to river sand.
- Exploring performance of mortar with FCAs is another advantage of this research to investigate the influence of the fine aggregates source on the sand – paste interface in concrete because coarse aggregate was the same for all mixtures in quantity and quality for the concrete samples.
- Analysing of different combinations of samples blending with natural sand is the best way to determine the optimum percentage of FCAs in the investigation of properties of fresh and hardened concrete.
- Development of a 40 MPa concrete mix with FCAs will be beneficial for different concrete structures where special requirements are not required, and it would be more economical and environmental friendly way of producing concrete.

1.4 Thesis outline

This thesis is divided into 7 chapters. Chapter 2 reviews the literature on the effect of aggregate characteristics on mortar and concrete performance on both fresh and hardened states. Also, it covers the requirements and use of FCAs in mortar and concrete applications and the influence of the properties of FCAs on the behaviour of mortar and concrete. As an example the properties such as particle size distribution, shape and texture and their influence on consistency, strength and durability of resulting mortar and concrete. Chapter 3 presents a detailed overview of experimental methods, applicable standards and basic information about the materials used in this research. Chapter 4 describes the methods, results and discussion of the FCAs characterisation study. Further, it compares the properties of FCAs to those of natural sand. The methodology, results and discussion of fresh and hardened mortar are presented in Chapter 5. Chapter 6 explains the methodology and results of concrete made with varying types and percentages of FCAs. Finally, conclusions are drawn from the experimental results and recommendations for future works are given in Chapter 7.

CHAPTER 2

2. LITERATURE REVIEW

2.1 Introduction

Concrete is a composite material usually made from cement aggregates and water. Aggregates are the major components of concrete that occupy about 70% to 80% volume. Usually there are two types of aggregates used in concrete named as coarse aggregates and fine aggregates. Fine aggregates percentage lies between 35 – 45% as a fraction of total aggregates in concrete. Obviously, this large fraction of aggregates influences the properties of concrete performance. Neville (1995) reported that aggregates may not only influence the limit of strength in concrete but also affect the durability and structural performance of concrete. Due to the large demand for aggregate in the market and due to the rapid depletion of natural sources, it has become essential to find alternative fine aggregates for natural sand in concrete. Large number of researches have been conducted to find suitable materials to replace natural sand in concrete. Fine crushed aggregate which is known as some other terms such as quarry dust, manufactured sand or crushed fine sand is one of the alternative materials which is a by-product of quarry operations. In order to ensure the quality of resulting concrete, number of specifications for aggregates have been developed and provided in many countries in the world. However, the fact is not always true that an aggregate which does not comply with a specification makes substandard quality concrete, but if an aggregate found to be failed to comply with many parameters unlikely to make satisfactory concrete (Neville, 1995).

This literature review explore various properties of fine aggregates and the effects of fine crushed aggregate as a partial replacement of natural sand in cement mortar and concrete.

2.2 Shape of aggregate

Shape of aggregate has been described with three different parameters: sphericity, form and roundness (Galloway, 1994). Sphericity is defined by how closely equal the three dimensions of a particle are. The term “shape factor” is used as a measure of the relationship between three principal dimensions of a particle. This is based on the ratios between the proportions of the long, medium and short axes of the particle. The difference between particles which are having similar numerical sphericity can be analysed using the shape factor (Hudson, 1999). Elongation factor and flatness factor are the other two parameters which are used to describe the shape of aggregate. If the principal dimensions of a particle are defined as long (L), intermediate (I) and Short (S), then sphericity, shape factor, elongation and flatness ratio are given by *Equations 2.1 to 2.4.*

$$\text{Sphericity} = \sqrt[3]{\frac{S\,I}{L^2}} \tag{2.1}$$

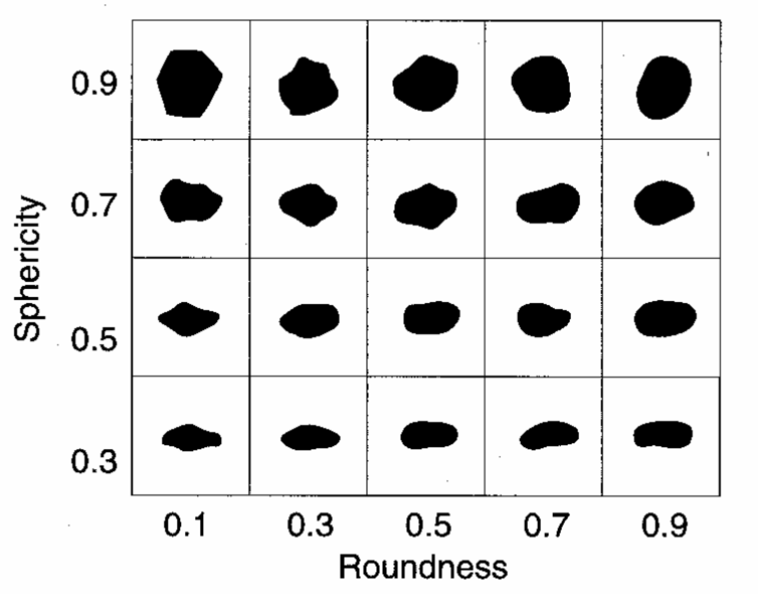
$$\text{Shape factor} = \frac{S}{\sqrt{L\,I}} \tag{2.2}$$

$$\text{Elongation} = I/L \tag{2.3}$$

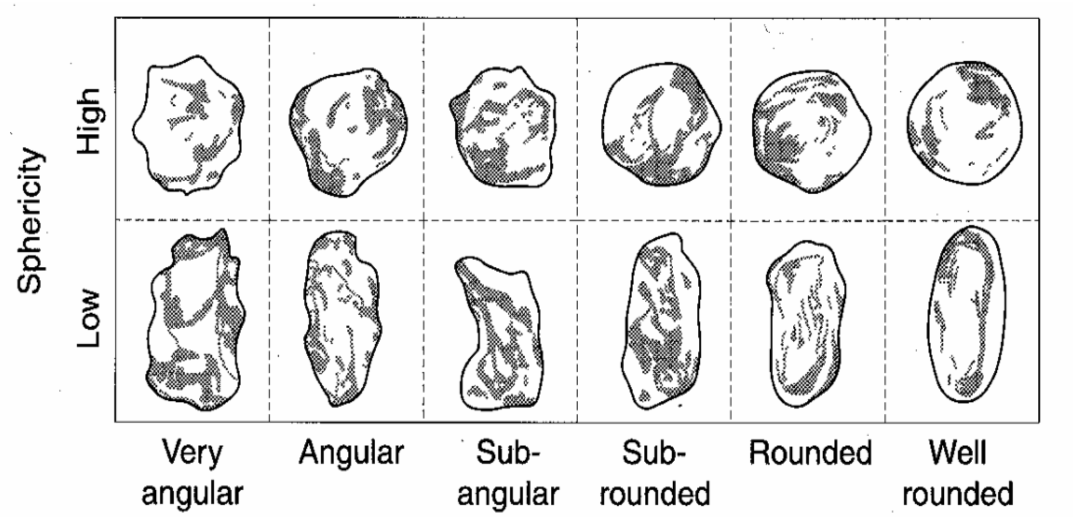
$$\text{Flatness ratio} = S/I \tag{2.4}$$

Kwan (2002) described the shape of a particle with two other terms known as roundness and angularity. Sharpness of edges and corners can be measured by angularity while roundness is used to describe the particle outline. Angularity is numerically defined as the ratio of the statistical average of radius of curvature of the corners and edges of the particle to the radius of the highest caved circle.

The shape of aggregates can be classified from very angular to well-rounded by using the sphericity and roundness parameters. Powers (1953) proposed the charts shown in *Figure 2-1 (a) and Figure 2-1 (b)* for comparison of aggregate shapes (Ahn et al. 2001).



(a)



(b)

Figure 2-1: Particle Shapes (Powers, 1953 and Krumbein, 1963).

However, there are some difficulties to use these methods in practice due to manual measurements along the primary axes of number of particles. Accuracy of data and then the shape and form of particles cannot be assured because of the practical errors. Later, more sophisticated methods were introduced to define the shape and form of aggregate. Photo technology, laser scanners and X-ray tomographs were introduced and data were analysed using mathematical tools such as dimensional analysis (Li, 1993 and Mora, 1998) and spherical harmonic functions (Garboczi, 2002).

Poorly shaped particles could be a reason for the strength reduction in hardened concrete due to high water demand. Apart from that, flaky particles may be oriented in a way it could affect the strength and durability properties when it is compacted (Galloway, 1994). Aggregate with cubical and rounded shapes has less specific surface areas than flat and longer particles. Therefore, the paste required in cubical and spherical particle system is lesser for a specific workability (Shilstone, 1999). Hudson (1997) found that the particles between 4.75mm (No. 4) and 150 µm (No. 100) has more critical effect in terms of specific surface. Shilstone (1990) describes the shape of particles through 4.75mm and 2.36 mm sieves have major effect. When it is considered the compressible packing model the packing density of fine particles has increasing importance (de Larrard, 2002). According to Kaplan (1959), compressive and flexural strengths can be increased by fine aggregates with angular shapes.

2.3 Surface texture of aggregate

The surface roughness is known as the surface texture of aggregate particles. This has been known as the sum of their minute surface features (Quiroga and Fowler, 2006). The texture of aggregate is greatly influenced by the structure of the rock and its degree of weathering. According to Ahn (2001) the surface texture affects the workability, cement content to produce quality mortar mixtures and also the bond between aggregate particles and paste in cement mortar. The improvement in bond strength with the roughness of aggregate increases. On the other hand, when the surface smoothness increases the contact area of aggregate with the paste decreases (Mather, 1966). Thus, particles with polished surface have less bond area in the matrix than rough particles of the same volume. However, particles with improved surface texture will require less paste to lubricate all around them compared to other rougher particles. Therefore, improved packing and equal workability properties can be achieved with lower paste.

Rhoades (1946) described a complex interrelation among the main textural features which can influence the aggregate bond to the cement paste. According to him roughness increases the bond strength to the paste, but it could negatively affect some other important parameters such as porosity, absorption and permeability of concrete zone immediately underlying the surface. However, porosity implied by high penetrability could be a reason to have lower tensile and shear strength. On the other hand, Quiroga et al. (2006) mentioned that the fine aggregates with higher absorption increases the strength while the durability is compromised. Therefore, only the absorption property cannot be considered as the governing parameter of bond characteristic.

Other investigators have reported that the bond strength of mortar produced with fine aggregate, which has very poor absorption, has poor durability performance compared those with slightly higher absorption. The interrelation between bond and absorption may account in part for the bleeding of concrete and can considerably be affected due to the shape and texture of fine aggregates. In fact, particles with rounded and smoot surfaces are more desirable where the bleeding of concrete is important (Washa, 1998 and Kosmatka, 1994).

According to Galloway (1994), grading and shape of aggregate have more influence on workability of concrete than the surface texture. However, surface irregularities which are known as the texture could influence the natural loose and solid packing, since rough textured particles could result in large void content values. The effect of surface texture becomes more important when the particle size is smaller (Hudson, 1999).

2.4 Influence of aggregate grading

Grading of aggregates, which is also known as particle size distribution (PSD), is the separation of aggregate particles to different size fractions, normally by using set of sieves with defined aperture sizes and a shaker. Standard specifications to determine the PSD have been developed in many countries depend on the requirements. In Australia AS 1141.11.1 – 2009 is used to analyse the grading of aggregates. The results usually plotted on a graph with a particle size on a logarithmic scale on X axis (horizontal) and the percentage pass on Y axis (vertical).

There is a difference between continuous and gap grading aggregates. This is shown in *Figure 2-2*. Existence of all particle size fractions are known as well graded or continuous grading of aggregates while the gap grading is defined as grading where one or more intermediate size fractions are not present (Neville, 1995).

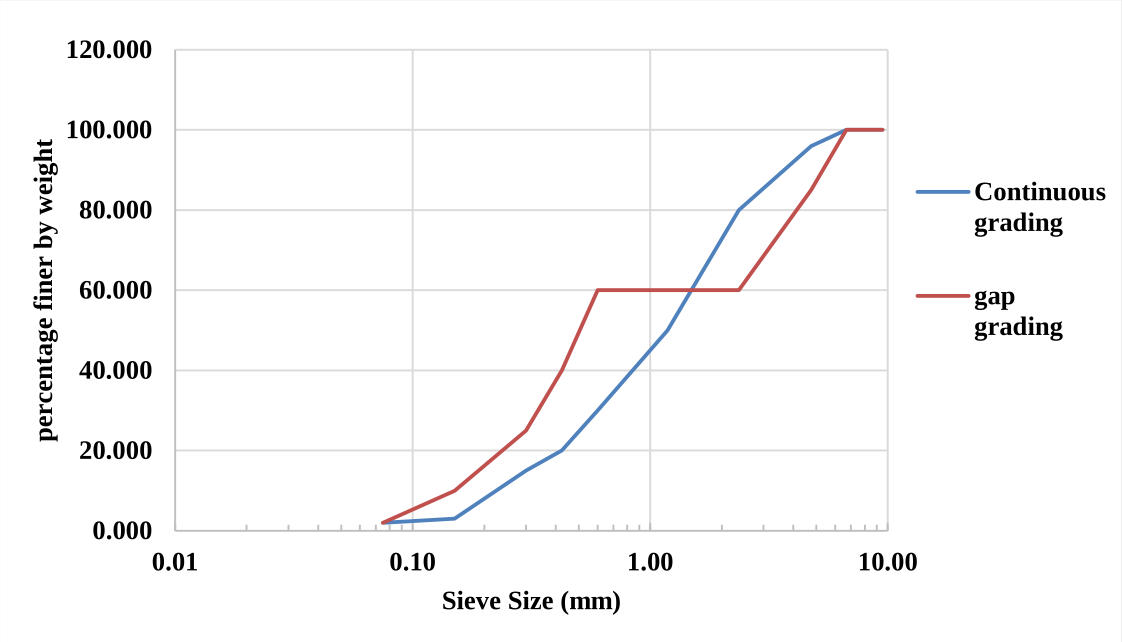


Figure 2-2: Continuous and gap grading curves.

The grading of aggregates influence the consistency of concrete. Consistency of concrete can affect the water and cement requirement, control segregations and has considerable influence on bleeding, placing and final finishing of concrete. These parameters could affect the properties such as strength, shrinkage and other durability parameters of hardened concrete. Newman (2003) explained that segregation and bleeding are controlled by interlocking of larger particles and the surface forces of attraction for smaller particles. Therefore, he concluded that the major cause of segregation and bleeding are poorly graded aggregates and excessive water content.

Grading of aggregate influences some fundamental properties such as packing density and void content, thus affecting workability, segregation, strength and durability properties of concrete. Many investigators showed that well graded aggregates produce more workable concrete than poorly graded fine aggregates (Golterman et al. 1997). When it is considered the grading of coarse and fine aggregates, Hewlett (2003) has concluded that the gradation of fine aggregate has more influence on the properties of concrete than that of coarse aggregates within the permitted standard limits. At one end of the range, coarse sand tends to produce concrete with low workability and harsh mix permitting more water for bleeding. At the other end, unusually fine sand may considerably increase the water demand due to large surface area, but it may provide better cohesiveness.

Marek (1995) has compared the effects of shape and particle size distribution of fine aggregates on properties of concrete. According to Marek (1995), aggregate grading requirements imposed by Portland Cement Association (PCA) is suitable for relatively spherical particles but not suitable for highly non-spherical particles. The test results proved that the use of microfines reduced the voids between aggregate particles lubricating the matrix with no extra water demand for the mixture. Marek (1995) concluded that microfine percentage can be considered to be increased by 5- 10 percent without clay or silt.

Aggregate grading requirements stated in ASTM C33 has become the basis for many of the specification in use today. Clelland (1980) reporting in a New Zealand standard bulletin, pointed out that some sands which are complied with the specification do not produce good quality concrete while some sands that do not fit into the grading curves have been successfully used in concrete. This indicates that the grading of fine aggregates should not be the single parameter to decide the suitability of aggregates for a particular application but their performance should be evaluated experimentally before come to a conclusion.

Aggregates with uniform size distribution gives higher packing resulting improved density and thereby lower permeability (Golterman et al. 1997) and higher abrasion resistance (Metha and Monteiro, 2005). Furthermore, mixtures with well-graded aggregates need comparatively small quantity of paste lowering bleeding, creep and shrinkage (Washa, 1998). Pumping and finishing could be difficult with the mixtures with unbalanced quantities of coarse and fine aggregate proportions due to inadequate paste and could be a reason for excessive bleeding and permeability (Shilstone, 1999).

2.5 Effect of water absorption

The amount of water that an aggregate can hold within its pores to reach saturated but surface dry state is defined as the water absorption. The excess water on the surface of aggregate particles including the water in pores known as the water content of aggregates. The absorption and water content of aggregates is important as it influence the effective water to cement ratio and then the consistency of concrete mixes. Water absorption of aggregates in dry condition will decrease the consistency of the mix considerably. On the other hand aggregates with extra water (larger than the absorption value) increase the effective water to cement ratio of the mix and increase the consistency of the mix consequently reducing the strength of concrete.

Poon et al. (2004) investigated the consistency and strength of concrete mixes with aggregates having different moisture states. They measured the initial slump and found that the oven dried sample showing the highest slump than that of the air dry, saturated and surface dry aggregates. They added extra water to each mix to compensate the absorption capacity of aggregates appropriately. But the rate of absorption is a time dependant process, resulting the extra water added to the mix contributed to the consistency of concrete. Therefore they concluded that the initial slump of the concrete mix dependant on the free moisture within the mix. The compressive strength of concrete at 28 days was found to be similar in air dry sample and the concrete with Saturated Surface Dry (SSD) sample. Strength of oven dried sample was found to be much lower as a result of stopping the absorption of extra water by the aggregate coating of cement paste. Eventually the extra water may have contributed to increase the effective amount of water in the mix and consequently having a high water to cement ratio. A similar study has been conducted by Alhozaimy (2009) and he has observed higher initial slump values for higher levels of initial free water in limestone aggregates. Furthermore, he has observed that most of the water was absorbed by the aggregates during the first 15 minutes after the mixing and it was 75% of its capacity for limestone in this study. Also he found that the strength of dry aggregates was higher than the wet ones and this was attributed to the higher w/c ratio as the extra water was not fully absorbed. It is very important to consider the water content and absorption capacity of aggregates during proportioning and mixing of concrete as these aggregate parameters may influence the properties of concrete at fresh and hardened states.

2.6 Mineralogy and coating

Properties of concrete fundamentally varies due to the influence of mineralogical composition of aggregates. Strength, stiffness and prolonged deformations of hardened concrete greatly affected by the aggregate type used for concrete (Alexander, 1996). Physical and chemical properties aggregates and particle shape and texture provided that a crusher is used to reduce its size, are mainly influenced by the type of parent rock. The chemical compassion of aggregates cannot be used alone to determine whether it will make good quality concrete (Neville, 1995). However, these properties can be used to identify minerals which could interfere with the cause of alkali-silica or alkali- carbonate reactions. Also it will be helpful to identify the presence of clay minerals in aggregates.

Aggregate particles may be covered by clay, silt or crushing dust coating around the surface. Water demand and the bond between the paste and aggregate can vary as a result of coating: the layer of material covering the surface of aggregate. Mather (1966) mentioned that the coatings can interact chemically with cement and can affect negatively in concrete.

2.7 Effect of maximum aggregate size

Large aggregate particles in a concrete mix consume small amount of water to wet the surface with cement paste. Therefore, increasing aggregate size causes a reduction in water demand for a specific workability requirement and cement content in concrete. Thus, the lower water to cement ratio increase the strength of concrete. However experimental results have shown that for cement content exceeding 300 kg/m^3, maximum size of aggregate is about 38mm to achieve the best compressive strength, as the benefit of water reduction for the smaller surface area. But, there are limitations in maximum aggregate size for structural concrete due to the thickness of the section of concrete element, congestion due to the less spacing of reinforcement (Neville, 1995 and Newman, 2003).

In an investigation done by Meddah et al. (2010) when the cement content remain constant, the compressive strength of normal concrete was increased with a larger maximum size of aggregates are used in the mix, although for high strength opposite trend was observed. He has concluded that for normal strength concrete, the weakest part of the concrete is considered to be the transition zone between the aggregates and cement paste. Therefore, larger maximum size aggregates reduces the surface area and the transition zone decreasing the volume of weakest phase. In high strength concrete the weakest phase to be considered as the aggregate bulk. Therefore, large coarse aggregate particles may have high probability of crack initiation through them reducing the compressive strength.

Concrete properties such as workability, strength, shrinkage and permeability are affected by the maximum size of aggregates. More workable concrete can be produced with large coarse aggregate because of the lower specific surface (Washa, 1998). In concrete with high strength performance and with less water - cement ratio and increased cement fraction, highest strength can be reached only with optimal maximum size of aggregates (Popovics, 2008 and Washa, 1998).

2.8 Effect of fines content of fine aggregates

Fines in AS 2758:2014 are defined as aggregate particle size fraction passing the 0.075 mm sieve. According to the standard percentages should not be exceeded, by 2% in coarse aggregates, 5% in natural fine aggregates and 20% in crushed fine aggregates in concrete applications. Moderate fine content is more desirable in concrete applications as it fills the voids and improves the cohesion and finishability in concrete (Newman, 2003). However, excessive use of fine content could result increasing water demand, reducing aggregate-cement paste bond which is directly impair the strength and durability properties of concrete. Furthermore, silt and clay particles within the fine content could increase the water demand considerably in order to wet the intrinsic large specific surface area. Another negative effect can be highlighted as the expansive nature of clay particles when contact with water, adversely affect the hardening process of concrete and the strength (Neville, 1995).

Norvell et al. (2007) investigated the consistence and strength of mortar replacing the fine aggregate content up to 4 % by different types of clay and clay-sized particles. It was found that clays demand more water and superplasticisers depending on their interlayer absorption capacity while clay sized particles do not influence significantly the water demand. Also, he found that the compressive strength is much lower in clays and clay-sized particles did not affect the compressive strength for the same water to cement ratio. Similar study was conducted by Fernandes et al. (2007) and he used clay contaminated sand to investigate the consistency and compressive strength of concrete. He concluded that all types of clay demanded more water for a fixed consistency and the strength subject to the relevant increase in water/cement ratio.

Jackson et al. (1996) presented an investigation report using higher fine content in Portland cement concrete. They concluded that the material passing from 0.075mm sieve contribute additional paste in mixes where the cement content is less than 275 kg/m^3 (lean mixes) increasing the workability and finish ability. Celik et al. (1996) examined the influence of crush fine filler aggregates with a partial replacement of fine aggregates in a concrete mix. They observed that the slump decreases with the increase of filler content as a result of increase in surface area demanding more water for a constant consistency. At the 10% replacement of filler content in the mix, the maximum compressive strength and flexural strength was observed. They concluded that the increase in strength is due to the void filling capacity of fine content increased. Further increase of fine content reduced the compressive strength as the insufficient paste to cover all the aggregate particles. The flexural strength followed the same pattern of compressive strength: increasing and decreasing with strength respectively.

Another investigation was conducted by Quiroga (2003) and he used fines in mortar and concrete and found that there is an important effect of fine content on mortar and concrete consistency. He also found that the increase in water demand for the increased fine content. It was observed that limestone fine required lower amount of water than granite and trap rock (basaltic igneous rock) while the trap rock reported highest strength in his study.

In summary, using very fine aggregate particles in concrete application especially in lean concrete mixes with angular aggregate particles is useful for the consistency and packing density. Also improves the strength and permeability characteristics. There is an optimum amount of fine to be used as the water demand increases with further increase of fine content due to the increase in specific surface area. This will outweigh the beneficial effects.

2.9 Effect of fine crushed aggregates or manufactured sand

This section discusses the researches on fine crushed aggregates (FCAs) in which the performance of FCAs and its influence on fresh and hardened properties of concrete have been investigated. This section will discuss various properties of concrete presenting some observations and conclusions from different research studies.

Fine aggregates for concrete and other engineering applications are mainly obtained from different sources such as natural sand derived from marine dredging, land based sand pits or river beds, manufactured sand as a by-product of quarry operations or purposely made FCAs and recycled aggregates by crushing of demolition waste. Due to the rapid depletion of natural resources, FCA is one of the significant alternate materials for fine aggregates, which can support the increasing global demand. Common variations of FCA are shape, texture and fine content in comparison with natural sand. These common characteristics detrimentally influence concrete while some properties are elevated. Due to these reasons, FCAs are reluctantly accepted within the construction industry (Harrison et al. 2000).

2.9.1 Fine content of FCA and limitations

Manufactured sand is a purpose-made crushed fine aggregate product from a suitable source material and designed for use in concrete or road construction. Usually, fine crushed sand consists of microfines in between 10% to 20%, which is much higher than natural sand. In natural sand, microfine consists of deleterious particles such as clay minerals and organic matters which demand more water in concrete (Hudson, 1999). Due to this reason, microfine content of natural sand has been limited in many specifications. For an example, AS 2758.1-2014 limits the fine content (passing through 0.075 mm sieve) of 2% for coarse aggregate, 5% for natural fine aggregates and 20% for manufactured fine aggregates. However, provision has been made to use more than 20% microfines in manufactured sand, if there is demonstrated history for successful use. *Table 2-1* shows the percentage of microfines limits in some countries.

Table 2-1: Limits of microfine in different countries (Quiroga, 2004).

Country	**Microfines Allowed (Percentage of crushed sand)**
United States	5% to 7% passing 75μm sieve
Spain	15% passing 63μm sieve (for crushed sand)
England	15% passing 63μm sieve
India	15% to 20%
Australia	25%
France	12% to 18% passing 63μm sieve depending on purpose of use.

Hudson (1997) stated that his research has proved fine crushed aggregates with 15 to 20 percent microfines can be used in concrete without negative effects on the quality of concrete. Furthermore, when the fine fraction of crushed sand is used in concrete, the behaviour of concrete could be improved if the particles are well shaped (Dewar and Anderson, 1992). According to Forster (1994), strength, workability and density of lean concrete mixtures can be improved by adding a small quantity of crushed fines passing 0.075 mm sieve. Hudson (1997) suggested that by adding suitably graded microfines in concrete, packing density can be improved resulting in low permeability. Bleeding and segregation can be considerably reduced by adding microfines in the mixture (Hudson, 1999 and Kalcheff, 1977). Large quantity of microfines could negatively affect on shrinkage properties (Hudson, 1997) and finishability could also be affected (Malhotra, 1985).

Considerable amount of research has been carried out on using quarry dust as a replacement of natural sand in concrete. The percentage of quarry dust used in different countries varied based on the availability of natural sand. On the other hand, limitations on the percentage of quarry dust have been imposed considering its effects on the properties of concrete such as slump or pump ability, finish ability and plastic shrinkage. The effects of the percentage of quarry dust on concrete properties have been studied by various researchers.

2.9.2 Effects of FCAs on consistency and water demand

With the understanding of the basic differences between FCAs and natural sand, this section will narrate the research investigations and their results and conclusions made for the combine effects of shape, texture and grading on properties of concrete and mortar.

Angular shape of the FCAs with the comparison of natural sand creates higher void content for the same grading (Marek, 1995). When the void content increases the water demand for constant consistency in a drop table test increases. Nevertheless, the inclusion of fines in his experiments were not influenced the consistency and no additional water required. According to his explanations, voids are filled with fines and more water is tied up in the system. But at the same time, microfines themselves lubricating the system and offset the reduction in consistency due to the less free water in the mixture. An opposite trend was observed by Celik et al. (1996) who observed a reduction in slump with the limestone quarry dust passed through 75 µm sieve in a partial replacement of FCAs in his experiments. This behaviour was discussed as the need of more water to cover the specific surface area increased with the increase of percentage of dust. Similar results were observed and discussed by Quiroga et al. (2006) where they concluded that there is an increase water demand in concrete for FCAs with high fine content.

Those differences in observations can be explained by the mix composition of concrete or mortar as discussed in Section 2.8 and as concluded by some researchers who used FCA concrete mixtures. For an example, Li et al. (2009) showed that increase of limestone filler up to 15% increased the constancy and strength for low strength concrete. But, in high strength concrete adding of filler up to 7% did not influence the workability while higher level decreased the slump. Goncalves et al. (2007) also supported with the same findings stating that the effects of fines in FCAs depend on the specific mix composition. They concluded that the improvement in consistency of mortar increasing the fine content at w/c ratio of 0.4. Kroh (2010) suggested the optimum fine content as 10% in use of limestone quarry dust as the consistency improved till that level and 15% inclusion level reduced the consistency. This indicates that up to 10% increase of fine content which lubricated the matrix and at 15%, the increase in specific surface area demanded more water from the paste to wet all the particles resulting reduction in consistency. According to Jones et al. (2003), reasons for these findings are due to the combine effects of shape, texture, packing, filler and mix composition.

2.9.3 Effects of FCAs on compressive strength and flexural strength

Balamurugan et al. (2013) conducted an experimental study to describe the variation in the strength of concrete when replacing sand by quarry dust from 0% to 100% in steps of 10% and reported that the sample with 50% replacement of river sand has marked the maximum strength. Mechanical properties of self-compacting concrete (SCC) incorporating quarry dust powder (QDP) (8%-10%) had been equal to or better than those of SCC prepared with either silica fumes

(SF) plus FCA or fly ash (FA) alone (Dehwah et al. 2007). Raju et al. (2011) reported that river sand can be completely replaced by quarry dust by 100%.
Shahul et al. (2009) reported that quarry rock dust and marble sludge powder as 100% substitutes for natural sand in concrete. It was found that compressive strength and splitting tensile strength of concrete made of quarry rock dust were 14% more than the conventional concrete. But the unit weight of concrete was not affected. However, the good performance was observed when limestone waste was used as fine aggregate, together with marble powder (Omar et al, 2012).

It was suggested that concrete containing mixtures of lateritic sand and quarry dust can be reasonably used in structural elements as for normal concrete (concrete with river sand as fine aggregate) by Joseph et al. (2012). Boskey et al. (2014) reported that quarry dust in addition to waste plastic as filler improves the mechanical properties of concrete when used along with super plasticizer. Also, they have studied about the effect of replacement of natural sand by quarry dust and waste plastic on compressive & split tensile strength of M20 concrete.

Franklin et al. (2014) reported that fine aggregate can be replaced by stone dust with 40% and at this replacement level compressive strength is more than reference concrete. 20% quarry dust had been chosen in the mix design of 60 MPa and 70 MPa of high-strength rice husk ash concrete incorporating quarry dust as a partial substitute for sand by Ramen et al. (2011). It was reported that the compressive strength is not affected much by replacement up to 40%; however, the flexural strength at all ages improved significantly at all the replacement levels (30, 40, 50, 60 and 70%), (Sandeep et al. 2014). Sai et al. (2014) conducted a SWOT analysis to evaluate the performance of concrete using quarry rock dust as a partial replacement of fine aggregate.

Chandana et al. (2013) reported that some properties of quarry dust and the suitability of those properties to enable them to be used as partial replacement materials as fine aggregate in concrete. He investigated that 50 % replacement of natural sand by crusher dust does not significantly effect on the reduction of mechanical properties such as compressive strength, flexural strength and split tensile strength in paving concrete.

2.10 Summary

In summary, this narrative literature review explored that the effects of aggregate characteristics on performance of concrete and cement mortar. Researchers have shown that the combination of type, shape, texture, grading, and amount of quality of microfines of FCAs plays a vital role in consistency and the compressive strength of concrete and mortar. Most of the researchers have paid their attention on the effects of grading, amount of fines or the parameters mentioned above. However, the combined influence of these parameters of FCAs are not fully observed and understood. Furthermore, the quantification of these parameters is difficult.

The present research attempts to understand various properties of three different FCAs of Western Australia and their performance of concrete and mortar.

CHAPTER 3

3. EXPERIMENTAL PROGRAMME

3.1 Overview

It was observed from a comprehensive literature review that different types of crushed fine aggregates generated in Western Australia have not been subjected to research. Therefore, assessing the properties of fresh and hardened concrete using these fine crushed aggregates would be beneficial for the local concrete industry. It will open some opportunities for sustainable utilisation of these by-products in place of natural sand. Three deferent types of fine crushed sands were used in this study. It was aimed to investigate the workability, strength and durability related properties of concrete utilising the fine crushed aggregates. Experiments were conducted in three stages. Material properties were investigated in Stage-1. Based on the material properties and to determine the effect of these properties on performance characteristics of mortar, a series of experiments were conducted on mortar in Stage-2. Concrete mix designs was carefully chosen on the basis of results obtained from a series of mortar test and tests of concrete were conducted in Stage-3. Testing methodology, analysis of results and discussion of material used, mortar and concrete are discussed in Chapters 4, 5 and 6, respectively. Experiments and relevant standards followed in every stage of experiments are summarised in this chapter. Also, the materials used in these experiments are identified and briefly discussed in this chapter.

3.2 Stage 1 – Determination of aggregate properties

In this study, three types of FCA locally available in Western Australia were used. All the other materials used in this study, such as coarse and fine aggregates, cement and water are those commercially available for the production of conventional concrete. Properties of coarse and fine aggregates were tested according to the Australian Standards as outlined in *Table 3-1*. The details of test procedure, results and discussions on the materials are presented in Chapter 4.

Table 3-1: Tests of aggregates and relevant standards.

Aggregate properties	Standard followed
Particle size distribution /fineness modulus	AS 1141.11.1-2009 (Standards Australia)
Apparent particle density – fine aggregate	AS 1141.5 – 2000
Dry particle density – fine aggregate	AS 1141.5 – 2000
SSD particle density – fine aggregate	AS 1141.5 – 2000
Water absorption – fine aggregate	AS 1141.5 – 2000
Apparent particle density –coarse aggregate	AS 1141.6.2 – 1996
Dry particle density – coarse aggregate	AS 1141.6.2 – 1996
SSD particle density – coarse aggregate	AS 1141.6.2 – 1996
Water absorption – coarse aggregate	AS 1141.6.2 – 1996
Sand flow test	NZS 3111 –New Zealand sand flow cone method

3.3 Stage 2 – Evaluations of mortar properties

After investigating the properties of materials, mortar tests were conducted in the second stage of experiments. In order to study the effects of FCA on fresh and hardened mortars, a series of mortar tests were conducted as shown in *Table 3-2*. The details of mixture proportions, mixing, casting of specimens, curing, test procedure, results and discussions on mortars are presented in Chapter 5.

Table 3-2: Tests of mortar and relevant standards.

Test	Standard followed
Flow of hydraulic cement mortar	ASTM C-1437 - 07
Potential alkali – silica reactivity (ASR)	AS 1141.60.1 – 2014 (accelerated mortar bar method)
Compressive strength	ASTM C109/C 109M-07 (ASTM standard 2008)

3.4 Stage 3 – Evaluation of concrete properties

In the third stage of experiments, concrete testing was planned based on the results of mortar tests and the effects of FCA on the fresh and hardened concrete properties were evaluated. Tests of concrete and relevant standards followed are shown in *Table 3-3*. The details of mixture proportions, mixing, casting of specimens, curing, test procedure, results and discussions on concretes are presented in Chapter 6.

Table 3-3: Tests to assess the characteristic of the concrete mixtures.

Properties	Tests	Standard followed
Fresh Concrete	Slump	AS 1012.3.1-2014 (Standards Australia)
	Bleeding	AS 1012.6-2014 (Standards Australia)
Hardened Concrete	compressive strength	AS 1012.9-2014 (Standards Australia)
	Drying shrinkage	AS 1012.13-1992 (Standards Australia)
	Splitting tensile strength	AS 1012.10-2000 (Standards Australia)

3.5 Descriptions of materials

3.5.1 Fine crushed aggregates (FCA)

Three different FCAs were selected from three different locations in Western Australia for this study. The types of the source rock were:

Type A: Granophyre

Type B: Basalt

Type C: Granite

The FCAs consisted of particles of varying shapes and textures. A commercially available natural sand from Western Australia was used as the reference type of sand. *Figure 3-1* shows the physical appearances of these three types of FCA. It can be seen that the proportions of finer particles were more in the FCA types B and C than in FCA type A. Relatively more elongated and flaky particles can be seen in FCA type B. FCA type A had a more rough texture than the other two types.

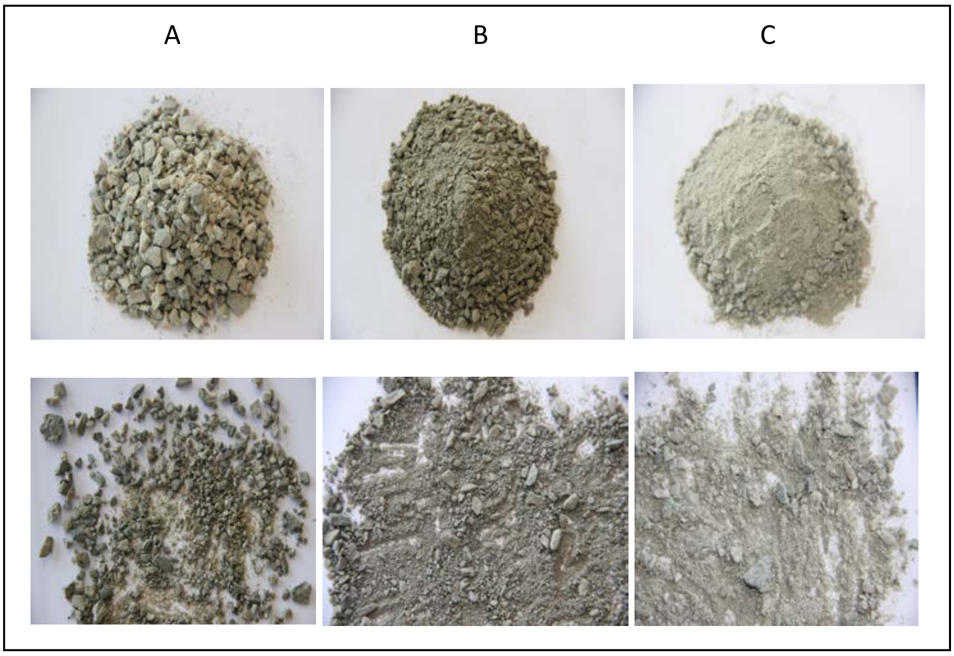


Figure 3-1: Physical appearance of FCAs (A – Granophyre, B- Basalt and C-Granite).

3.5.2 Fine aggregates (natural sand as control sample)

Fine aggregate which is locally commercially available in Western Australia was used as the reference fine aggregate. Physical appearance of the natural sand used is shown in *Figure 3-2*. The sand particles were of approximately spherical in shape and of much more uniform in sizes than the FCAs.

Figure 3-2: Physical appearance of natural sand.

3.5.3 Ordinary Portland cement (OPC)

A general purpose cement complying with the Australian Standard (AS-3972, 2010) was used in the experiments. Calcium, silicon, aluminium and iron are the main components of OPC. Calcium is usually produced from limestone and the other ingredients such as iron, silica and alumina are extracted from clay, sand and iron ores. The chemical composition and physical properties of the used OPC, as provided by the supplier, are given in *Table 3-4* and *Table 3-5*, respectively. It can be seen that the compositions and the physical properties of the cement were within the limiting values recommended by the Australian Standard.

Table 3-4: Chemical compositions of cement (mass %).

Parameter	Typical value	Range	specification as per AS3972-2010
SiO_2	21.1	20.4-21.8	-
Al_2O_3	4.7	4.3-5.1	-
Fe_2O_3	2.7	2.5-2.9	-
CaO	63.6	62.6-64.6	-
MgO	2.6	2.4-2.8	-
SO_3	2.5	2.2-2.8	3.5% max
LOI_3	2	1.0-3.0	-
Chloride	0.01	0.01-0.03	-
Na_2O equivalent	0.5	0.40-0.60	-

Table 3-5: Physical properties of cement.

Parameter	Test method	Typical value	Range	specification as per AS3972-2010
Fineness index (m^2/kg)	AS2350.8	400	370-430	-
Normal consistency (%)	AS2350.3	28.5	27.5-29.5	-
Soundness (mm)	AS2350.5	1	0-2	5 mm max
Initial setting time (min)	AS2350.4	120	90-150	45 mins minimum
Final setting time (min)	AS2350.4	195	165-225	10 hrs max
Compressive strength (MPa)	3 days	38	35-42	-
	7 days	47	44-51	25 MPa min
	28 days	60	56-64	40 MPa min

3.5.4 Coarse aggregates

Coarse aggregate plays a vital role on the performance of concrete. Nominal maximum sizes of 10/7 mm, 14 mm and 20 mm of crushed granite that are commercially available in Western Australia were used throughout the experiments. Since grading of coarse aggregate influences fresh and hardened properties concrete, the particle size distributions of aggregates were examined for its suitability according to the Australian Standard (AS 2758.1 -1998). It is very important to consider the surface texture of aggregate as it has an effect on the bond between aggregates and the binder. A rough surface texture gives the cementing material something to grip, producing a stronger bond, and thus creating stronger concrete. It was found that the coarse aggregates used in this study complied with requirements stated on the Australian Standard (AS 2758.1) Table B5.

Water absorption of aggregates is another important parameter which affects the water demand of a concrete mixture. Therefore water absorption of all fractions of coarse aggregates were examined and checked against the requirements of Australian Standard.

3.5.5 Water

Pollutions in blending water, when over the top, may influence not just setting time, strength of concrete, and volume constancy (length change), yet may likewise bring about corrosion of reinforcement (ACI 318 segment 3.4). The consumable faucet water utilized as a part of the mixture was taken from the Curtin University research laboratory which is initially provided by Water Disseminating Authority of Perth, Australia.

3.6 Summary

Based on a comprehensive literature review in Chapter 2 and having a basic understanding of the materials going to be used in the experiments, a series of testing to evaluate material properties was planned. This chapter identified the properties of FCAs to be tested in order to characterise the materials. The properties of mortars and concretes in order to evaluate the effects of three types of FCA were also identified. The relevant test methods for FCAs, mortars and concretes were tabulated and briefly presented in this chapter. The details of the tests and results are presented in the Chapters 4, 5 and 6.

CHAPTER 4

4. PHYSICAL PROPERTIES DIFFERENT CRUSHED AGGREGATES

4.1 Investigation of material properties

It is important to determine the material properties such as particle size distribution, water absorption, relative densities, void content and packing density of fine aggregates in order to characterise the material and understand its effects on the properties of mortar and concrete. The test methods for these properties and the results are comprehensively discussed in this chapter.

4.1.1 Particle-size distribution

This test is conducted to determine the proportions of particles of various sizes in a specific aggregate. The method involved using a tower of interlocking sieves with openings that gradually decreased in size from the largest at the top to the smallest at the bottom. The test was conducted in accordance with the AS 1141.11.1-2009.

For fine aggregates:

The procedure for particle size distribution test for fine aggregates is as follows:

- The test portion of (1kg) fine aggregates was dried to a consistent weight at a temperature of 110 ± 5 ^{o}C in an oven and weighed.
- For the test, 800g of oven dried fine aggregate was taken for type A (Granophyre) because of the nominal size of 10mm and 500g for type B (Basalt) and C (Granite) considering the nominal size of 7 mm. The aggregates test was isolated in two sections as the mass of the tried sample was surpassing than the prescribed limits outlined in AS1141.11.1 -2009. Toward the finish of the test the held weight of particles on each sieve was merged together and the combined value was considered as single strainer capacities.

- An arrangement of sieves (9.50 mm, 6.70mm, 4.75mm, 2.36mm, 1.18mm, 600μm, 425μm, 300μm, 150μm, 75μm) were shaken by a mechanically operated shaker after including the test sample.
- On completion of the shaking for about 10 minutes, weight of the material on each sieve was measured by an electrically operated digital balance.
- The percentage of materials passing through each sieve was calculated on the basis of the total mass including the 75 μm sieve.

For coarse aggregates:

The procedure for particle size distribution test described in fine aggregates was followed with the difference described below.

- Aperture size of sieve set was changed in descending order from 26.5mm, 19mm, 9.5mm, 4.75mm, 2.36mm and 1.18mm and shaking was conducted approximately for 10 minutes.

4.1.2 Water absorption and relative density

Water absorption and relative density of aggregates including coarse, fine aggregates and FCAs were determined to understand the capacity of water that each material can hold in dry and SSD conditions. These tests were conducted as per the steps described below.

For fine aggregate:

- The test method described in AS 1141.5– 2000 was carefully studied and followed in determining the water absorption and relative density of fine aggregate.
- Initially the test sample was submerged in water for 24 hours. Air entrapped was removed by gentle agitation with a rod till no air bubbles appeared on the surface.
- After 24 hours, test sample was drained off and spread on an impervious surface. Then the sample was progressively and evenly dried with a moving current of warm air and loosely placed in a conical mould.

- The sample was compacted by tamping 25 times with a tamping rod in such a way that the tamping rod was dropped just from 10mm above the surface.
- Then the cone was lifted carefully and the slump was observed not at the first attempt but the following attempt. If the material was too dry at the first time, some water was added and sample was left for 30 minutes. Slumping of aggregate indicate that it has reached to saturated surface dry condition.
- At the point that sample reached to the SSD condition total mass (m_2) of the sample was determined.
- The aggregate sample was placed into the pycnometer and filled with water up to 500ml mark. Then it was shaken to remove air bubbles and final adjustment for the water level was done. The mass of the pycnometer and its content (m_3) was determined.
- Then the aggregate sample was carefully spread on a tray and oven dried at 105°C to 110°C for a constant mass and the weight (m_1) was determined.
- At last, mass of the pycnometer filled with water (m_4) was determined.

For coarse aggregate:

The procedure described in AS 1141.6.2 – 1996 was used to determine the apparent particle density, dry particle density, saturated surface dry density and water absorption of coarse aggregates. Steps followed in the previously described procedure for fine aggregates are similar to the coarse aggregates except the method to determine the SSD state of coarse aggregate. Saturated surface dry condition was achieved in coarse aggregate by rolling them on a dry cloth for bigger particles and a warm current of air for small particles retained on 4.75 mm sieve. Approximately 2 kg of materials was used in this experiment.

Equations 4.1 to 4.4 were used to determine the apparent particle density, dry particle density, saturated surface dry density and water absorption of both coarse and fine aggregates.

The apparent particle density (t / m^3)

$$\rho_a = \frac{m_1 \times \rho w}{m_4 + m_1 - m_3} \text{ -- } (4.1)$$

The particle density on dry basis (t / m^3)

$$\rho_{bd} = \frac{m_1 \times \rho w}{m_4 + m_2 - m_3} \text{ -- } (4.2)$$

The particle density (SSD) (t / m^3)

$$\rho_{bs} = \frac{m_2 \times \rho w}{m_4 + m_2 - m_3} \text{ -- } (4.3)$$

The water absorption (%)

$$W_a = \frac{(m_2 - m_1) \times 100}{m_1} \text{ -- } (4.4)$$

where:

ρ_w = the density of water at the test temperature in t / m^3

m_1 = weight of oven dried test sample in air, g.

m_2 = weight of SSD sample, g

m_3 = weight of pycnometer and its content, g and

m_4 = weight of pycnometer filled only with water, g

4.1.3 Flow test of fine aggregates by the New Zealand aggregates flow cone method

Three series of aggregates flow tests for each type of FCA (A, B and C) were conducted replacing natural sand by 20% increments from 0% to 100%, in accordance with the NZS 3111 Standard. *Figure 4-1* shows the aggregate flow cone test used in this study.

- For the aggregates flow test, sufficient amount of aggregates (to obtain a sample of 2500 g after cooling) was dried at 110 ºC to a constant mass and it was then sieved on 4.75mm mesh after cooling to the room temperature.
- Weight of the material retained on the sieve was determined and recorded as a percentage to the mass of original sample amount. This is known as the percentage oversize material in the aggregates.
- A mass of aggregates which is 0.38 times its dry density was taken from the material smaller than 4.75 mm. This mass of aggregates was mixed vigorously for 30 seconds and used for the aggregates flow test.
- Dry density of a mixture of natural sand and FCA was calculated by Equation 4.5, and the required mass of mixture was calculated.
- This well mixed mass of aggregates was placed carefully with the finger over the orifice, in to the flow cone which is mounted its top ring horizontally and centrally above the overflow can with the receiving can.
- The finger was removed quickly from the orifice and the stop watch was started simultaneously.
- The time taken for the aggregates to run out of the cone was recorded and the mass of aggregates in the receiving can was measured. The same test procedure was repeated after blending the aggregates with overflow can to obtain three measurements of flow time.
- Void content of the tested sample was calculated using Equation 4.6.

Figure 4-1: New Zealand flow cone test of fine aggregates.

The equation to calculate dry density of a mixture of natural sand and FCA reads:

$$\boldsymbol{\gamma_{mix}} = \frac{\gamma_n \times \gamma_{mfs}}{\gamma_{mfs}(n\%) + \gamma_n(1-n)\%} \quad \text{-- (4.5)}$$

where,

γ_{mix} = the dry density of the mixture

γ_n = the dry density of natural sand

γ_{mfs} = the dry density of FCA

n = the percentage of natural sand and

(1- n) = the percentage of FCA.

Void content $Vc = \left(1 - \frac{1000\,B}{AD}\right) \times 100$--- (4.6)

where,

A = the mass in grams of water required to fill the receiving can

B = the mass in grams of aggregates contained in the receiving can as obtained from the average of three runs, and

D = the density of aggregates in dry basis.

4.1.4 Particle shape and texture analysis by photographs

In this part of experiment, a new procedure has been suggested to analyse the particle shape and texture of fine aggregates. A visual judgement can be made to compare the shape and texture of fine aggregates with this methodology. Following steps were taken in this method.

- Enough fine aggregate sample was taken as it is for the particle size distribution.
- Sieved the samples and segregated each fraction of aggregates and labelled them with the sieve number.
- A Canon 550 D camera was fixed above a horizontal table to have enough focal length to focus the materials underneath.
- The material was spread on a white colour paper and a photo was taken.
- This procedure was repeated for all types of materials.
- The photos were printed and compared with the natural sand.

4.2 Results and discussion

4.2.1 Particle size distribution (PSD)

Fine aggregates:

Particle size distribution test was performed in accordance with the AS1141.11.1-2009. Variation of the particle size of natural sand is shown in *Figure 4-2 (a)*. Particle size distribution of type A, B and C fine crushed aggregates is shown in *Figure 4-2 (b)*. Upper limit and lower limit for both natural and fine crushed aggregates have been plotted in both the figures.

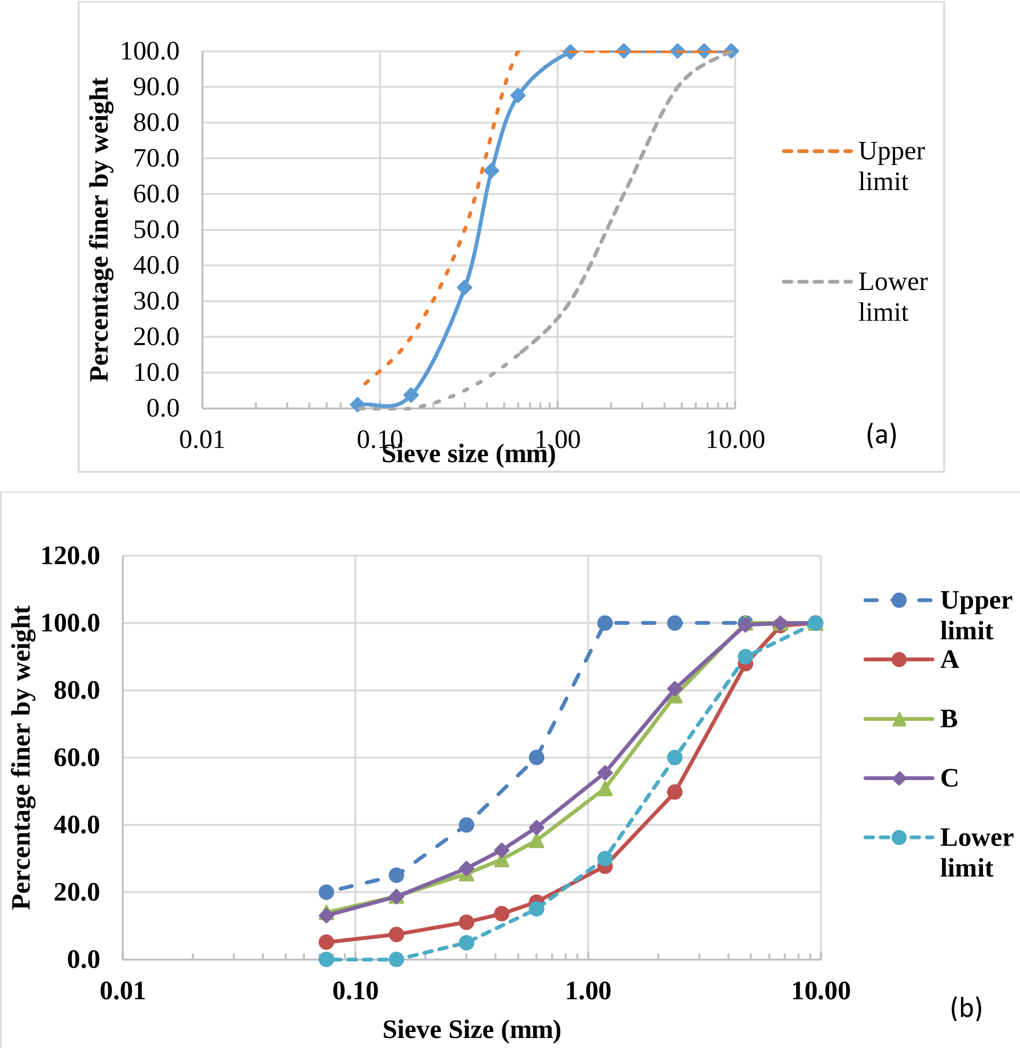


Figure 4-2: (a). Particle size distribution of natural sand (control) (b). Particle size distributions of FCAs (A – Granophyre, B- Basalt and C-Granite).

It can be seen from the comparison that the size distribution of natural sand has a narrower range than that of the fine crush aggregates. In general natural sand consists of particles with limited particle sizes than fine crushed aggregates. Maximum retention of Granophyre (A) was noticed on the sieve 2.360 mm (passed through 4.750 mm) approximately 38% while Basalt (B) and Granite (C) are 22% and 19% respectively. Maximum retention of Basalt (B) and Granite (C) could be noticed on the sieve 1.180 mm (passed through 2.360 mm) and that is 28% and 25%, respectively. Corresponding retention values of A is 22%. The maximum retention of natural sand is on 0.600mm sieve and marked the value as 32%. Based on the particle size distribution of these materials, a sequential arrangement can be made in terms of coarser to finer: Granophyre (A), Granite (C) and natural sand (control). Furthermore, the microfine content (smaller than 0.075 mm) of the fine aggregate are at the order of control – 0%, A - 5%, C – 13% and B - 17%. According to the Australian Standard (AS2758.1:2014) for aggregates and rock for engineering purposes, the allowable percentage of particles fine than 0.075mm is 20% for FCA and 5% for natural fine aggregates. Therefore, the particle size distribution and the fine contents are in acceptable limits for the construction work. Particle size distribution of FCAs and natural sand are given in *Table A1* of Appendix A.

Coarse aggregates:

Crushed granite aggregates were used as coarse aggregates. Coarse aggregates were 20mm, 14mm and 10/7 mm in sizes and different proportions were used. Therefore, the PSD of these materials were tested as per AS 1141.11.1 – 2009. Particle size distribution of 20mm, 14mm and10/ 7 mm aggregates are shown in *Table 4-1*, *Table 4-2* and *Table 4-3*, respectively. Percentage passing of materials have been compared with the values taken from Table B1 of AS 2758.1- 2014 (aggregates and rock for engineering purposes, part 1). Nominal size of single size aggregates was considered in this comparison.

Table 4-1: Percentage passing of 20 mm aggregates and recommended grading requirements as per AS 2758.1-2014.

Sieve size/ (mm)	% passing	Table B1 (AS2758.1:2014)	
		Lower limit	Upper limit
19.000	96.0	85.0	100.0
13.200	14.2	-	-
9.500	1.9	0.0	20.0
6.700	0.7	-	-
4.750	0.3	0.0	5.0
2.360	0.3	-	-
1.180	0.3	-	-
0.600	0.3	-	-
0.425	0.3	-	-
0.300	0.3	-	-
0.150	0.3	-	-
0.075	0.3	0.0	2.0

When the particle size distribution of 20 mm single sized aggregates is considered, approximately 82% of aggregates are in similar size which retained in 13.2 mm sieve.

Table 4-2: Percentage passing of 14 mm aggregates and recommended grading requirements as per AS 2758.1-2014.

Sieve size	% passing	Table B1(AS2758.1:2014)	
		Lower limit	Upper limit
19.000	100.0	100.0	100.0
13.200	100.0	85	100
9.500	92.2	-	-
6.700	27.6	0.0	20.0
4.750	2.2	-	-
2.360	2.2	0.0	5.0
1.180	2.2	-	-
0.600	2.2	-	-
0.425	2.2	-	-
0.300	2.2	-	-
0.150	2.2	-	-
0.075	2.2	0.0	2.0

It could be noticed that the percentage passing through 6.7mm sieve has been exceeded approximately by 7% of its upper limit. 92 % of 10 mm aggregates passed through 9.5mm sieve and retained on 6.7 mm sieve. This results indicates that the PSD curves are shifted from coarse to fine direction due to the excess smaller particles than expected. Graphical representation of fine and coarse aggregates are shown in *Figure A-2* of Appendix A.

Table 4-3: Percentage passing of 10/7 mm aggregates and recommended grading requirements as per AS 2758.1-2014.

Sieve size	**% passing**	**Table B1 (AS2758.1:2014)**	
		Lower limit	**Upper limit**
19.000	100.0	100.0	100.0
13.200	100.0	-	-
9.500	100.0	85.0	100.0
6.700	94.6	-	-
4.750	41.7	0.0	20.0
2.360	2.2	0.0	5.0
1.180	1.0	-	-
0.600	0.8	-	-
0.425	0.7	-	-
0.300	0.6	-	-
0.150	0.4	-	-
0.075	0.1	0.0	2.0

Table 4-3 shows the particle size distribution of 7 mm single sized coarse aggregates. *Figure 4-3* shows the particle size distribution of the combine coarse aggregates of 20, 14 and 10/7 mm. Lower limit and upper limits were obtained from the Australian Standard AS 2758, 1:2014. The percentage combination of different size fractions were determined according to the mix composition described in *Table 6-1* in Chapter 6. The combine coarse aggregate distribution has been plotted within the lower and upper limits which is suitable for concrete works.

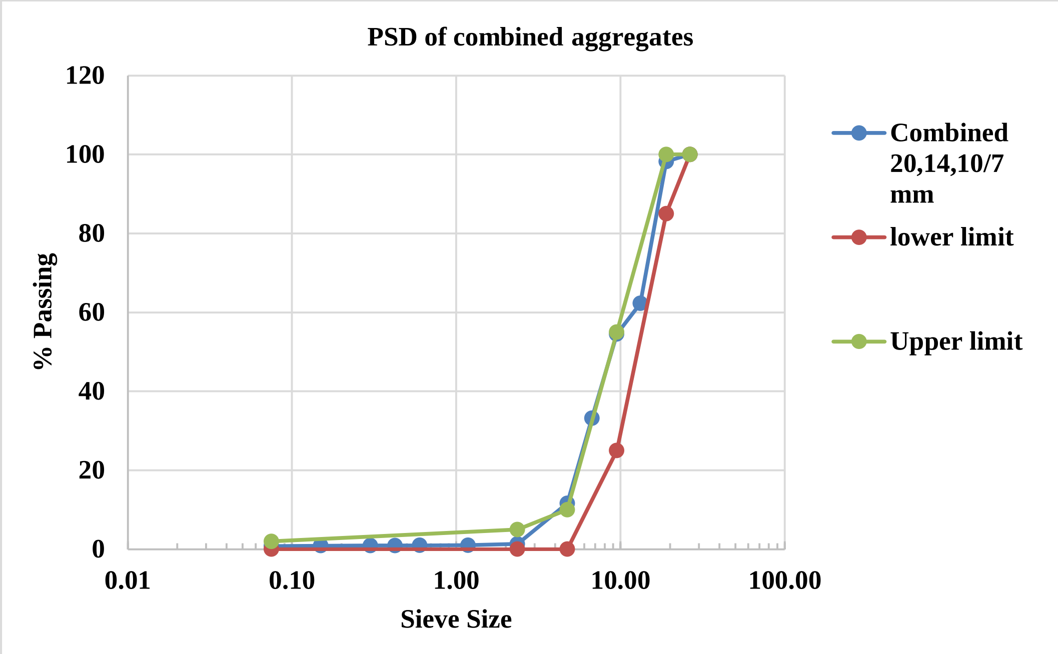


Figure 4-3: Particle size distributions of combined aggregates 20, 14, 10/7 mm.

4.2.2 Water absorption and relative density

Fine aggregates:

Apparent particle density, dry particle density, saturated surface dry (SSD) density and water absorption were determined using the procedure described in AS1141.5 – 2000. Results of the experiments are shown in*Table 4-1*. Particle density of normal weight aggregates is within the range of 2.1 t/m^3 and 3.2 t/m^3 as recommended in AS 2758.1:2014. It can be seen that that the particle densities of the FCAs are within this range and are similar to the particle density of natural sand. Natural sand has the lowest water absorption value which is 0.32% while type B (Basalt) has the highest value of 4.2%. According to the aforementioned Australian Standard water absorption for natural sand is about 2% and for normal weight aggregates higher values are allowed based on local performance records. In order to minimize the effect of absorption variations pre wetted aggregates can be used in mixing process.

Table 4-4: Physical properties of fine crushed aggregates and natural sand.

Property	A - Granophyre	B - Basalt	C - Granite	Control
Apparent particle density (t/m³)	2.60	2.93	2.63	2.61
Dry particle density (t/m³)	2.54	2.56	2.52	2.59
SSD particle density (t/m³)	2.56	2.69	2.63	2.60
Water absorption	1.0	4.2	0.7	0.3

Coarse aggregates:

Physical properties such as particle density and water absorption of coarse aggregates are presented in *Table 4-5*. Accepted limitations according to the AS 2758.1:2014 are similar in both fine aggregates and coarse aggregates. All the values presented in the following table are acceptable in concrete construction.

Table 4-5: Physical properties of coarse aggregates.

Property	Coarse - 20mm	Coarse – 10mm	Coarse – 7mm
Apparent particle density (kg/m³)	2.8	2.85	2.66
Particle density -dry (kg/m³)	2.77	2.73	2.62
Particle density - SSD (kg/m³)	2.78	2.83	2.63
Water absorption	0.4	0.4	0.6

4.2.3 New Zealand flow cone (NZFC) test results of fine aggregates

The ministry of works in New Zealand tested different types of aggregates by the flow cone test method and evaluated their influence on the properties of fresh concrete. Utilizing these results, an envelope was developed in terms of the flow time and void content, as shown in *Figure 4-4*. This envelop, known as the NZS3121 flow time limits, can be used to characterise fine aggregates and predict their effect on the properties of mortar and concrete mixtures. It is important to note that this procedure has been developed based on the experience with natural sands. Therefore using this procedure to evaluate properties of FCAs is questionable. However, Goldsworthy (2005) reported that this test method has been used to evaluate FCAs and blends with natural sand by aggregates industries in New Zealand and Australia. The flow time versus void content of a fine aggregate plotting within the standard envelop is considered to be suitable for using in concrete and mortar mixtures. Thus, number of trials to obtain the optimum blend for a specific aggregate can be reduced.

The flow cone test results of the FCA types A, B and C are plotted in *Figure 4-4*. It can be seen from the figure that the blending of natural sand with 20%, 40% and 60% FCA types B and C are plotted inside the envelope and those with 80% and 100% FCA types B and C are plotted outside the envelop. All the points have been labelled as the type of FCAs and the percentage replaced for easy identification. The highest oversized particles were recorded in type A and the least was recorded in type B (*Table 4-6*). For the FCA type A, it was found that the aggregate did not flow through the cone unless it was sieved on 2.36mm mesh. After sieving through 2.36 mm sieve, blending of natural sand with 20%, 40% and 60% FCA type A plotted inside the envelope and that with 80% FCA type A just plotted on the boundary. Thus, on the basis that the governing factor for the flow time measurement is grading, shape and texture of the fine aggregates, the results suggest that the FCAs are suitable for replacement of natural sand by up to 60% for use in concrete and mortar mixtures.

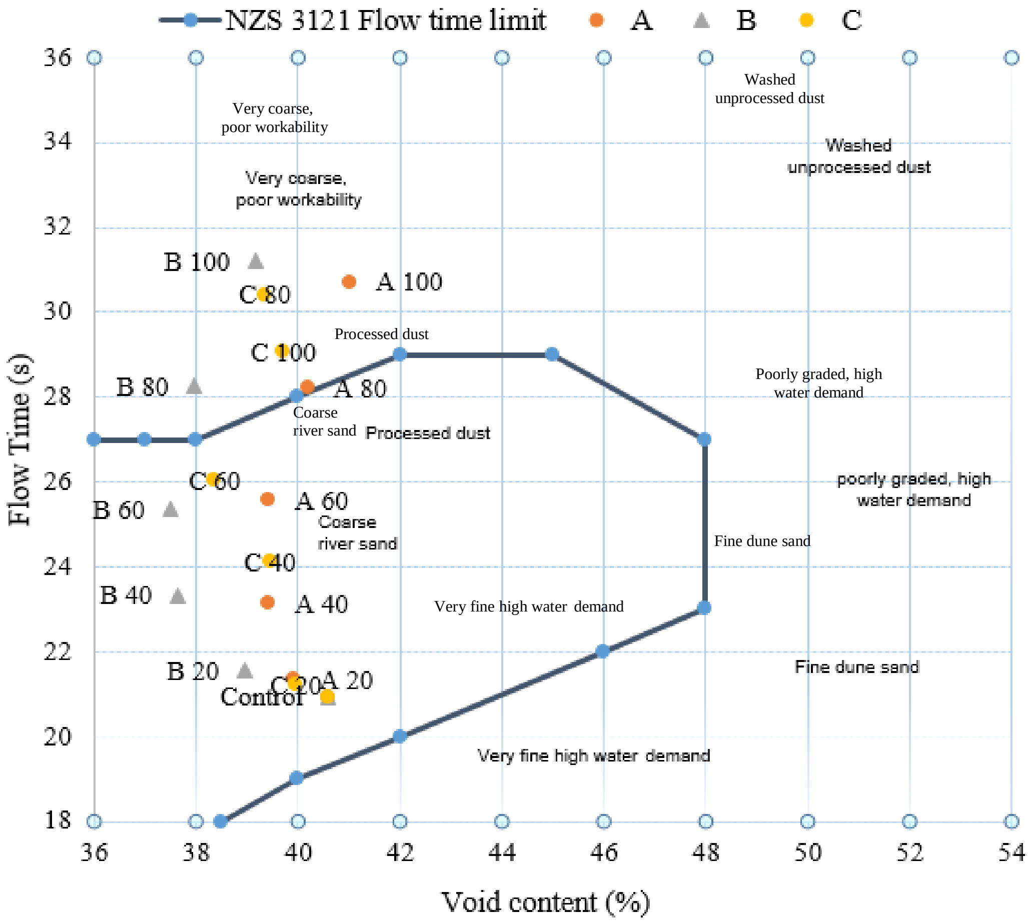


Figure 4-4: NZFC results.

The flow time and void content of the fine aggregates with respect to the percentage of FCA types A, B and C are plotted in *Figure 4-5* to *Figure 4-10*. It can be seen that the flow time of natural sand is the lowest due to the similar size particles, spherical shape, and the weathered and smooth texture. The reason that FCA type A stuck in the flow cone was as a result of the high friction generated by more angular, flaky and rougher particles in the type A material. Another reason could be the oversize particles in type A material which detrimental the flow. From *Figure 4-5*, *Figure 4-7* and *Figure 4-9*, it can be seen that the flow time increased as the percentage of FCA increased. A gradual increment of flow time by about 10 seconds can be seen in types A and B FCAs with the increment of FCA from 20 % to 100%. From Figure 4-9, the flow time gradually increased as the FCA type C increased up to 80 % and flow time then decreased at 100%. FCA type C had the lowest dry density and second highest fines content as compared to the other two types of FCA. This can be the reason for slight decrease in flow time at 100% FCA. From *Figure 4-6*, *Figure 4-8* and *Figure 4-10,* it is observed that void content decreased gradually for up to 60 %, where the natural sand fraction is dominant (100% - 40%) and, as voids are filled up by the fine particles present in FCAs of all three types. With further increase in the percentage of the FCAs, the percentage of voids gradually increased due to more angular, elongated and flaky particles contributed by large fraction of FCAs which trend to pack loosely. Higher packing density of a particle system would lead to a higher flow ability at the same water content (Kwan et al. 2009). FCA type B had the least percentage of voids while type A had the highest percentage of voids. Inversely, it can be observed from *Figure 4-11* that FCA type B had the highest percentage loose density while type A had the lowest. According to Marek (1992) and Hudson (1997), increasing the amount of fines in FCAs, improves the packing density which is supported by these results. Flow time measurements and calculation of the void content are shown in *Table A-3* – A-5 of Appendix A.

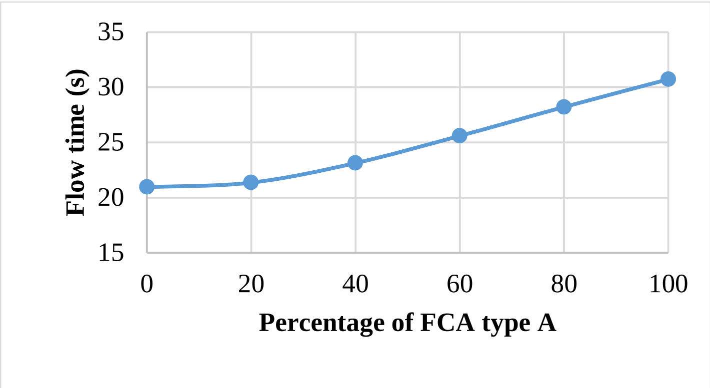


Figure 4-5: Variation of flow time with the % of FCA – A.

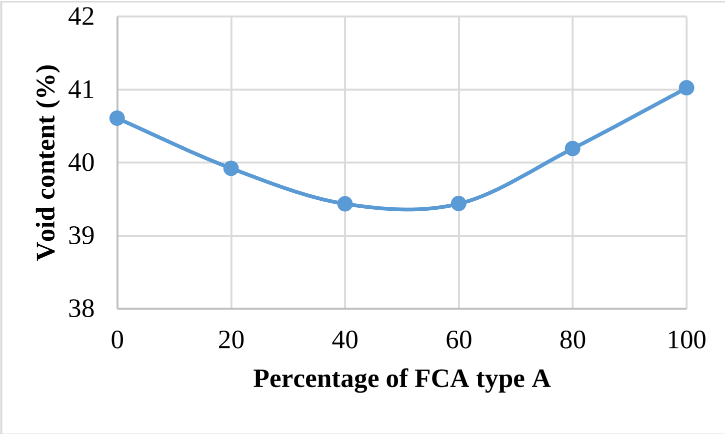


Figure 4-6: Variation of void content with the % of FCA –A.

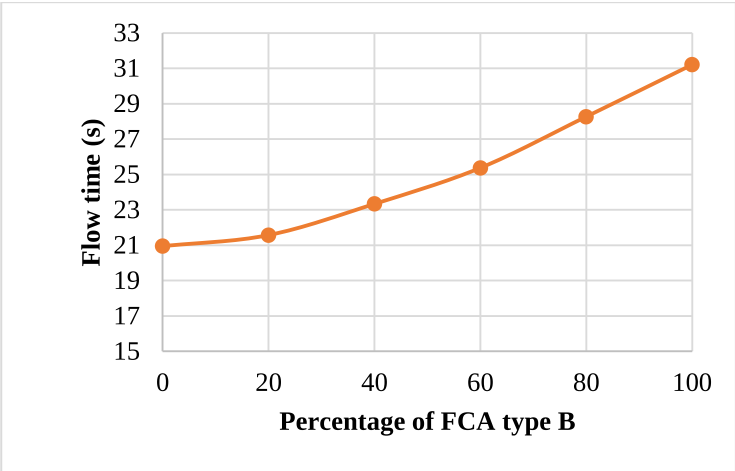


Figure 4-7: Variation of flow time with the % of FCA – B.

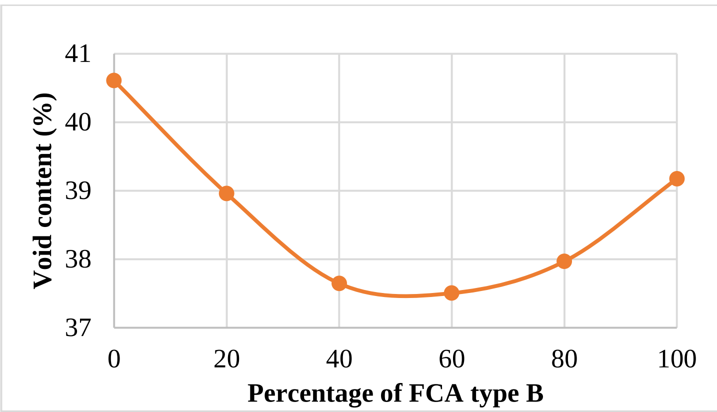


Figure 4-8: Variation of void content with the % FCA – B.

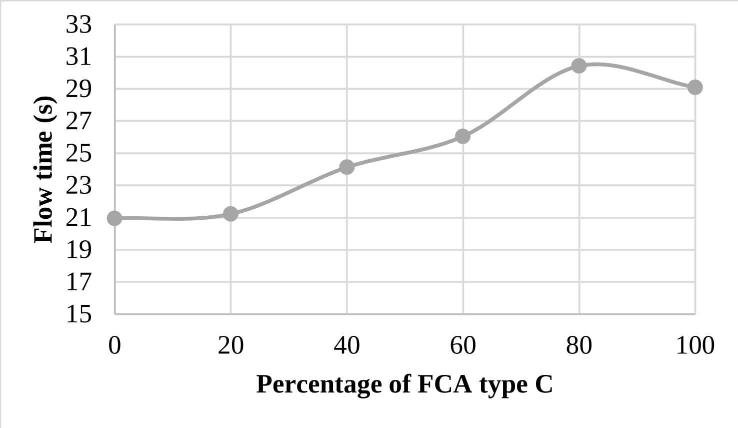


Figure 4-9: Variation of flow time with the % FCA – C.

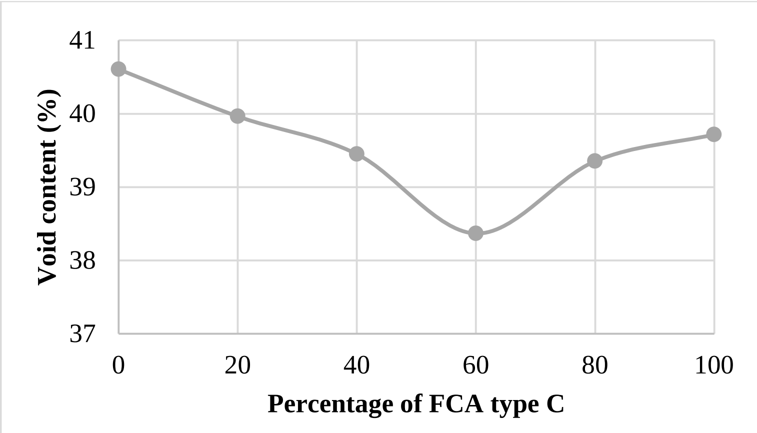


Figure 4-10: Variation of void content with the % of FCA – C.

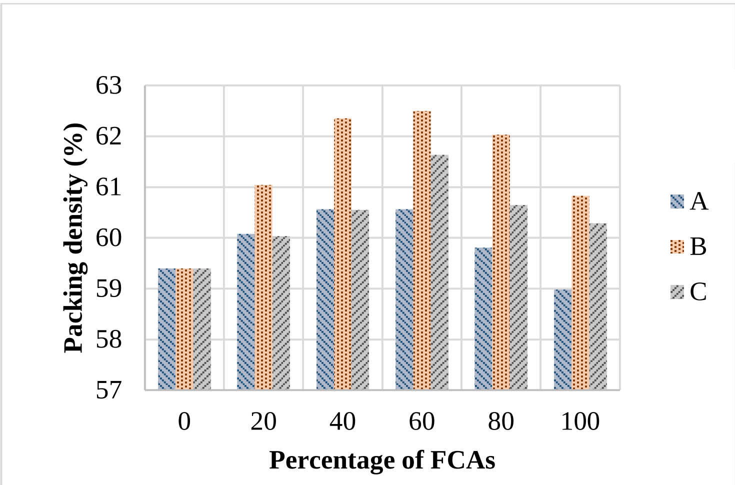


Figure 4-11: Variation of packing density with the % of FCA.

Table 4-6: Oversize particles in FCAs.

Material	% Oversize
A	9.1
B	0.1
C	0.3
Control	0

4.2.4 Shape and texture analysis

To identify the visible differences in particle shape and texture of each fraction of aggregates, photographs were taken on materials retained on each sieve and compared with natural sand. Photos were taken with equal zoom and distance approximately in all the cases. However, zooming of photos does not affect to analyse the shape and texture but the clarity of the picture. Therefore, the differences in shape and texture of each fraction of aggregates were analysed visually by using enlarged photographs. According to *Figure 4-12* to *Figure 4-20* it is clear that the shape of type A, B and C are different from each other.

Size fractions retained on 6.7 and 4.75 mm sieves:

Figure 4-12 and *Figure 4-13* show the physical appearance of type A retained on 6.7 mm sieve and type A and C retained on 4.75 mm sieve, respectively. Type B, C and natural sand 100% passed through the 6.7 mm sieve while type B and natural sand 100% passed through 4.75 mm sieve. A significant difference cannot be highlighted between the type A and B material in shape. However it is visible that type A has more equidimensional particles than type C. Type C contained more flaky and elongated compared to type A.

A – Retained on 6.7 mm sieve

Figure 4-12: Physical appearance of FCA (Retained on 6.7 mm sieve).

A – Retained on 4.75 mm sieve C - Retained on 4.75 mm sieve

Figure 4-13: Physical appearance of FCA (Retained on 4.75 mm sieve).

Size fractions retained on 2.36 and 1.18 mm sieves:

FCAs retained on 2.36 and 1.18 mm sieves are shown in *Figure 4-14* and *Figure 4-15*. These size fractions show differences in their shapes up to a noticeable extent. It is important to notify that the maximum size of natural sand particles are retained on 1.18 mm sieve. Type A and C have more three dimensional particles than type B. It is very clear that the natural sand particles are rounded and smooth in shape and texture resulting less flow time in NZFC test.

A – Retained on 2.36 mm sieve

B – Retained on 2.36 mm sieve

C – Retained on 2.36 mm sieve

Figure 4-14: Physical appearance of FCA (Retained on 2.36 mm sieve).

A – Retained on 1.18 mm sieve

B – Retained on 1.18 mm sieve

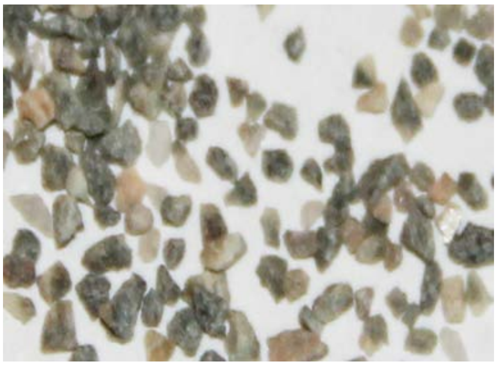
C – Retained on 1.18 mm sieve

control – Retained on 1.18 mm sieve

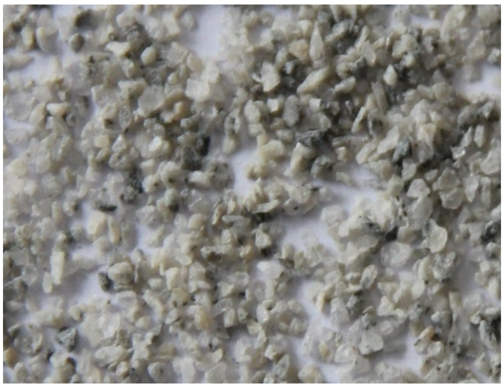
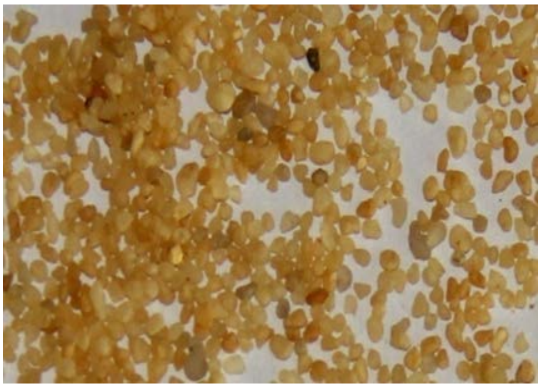
Figure 4-15: Physical appearance of FCA (Retained on 1.180 mm sieve).

Size fractions retained on 0.600 and 0.300 mm sieves:

Images of size fractions of 0.600 and 0.300 mm are shown in *Figure 4-16* and *Figure 4-17*. These two size fractions can be the lowest sizes that are visible to analyse the shape of FCAs by normal image enlarged method. Slight differences can be seen in shape of type A, B and C FCAs as described in previous size fractions.

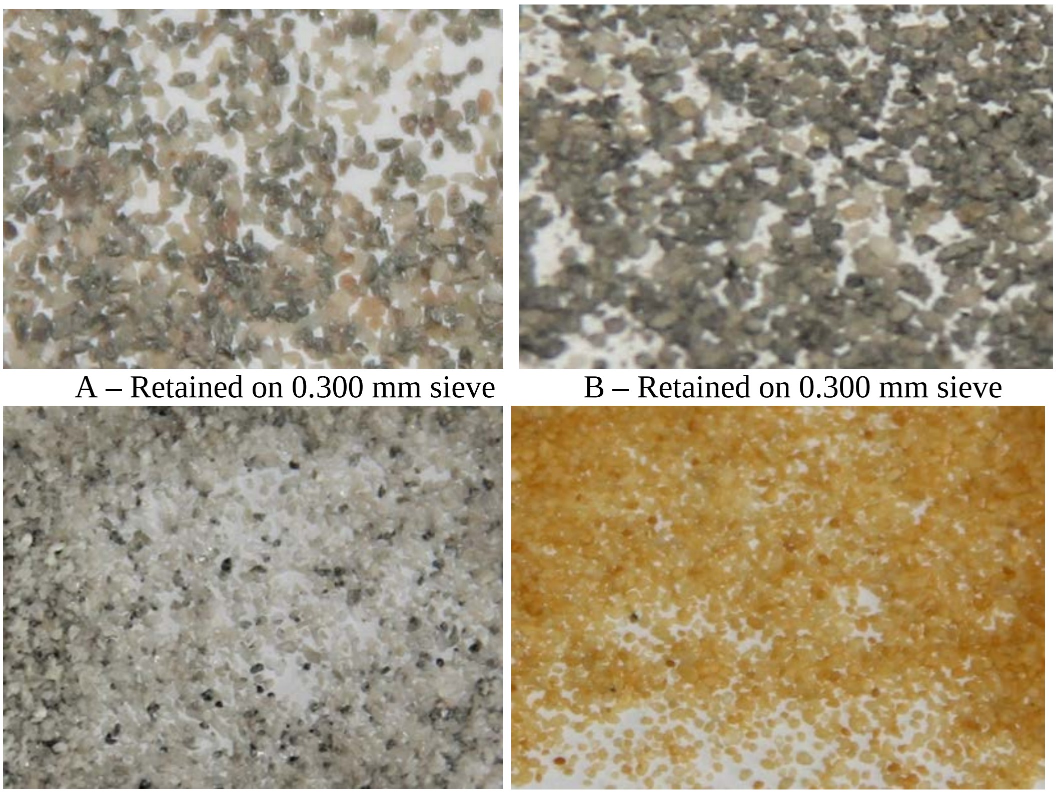



A – Retained on 0.600 mm sieve B – Retained on 0.600 mm sieve

C – Retained on 0.600 mm sieve Control – Retained on 0.600 mm sieve

Figure 4-16: Physical appearance of FCA (retained on 0.600 mm sieve).



A – Retained on 0.300 mm sieve   B – Retained on 0.300 mm sieve

C – Retained on 0.300 mm sieve   Sand – Retained on 0.300 mm sieve

Figure 4-17: Physical appearance of FCA (Retained on 0.300 mm sieve).

Size fractions retained on 0.150, 0.075 mm sieve and pan:

The shape of the images shown in *Figure 4-18, Figure 4-19* and *Figure 4-20* are not clear due to the fine size fraction. An advance method should be utilised to investigate the shape and texture of these fractions of FCAs including natural sand.

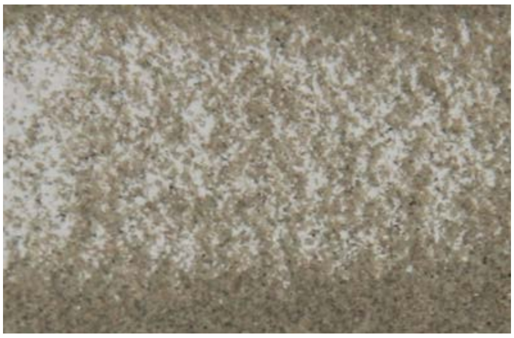
A – Retained on 0.150 mm sieve

B – Retained on 0.150 mm sieve

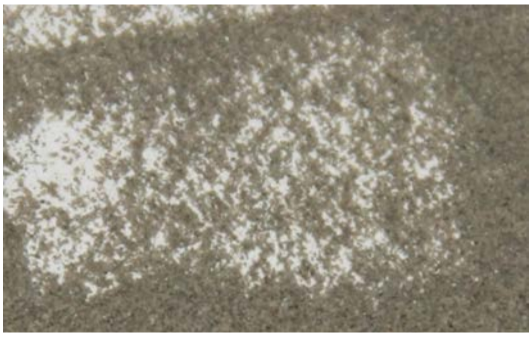
C – Retained on 0.150 mm sieve

Sand – Retained on 0.150 mm sieve

Figure 4-18: Physical appearance of FCA (Retained on 0.150 mm sieve).



A – Retained on 0.075 mm sieve

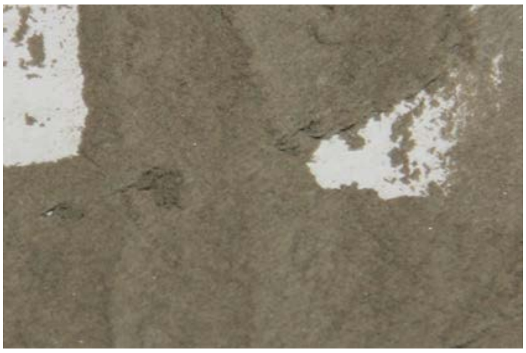


B – Retained on 0.075mm sieve

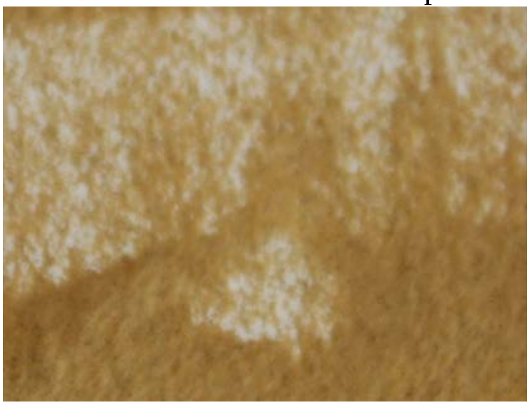
C – Retained on 0.075 mm sieve

Sand – Retained on 0.075 mm sieve

Figure 4-19: Physical appearance of FCA (Retained on 0.075 mm sieve).

A – Retained on pan B – Retained on pan

C – Retained on pan Sand – Retained on pan

Figure 4-20: Physical appearance of FCA smaller than 0.075 mm (retained on pan).

4.3 Summary

The properties of three types of fine crushed aggregates, natural sand and coarse aggregates are presented in this chapter. There was no significant difference in the particle densities among the three types of FCAs and natural sand. However, the water absorption value of FCA type B was much higher than those of types A and C. The water absorption was lowest for natural sand among all the fine aggregates. The combinations of fine aggregates for sand replacements by FCAs Type A and B up to 60% and type C up to 80% plotted inside the New Zealand flow time envelope. When the shape and texture of FCA is considered, natural sand has rounded and smooth surface while the FCAs have elongated, conical and rough texture.

CHAPTER 5

5. PROPERTIES OF MORTAR USING DIFFERENT FINE CRUSHED AGGREGATES

5.1 Introduction

After completing FCAs and natural sand characterization tests, mortar tests were conducted to investigate the influence of FCAs on the mortar paste. This section outlines the methodology, results and discussion of tests of mortars at fresh and hardened states. The test results of mortar were the basis to select type and percentage of FCAs to be used in the next experimental stage in concrete testing.

5.2 Mixture proportions

Mortar mix design was done according to the Australian Standard related to specific test method. As an example mix proportions to evaluate the compressive strength of mortar is different from the requirement of the Alkali aggregate reactivity. Therefore, the mix proportions were decided according to the test and relevant standard. Three series of experiments were designed for FCAs type A, B and C. Total fine aggregate percentage was maintained as a constant as per the original design mix while the FCAs introduced to the mix and gradually increased the percentage replacement for the natural sand. All the three series of experiments were conducted replacing natural sand by FCAs from 0% to 100% with the steps of 20%.

Table 5-1: Mix proportions of mortar for different tests.

Test	Water / cement	Fine aggr./ cement	Cement (g)	Water (g)	Fine aggregate (g)	Test method
Mortar flow and compressive strength	0.485	2.75	500	242.5	1375	ASTM C 1437 -07, ASTM C109/C 109M-07:2008
Alkali-silica reactivity	0.47	2.25	440	206.8	990	AS1141.60.1: 2014

5.3 Preparation for mortar tests

5.3.1 Mortar flow test and compressive strength test

A single mix design was followed to conduct the mortar flow test and compressive strength test as directed by the ASTM C 1437 -07 (2007) and ASTM 109C 109/M - 07 (ASTM Standard, 2008) respectively. Therefore, preparation for these two tests was done simultaneously. A flow table conforming to the ASTM C230 /C 230M Standard was used in the flow test. The flow table and cone was thoroughly cleaned with a damp cloth before using.

5.3.2 Preparation of fine aggregate to SSD condition

Fine aggregate including fine crushed aggregates were prepared to saturated surface dry (SSD) condition. The preparation of aggregate to SSD condition was accomplished by submerging it in water for 24 hours and air-drying inside the lab. The aggregates were put away in sealed containers when they came to SSD condition. The actual amount of water in aggregates was determined before each mixing. For this, around 1 kg of aggregate was set in a dish. At that point, the dish was put in the oven at 105 0C for 24 hours. The container was then taken out from the oven and the mass of the pan was subtracted in order to find the weight of completely dried aggregate. This difference in weight represents the total amount of water in aggregate. By knowing the Actual water content and the SSD density of aggregates final adjustment of water was done before mixing.

5.3.3 Preparation of specimen moulds

Six numbers of 50×50×50mm cube moulds were cleaned and fixed prior to use. Internal surfaces of moulds were applied a thin coat of mould release agent.

5.3.4 Mixing of mortar and casting of specimens

Mixing of mortar was conducted according to the ASTM C305 Standard. The following steps were followed in mixing of the mortar:

- The mixer was cleaned with water and wiped out with a cloth. Then the paddle was fixed and poured the water measured in to the mixing bowl.
- Then added cement in to the bowl and mixed at low speed for 30 seconds.
- Carefully added the entire quantity of sand in to the bowl in 30 seconds.
- Then the machine was stopped and changed it to the medium speed and mixed for 30 seconds.
- The mixer was stopped and let the mortar stand for 90 seconds. In the first 15 seconds mortar stuck on the face of the bowl was mixed by a scrapper and covered the bowl with the lid.
- Started the mixer again and mixing in medium speed was terminated in 60 seconds.
- Cube moulds were loaded with the mortar and compacted by a table vibrator until the shine surface of mortar is appeared and no more air bubbles appear on the surface.
- Finally samples were demoulded on the next day and transferred to the lime saturated and temperature controlled curing tank.

Figure 5-1 shows the mechanical mixture used for the experiments. *Figure 5-2* shows the moulds with compacted mortar.

Figure 5-1: Mechanical mixture used for the experiments.

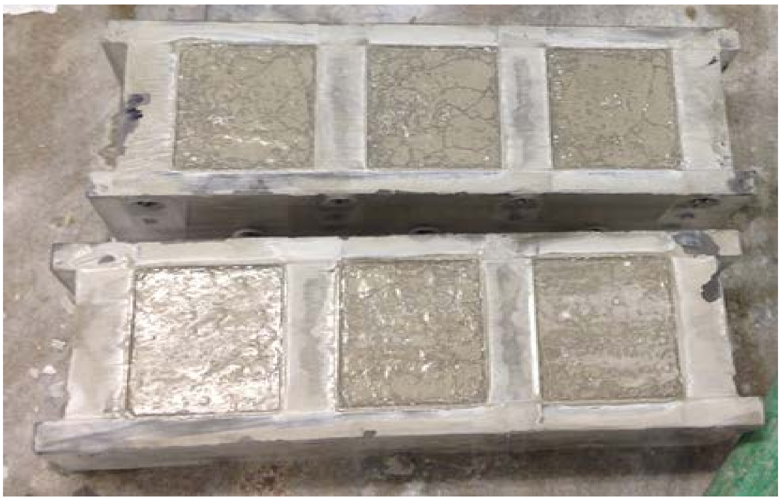


Figure 5-2: Mortar in mould after compaction.

5.4 Tests on fresh mortar (mortar flow and slump tests)

The mortar flow test is a simple and inexpensive method that can be readily available in the field to describe the rheological behaviour of cement mortar. The mortar flow test (flow table method) was conducted to determine the workability of cement mortar in accordance with the ASTM C-1437 Standard. In this test procedure, the mould was filled in two layers with 20 temping for each layer. Temping pressure was maintained in such a way that it was just sufficient to ensure uniform filling of the mould. A straight edge was used to cut off the surface across the top of the mould before lifting it. Immediately after filling the mould, the table was dropped 25 times in 15 seconds. The drop of slump was then recorded. *Figure 5-3* shows the measuring of slump of a typical test while *Figure 5-4* shows the measuring of the flow of mortar. Diameter of the mortar spread was measured along the four lines scribed on the table top and the average value is reported. The flow was calculated as the resulting increase in average base diameter of the mortar, as a percentage of the original base diameter by using *Equation 5.1*:

$$\text{Flow} = \left(\frac{D_{25} - D_0}{D_0}\right) \times 100\% \quad \text{---} \quad (5.1)$$

where,

D_{25} = the average diameter of mortar spread measured along the four lines marked.

D_0 = the base diameter

Figure 5-3: Measuring the slump of mortar.

Figure 5-4: Measuring the flow of mortar.

5.5 Tests on hardened mortar

5.5.1 Compressive strength of mortar

Six mortar cubes (50×50×50 mm) were cast, cured under lime saturated water and tested for compressive strength at the ages of seven and twenty eight days. This test was conducted according to the ASTM C109/C 109M-07. The machine MCC8 was used to determine the compressive strength of mortar cubes. Following steps were taken in testing mortar cubes:

- Test specimens were wiped out with dry cloth and carefully placed at the base plate and centrally bellow the upper block.
- Then the load was applied to the specimen that where in contact with the true plane surface of the mould.
- Failure load was recorded and compressive strength was calculated using *Equation 5.2*.

$$f_{cm} = \frac{P}{A} \qquad \text{-- (5.2)}$$

where

f_{cm} = Compressive strength in MPa

P = Maximum load at failure in N

A = Area of the loaded surface in mm^2

5.5.2 Potential alkali – silica reactivity by accelerated mortar bar method

Preparation of sodium hydroxide solution

This experiment was conducted in accordance with the AS 1141.60.1-2014 Standard. According to the standard, sodium hydroxide solution was prepared by dissolving 40g of NaOH in 900ml of distilled water. Then the total volume was adjusted to one litre by adding 100 ml of same water. The required volume of solution was prepared for each series of specimens following this procedure.

Preparation of samples

- Standard moulds having the dimensions of 25mm × 25mm × 285mm with gauge length of 250mm were used to cast the specimens. A thin layer of mould release agent was applied inside walls of the mould, after fixing the gauge stud at both ends on it. Three samples were prepared for each mixture.
- Mixing of materials was done as per the referred standard: 1: 2.25 cement: aggregates and water to cement ratio of 0.47.
- Moulds were filled in two layers with mortar taking care of the edge studs and compacted with a tamping rod until a homogenous mix was obtained. After the top layer was compacted surplus material was cut off by a shape edge and was finished to smooth surface by a trowel.

Storage and zero reading

- Specimens were covered by a polythene sheet immediately after casting and transferred them to the humidity control room and the specimens were demoulded after 24 hours of casting with no damage to the edge studs.
- Specimens were placed in a container and filled with sufficient water and the container was stored in an oven at 80 ^{o}C for 22 hours. Then the samples were taken out and wiped with a towel before taking the zero reading.
- All the specimens were placed in the sodium hydroxide (1 mol /L) container and sealed properly before it was transferred to the oven at 80 ± 2 ^{o}C.

The test was conducted based on the requirements of the standard AS 1141.60.1-2014. Three samples were cast in each mix and three series of experiments for type A, B and C replacing natural sand from 0% to 100% with 20% replacement steps was designed. Comparator readings of the samples were taken at 1, 3, 7, 10, 14 and 21 days after initial reading. Samples were taken from the sodium hydroxide bath and comparator readings were taken in 10 seconds and replaced the sample before starting with the next sample. The expansion of each specimen was calculated using *Equation 5.3*. Mean value of three specimens was calculated after finding the expansion of each specimen. Measuring of the expansion is shown in *Figure 5-5*.

$$En = \left(\frac{l_n - l_z}{lg}\right) \times 100 \quad \text{---} \ (5.3)$$

where,

E_n = expansion after *n* days

l_n = length of the specimen after *n* days

l_z = length of the specimen at the zero reading

l_g = effective gauge length of the specimen (250mm)

Figure 5-5: Measuring the expansion by using the comparator.

5.6 Results and discussion

5.6.1 Flow and slump of mortar

FCA type A:

Figure 5-6 and *Figure 5-7* show the variation of flow and slump of mortar with the percentage of FCA type A, respectively. The flow of 100% natural sand and 20% of FCA type A mortar samples does not show a significant difference, either in flow values or slump values. Further increase of FCA, from 40% to 80%, increases the flow as well as slump. This behaviour can be explained, fine content of the mortar mix increases with the amount of FCAs increases resulting fine particles themselves lubricating the matrix, consequently improves the consistency of the mix. For an example, Li et al. (2009) showed that increase of limestone filler up to 15% increased the constancy and strength for low strength concrete. Further increase of FCAs demand more water to maintain the same consistency.

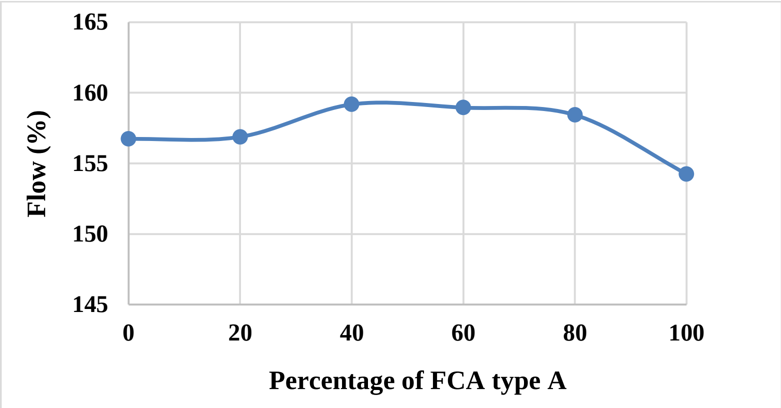


Figure 5-6: Variation of flow with the % of FCA – A.

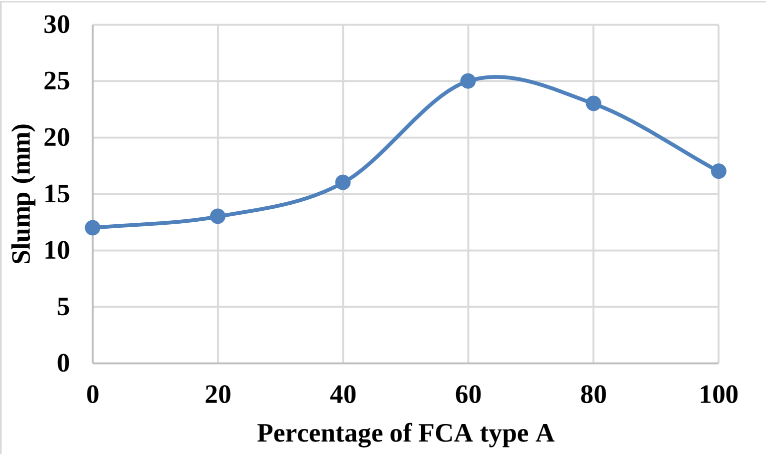


Figure 5-7: Variation of slump with the % of FCA – A.

FCA type B:

The variation of flow and slump of FCAs type B are presented in *Figure 5-8* and *Figure 5-9.* Lowest flow could be observed in FCA type B with a 100% replacement of natural sand. Corresponding slump value was 10 mm. The flow ability of mortar is affected by the shear resistance produced by the angular particles of the FCAs. On the other hand, angular particles yield looser packing density and higher frictional resistance. Cortes at el. (2008) showed that both packing and frictional effects reduced flow for the same volume ratio of aggregate to paste as the particle angularity increased. Having more paste, angular particles can be kept apart decreasing their friction and the flow can be increased. Higher finer content of FCA type B, demand more water from the paste and flow could have been disturbed due to the lack of viscous effect in the paste. As shown in

Figure 4-12 and *Figure 4-13* in Chapter 4, the shape of type B material is more elongated, flaky and conical compared to those of type A and C. It is clear that the flow decreases with the increase of FCAs type B. As it was shown in Section 4.2.1, FCA type B has the maximum fine content which is 17% which may influence the consistency of mortar. Slump values have not been affected significantly as the rough particle make sound matrix to hold each other when there is no external forces are given.

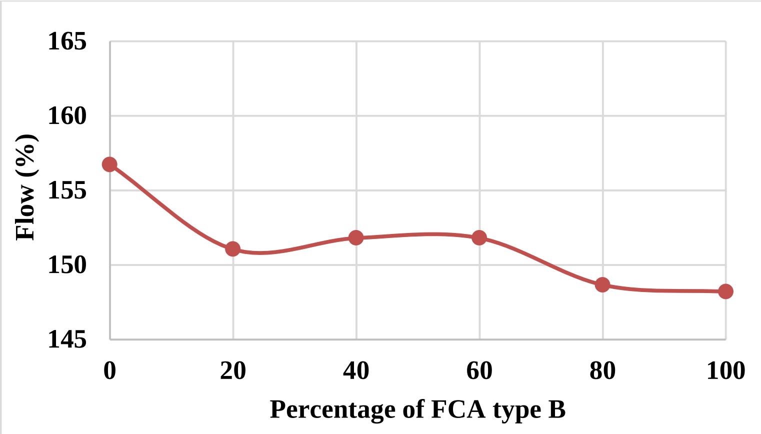


Figure 5-8: Variation of flow with the % of FCA – B.

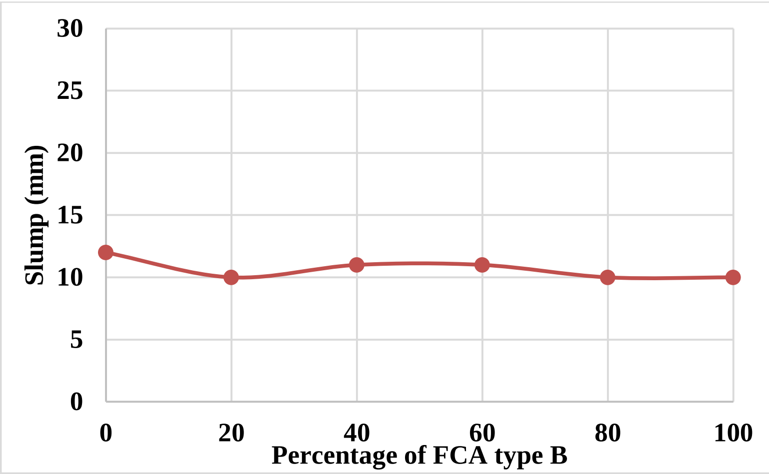


Figure 5-9: Variation of slump with the % of FCA – B.

FCA type C:

Figure 5-10 and *Figure 5-11* present the flow and slump results, respectively of FCA type C. From 0% to 40% replacement of FCA type C mortar maintained approximately a similar consistency. At 60% replacement sample has shown slightly higher value which is 158% flow and corresponding slump value is 16mm. Further increase of FCA type C in mortar resulted lower slump and flow. Type C material show the intermediate characteristics with respect to fine content (13%) and shape characteristics as shown in *Figure 4-13* and *Figure 4-14* in Section 4.2.4. Therefore the flow and slump properties of FCA type C mortar are in between type A and B. Calculation of mortar flow for FCAs are shown in *Table B-1* of Appendix B.

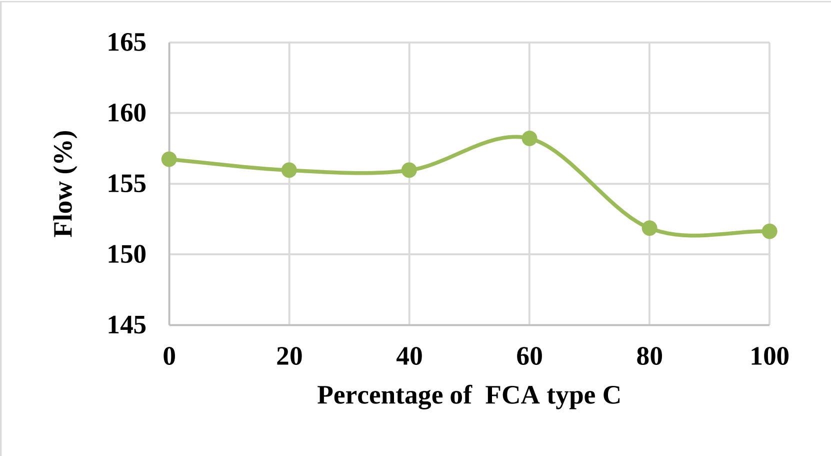


Figure 5-10: Variation of flow with the % of FCA - C.

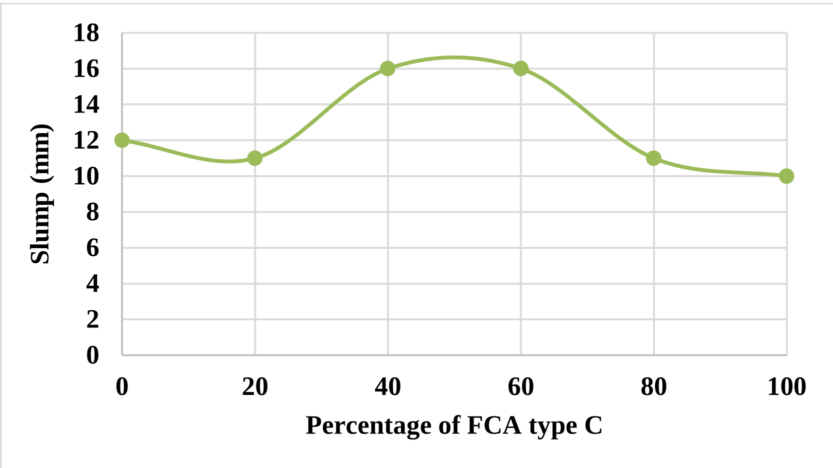


Figure 5-11: Variation of slump with the % of FCA - C.

5.6.2 Compressive strength

The compressive strength results of the mortar specimens containing different percentages of FCA type A, B and C are presented in *Figure 5-12* to *Figure 5-17*. It can be noticed from these figures that the sand type has significant influence on the compressive strength of mortar.

FCA type A:

Compressive strength results of mortar containing FCA type A are presented in *Table 5-2* and plotted on *Figure 5-12* and *Figure 5-13*. Variation of compressive strength from 0% to 100% has plotted a parabolic curve marking its maximum value of 48 MPa at 7days and 55 MPa at 28 days at the replacement level of 60%. At 60% replacement of FCA type A, the amount of high fines in the mix is about 3% from the total fine aggregate fraction and this could be the optimum percentage of finer particles less than 0.075mm to attain maximum strength in mortar phase for this specific aggregate type. However the investigations carried out by Celik et al. (1996). He examined the influence of crush fine filler aggregates with a partial replacement of fine aggregates in a concrete mix. He observed that at the 10% replacement of filler content in the mix, showed the maximum compressive strength and flexural strength. It is noticeable from the results that the FCA type A shows higher compressive strength than the control sample up to 80% replacement.

Table 5-2: Compressive strength at 7 and 28 days – FCA type A.

% of FCA	7 Days (Mpa)	28 Days (Mpa)
0	45.0	50.4
20	46.0	52.2
40	47.2	54.0
60	47.9	54.7
80	45.2	52.5
100	43.2	48.4

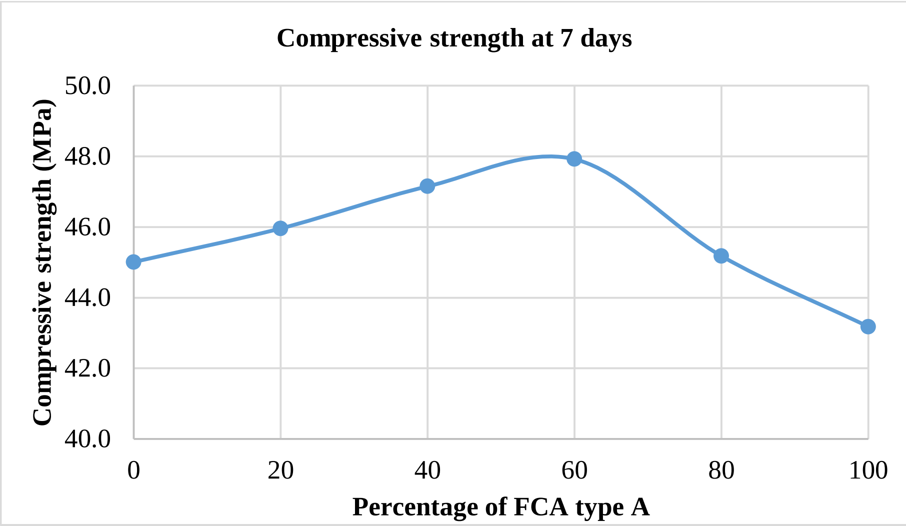


Figure 5-12: Variation of compressive strength at 7 days with the % of FCA – A.

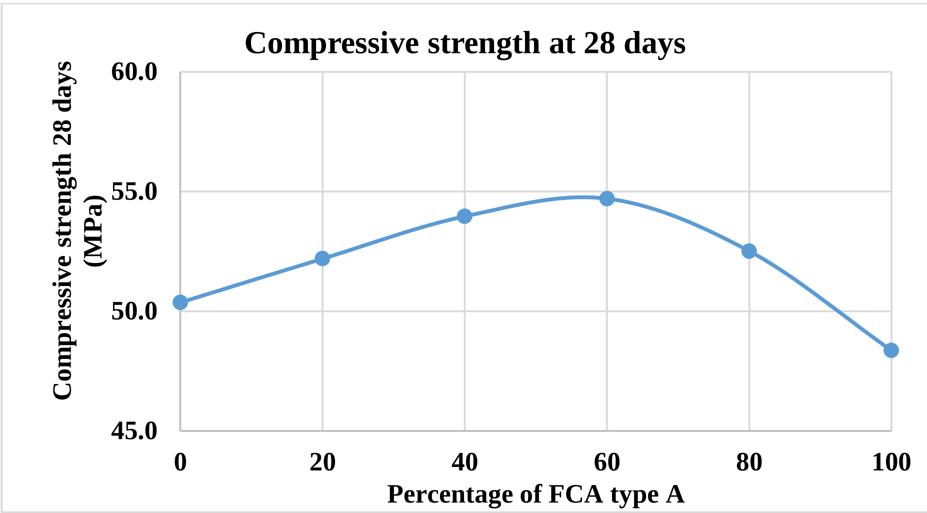


Figure 5-13: Variation of compressive strength at 28 days with the % of FCA – A.

FCA type B:

The strength development of mortar containing type B material at 7 days and 28 days are shown in *Figure 5-14* and *Figure 5-15* and values are given in *Table 5-3*. Slight improvement of compressive strength can be seen up to 60% replacement of FCAs and these values are higher than the compressive strength of control sample. The compressive strength development behaviour of FCA type B comparatively less than other two types. Packing orientation of angular, flaky and conical particles of FCA type B could result poor packing pattern in the sample in addition to its highest powder content. These properties could result the lower strength than other two types of FCA.

Table 5-3: Compressive strength at 7 and 28 days – FCA type B.

% of FCA	7 Days (MPa)	28 Days (MPa)
0	45.0	50.4
20	46.3	51.1
40	47.3	51.7
60	45.6	51.8
80	45.1	48.8
100	37.3	47.1

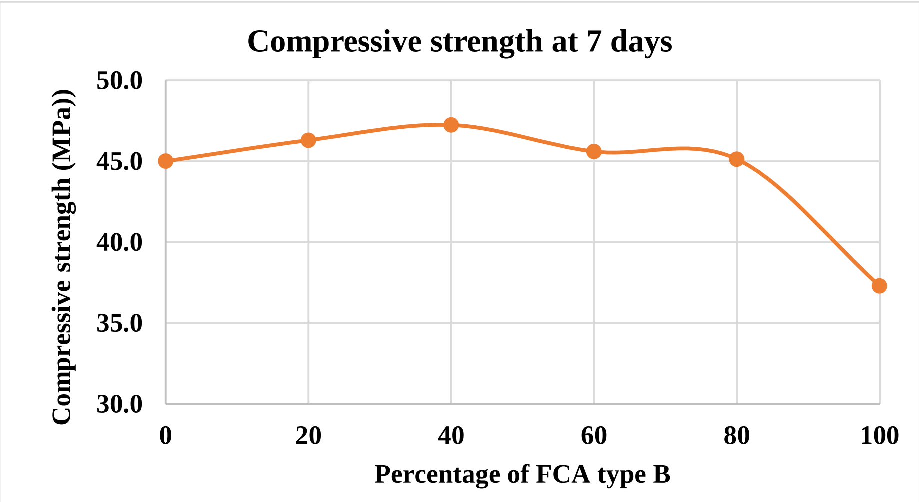


Figure 5-14: Variation of compressive strength at 7 days with the % of FCA – B.

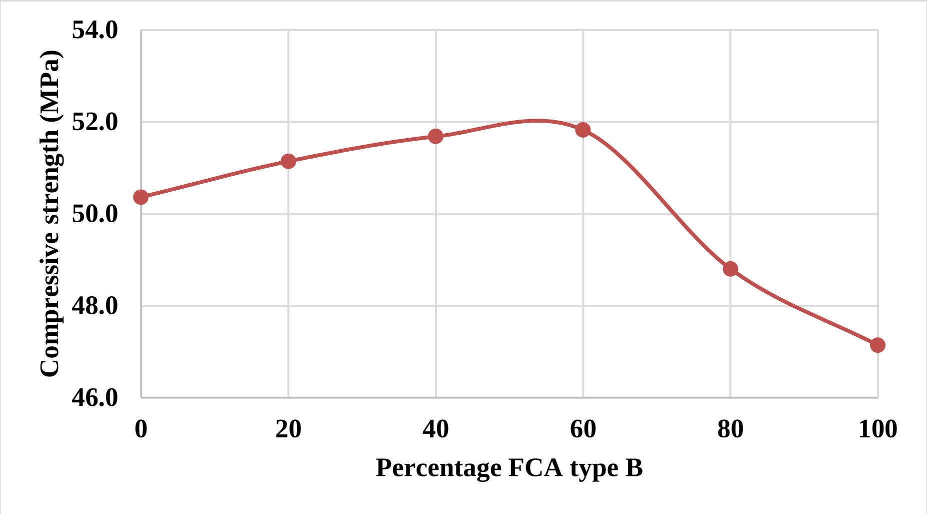


Figure 5-15: Variation of compressive strength 28 days with the % of FCA - B.

FCA type C:

Table 5-4 and *Figure 5-16* and*Figure 5-17* show the compressive strength of FCA type C at 7 days and 28 days. It can be seen that compressive strength increased with the increase of FCAs of up to 60% and then declined with further increase of FCAs at 28 days. The strength increase by the FCAs is considered to be because of the increased interlocking between the angular particles and the strength decrease is attributed to the increase of voids contents beyond 60% FCA. FCA types C showed lower compressive strength than type A. This is attributed to the higher water demand of the FCA type C due to its higher fines contents as compared to FCA type A.

Table 5-4: Compressive strength at 7 and 28 days – FCA type C.

%of FCA	7 Days (MPa)	28 Days (MPa)
0	45.0	50.4
20	47.6	51.4
40	48.3	52.2
60	47.4	52.4
80	44.8	51.6
100	41.0	48.6

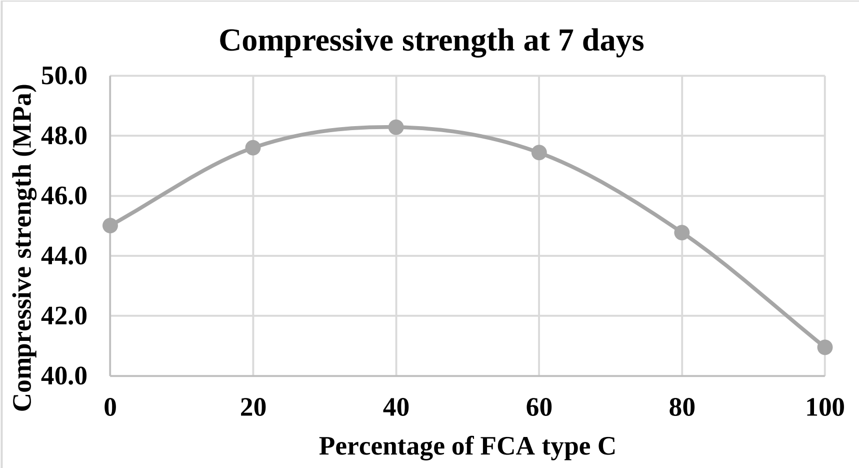


Figure 5-16: Variation of compressive strength at 7 days with the % of FCA – C.

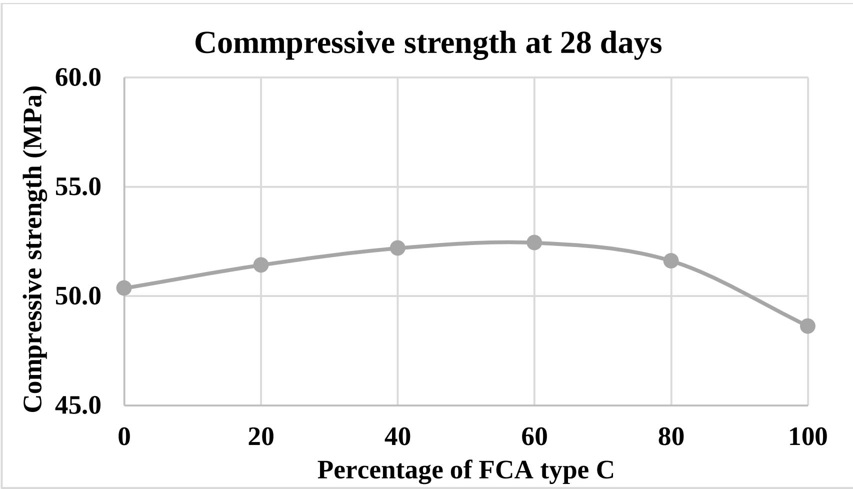


Figure 5-17: Variation of compressive strength at 28 days with the % of FCA – C.

5.6.3 Alkali–silica reactivity (ASR)

Potential alkali – silica reactivity of FCAs and natural sand was examined in accordance with the AS 1141.60.1-2014. This test method permits to find the potential for deleterious alkali-silica reaction of aggregates using mortar bars submerged in a solution of sodium hydroxide over a period of 21 days. However, the test was continued for an extended duration to investigate the delayed expansion. Alkali- silica reactivity test results and detail calculations for FCAs A, B and C are shown in *Table B-3 – B-5* in Appendix B. According to the standard, certain rock types such as granite and granitic gneisses and some metabasalts may not show reactivity in these experiments, though they can be expansive in the field. In contrast, some glassy basalt aggregates are not reactive in concrete when used as coarse aggregates, but may cause excessive expansion when used as fine aggregates in this test. Results obtained from this experiments are assessed against the aggregate reactivity chart of AS 1141.60.1-2014 standard, as given in *Table 5-5*.

Table 5-5: Aggregate reactivity classification as per AS 1141.60.1 -2014.

AS 1141.60.1 Aggregate reactivity classification		
Mean mortar bar expansion(E),%		**AS 1141.60.1 Aggregate reactivity classification**
Duration of specimens in 1 mol/L NaOH at 80°C		
10 days	**21 days**	
-	E< 0.10*	Non-reactive
E<0.10*	0.10*≤ E <*0.30*	Slowly reactive
E≥ 0.10*	-	Reactive
-	0.30 ≤ E	Reactive

FCA type A:

Variation of average expansion of FCA type A (Granophyre) with the age is shown in *Figure 5-18*. It can be seen that 100% natural sand showed the lowest expansion, as expected. When the 10-days 21-days expansions of specimens with FCA type A are compared with the limiting values of *Table 5-5*, the mixtures with 20%, 40%, 60% and 80% FCA are classified as non-reactive while that with 100% FCA is classified as slowly reactive. Expansion, approximately during the first five days is negative. In fact, a contraction of specimens has taken place during this time period. Saha and Sarker (2016) has described that the initial shrinkage could be attributed to the initial autogenous shrinkage and low expansion of the constituent used in the cement mortar.

In a petrographic investigation for type A (Granophyre), it has been disclosed that it contains 4% finely micro-crystalline which is considered to be insufficient to be deleterious. This could be the reason for FCA type A to show relatively low reaction on alkali-silica reactivity test.

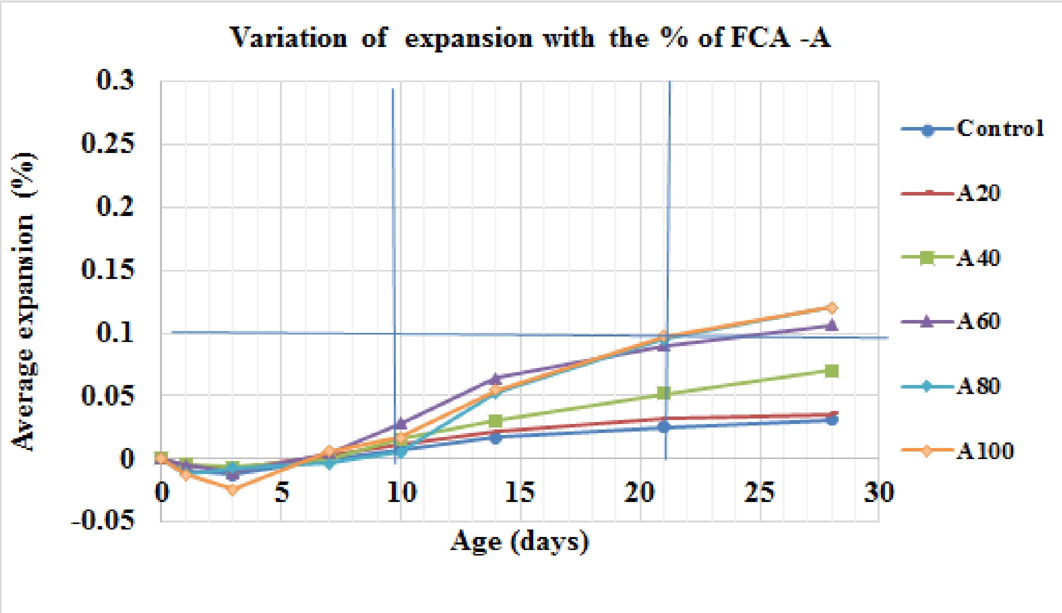


Figure 5-18: Variation of average expansion (%) of Granophyre (A) against the age (days).

FCA type B:

Variation of percentage expansion of FCA type B (Basalt) is shown in *Figure 5-19*. Use of 20% to 60% FCA type B showed non-reactive results in alkali-silica reaction test. However, 80% and 100% FCA were classified as slowly reactive. 100% replacement of Basalt has reached to its highest expansion value which is 0.25% at 28 days. It can be seen from the pattern of the graphs that the rate of increment of expansion from 20% to 100% gradually increased. For the 20 % and 40% replacement tests the dominant part of fine aggregates is natural sand and hence the expansion is relatively low.

It has been found that the FCA type B (Basalt) may contain silica saturated or over saturated (i.e. capable of crystallizing free silica minerals or concealing excess silica within a glassy component). Also the petrographic information predicted that much of the late glass has been completely altered to smectite clay, but there could be a minor microcrystalline fraction present in the basaltic glass mesostasis. Thus, the FCA type B 80% and 100% replacement which is the dominant part of fine aggregate is FCA fraction, has shown potentially slow reactive in alkali-silica reactivity test.

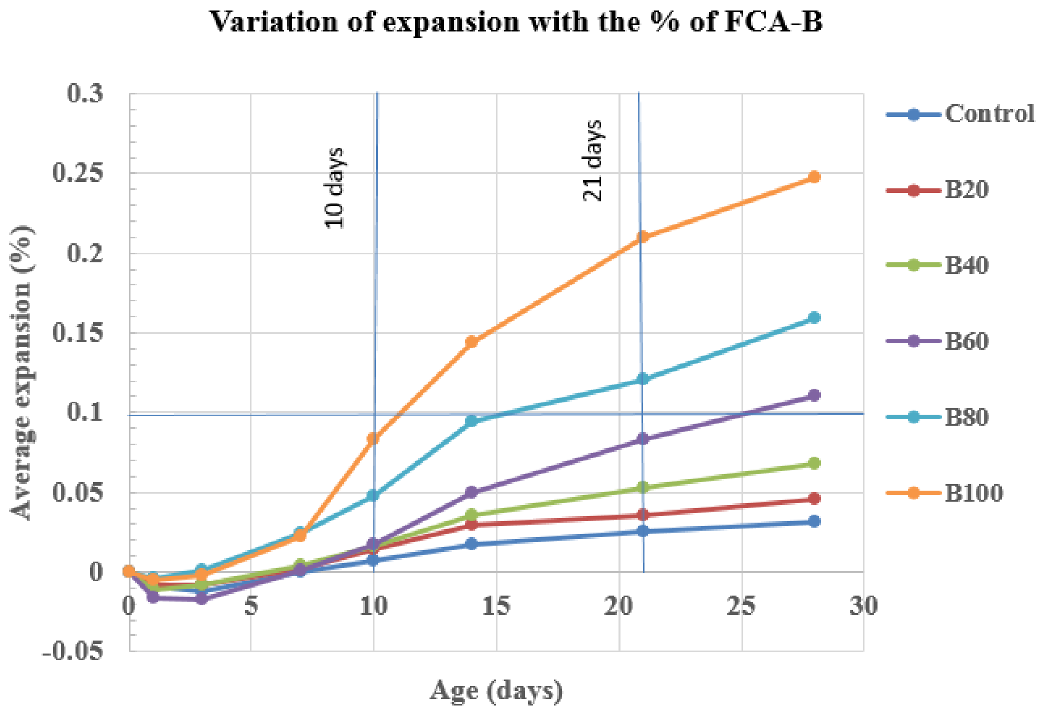


Figure 5-19: Variation of average expansion (%) of Basalt (B) with age (days).

FCA type C:

According to *Figure 5-20*, which shows the expansion of Granite, 20% to 80% FCA are classified as non-reactive. 100% of replacement has shown slowly reactive like other two materials. Granite has shown high fine content in PSD and has average absorption values and densities. These material properties could be a reason to have higher expansion values at 100% replacement.

Petrographic analysis of FCA type C (Granite) has shown that it contains about 15% of moderately strained quartz which may consists of deleterious silica substances. This could be the reason that 100% replacement of FCA type C to show slow reactivity on alkali-silica reactivity investigations.

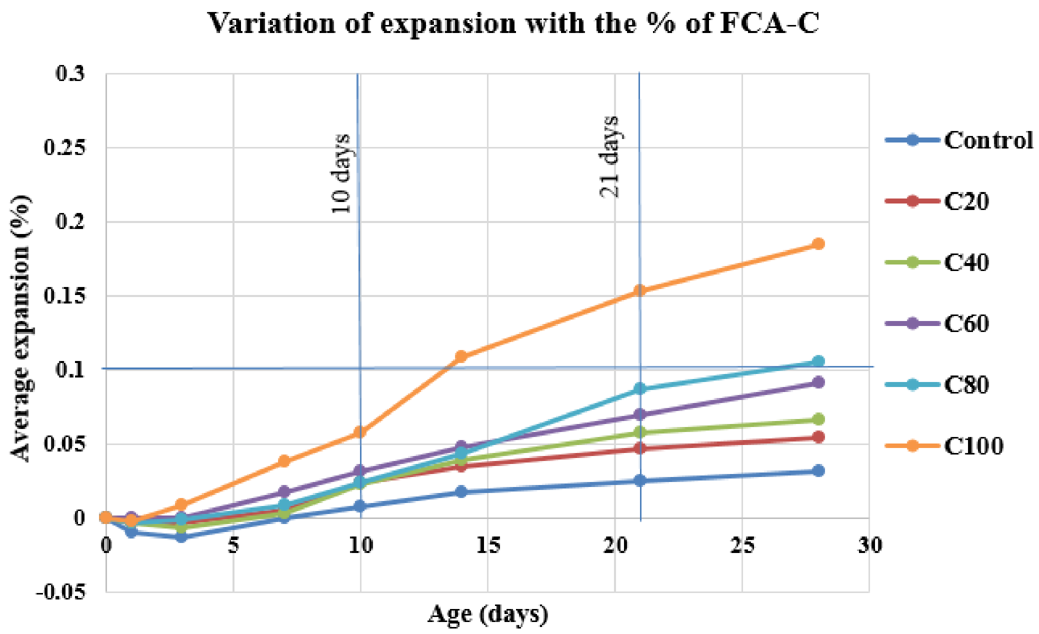


Figure 5-20: Variation of average expansion (%) of Granite (C) against the age (days).

Figure 5-21 to *Figure 5-25* show the comparison of ASR results of the same percentage of FCAs A, B and C with the replacement percentage from 20% to 100% respectively. According to the graphs of 20% and 40% replacement of FCAs, a significant deference cannot be highlighted in these three materials. Also, 60% replacement of FCAs did not behave potentially alkali-silica reactive in this investigation. In 80% only type B material showed mild or slow reactive for ASR test while other two materials are non- reactive for the same percentage of replacement. In 100% replacement FCAs B and C has shown slow reaction and FCA type B has marked its highest expansion which is 2.5% at 28 days.

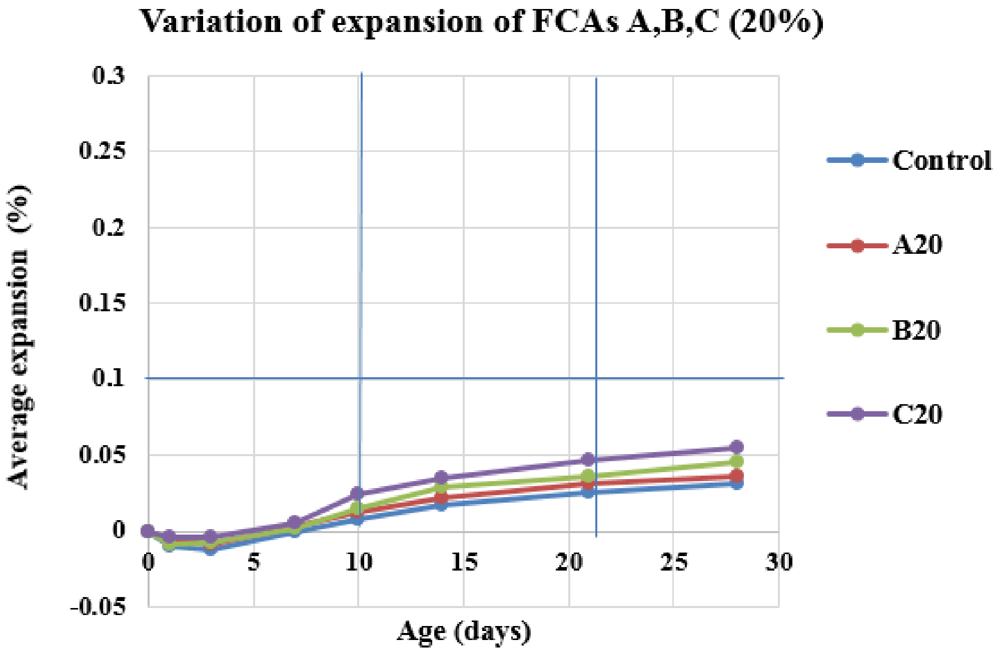


Figure 5-21: Variation of average expansion (%) of FCAs A, B and C - 20% replacement.

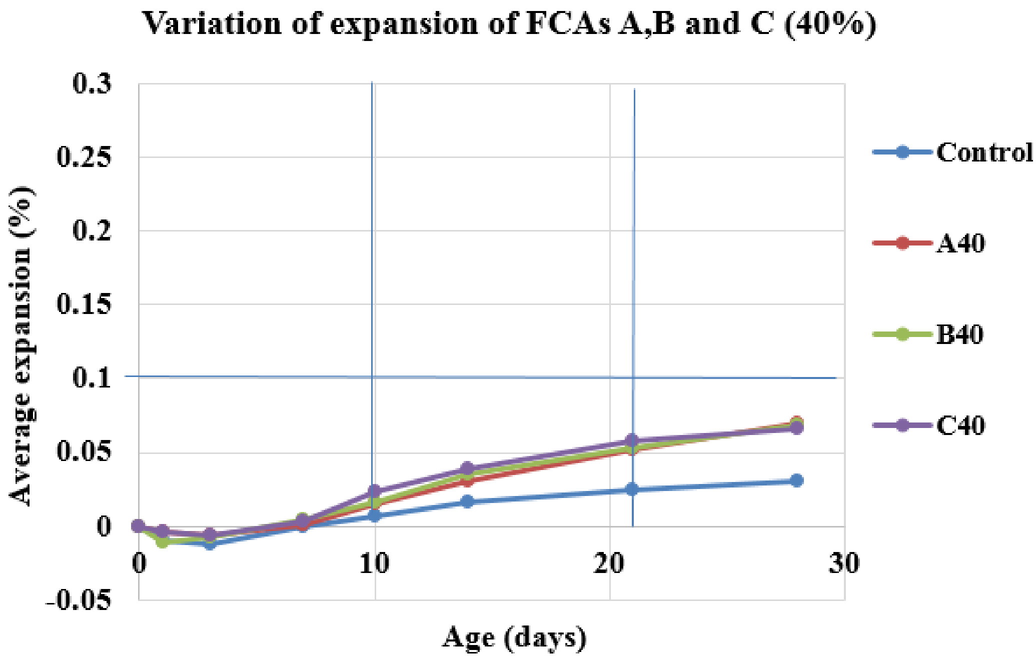


Figure 5-22: Variation of average expansion (%) of FCAs A, B and C - 40% replacement.

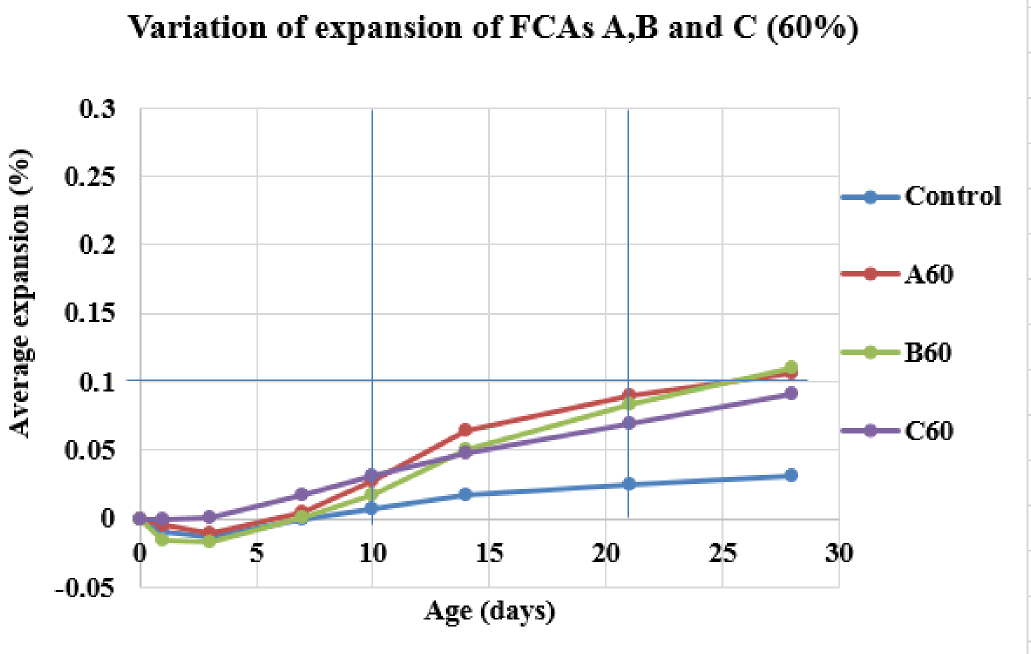


Figure 5-23: Variation of average expansion (%) of FCAs A, B and C - 60% replacement.

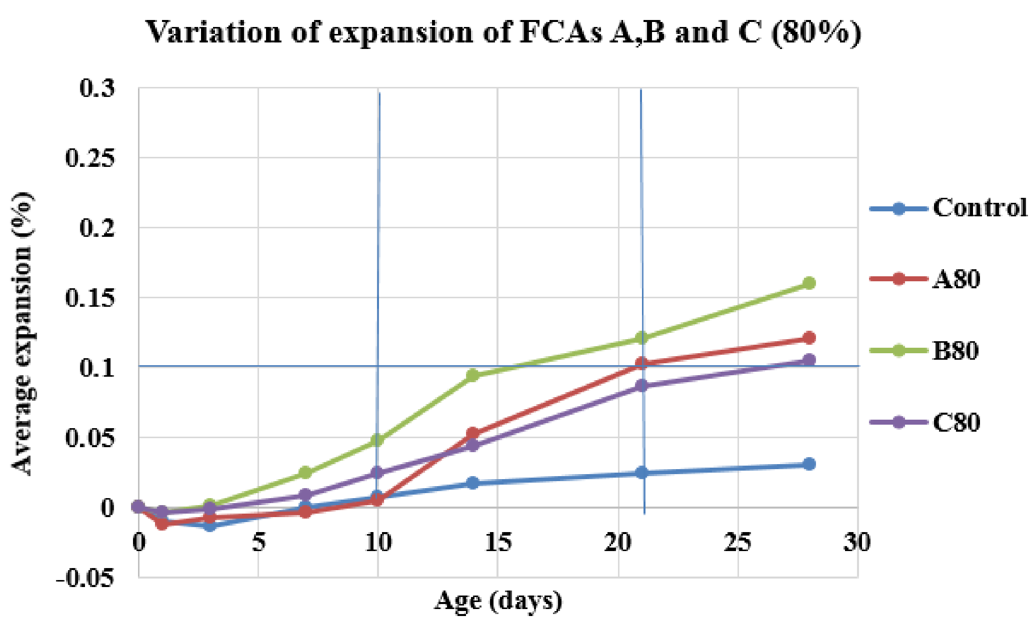


Figure 5-24: Variation of average expansion (%) of FCAs A, B and C - 80% replacement.

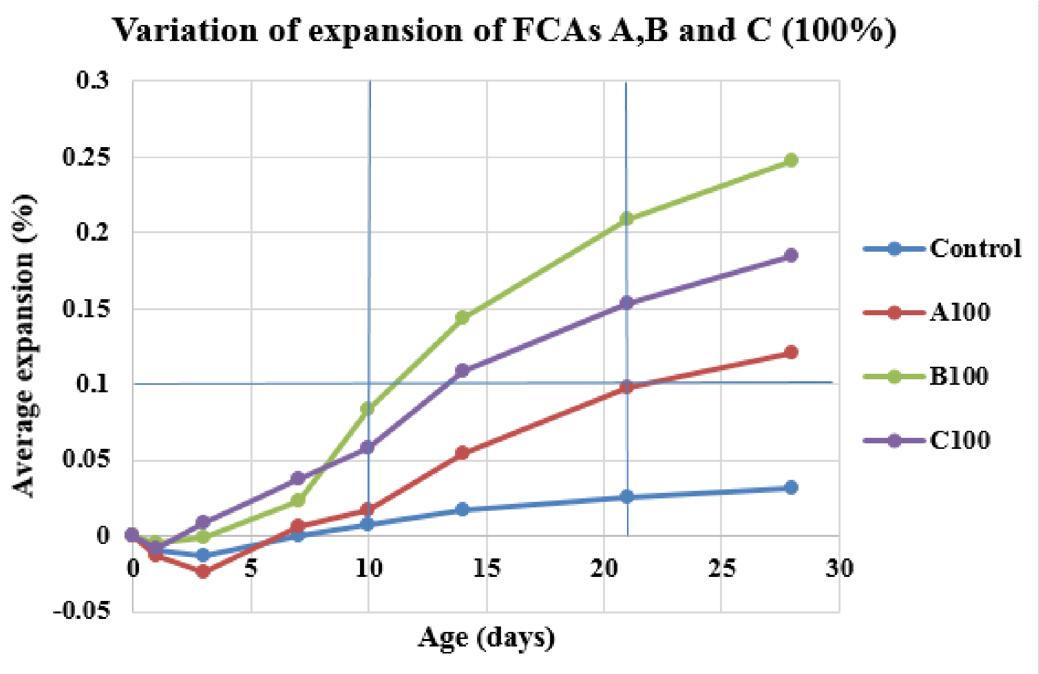


Figure 5-25: Variation of average expansion (%) of FCAs A, B and C - 100% replacement.

5.7 Summary

A detailed investigation of the FCAs was carried out by tests of mortars replacing natural sand at rates of 0-100% for all three materials A, B and C. Mortar flow and slump tests were conducted to determine the rheological properties of mortar containing the FCAs. Compressive strength and alkali-silica reactivity tests were conducted to investigate the durability properties of FCAs. FCAs A and C have shown better flow characteristic which varied between 150% -160% of flow than C, the flow of which varied from 140% to 150%. Similarly, FCAs A and C have depicted better compressive strength characteristic than type B. It could be clearly noticed that the flow and compressive strength parameters drawing parabolic curves with the increase of percentage of FCAs from 0 to 100%. Also, it was clear that the maximum of these curves lied between 40% and 80% replacement by the FCAs. FCAs A and C showed less alkali-silica reaction than B. Based on these mortar test results, concrete tests series were designed in third stage of experiments, as presented in the next chapter.

CHAPTER 6

6. PROPERTIES OF CONCRETE: TESTING, RESULTS AND DISCUSSION

6.1 Introduction

According to the mortar test results discussed in Chapter 5, concrete tests were done giving priority to FCA type C (Granite) which is locally available in Perth, Western Australia. Therefore, the percentage of FCA type C varied from 20% to 60%, and that of FCA types A and B was fixed to 40%. All the parameters such as water to cement ratio, cement content, coarse aggregate content and total fine aggregate content was fixed in all the mix designs. Performance of concrete with different type and percentage of the FCA was evaluated by experimental work. Effects of the FCAs on workability, bleeding, compressive strength, splitting tensile strength and drying shrinkage were studied.

6.2 Concrete mixtures

Concrete mix design was conducted by the absolute volume method. The 28-day target strength was 48 MPa for an S40 Grade concrete. According to specification 820, concrete for structures, Main Roads Western Australia (MRWA), the minimum cement content is 400 kg/m^3, maximum aggregate size is 20mm and the minimum aggregate/cement ratio is 4.0 for the S40 Grade concrete. The maximum water/cement ratio is 0.43 and this was slightly modified to 0.45 in order to enhance the workability of concrete incorporated with fine crushed aggregates. According to the literature review in Chapter 2, low water/cement ratio directly impairs the workability of concrete containing fine crushed aggregates. Also, it was expected that the durability properties would not to be compromised due to the slight increase of water/cement ratio. Furthermore, the water/cement ratio 0.45 is typical for S40 concrete as per industry applications.

Six different concrete mixes were used in this study. The control mix used 100% natural sand. type A (Granophyre) and B (Basalt) FCAs were used as 40% replacements of natural sand in the mixtures A40 and B40, respectively. Type C (Granite) FCA was used as 20%, 40% and 60% replacements of natural sand in the mixtures C20, C40 and C60, respectively. The mix proportions are given in *Table 6-1*.

Table 6-1: Proportions of the concrete mixtures.

Mix	Cement (kg/m^3)	Coarse (20mm) (kg/m^3)	Coarse (14mm) (kg/m^3)	Coarse (10/7mm) (kg/m^3)	Fine (Natural) (kg/m^3)	FCS (kg/m^3)	Water (kg/m^3)
Control	400	485	340	290	750	0	180
A40	400	485	340	290	450	300	180
B40	400	485	340	290	450	300	180
C40	400	485	340	290	450	300	180
C20	400	485	340	290	600	150	180
C60	400	485	340	290	150	450	180

6.3 Concrete test specimens

6.3.1 Preparation of coarse and fine aggregates

Aggregates were prepared to SSD condition by following the same procedure as described in Chapter 5.

Moulds for casting of test specimens

Concrete casting moulds were set up prior to cast the specimens. Cylinder samples (100 × 200 mm) were cast for the compressive strength test. Samples of 150 × 300 mm cylinders and 75 × 75 × 285 mm prisms were cast for the split tensile strength and drying shrinkage tests, respectively. Moulds used for concrete samples are shown in *Figure 6.1*.

Figure 6-1: Moulds ready for casting.

Each mould was cleaned and fixed to keep up the correct measurement amid casting. A thin coat of mould release agent was applied in the inward surface of the moulds to make easier for demoulding of hardened samples without any damage to the concrete sample.

6.3.2 Mixing of concrete and casting samples

The concrete was mixed in a 70-litre pan type mixer as shown in *Figure 6-2*. The mixing was carried out according to the procedure of AS 1012.2, (2014). The mixer was thoroughly cleaned with water and dried with a piece of cloth before loading the ingredients. Coarse aggregates were loaded in the mixing pan and followed by FCAs and natural sand well mixed in advance. The dry materials were mixed for three minutes. After mixing coarse and fine aggregates, cement was added and covered with aggregates. Then, the content was mixed for two minutes. Finally, water was added and mixed until it was a uniform mixture.

Figure 6-2: Concrete mixing.

Slump test was carried out as per AS 1012.3.1-2014 for the freshly mixed concrete. The moulds were then filled up by concrete and each layer was compacted by a vibrating table. The vibration was ceased when no more air pockets were freeing and aggregates were quite recently submerged in the slurry.

6.3.3 Demoulding of concrete specimen and curing

The specimens were demoulded 24 hours after casting and placed in the lime saturated curing tank located in the temperature controlled curing room. Amid the demoulding time additional care was taken to avoid any kind of damage of the samples. Concrete samples were cured under lime saturated water and tested at 7 days and 28 days of age. The concrete specimens after demoulding and curing of the specimens are shown in *Figure 6-3* and *Figure 6-4*, respectively.

Figure 6-3: Samples after demoulding.

Figure 6-4: Concrete specimen curing under lime saturated water.

6.4 Tests of fresh concrete

6.4.1 Procedure of slump test

Workability test of freshly mixed concrete was carried out as per AS 1012.3.1 – 2014. A conical mould made up of steel, with the dimensions of 300mm in height, 100mm diameter at top and 200mm diameter at the bottom was utilized to quantify the slump. The slump test is shown in *Figure 6-5*. The following steps were followed in the test:

- The inside surface of the mould was thoroughly cleaned with water and wiped with a damp cloth just before the test to avoid any frictional forces which would be created by the rough surface due to the concrete laitance.
- The cleaned mould was placed firmly on the base plate and held immovably set up by remaining on the foot pieces.
- Enough quantity of fresh concrete was transferred from the mixing drum to a bucket within 3 minutes of the completion of mixing. Concrete was placed in three layers and subsequently each layer was given an even compaction by 25 strokes of a standard tamping rod. Dimensions of the tamping rod are 600mm in length and 15mm in diameter. When tamping on second and third layers, care was taken to penetrate the rod approximately 25 mm below the previous layer. This was done to ensure proper blending of concrete at layers.
- The top layer was horizontally cut by a trowel to remove excessive concrete and levelled the surface. Then the cone was lifted vertically in three seconds with no horizontal or torsional displacement.
- Finally, the drop of slump (height of the mould and the edges of the top surface of the concrete) was measured and recorded, as shown in Figure 6-5.

Figure 6-5: Workability test and measuring the slump of concrete.

6.4.2 Bleeding test procedure

Bleeding test of concrete was conducted in accordance with the AS 1012.6 (2014) Standard. A cylindrical bleeding pot with 250mm diameter and 280 mm height was used in this experiment. Freshly mixed concrete was placed in the mould in two layers evenly to a level of 5 mm below the top edge. Each layer was compacted by an external vibrator (vibration table) till the surface was free from air bubbles and the concrete surface become relatively smooth.

The mould filled with concrete was placed on a flat surface and covered by a polythene sheet all the time except for collection of the bleeding water. The bleeding pot was tilted and carefully placed a 50mm block under the bottom surface to make easier the collection of bleeding water. After collecting the water by a pipette, the vessel was carefully placed on the levelled surface just by removing the block underneath. The bleeding water was withdrawn at 15 minutes intervals during the first hour and then in every 30 minutes until the bleed water collected during 30 minutes period was less than 5mm. Then, the bleeding water was transferred to a measuring cylinder and the time and the accumulated bleed water volume was recorded. Rate of bleeding was calculated by *Equation 6.1*.

$$\text{Rate of bleeding} = \left(\frac{V}{At}\right) \quad \text{ml/ mm}^2\text{/ min} \quad \text{---}(6.1)$$

where,

V = total volume of water collected in ml

A = internal cross sectional area of the bleeding pot in mm^2

t = selected time interval in min

The bleeding of concrete expressed as a percentage of the free mixing water in the test specimen was calculated by *Equation 6.2*.

$$\text{Bleeding} = \frac{V1 \times M}{S \times V2 \times 10}\ \% \text{ -- } (6.2)$$

where,

V_1 = total quantity of bleed water collected during the test, in millilitres

M = total batch mass of concrete from which the sample was taken, in kilograms

V_2 = volume of free mixing water in the batch from which the concrete was taken, in litres (i.e. total water less that absorbed by the aggregates to their saturated surface dry conditions)

S = mass of concrete in test specimen, in kilograms

Figure 6-6: Bleeding test and bleed water collection.

6.5 Tests of hardened concrete

6.5.1 Testing of compressive strength

Compressive strength of concrete was determined by testing of cylindrical test specimens with 200mm height and 100mm diameter. Testing was carried out in accordance with the AS 1012.9- 2014. Samples were cured in lime saturated water for periods of 7 days and 28 days before testing. The test machine of MCC8 was used in testing of compressive strength. The average value for the compressive strengths from three specimens was reported to the nearest 0.5 MPa. The procedure used to test the samples was as follows:

- Dimensions of the sample (height and diameter) was measured at two locations and the average values were recorded in order to find the cross sectional area and the volume of test specimen.
- Then the test specimen was wiped with dry cloth and the rubber capping was fixed at the top surface where the load would be applied. Then the specimen was placed at the centre of the base plate of the test machine and loaded with a steady rate of 0.33 MPa / sec until failure.
- Any sorts of imperfections in the samples tested, identification of the sample, test age, maximum load and compressive strength at the failure were recorded.

Figure 6-7: Compressive strength tests and failure of failure a specimen.

Equation 6.3 is used to calculate the compressive strength of a specimen.

$$f_c = \frac{1000 \times P}{A} \quad \text{--} \quad (6.3)$$

where,

f_c = compressive strength (MPa)

P = maximum force applied (kN),

A = cross sectional area (mm^2)

6.5.2 Test procedure for indirect tensile strength

The splitting tensile strength of concrete was determined at 7 days and 28 days in accordance with the AS 1012.10-2000 test method. A cylindrical sample of 300mm height and 150 mm diameter was placed its axis horizontally on the testing jig and was loaded along the length through a vertical plane at the centre in a MCC8 testing machine. The following steps were followed in the test:

- Sample diameter was determined to the nearest 0.2mm by averaging three measurements taken at near ends and the middle. Length of the sample was determined by averaging two reading taken from opposite directions.
- A hardboard bearing strip was aligned in the testing jig at the top and bottom of the platen of the specimen and testing jig was positioned at the centre of the lower platen. Load was applied without any shock and increased gradually at a rate of 1.5 ± 0.15 MPa/min indirect tensile stress until no increase in force could be sustained.
- Failure load was recorded to calculate the maximum tensile stress.

Figure 6-8: A sample subjected to indirect tensile strength test.

Equation 6.4 was used to calculate the indirect tensile strength. Two cylinders were tested at each test age and average value is reported.

$$f_{ct} = \frac{2000P}{\pi LD} \quad (6.4)$$

where,

f_{ct} = indirect tensile strength (MPa),

P = maximum load (kN),

L = average length of the sample (mm),

D = average diameter of the sample (mm)

6.5.3 Drying shrinkage test procedure

Drying shrinkage test was conducted using the method described in the AS 1012.13 - 1992 Standard. Test samples of 75×75×285 mm prisms with the gage studs fixed at both ends were used to determine the drying shrinkage. Methodology followed in this study is briefly discussed below.

- Inside surface of moulds were lubricated with mould release agent and end studs were carefully assembled.
- Moulds were filled with fresh concrete in two layers and compacted using a vibrating table.
- Samples were covered and left in the laboratory where the temperature (23 ± 2 ^{o}C) and humidity (50 ± 5 %) is controlled. Then the samples were demoulded 24 hours after casting and placed in lime saturated water for 7 days.
- After seven days of casting samples were removed from water and wiped with a dry cloth. The sample was then put in the comparator such a way that its axis aligned with the measuring anvil to take the initial reading, as shown in Fig. 6.10. Five measurements were taken with similar orientation of the sample and average was recorded.
- After the initial reading was taken, the samples were placed spaciously (minimum 50mm from all sides) in the rack of drying shrinkage room of the laboratory.
- Subsequent measurements were taken at 14, 21 and 28 days.
- Three measurements were taken for every sample and the average value is reported. The length change was calculated using Equation 6.5.

Figure 6-9: Length measurement by a horizontal length comparator.

$L_{ds} = (L_t - L_i) \times 10^6 / L$ -- (6.5)

where,

L_{ds} = drying shrinkage in micro strain.

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 (250mm)

6.6 Results and discussion of fresh concrete

6.6.1 Workability of fresh concrete

The variation of workability of fresh concrete was measured in terms of slump. A comparison of slumps has been made at 40 % sand replacement by FCAs A, B and C with that of the control mixture, as shown in *Figure 6-10*. Slump of the control mixture was 140 mm and those of the mixtures with 40% FCAs varied from 120 mm to 125 mm. There was no significant difference in slump values at 40% replacement of FCA types A, B and C. Replacement of natural sand by 40% FCAs increased fine particles of the mix as compared to that with 100% natural sand. Furthermore, FCA particles are flat, elongated and rough in texture. These facts are attributed to reduce the rheological properties of fresh concrete which is reflected in reduction of slump from 140 mm to 120 mm. This result reconfirmed that the increase of fine content in concrete mixtures needs extra amount of water to maintain the same workability in order to wet and minimise the frictional forces generated by the viscosity of paste. Wills (1967) studied the effect of shape characteristics of fine and coarse aggregate on water demand of concrete and found that an equal change in shape characteristics caused fine aggregate to increase the water demand of the mixture two or three times more than the coarse aggregates. Similar results are also reported by Koehler et al. (2009).

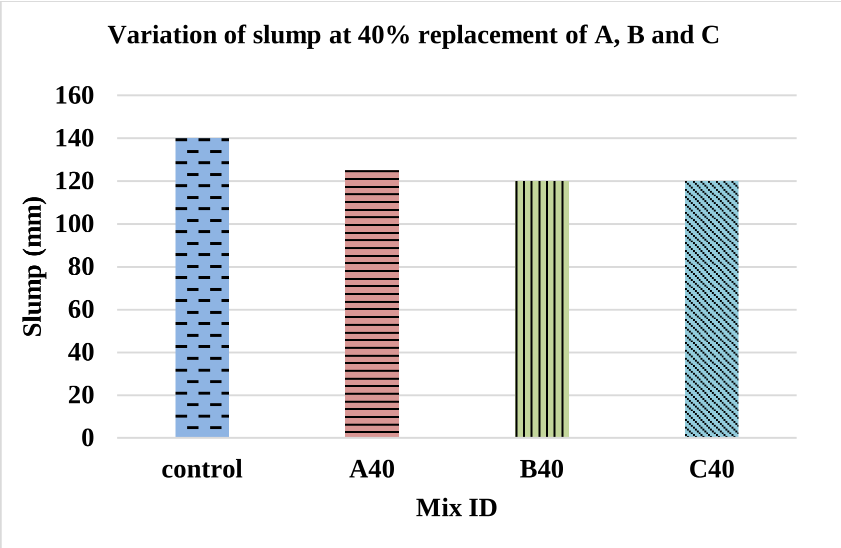


Figure 6-10: Slumps of concrete containing 40% FCAs type A, B and C.

Figure 6-11 shows the variation of slump with the percentage of FCA type C (Granite). The results show that there was no noticeable effect on slump by 20% FCA type C. However, slump decreased from 140 mm to 125 mm by 40% FCA and further to 80 mm by 60% FCA. Thus, the increase of fine particles and particles with poor shape and texture significantly affected the workability of fresh concrete by FCA as sand replacement beyond 20%. The reduction of slump was more prominent at higher percentages of sand replacement. Cepuritis et al. (2016) stated that different aggregate size fractions affect the rheology of the fresh concrete by two known phenomena. The first is the fundamental findings of Krieger et al. (1959) who showed that the effect of mono-sized sphere particles on the flow (viscosity) in a concentrated suspension strongly depends on their normalised solid concentration, *i.e.* the maximum packing fraction ψ/ψ_m (where ψ is solid concentration and ψ_m is maximum solid concentration or maximum packing). Ferraris et al. (1998) showed the importance of the same parameters for concrete. ψ_m mainly depends on particle size distribution and shape. Therefore, particle size distribution and shape establish the rheology of concrete. Thus, 60% replacement of FCA in the mixture has significantly reduced the workability of concrete due to poor shape and higher fines content contributed by FCA.

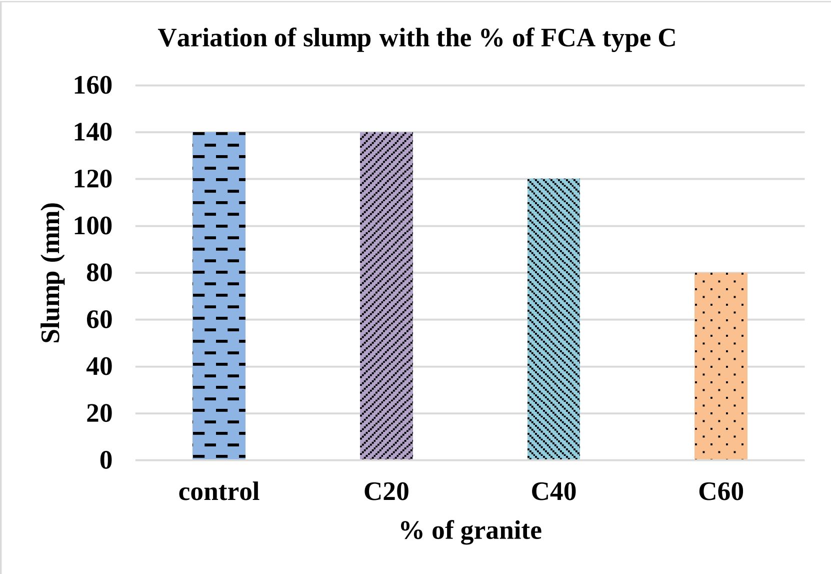


Figure 6-11: Variation of slump with the % of FCA type C.

6.6.2 Concrete bleeding results and discussion

When freshly mixed concrete is placed in mould and compacted, water rises or bleeds to the surface. Bleeding occurs by rising of water in the mixture and settlement of solid particles. It is caused by the inability of the solid constituents of the mix to hold all the mixing water when they settle after compaction (Cheng-ju, 1994). According to Cheng-ju (1994), two independent actions that cause bleeding are gravity and capillary suction. Bleeding rate of mixes where it was observed, was initially constant and then decreased steadily. There are many factors affecting the bleed capacity of concrete. Neville (1995) stated that the properties of cement are the most important among other parameters. Other factors affecting the bleeding of concrete include very fine aggregates, admixtures and temperature (Neville, 1995).

The bleeding result of concrete with 100% natural sand has been compared with those of concrete with 40% FCA types A, B and C, as shown in *Figure 6-12*. Highest bleeding was observed in the concrete with 100% natural sand. There is no significant difference among the bleeding values for 40% replacement of FCA types A, B and C. However the bleeding values of FCAs at 40% replacement are approximately half of that for 100% natural sand. The reason could be the high resistance force by the friction against the flow exerted by the rough texture of FCA particles. Also, the dense concrete with fine particles may disturb the capillary paths through which water is transferred to the surface. Furthermore, in FCAs more water is occupied to cover more aggregate surface areas in concrete due to the high fine content and less free water is left to cause bleeding. It can be clearly seen from the *Figure 6-13* that the bleeding of concrete gradually decreased with the increase of FCA. Zero bleeding was recorded for 60% replacement of FCA.

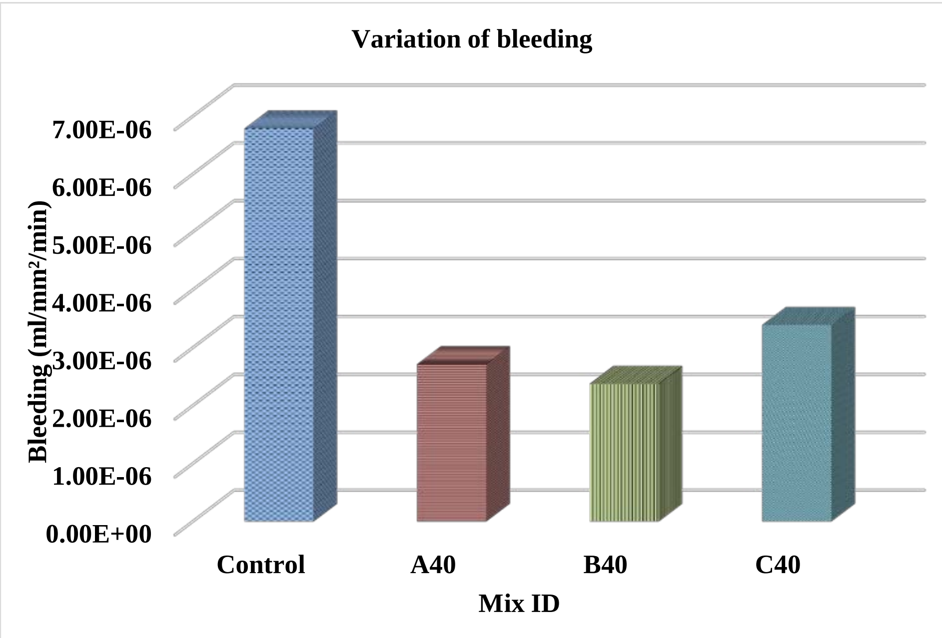


Figure 6-12: Comparison of bleeding at 40% replacement by A, B and C against the control sample.

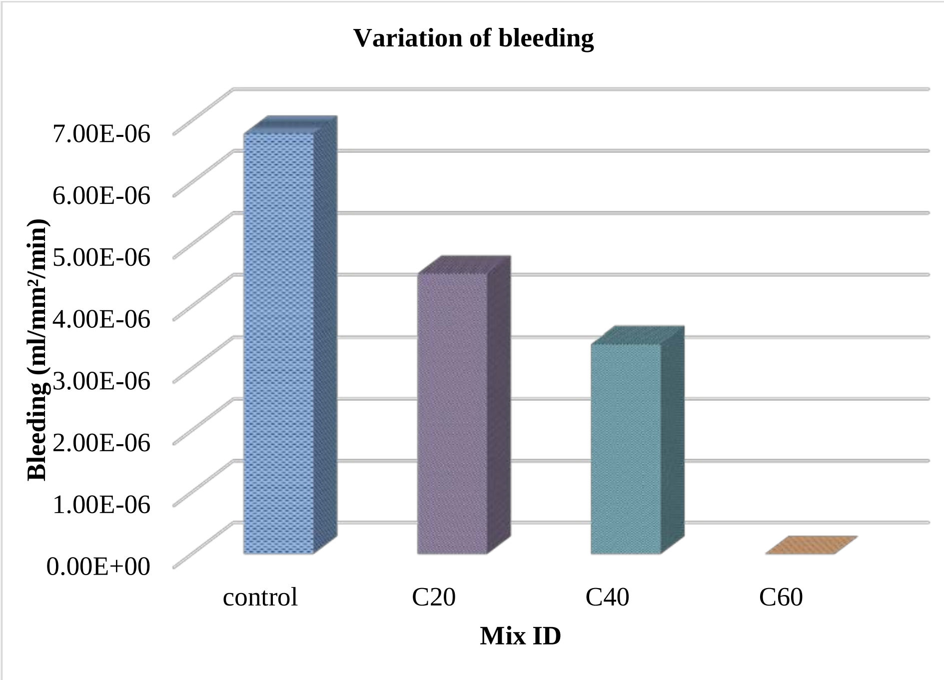


Figure 6-13: Variation of bleeding with the % of FCA type C.

Figure 6-14 and *Figure 6-15* show the bleeding as a percentage of free mixing water in the mixture. Concrete with 100% natural sand showed the highest percentage (0.62%) of bleeding against the amount of mixing water. It can be seen that FCA type C marked the second highest and FCA type A showed the lowest percentage of bleeding. This indicates that the amount of free water available for the bleeding was very low for FCA type A. According to Lafrenz (1997), aggregate characteristic such as shape texture and grading influence workability, finish ability, bleeding and pump ability of fresh concrete. According to Dao et al. (2010), certain level of bleeding is required to replace the water loss by evaporation thus to prevent concrete surface from drying quickly before getting enough strength to resist cracking. However, the bleeding rate of concrete is usually less than 1.0 kg/m^2/ h (Almusallam et al. 1998). Thus, the bleeding results of concrete with 60% replacement of FCA type C should not be a reason to undermine the idea of using FCAs in high percentage in concrete construction. Furthermore, because it is generally desirable to control bleeding to obtain concrete with better mechanical properties and to reduce permeability.

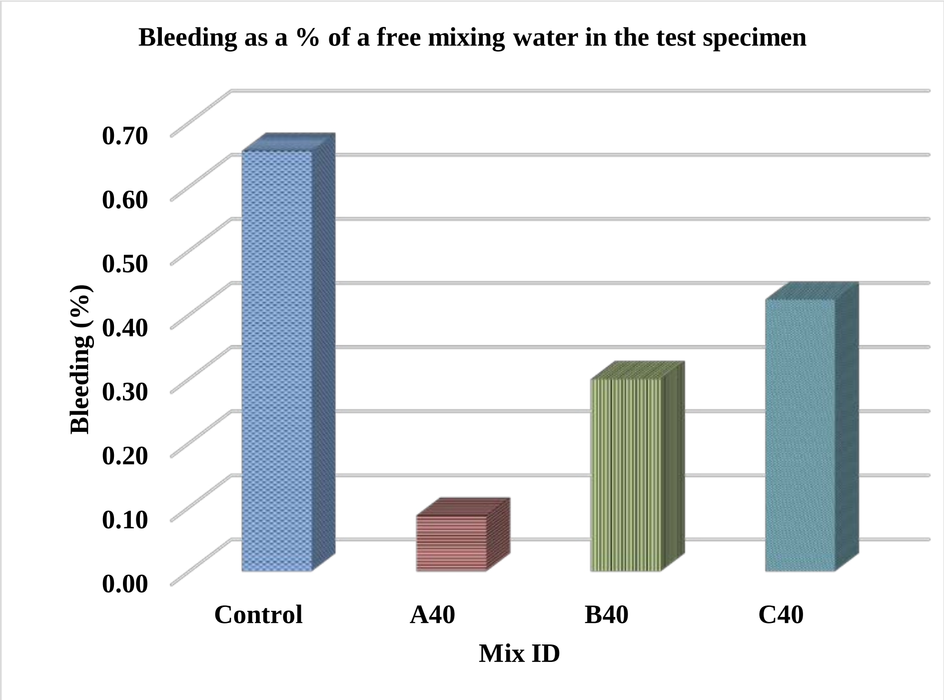


Figure 6-14: Comparison of bleeding as a % of free mixing water with 40% FCA type A, B and C against the control sample.

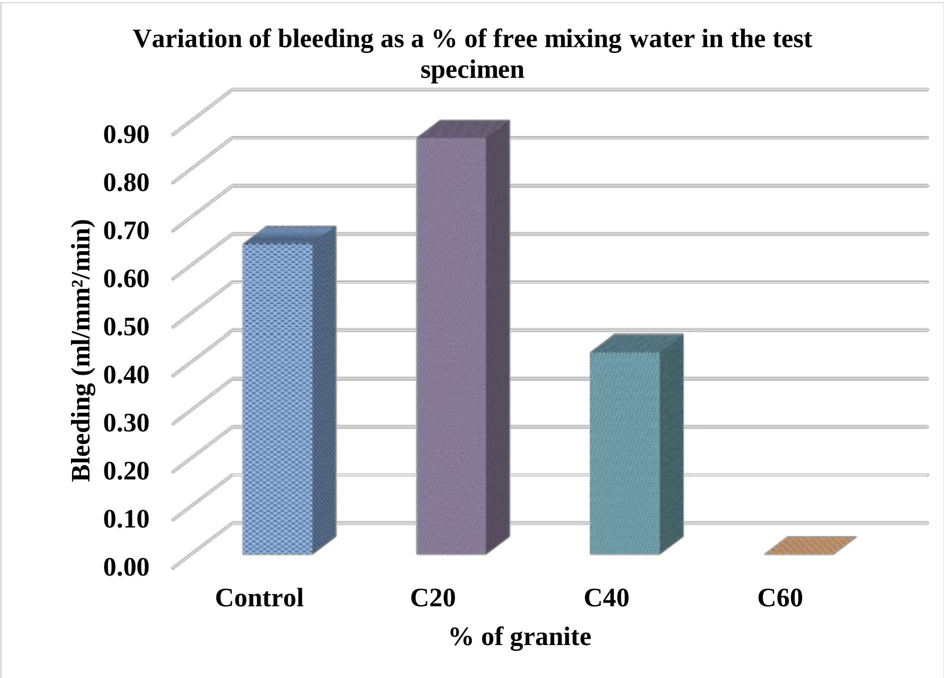


Figure 6-15: Variation of bleeding as a % of free mixing water with the % of FCA type C.

6.7 Results and discussion of hardened concrete properties

6.7.1 Compressive strength development

The 7-day and 28-day compressive strengths concrete are given in *Table 6-2*. The comparisons of compressive strengths for different percentages of FCA type C and for different types of FCAs are shown in *Figure 6-16* and *Figure 6-17*, respectively. There is no significant difference in compressive strength of A, B and C at 7 and 28 days at the replacement of 40% FCAs. Compressive strength of concrete at 40% replacement of FCAs A, B and C at 28 days are approximately 50MPa.Compressive strength of control sample with 100% natural sand is 46.5 MPa which is slightly lower than the values at 40% replacement. 40% replacement of B has shown the highest strength at 7 days while 20% of C has shown the lowest for the same age. When the compressive strength development of type C material at 28 days is considered, it is clear that there is a slight increment of strength with the each step of increment of FCA from 0% to 60%. For the 7 days compressive strength of the same material, same amount of increment can be observed. However there is no significant deference compared to the control sample in both 7 and 28 days compressive strength values.

Table 6-2: Compressive strength of concrete.

Mix ID	Average compressive strength (MPa)	
	7 days	28 days
Control	40.0	46.5
A40	39.8	50.0
B40	44.0	50.3
C20	39.6	48.3
C40	40.2	49.2
C60	42.0	50.2

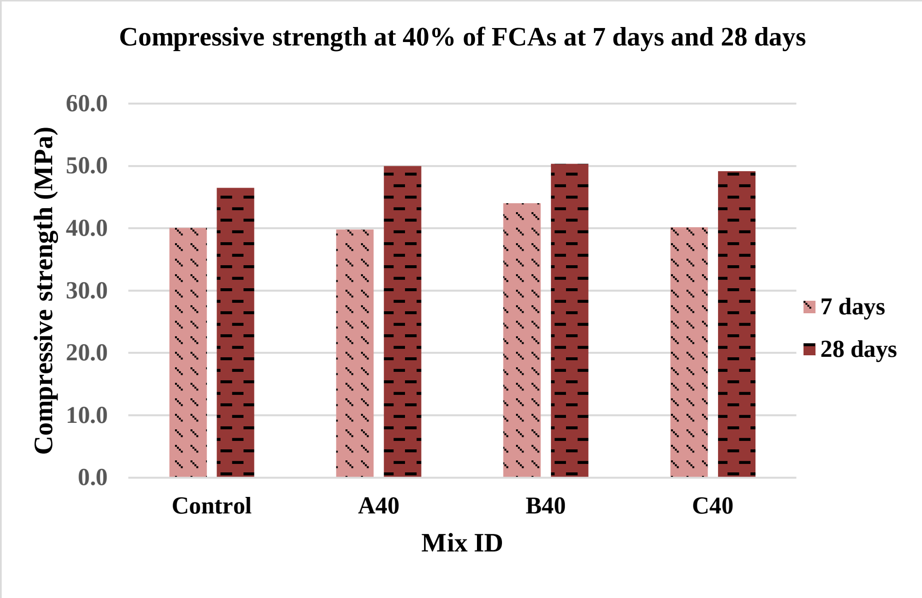


Figure 6-16: Comparison of compressive strength at 40% replacement A, B and C against the control sample.

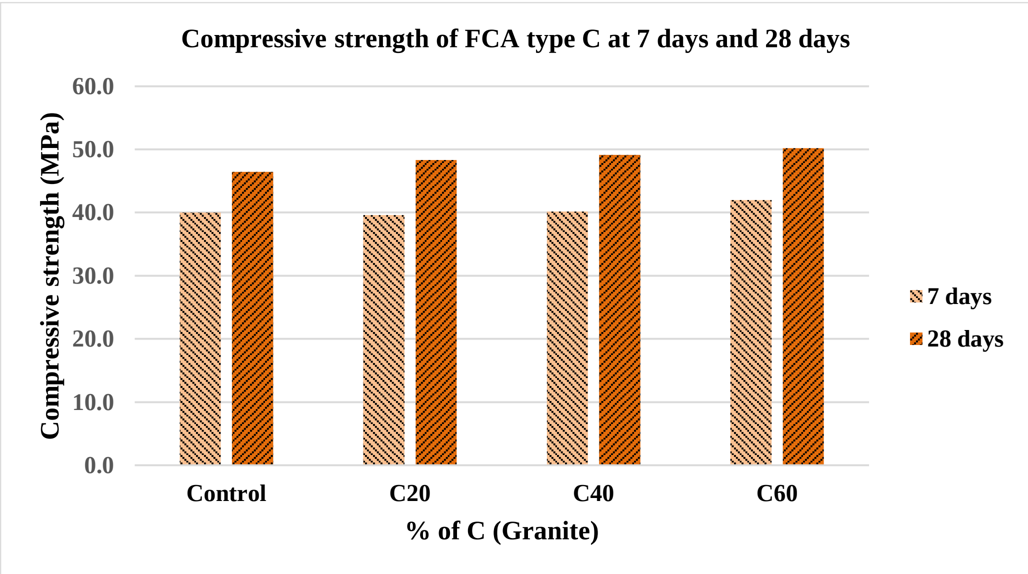


Figure 6-17: Variation of compressive strength with the % of FCA type C.

The small increase in the compressive strength of concrete with the increase of FCAs could be attributed by the compactness enhancement due to particle packing. Increase of FCAs in the mixture increased the fines content which helped to increase the density of concrete filling the voids between aggregates with the finer particles. Further, the rough and irregular shape of FCAs improved the mechanical bond between the fine aggregate particles and paste. On the other hand, frictional forces between particles are higher in concrete with FCAs as a result of better interlocking due to the rough texture of FCAs. As all the concrete samples had the same paste (cement content and w/c ratio) and the coarse aggregate interface was same in quality and quantity, then the increase in compressive strength of concrete with FCA type C (Granite) was related to the strong paste – fine aggregate interface. Goble et al. (1999) showed that the sand surface area has a significant influence on the mechanical properties of Portland cement mortar. According to Aitcin et al. (1998), the improvement of the paste-fine aggregates transition zone could be attributed to the rough texture of crushed granite fine aggregate, which increases the mechanical interlocking with the cement paste. In contrast, it was reported that the presence of mica in granite rocks resulted in unfavourable condition because of the poor cleavage planes which may initiate failure in the coarse aggregate. However the positive behaviour of granite can be explained by the fact that the fine crushed aggregates are produced in the crushing process, leaving the remaining particles free from flows or weak zones.

Donza et al. (1996) conducted a comprehensive study about the influence of shape, texture and mineralogical composition of sand in concrete. Concrete was cast with crushed sand without dust, 0-100% with the step of 25% replacing natural sand and with water to cement ratio of 0.3 in their experiments. It was found that there was no significant difference in compressive strength at later ages such as 28 and 90 days. The compressive strength of all mixtures were 62 ± 2 MPa. Consequently, the authors concluded that the influence of fine aggregate on compressive strength was not significant when the paste volume remained constant and the crushed sand is dust free. Thus, the compressive strength results of this study are consistent with the results reported in literature on the effect of similar crushed fine aggregates.

6.7.2 Comparison of mortar and concrete compressive strengths

Compressive strengths of concrete and mortar specimens for similar mixtures are compared in *Table 6-3* and its graphical presentation is given in *Figure 6-18*. All the concrete mixtures were produced with a fix water to cement ratio of 0.45 and the mortar with 0.485. Concrete with a lower water to cement ratio than in mortar has given a low compressive strength in each case. Knowing the fact that higher water/cement ratio proven to result in low compressive strength for both concrete and mortar, with high water to cement ratio (i.e. 0.48) has shown higher compressive strength in mortar. Therefore, it is clear that compressive strength is directly related to strength of the mortar phase. However concrete with FCAs despite the type has shown better performance than natural sand concretes because of their mortar strength. This results depicts that the influence of the fine aggregates source on the interface between fine aggregate and paste in concrete because coarse aggregate was the same for all mixtures. Donza et al. (2002) reported similar trend of compressive strength results using crushed fine aggregates of granite, limestone and dolomite.

Table 6-3: Compressive strengths of mortar and concrete.

Mix ID	**Concrete (w/c = 0.45**	**Mortar (w/c = 0.48**
Control	46.5	50.4
A40	50.0	54.0
B40	50.3	51.7
C20	48.3	51.4
C40	49.2	52.2
C60	50.2	52.4

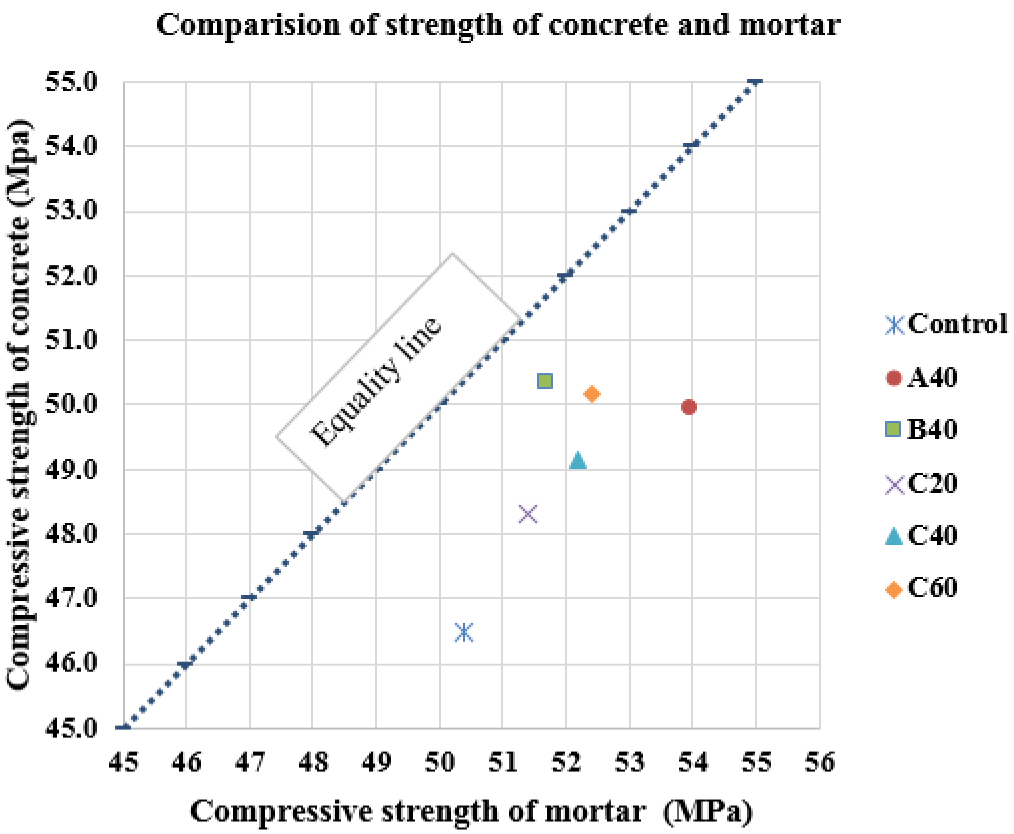


Figure 6-18: Comparisons of compressive strengths of concrete and mortar.

6.7.3 Splitting tensile strength results and discussion

The 28-day concrete splitting tensile strength results are given in *Table 6.4* and their graphical representations are shown in *Figure 6-19* and *Figure 6-20*. The maximum value for the split tensile strength of 4.79 MPa was obtained for FCA type A (Granophyre) at 40% replacement. This is slightly higher than the split tensile strength for 100% natural sand which is 4.64MPa. FCA type B showed 4.44 MPa tensile strength at the same replacement of natural sand. FCA type C (Granite) showed the lowest splitting tensile strength which is 4.01 MPa at 40 % replacement of natural sand. This value is slightly higher than that for 100% natural sand. However the results of split tensile strength for all FCAs at 40 % replacement including 100% natural sand were reported between 4 MPa and 5 MPa. As shown in Figure 6-20, when FCA type C (Granite) is considered, split tensile strength decreased with increase of the percentage of FCA. The splitting tensile strength gradually decreased from 4.09 MPa to 3.89 MPa as the percentage of FCA increased from 20% to 60%. Ukpata et al. (2012) observed similar variation of split tensile strength with the increase of quarry dust by 25 %, 50% and 75% in their experiments.

Table 6-4: Splitting tensile strength of concrete at 28 days.

Mix ID	Comp. strength at 28 days (MPa)	Tensile strength at 28 days (MPa)	Tensile Strength/Comp.strength
Control	46.5	4.64	0.10
A40	50.0	4.79	0.10
B40	50.3	4.44	0.09
C20	48.3	4.01	0.08
C40	49.2	4.09	0.08
C60	50.2	3.89	0.08

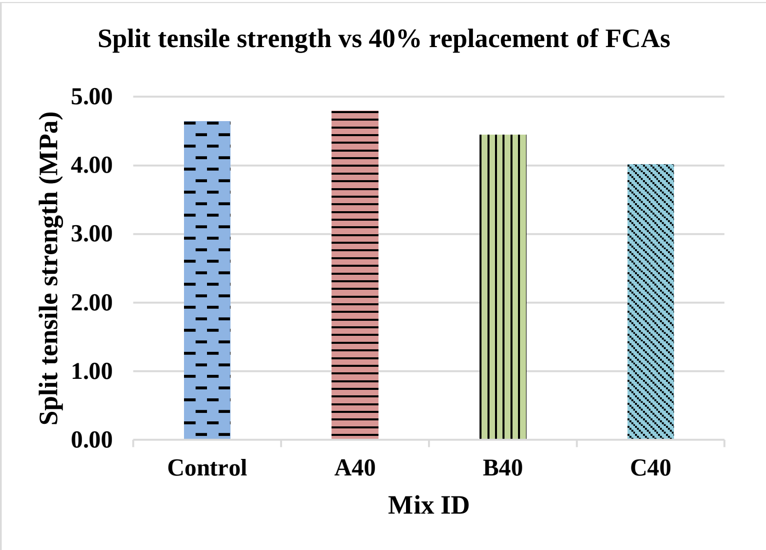


Figure 6-19: Splitting tensile strengths of concrete with 40% FCA types A, B and C.

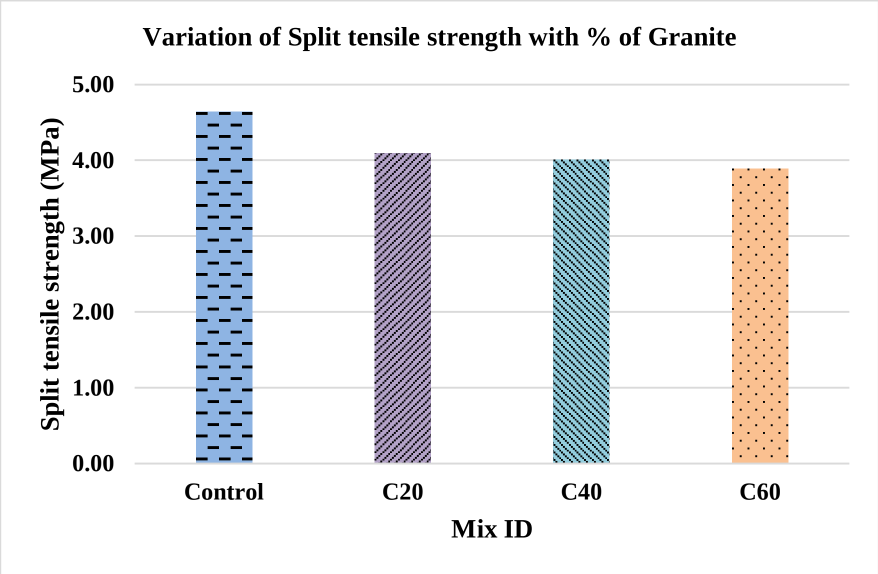


Figure 6-20: Variation of split tensile strength with the % of FCA type C.

6.7.4 Correlation of the split tensile strength with compressive strength

A definite relationship could be observed between split tensile strength and compressive strength where natural fine aggregate is used in concrete applications. Therefore, various concrete design standards have suggested equations in terms of compressive strength to predict tensile strength. According to *Table 6-5*, it is clearly shown that the ratio of split tensile strength to compressive strength is 0.10 for 100% natural sand. The corresponding ratio for FCA concrete is in the range of 0.08 - 0.10. Thus, it can be concluded that the correlation between split tensile strength and compressive strength of concrete with natural fine aggregate is same as that of concrete with FCAs.

Based on this relationship between split tensile strength and compressive strength, design standards have suggested simple formulas to estimate the split tensile strength multiplying the compressive strength by a coefficient. *Table 6-5* Summarises the experimental and estimated split tensile strength according to AS 3600 (2009) and ACI Code 318 (2008). The ratio between the experimental and estimated split tensile strength for natural sand is 1.2 as per the AS 3600 and 1.3 as per ACI Code 318. The corresponding ratios for FCA concrete is in the range of 1.0 to 1.2 and 1.1 to 1.3 for the AS 3600 and ACI 318, respectively. Thus, it can be concluded that the split tensile strength of concrete containing FCAs can be predicted by the design standards conservatively and with the similar accuracy for concrete with natural sand.

Table 6-5: Comparison of experimental and predicted splitting tensile strength of concrete at 28 days.

Mix ID	Split tensile strength at 28 days (MPa)			Experimental /Calculated	
	Experimental	Calculated as per AS 3600	Calculated as per ACI 318	AS 3600	ACI 318
Control	4.64	3.82	3.44	1.2	1.3
A40	4.79	3.96	3.58	1.2	1.3
B40	4.44	3.97	3.60	1.1	1.2
C20	4.09	3.89	3.51	1.1	1.2
C40	4.01	3.93	3.55	1.0	1.1
C60	3.89	3.97	3.59	1.0	1.1

6.7.5 Drying Shrinkage behavior of concrete

The drying shrinkage results of FCAs and 100 % natural sand concrete are given in *Table 6-6* and the variations with the age are shown in *Figure 6-21*. Drying shrinkage measurements are given in *Table C-3* of Appendix C. The deformation of concrete is prominent during the early ages and it has become stable after 28 days even though a slight increment was noticed. Concrete samples with 40% Granophyre (type A) and 60% of Granite (type C) has a similar behaviour after 21 days. Granophyre at 40 % replacement has shown slightly higher shrinkage than Granite with 60% replacement at the initial stage. The shrinkage of Basalt (type B) and Granite at 40% replacement displayed similar variation with the age. Concrete samples of Granite at 20% replacement has shown better shrinkage properties compared to 100% natural sand (control sample) in this study.

Given that the cement content remains constant, the reason could be the optimum dust content contributed by Granite to absorb free water after the hydration process was taken placed. According to Tangchirapat et al. (2010), when the replacement ratio exceed a critical level, the drying shrinkage caused by the free water evaporation becomes dominant. Thus, the C60 and A40 showed the largest drying shrinkage. The 56-day drying shrinkage of the mixtures varied in the range of 402 micro strain to 520 micro strain. These shrinkage values are well below the limiting value recommended by the Australian Standard (AS3600, 2009) for general applications.

Table 6-6: Drying shrinkage of concrete.

Age/ (days)	Shrinkage values (micro strain)					
	Control	A40	B40	C20	C40	C60
0	0	0	0	0	0	0
7	138	261	161	113	121	198
14	266	398	300	229	266	357
21	346	466	405	320	391	463
28	405	498	439	384	445	500
56	427	514	452	402	459	520

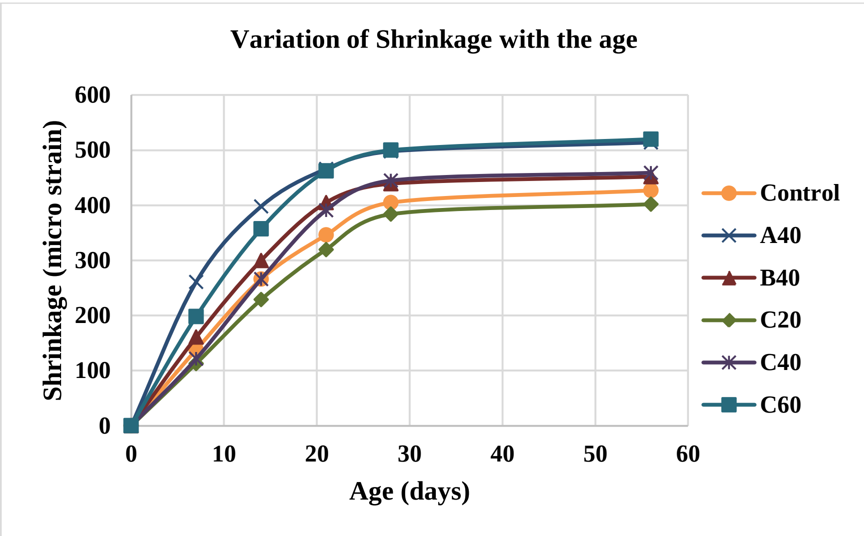


Figure 6-21: Variation of drying shrinkage with the age.

6.8 Summary

A comprehensive experimental work was conducted on concrete with FCAs as partial replacements of natural sand. In the investigation of performance of fresh concrete, the workability of concrete was determined by means of slump. There was no significant difference in slumps for the types of FCA when sand was replaced by 40%. The optimum fines content less than 0.075 mm which would lubricate the mix could be met with 40% replacement of FCAs in this particular mixtures. However, concrete even with the 60% replacement of FCA type C showed 80 mm slump which can be considered adequate for many applications. Bleeding performance of concrete was enhanced with 20% replacement of sand by FCA type C. However, a considerable decrease in bleeding was observed with the increase of the percentage of FCAs. Zero bleeding was found at the 60% replacement of sand FCA type C.

Compressive strength of concrete with 40% replacement of FCAs type A, B and C did not show a significant difference and attained approximately 50 MPa at 28 days. Slight increment of compressive strength was observed with the increment of FCA type C. Compressive strength as a percentage with respect to 100% natural sand, FCA type C at 60% replacement has exceeded by 8%. Use of FCAs in concrete improves the compressive strength due to the mechanical bond improved as a result of rough texture of FCAs. Also it was observed that the interface of binder to FCA played a vital role in relation with the compressive strength. Split tensile strength has not shown a substantial difference among these three types of FCAs. However, a slight fall was observed in splitting tensile strength with the increase of FCAs. Also it was analytically proved that split tensile strength can be conservatively predicted by using empirical equations in different design standards. Drying shrinkage of concrete containing 40% FCAs was approximately similar in type B and C which is 450 micro strains, while type A showed slightly higher value which is 500 micro strain for the same percentage of FCA. The highest drying shrinkage among the mixes was 520 micro strain and it was for the concrete containing 60% FCA type C.

CHAPTER 7

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

This experimental research study consisted of three main stages. The first stage of the experiments was to assess material characteristics. Three types of FCAs and natural sand which are locally available in Western Australia were used in this study. The second stage of experiments was mortar testing to evaluate the use of FCAs in mortar. The replacement percentage of FCAs were varied from 0% to100% in steps of 20%, while the w/c ratio was fixed. In third stage of experiments, performance of concrete incorporated with FCAs was investigated for fixed w/c ratio while 40% replacement for types A and B, and 0%- 60% in 20% steps for type C were used.

After completing the experimental investigations, results and discussions for material characterisation, mortar and concrete, the conclusions presented in the following sections are drawn.

7.2 Properties of FCAs

The properties of FCAs were examined via seven tests for three rock types named as Granophyre (type A), Basalt (type B) and Granite (type C) and the following properties were determined:

1. Particle size distribution of FCAs showed high microfine content ie., 5% for Granophyre, 13% for Basalt and 17% for Granite. These microfine contents are well below the limits given in Australian Standard (AS2758.1:2014) for aggregates and rock for engineering purposes.
2. Water absorption of FCA type B was found to be 4.2%, which is slightly higher than types A and C. However in Australian Standard AS2758.1 (2014) permits the higher values of water absorption than 2% unless many of the properties of concrete are not affected.

3. In the flow cone test, flow time increased with the increase of the percentage of FCAs because of their angular shape and rough surface texture. The lowest void contents were observed at 40% to 60% FCAs. FCA type B showed the maximum loose density and minimum flow time when compared with the other two types of FCAs.

7.3 Mortar properties

The following conclusions were drawn on the mortar containing the FCAs:

1. Generally, the percentages of FCAs that plotted inside the NZS 3121 flow time envelope showed better results in mortar flow and compressive strength.
2. FCA type A showed better flow characteristics in the mortar test. The performance of type C can be rated as intermediate and type B showed low flow characteristics in the same test. As the flow test is not static instead it is dynamic, flow rate is influenced by several parameters such as microfine content, shape and surface texture of particles.
3. Alkali-silica reactivity test results were assessed against the aggregate reactivity chart of AS 1141.60.1-2014 standard, as given in Table 5-2. It was found that FCA type A as 0% -100% replacement of natural sand were non-reactive, 80% and 100% replacement by type B were slowly reactive and 100% replacement by type C also slowly reactive.
4. Compressive strength increased with the increase of FCA up to 60% for all the three types of FCA. Strength declined with the increase of FCA beyond 60%. The strength increase by FCAs is considered to be contributed by the better interlocking of the angular particles. The decline of strength for FCAs beyond 60% is attributed to the increased void content by the angular particles.

7.4 Investigation of concrete properties

The following conclusions are drawn on the properties of concrete containing the FCAs:

1. Workable concrete can be made incorporating FCAs up to 60%. The highest workability was in concrete containing 100% natural sand. There was no significant difference in the slumps of concrete containing the three types of FCAs at 40% replacement level. FCA type C at 60% replacement level considerably reduced the slump.
2. Bleeding of concrete is significantly influenced by increasing the amount of FCAs. Highest bleeding was observed at 20% replacement of FCA type C while zero bleeding was observed at 60% FCA of the same type.
3. Generally, the percentages of FCAs that plotted inside the NZS 3121 flow time envelope showed better results in concrete compressive strength. FCAs with flow time in the range of 23 to 25 seconds and un-compacted void content in the range of 37% - 40% produced concrete with higher compressive strength than 100% natural sand concrete. Therefore there is an optimum grading when the particle shape and texture is particularly considered resulting higher compressive strength that can be evaluated by NZFC test.
4. When the compressive strengths of mortar and concrete are considered, it can be concluded that the compressive strength is directly related to strength of the mortar phase. Compressive strength of concrete with FCAs type A, B and C has shown better performance than 100% natural sand concretes because of their high strength in mortar phase.
5. A significant difference cannot be identified in the 28-day splitting tensile strengths of concrete with FCAs and natural sand. However, slight reduction was observed with the increase of percentage of FCA type C.
6. Conservative predictions of splitting tensile strength of concrete with FCAs can be made by using the equations given in design standards such as Australian standards and ACI codes for conventional concrete.

7. The 56-day drying shrinkage of the mixtures varied in the range of 402 micro strain to 520 micro strain. These shrinkage values are well below the limiting value recommended by the Australian Standard (AS3600, 2009) for general applications.

7.5 Recommendations

This study explored the effects of FCAs on properties of mortar and concrete made with one type and fixed content of cement. Thus the influence of FCAs on mortar and concrete with different types and content of cement and cement replacement materials could be investigated in future. This will determine whether the trends observed in this study for FCAs hold true at different types and content of cement.

This study has taken only a limited consideration on evaluating durability properties of mortar and concrete. Durability of mortar and concrete should be considered in order to avoid unnecessary repair costs in terms of money, time and other resources. Norvell et al. (2007) and Kenait et al. (2008) observed an increase in drying shrinkage and permeability as a result of high fine content and clay in fine aggregates. This will lead to have shrinkage cracks and potential for corrosion of reinforcement. Thus a study focusing on the effects of shrinkage cracks, permeability and other durability parameters of concrete and mortar with FCAs would add more information about the performance of FCAs.

For some particular application of FCAs, field test to be conducted to find the effects of angularity and high fines content on pump ability and use of admixtures to improve flow ability of concrete and mortar with FCAs. FCAs are being used in road construction work and other decorative elements for landscaping work where there can be a potential influence on quality of ground water.

REFERENCES

Ahn, N.-S., & Fowler, D. W. (2001). *An experimental study on the guidelines for using higher contents of aggregate microfines in Portland cement concrete*.

Aitcin, P., & Mindess, S. (1998). High-performance concrete: science and applications. *Capitulo, 10*, 477-512.

Alexander, M.G., "*Aggregates and the Deformation Properties of Concrete,*" ACI Materials Journal, Vol. 93, No. 6, 1996, p. 569.

Alexander, M., & Mindess, S. (2005). *Aggregates in concrete*: CRC Press.

Alhozaimy, A. M. (2009). Effect of absorption of limestone aggregates on strength and slump loss of concrete. *Cement and Concrete Composites, 31*(7), 470-473.

Almusallam, A., Maslehuddin, M., Abdul-Waris, M., & Khan, M. (1998). Effect of mix proportions on plastic shrinkage cracking of concrete in hot environments. *Construction and Building Materials, 12*(6), 353-358.

Anderson, R., & Dewar, J. (2003). *Manual of ready-mixed concrete*: CRC Press.

Anitha-selva, S., Gayathri, R., & Swathi, G. (2013). Experimental investigation on quarry dust concrete with chemical admixture. *Int. J. Lat. Res. Sci. Technol, 2*, 91-94.

ASTM, C. (2003). 125 Standard terminology relating to concrete and concrete aggregates. *Annual Book of ASTM Standards, 4*.

ASTM C 33 Standard Specification for Concrete Aggregates, Philadelphia, PA: American Society for Testing and Materials, 2003.

ASTM C 203/C230 M Standard Specification for flow table for use in tests of hydraulic cement, Philadelphia, PA: American Society for Testing and Materials, 2008.

ASTM C 1437 Standard test method for flow of hydraulic cement mortar, Philadelphia, PA: American Society for Testing and Materials, 2007.

Balamurugan, G., & Perumal, P. (2013). Use of quarry dust to replace sand in concrete–An experimental study. *International Journal of Scientific and Research Publications, 3*(12).

Boskey, B., Parbat, D.K., Nagarnaik,P.B., Wagh, U.P., *Sustainable utilization of quarry dust and waste plastic fibers as a sand replacement in conventional concrete* (2014). ICSCI 2014 ASCE India section, Oct 17-18, 2014, Hitex,Hydrabad, Telangana, India.

Celik, T., & Marar, K. (1996). Effects of crushed stone dust on some properties of concrete. *Cement and Concrete Research, 26*(7), 1121-1130.

Cepuritis, R., Jacobsen, S., Pedersen, B., & Mørtsell, E. (2016). Crushed sand in concrete–effect of particle shape in different fractions and filler properties on rheology. *Cement and Concrete Composites, 71*, 26-41.

Cepuritis, R., Wigum, B., Garboczi, E., Mørtsell, E., & Jacobsen, S. (2014). Filler from crushed aggregate for concrete: Pore structure, specific surface, particle shape and size distribution. *Cement and Concrete Composites, 54*, 2-16.

Chandana, S., Katakam, B.K., Sri Lakshmi, S.T.P., Kanakambara, R.S., Partial Replacement of Sand with Quarry Dust in Concrete, *International Journal* *of Innovative Technology and Exploring Engineering (IJITEE) ISSN: 2278-3075, Volume-2, Issue-6, May 2013.*

Clelland, J. (1980). Sand for Concrete, a new test method. *New Zealand Standards Bulletin*, 22-26.

Cortes, D., Kim, H.-K., Palomino, A., & Santamarina, J. (2008). Rheological and mechanical properties of mortars prepared with natural and manufactured sands. *Cement and Concrete Research, 38*(10), 1142-1147.

Dao, V., Dux, P., Morris, P., & O'Moore, L. (2010). Plastic shrinkage cracking of concrete. *Australian Journal of Structural Engineering, 10*(3), 207-214.

De Larrard, F., & Sedran, T. (2002). Mixture-proportioning of high-performance concrete. *Cement and Concrete Research, 32*(11), 1699-1704.

Dehwah, H. (2012). Mechanical properties of self-compacting concrete incorporating quarry dust powder, silica fume or fly ash. *Construction and Building Materials, 26*(1), 547-551.

Dewar, J.D. and Anderson, R., *Manual of Ready-Mixed Concrete*, Blackie Academic and Professional, 2nd ed., 1992, London.

Donza, H., & Cabrera, O. (1996). *The influence of kinds of fine aggregate on mechanical properties of high strength concrete.* Paper presented at the Proc. 4th International Symposium on Utilization of High-Strength/High-Performance Concrete.

Donza, H., Cabrera, O., & Irassar, E. (2002). High-strength concrete with different fine aggregate. *Cement and Concrete Research, 32*(11), 1755-1761.

Ephraim, M., & Rowland-Lato, E. (2015). Compressive Strength of Concrete Made with Quarry Rock Dust and Washed 10mm Washed Gravel as Aggregates. *American Journal of Engineering, Technology and Society, 2*(2), 26-34.

Fernández-Jiménez, A., Garcia-Lodeiro, I., & Palomo, A. (2007). Durability of alkali-activated fly ash cementitious materials. *Journal of Materials Science, 42*(9), 3055-3065.

Ferraris, C. F., & de Larrard, F. (1998). *Testing and modelling of fresh concrete rheology*: US Department of Commerce, Technology Administration, National Institute of Standards and Technology.

Forster, S.W., "*Soundness, Deleterious Substances, and Coatings*," ASTM Special
Technical Publication No. 169C, Philadelphia, 1994, pp. 411-420.

Franklin, E. K., Vikas, S., Agarwal, V.C., Anjelo, Denis, F., and Ehsan, A., *Stone Dust as Partial Replacement of Fine Aggregate in Concrete*. Journal of Academia and Industrial Research (JAIR) Volume 3, Issue 3 August 2014, pp 148-151.

Galloway, J. E. (1994). Grading, shape, and surface properties. *ASTM special technical publication, 169*, 401-410.

Goble, C. F., & Cohen, M. D. (1999). Influence of aggregate surface area on mechanical properties of mortar. *Materials Journal*, *96*(6), 657-662.

Goldsworthy, S. (2005). Manufactured sands in Portland Cement Concrete. *Proceedings of the Third Annual International Center for Aggregates Research, Austin, Texas*.

Goltermann, P., Johansen, V., & Palbøl, L. (1997). Packing of aggregates: an alternative tool to determine the optimal aggregate mix. *ACI Materials Journal, 94*(5), 435-443.

Gonçalves, J., Tavares, L., Toledo Filho, R., Fairbairn, E., & Cunha, E. (2007). Comparison of natural and manufactured fine aggregates in cement mortars. *Cement and Concrete Research, 37*(6), 924-932.

Harrison, D., Wilson, D., Henney, P., & Hudson, J. (2000). *Crushed Rock Sand in South Wales: A Reconnaissance Survey*. Retrieved from

Hudson, B. (1997). Manufactured Sand: Destroying Some Myths. *Quarry, October*, 57-62.

Hudson, B. (1997). Manufactured Sand: Destroying Some Myths. *Quarry, October*, 57-62.

Hudson, B. (1999). Concrete workability with high fines content sands. *URL: http://www. agmman. com/pages/agg, 200299*.

Hudson, B. (1999). *Modification to the fine aggregate angularity test.* Paper presented at the Proceedings, Seventh Annual International Center for Aggregates Research Symposium, Austin, TX.

Jackson, N., & Brown, R. (1996). *Use of higher fines contents in Portland cement concrete.* Paper presented at the ICAR 4th annual symposium.

Jones, M., Zheng, L., & Newlands, M. (2003). Estimation of the filler content required to minimise voids ratio in concrete. *Magazine of Concrete Research, 55*(2), 193-202.

Joseph, Ukpata,O., and Maurice, E., Ephraim. Flexural and tensile strength properties of concrete using lateritic sand and quarry dust as fine aggregates. 2012 *ARPN Journal of Engineering and Applied Sciences pp 324-331.*

Kalcheff, I. V. (1977). Portland cement concrete with stone sand.

Kaplan, M. (1959). *Flexural and compressive strength of concrete as affected by the properties of coarse aggregates.* Paper presented at the Journal Proceedings.

Kaya, T. (2009). *The development of sand manufacture from crushed rock in Japan, using advanced VSI technology. Importance of fine aggregate shape and grading on properties of concrete.* Paper presented at the Proceedings of 17th Annual Symposium of International Centre for Aggregates Research, Austin, Texas.

Koehler, E., Jeknavorian, A., Chun, B., & Zhou, P. (2009). *Ensuring Concrete Performance for Various Aggregates.* Paper presented at the 17th Annual ICAR Symposium.

Kosmatka, S., "*Bleeding*," ASTM Special Technical Publication No. 169C, Philadelphia, 1994, pp. 89-111.

Krieger, I. M., & Dougherty, T. J. (1959). A mechanism for non-Newtonian flow in suspensions of rigid spheres. *Transactions of the Society of Rheology, 3*(1), 137-152.

Kroh, T. A. (2010). *Use of Manufactured Sand as a Replacement Material for Dredged Sand in Mortar.* Cardiff University.

Krumbein, W.C., and L.L. Sloss. Stratigraphy and Sedimentation. Second ed. San Francisco: Freeman, 1963.

Kwan, A., Ng, P., & Huen, K. (2014). Effects of fines content on packing density of fine aggregate in concrete. *Construction and Building Materials, 61*, 270-277.

Lafrenz, J. (1997). *Aggregate grading control for PCC pavements: improving constructability of concrete pavements by assuring consistency of mixes.* Paper presented at the Proceedings, Fifth Annual International Center for Aggregates Research Symposium, Austin, Texas.

Li, B., Wang, J., & Zhou, M. (2009). Effect of limestone fines content in manufactured sand on durability of low-and high-strength concretes. *Construction and Building Materials, 23*(8), 2846-2850.

Li, H., Huang, F., Cheng, G., Xie, Y., Tan, Y., Li, L., & Yi, Z. (2016). Effect of granite dust on mechanical and some durability properties of manufactured sand concrete. *Construction and Building Materials, 109*, 41-46.

Li, L., Chan, P., Zollinger, D. G., & Lytton, R. L. (1993). Quantitative analysis of aggregate shape based on fractals. *Materials Journal, 90*(4), 357-365.

Manning, D.A.C. (2004), MIRO – final report, *Exploitation and Use of Quarry Fines* Report No. 087/MIST2/DACM/01

Marek, C. (1995). Importance of fine aggregate shape and grading on properties of concrete. *Proceedings of the Third Annual International Center for Aggregates Research, Austin, Texas*.

Mather, B. (1966). Shape, surface texture, and coatings *Significance of Tests and Properties of Concrete and Concrete-Making Materials*: ASTM International.

Meddah, M. S., Zitouni, S., & Belâabes, S. (2010). Effect of content and particle size distribution of coarse aggregate on the compressive strength of concrete. *Construction and Building Materials, 24*(4), 505-512.

Mehta, P., & Monteiro, P. Concrete: Structures, Properties and Materials, 2005: New York: McGraw-Hill Professional.

Mitchell, C. J., Mitchell, P., & Pascoe, R. (2008). *Quarry fines minimisation: Can we really have 10mm aggregate with no fines?*

Neville, A. M. (1995). *Properties of concrete* (Vol. 4): Longman London.

Norvell, J. K., Stewart, J. G., Juenger, M. C., & Fowler, D. W. (2007). Influence of clays and clay-sized particles on concrete performance. *Journal of Materials in Civil Engineering, 19*(12), 1053-1059.

Omar, O. M., Elhameed, G. D. A., Sherif, M. A., & Mohamadien, H. A. (2012). Influence of limestone waste as partial replacement material for sand and marble powder in concrete properties. *HBRC Journal, 8*(3), 193-203.

Popovics, S., & Ujhelyi, J. (2008). Contribution to the concrete strength versus water-cement ratio relationship. *Journal of Materials in Civil Engineering, 20*(7), 459-463.

Powers, M. C. (1953). A new roundness scale for sedimentary particles. *Journal of Sedimentary Research, 23*(2).

Quiroga, P. N., Ahn, N., & Fowler, D. W. (2006). Concrete mixtures with high microfines. *ACI Materials Journal, 103*(4), 258-264.

Raju, M. R., Vivek, K., Reddy, D. T. S. S., & Reddy, P. S. (2011). Study of Properties of SCC using 'Quarry Dust'and 'Fly Ash. *International Journal of Engineering Sciences Research-IJESR, 2*(04).

Raman, S.N.,Ngo, T., Mendis, P., Mahmud,H.B., High- strength rice husk ash concrete incorporating quarry dust as a patial substitute for sand. *Construction and building materials 25(2011) 3123-3130.*

Rhoades, R., & Mielenz, R. C. (1946). *Petrography of concrete aggregate.* Paper presented at the Journal Proceedings.

Saha A.K., Sarker P. K. (2016). Expansion due to alkali-silica reaction of ferronickel slag fine aggregate in OPC and blended cement mortar. Construction and Building Materials, 123, 135-142.

Sai, K.K., Sameer, K.S., Prasad, M.L.V., Quarry rock dust as a partial replacement of fine aggregate. Conference: *All India seminar Innovations in Green Building Technology (IGBT) 2014.*

Sandeep, K.S., Vikas, S., Agarwal, V.C., Rakesh, K., and Mehta, P.K., an Experimental Investigation on Stone Dust as Partial Replacement of Fine Aggregate in Concrete. *Journal of Academia and Industrial Research (JAIR) Volume 3, Issue 5 October 2014, pp 229-232.*

Shahul, H.M., and Sekar, A. S. S., Properties of green concrete containing quarry rock dust and marble sludge powder as fine aggregates. *ARPN Journal of Engineering and Applied Sciences, VOL. 4, NO. 4, JUNE 2009, pp 83-89.*

Shilstone, J. M. (1999). *The aggregate: The most important value-adding component in concrete.* Paper presented at the Proceedings of the Seventh Annual Symposium International Center for Aggregates Research, Austin, Texas.

Specification 820, *Concrete for structures,* Main roads Western Australia. (17/06/13), 1-28.

Standards Australia. (1994). *Methods of testing concrete - Preparation of concrete mixes in the laboratory.* (AS 1012.2-1994), retrieved from http:// www.saiglobal.com

Standards Australia. (1996). *Particle density and water absorption of coarse aggregate – Pycnometer method* (AS 1141.6.2-1996), retrieved from http:// www.saiglobal.com

Standards Australia. (1999). *Methods of testing concrete - Determination of the compressive strength of concrete specimens*. (AS 1012.9-2014), retrieved from http:// www.saiglobal.com

Standards Australia. (2000). *Methods of testing concrete - Determination of indirect tensile strength of concrete cylinders.* (AS 1012.10-2000), retrieved from http:// www.saiglobal.com

Standards Australia. (2000). *Methods of testing concrete - Determination of the drying shrinkage of concrete for samples prepared in the field or in the laboratory.* (AS 1012.13-1992), retrieved from http:// www.saiglobal.com

Standards Australia. (2000). *Particle density and water absorption of fine aggregate.* (AS 1141.5-2000), retrieved from http:// www.saiglobal.com

Standard Australia. (2009). *Concrete structures*. (AS 3600-2009), retrieved from http:// www.saiglobal.com

Standard Australia. (2009). *Particle size distribution – Sieving method*. (AS 1141.11.1-2009), retrieved from http:// www.saiglobal.com

Standard Australia. (2010). *General purpose and blended cements.* (AS 3972-2010), retrieved from http:// www.saiglobal.com

Standard Australia. (2014). *Aggregates and rock for engineering purposes - Concrete aggregates.* (AS 2758.1-2014), retrieved from http:// www.saiglobal.com

Standard Australia. (2014). *Detrmination of properties related to the consistency of concrete – Slump test.* (AS 1012.3.1-2014), retrieved from http:// www.saiglobal.com

Standard Australia. (2014). *Determination of bleeding of concrete.* (AS 1012.6-2014), retrieved from http:// www.saiglobal.com

Standard Australia. (2014). *Determination of indirect tensile strength of concrete cylinders ('Brazil' or splitting test),* (AS 1012.10-2014), retrieved from http:// www.saiglobal.com

Standard Australia. (2014). *Methods for sampling and testing aggregates - Potential alkali-silica reactivity - Accelerated mortar bar* (AS 1141.60.1-2014), retrieved from http:// www.saiglobal.com

Standard New Zeeland (1986). *Method for determining voids content, flow time and percentage over size material in sand* (NZS 3111:1986).

Standard test method for *Flow of hydraulic cement mortar*, ASTM C 1437-07. Retrieved from <http;//www.siaglobal.com>

Standard test method for *compressive strength of hydraulic cement mortars (using 2-in. or [50mm] cube specimens)*, ASTM C109/C 109M-07. Retrieved from <http;//www.siaglobal.com>

Tangchirapat, W., & Jaturapitakkul, C. (2010). Strength, drying shrinkage, and water permeability of concrete incorporating ground palm oil fuel ash. *Cement and Concrete Composites, 32*(10), 767-774.

Ukpata, J. O., & Ephraim, M. E. (2012). Flexural and tensile strength properties of concrete using lateritic sand and quarry dust as fine aggregate. *ARPN Journal of engineering and applied sciences*, *7*(3), 324-331.

Washa, G. W. (1998). Concrete construction handbook. *ed. Dobrowolski, J., McGraw-Hill, New York, USA.*

Wills, M. H. (1967). How aggregate particle shape influences concrete mixing water requirement and strength. *Journal Materials*.

APPENDIX – A: MATERIAL CHARACTERIZATION

Table A-1: Particle size distribution (PSD) of fine crushed aggregates (FCAs)

Summery- Particle size distribution of FCA & natural sand					Table B1(AS2758.1:2014)	
Sieve Size/mm	% Passing				Upper limit	Lower limit
	A	B	C	Natural		
9.500	100.0	100.0	100.0	100.0	100.0	100
6.700	99.2	100.0	99.9	100.0		
4.750	87.9	100.0	99.4	99.7	100.0	90
2.360	49.8	78.4	80.5	87.6	100.0	60
1.180	27.7	50.8	55.5	66.5	100.0	30
0.600	17.0	35.4	39.2	33.8	60.0	15
0.425	13.6	29.7	32.5	3.7		
0.300	11.1	25.5	27.0	1.0	40.0	5
0.150	7.4	18.8	18.7	0.0	25.0	0
0.075	5.1	14.0	13.1	0.0	20.0	0
Finer 0.075	5.0	16.8	12.9	0.0	0.0	

Table A-2: Particle size distribution (PSD) of coarse aggregates 20mm/14mm/10-7 mm

Sieve size	%Passing			
	20mm	14mm	10/7mm	Combined
19.000	96.0	100.0	100.0	98.7
13.200	14.2	100.0	100.0	71.4
9.500	1.9	92.2	100.0	64.7
6.700	0.7	27.6	94.6	41.0
4.750	0.3	2.2	41.7	14.7
2.360	0.3	2.2	2.2	1.5
1.180	0.3	2.2	1.0	1.1
0.600	0.3	2.2	0.8	1.1
0.425	0.3	2.2	0.7	1.0
0.300	0.3	2.2	0.6	1.0
0.150	0.3	2.2	0.4	0.9
0.075	0.3	2.2	0.1	0.9

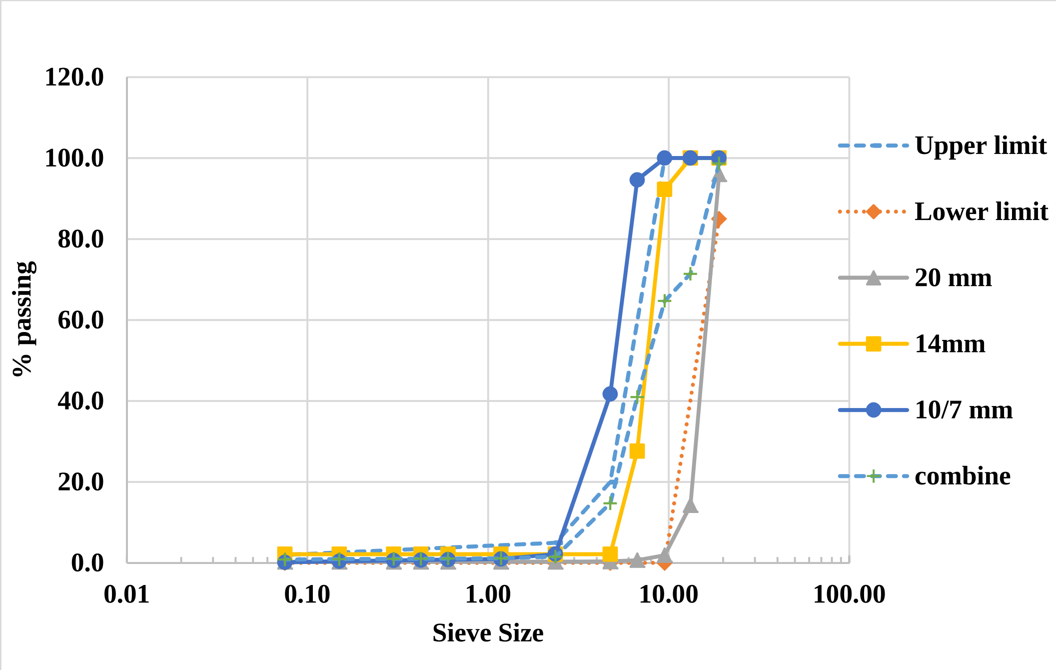


Figure A-1: Particle size distribution (PSD) of coarse aggregates (FCAs)

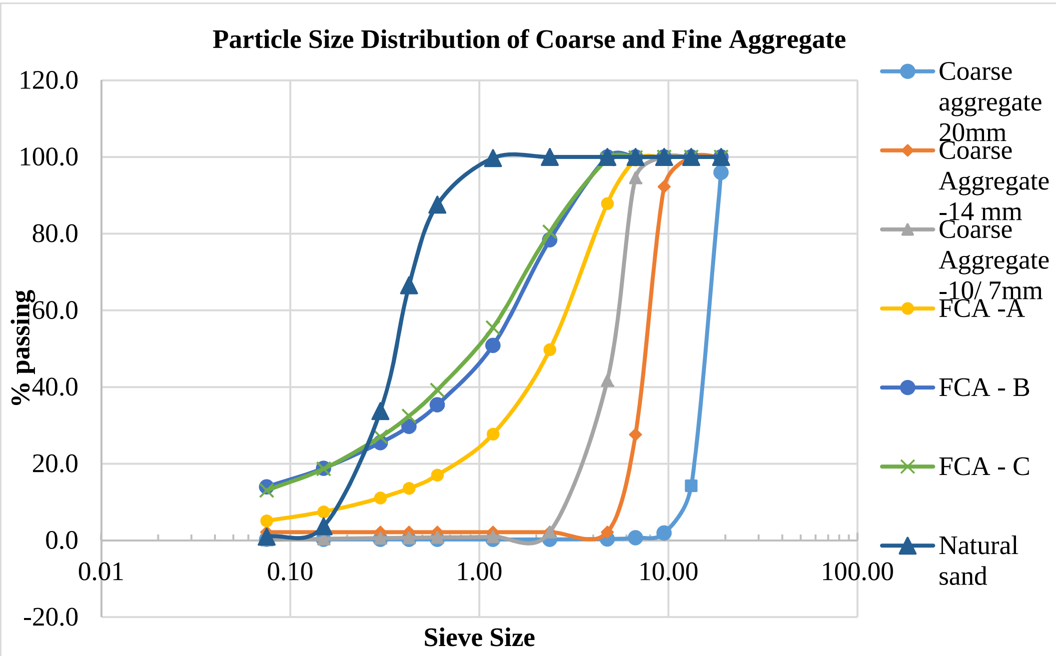


Figure A-2: Particle size distribution (PSD) of coarse aggregates (FCAs)

TableA-3: NZFC test- flow time measurements and calculation of void content: FCA – A

Mix ID	Flow time (seconds)				Weight of sand (g)				Weight of water (g) - A	Density (Dry) - D	P=1000 *B/AD	Void cont. = (1-P)*100
	T1	T2	T3	T (AVG)	B1	B2	B3	B (AVG)				
Natural Sand	21.06	21	20.78	20.95	1737.46	1737.27	1736.95	772.23	502	2590	0.59	40.61
A -20%	21.62	21.31	21.15	21.36	1745.12	1742.72	1743.30	778.71	502	2582	0.60	39.92
A-40%	23.10	23.41	22.88	23.13	1746.31	1748.18	1746.43	781.97	502	2572	0.61	39.44
A-60%	25.72	25.53	25.53	25.59	1742.25	1743.74	1744.83	778.61	502	2561	0.61	39.44
A-80%	27.72	28.69	28.22	28.21	1733.55	1732.90	1730.73	767.39	502	2556	0.60	40.19
100%	30.47	31.06	30.63	30.72	1717.22	1714.50	1719.35	752.02	502	2540	0.59	41.02

TableA-4: NZFC test- flow time measurements and calculation of void content: FCA – B

Mix ID	Flow time (seconds)				Weight of sand (g)				Weight of water (g) -A	Density (Dry) - D	P=1000*B/AD	Void cont.= (1-P)*100
	T1	T2	T3	T (AVG)	B1	B2	B3	B (AVG)				
Natural Sand	21.06	21	20.78	20.95	1737.46	1737.27	1736.95	772.23	502	2590	0.59	40.61
B -20%	21.75	21.53	21.44	21.57	1757.66	1758.77	1756.76	792.73	502	2587	0.61	38.96
B-40%	23.59	23.37	23.05	23.34	1771.57	1770.99	1776.14	807.90	502	2581	0.62	37.65
B-60%	25.69	25.03	25.40	25.37	1770.70	1772.99	1773.92	807.54	502	2574	0.62	37.50
B-80%	28.16	28.40	28.25	28.27	1763.97	1764.40	1765.66	799.68	502	2568	0.62	37.97
B-100%	30.93	31.04	31.66	31.21	1746.54	1748.23	1747.10	782.29	502	2562	0.61	39.17

Table A-5: NZFC test- flow time measurements and calculation of void content: FCA – C

Mix ID	Flow time (seconds)				Weight of sand (g)				Weight of water (g) -A	Density (Dry) - D	P=1000 *B/AD	Void cont.= (1-P)*100
	T1	T2	T3	T (AVG)	B1	B2	B3	B (AVG)				
Natural Sand	21.06	21	20.78	20.95	1737.46	1737.27	1736.95	772.23	502	2590	0.59	40.61
C -20%	21.15	21.28	21.25	21.23	1742.51	1740.67	1741.80	776.66	502	2577	0.60	39.96
C-40%	24.12	24.09	24.16	24.12	1742.18	1739.60	1738.76	775.18	502	2562	0.60	39.45
C-60%	25.65	26.21	26.28	26.05	1753.64	1751.07	1753.41	787.71	502	2546	0.62	38.37
C-80%	30.40	30.16	30.70	30.42	1735.81	1736.38	1734.48	770.56	502	2531	0.61	39.35
C-100%	28.32	29.40	29.56	29.09	1725.96	1726.45	1726.79	761.40	502	2516	0.60	39.72

Table A-6: Packing density of FCAs

FCA (%)	Packing Density		
	A	B	C
0	59.4	59.4	59.4
20	60.1	61.0	60.0
40	60.6	62.4	60.6
60	60.6	62.5	61.6
80	59.8	62.0	60.6
100	59.0	60.8	60.3

APPENDIX – B: MORTAR TESTING

Table B-1: Workability test results of mortar

FCA (%)	A		B		C	
	Flow (%)	Slump (mm)	Flow (%)	Slump (mm)	Flow (%)	Slump (mm)
0	157	50	157	50	157	50
20	157	52	151	51	156	51
40	159	54	152	52	156	52
60	159	55	152	52	158	52
80	158	53	149	49	152	52
100	154	48	148	47	152	49

Table B-2: Compressive strength results of mortar (MPa)

FCA (%)	A		B		C	
	7 Days	28 Days	7 Days	28 Days	7 Days	28 Days
0	45.0	50.4	45.0	50.4	45.0	50.4
20	46.0	52.2	46.3	51.1	47.6	51.4
40	47.2	54.0	47.3	51.7	48.3	52.2
60	47.9	54.7	45.6	51.8	47.4	52.4
80	45.2	52.5	45.1	48.8	44.8	51.6
100	43.2	48.4	37.3	47.1	41.0	48.6

Table B-3: Alkali-silica reactivity test results – FCA type A

% of FCA	Days	Zero Reading 1	Final Reading 1	Zero reading 2	Final Reading 2	% Exp. 1	% Exp. 2	Avg. Exp.
Control	0	16.058	0.000	16.452	0.000	0	0	0
	1	16.058	16.023	16.452	16.433	-0.01250	-0.00679	-0.00964
	3	16.058	16.001	16.452	16.438	-0.02036	-0.00500	-0.01268
	7	16.058	16.062	16.452	16.448	0.00143	-0.00143	0.00000
	10	16.058	16.098	16.452	16.453	0.01429	0.00036	0.00732
	14	16.058	16.142	16.452	16.462	0.03000	0.00357	0.01679
	21	16.058	16.161	16.452	16.489	0.03679	0.01321	0.02500
	28	16.058	16.177	16.452	16.507	0.04250	0.01964	0.03107
A20	0	16.321	0.000	16.278	0	0.00000	0.00000	0.00000
	1	16.321	16.309	16.278	16.263	-0.00429	-0.00536	-0.00482
	3	16.321	16.302	16.278	16.251	-0.00679	-0.00964	-0.00821
	7	16.321	16.331	16.278	16.282	0.00357	0.00143	0.00250
	10	16.321	16.369	16.278	16.297	0.01714	0.00679	0.01196
	14	16.321	16.395	16.278	16.324	0.02643	0.01643	0.02143
	21	16.321	16.427	16.278	16.349	0.03786	0.02536	0.03161
	28	16.321	16.442	16.278	16.356	0.04321	0.02786	0.03554
A40	0	16.563	0	16.548	0	0.00000	0.00000	0.00000
	1	16.563	16.562	16.548	16.524	-0.00036	-0.00857	-0.00446
	3	16.563	16.558	16.548	16.517	-0.00179	-0.01107	-0.00643
	7	16.563	16.574	16.548	16.539	0.00393	-0.00321	0.00036
	10	16.563	16.609	16.548	16.589	0.01643	0.01464	0.01554
	14	16.563	16.662	16.548	16.617	0.03536	0.02464	0.03000
	21	16.563	16.711	16.548	16.691	0.05286	0.05107	0.05196
	28	16.563	16.754	16.548	16.75	0.06821	0.07214	0.07018
A60	0	16.051	0	16.457	0	0.00000	0.00000	0.00000
	1	16.051	16.043	16.457	16.438	-0.00286	-0.00679	-0.00482
	3	16.051	16.012	16.457	16.435	-0.01393	-0.00786	-0.01089
	7	16.051	16.071	16.457	16.461	0.00714	0.00143	0.00429
	10	16.051	16.136	16.457	16.528	0.03036	0.02536	0.02786
	14	16.051	16.258	16.457	16.611	0.07393	0.05500	0.06446
	21	16.051	16.332	16.457	16.679	0.10036	0.07929	0.08982
	28	16.051	16.401	16.457	16.704	0.12500	0.08821	0.10661

A80	0	15.796	0	15.967	0	0.00000	0.00000	0.00000
	1	15.796	15.743	15.967	15.953	-0.01893	-0.00500	-0.01196
	3	15.796	15.772	15.967	15.951	-0.00857	-0.00571	-0.00714
	7	15.796	15.784	15.967	15.959	-0.00429	-0.00286	-0.00357
	10	15.796	15.832	15.967	15.962	0.01286	-0.00179	0.00554
	14	15.796	15.929	15.967	16.128	0.04750	0.05750	0.05250
	21	15.796	16.065	15.967	16.231	0.09607	0.09429	0.09518
	28	15.796	16.145	15.967	16.292	0.12464	0.11607	0.12036
A100	0	16.166	0	16.054	0	0.00000	0.00000	0.00000
	1	16.166	16.13	16.054	16.02	-0.01286	-0.01214	-0.01250
	3	16.166	16.102	16.054	15.981	-0.02286	-0.02607	-0.02446
	7	16.166	16.149	16.054	16.104	-0.00607	0.01786	0.00589
	10	16.166	16.128	16.054	16.189	-0.01357	0.04821	0.01732
	14	16.166	16.247	16.054	16.281	0.02893	0.08107	0.05500
	21	16.166	16.401	16.054	16.365	0.08393	0.11107	0.09750
	28	16.166	16.454	16.054	16.44	0.10286	0.13786	0.12036

Table B-4: Alkali-silica reactivity test results – FCA type B

% of FCA	Days	Zero Reading 1	Final Reading 1	Zero reading 2	Final Reading 2	% Exp. 1	% Exp. 2	Avg. Exp.
Control	0	16.058	0.000	16.452	0.000	0	0	0
	1	16.058	16.023	16.452	16.433	-0.0125	-0.0068	-0.0096
	3	16.058	16.001	16.452	16.438	-0.0204	-0.0050	-0.0127
	7	16.058	16.062	16.452	16.448	0.0014	-0.0014	0.0000
	10	16.058	16.098	16.452	16.453	0.0143	0.0004	0.0073
	14	16.058	16.142	16.452	16.462	0.0300	0.0036	0.0168
	21	16.058	16.161	16.452	16.489	0.0368	0.0132	0.0250
	28	16.058	16.177	16.452	16.507	0.0425	0.0196	0.0311
B20	0	16.495	0.000	16.554	0	0.0000	0.0000	0.0000
	1	16.495	16.478	16.554	16.524	-0.0061	-0.0107	-0.0084
	3	16.495	16.485	16.554	16.521	-0.0036	-0.0118	-0.0077
	7	16.495	16.498	16.554	16.561	0.0011	0.0025	0.0018
	10	16.495	16.538	16.554	16.593	0.0154	0.0139	0.0146
	14	16.495	16.587	16.554	16.624	0.0329	0.0250	0.0289

	21	16.495	16.591	16.554	16.657	0.0343	0.0368	0.0355
	28	16.495	16.634	16.554	16.672	0.0496	0.0421	0.0459
B40	0	16.378	0	16.218	0	0.0000	0.0000	0.0000
	1	16.378	16.348	16.218	16.184	-0.0107	-0.0121	-0.0114
	3	16.378	16.355	16.218	16.196	-0.0082	-0.0079	-0.0080
	7	16.378	16.386	16.218	16.235	0.0029	0.0061	0.0045
	10	16.378	16.406	16.218	16.279	0.0100	0.0218	0.0159
	14	16.378	16.468	16.218	16.327	0.0321	0.0389	0.0355
	21	16.378	16.499	16.218	16.392	0.0432	0.0621	0.0527
	28	16.378	16.56	16.218	16.419	0.0650	0.0718	0.0684
B60	0	16.55	0	16.487	0	0.0000	0.0000	0.0000
	1	16.55	16.492	16.487	16.453	-0.0207	-0.0121	-0.0164
	3	16.55	16.516	16.487	16.424	-0.0121	-0.0225	-0.0173
	7	16.55	16.552	16.487	16.491	0.0007	0.0014	0.0011
	10	16.55	16.628	16.487	16.508	0.0279	0.0075	0.0177
	14	16.55	16.719	16.487	16.597	0.0604	0.0393	0.0498
	21	16.55	16.791	16.487	16.712	0.0861	0.0804	0.0832
	28	16.55	16.852	16.487	16.801	0.1079	0.1121	0.1100
B80	0	14.844	0	15.916	0	0.0000	0.0000	0.0000
	1	14.844	14.832	15.916	15.906	-0.0043	-0.0036	-0.0039
	3	14.844	14.841	15.916	15.927	-0.0011	0.0039	0.0014
	7	14.844	14.891	15.916	16.004	0.0168	0.0314	0.0241
	10	14.844	14.922	15.916	16.107	0.0279	0.0682	0.0480
	14	14.844	15.04	15.916	16.248	0.0700	0.1186	0.0943
	21	14.844	15.128	15.916	16.308	0.1014	0.1400	0.1207
	28	14.844	15.279	15.916	16.374	0.1554	0.1636	0.1595
B100	0	16.8	0	16.469	0	0.0000	0.0000	0.0000
	1	16.8	16.785	16.469	16.457	-0.0054	-0.0043	-0.0048
	3	16.8	16.798	16.469	16.462	-0.0007	-0.0025	-0.0016
	7	16.8	16.914	16.469	16.481	0.0407	0.0043	0.0225
	10	16.8	17.094	16.469	16.643	0.1050	0.0621	0.0836
	14	16.8	17.202	16.469	16.874	0.1436	0.1446	0.1441
	21	16.8	17.394	16.469	17.048	0.2121	0.2068	0.2095
	28	16.8	17.451	16.469	17.201	0.2325	0.2614	0.2470

Table B-5: Alkali-silica reactivity test results – FCA type C

% of FCA	Days	Zero Reading 1	Final Reading 1	Zero reading 2	Final Reading 2	% Exp. 1	% Exp. 2	Avg. Exp.
Control	0	16.058	0.000	16.452	0.000	0.0000	0.0000	0.0000
	1	16.058	16.023	16.452	16.433	-0.0125	-0.0068	-0.0096
	3	16.058	16.001	16.452	16.438	-0.0204	-0.0050	-0.0127
	7	16.058	16.062	16.452	16.448	0.0014	-0.0014	0.0000
	10	16.058	16.098	16.452	16.453	0.0143	0.0004	0.0073
	14	16.058	16.142	16.452	16.462	0.0300	0.0036	0.0168
	21	16.058	16.161	16.452	16.489	0.0368	0.0132	0.0250
	28	16.058	16.177	16.452	16.507	0.0425	0.0196	0.0311
C20	0	16.357	0.000	16.401	0	0.0000	0.0000	0.0000
	1	16.357	16.347	16.401	16.391	-0.0036	-0.0036	-0.0036
	3	16.357	16.349	16.401	16.388	-0.0029	-0.0046	-0.0037
	7	16.357	16.374	16.401	16.412	0.0061	0.0039	0.0050
	10	16.357	16.419	16.401	16.475	0.0221	0.0264	0.0243
	14	16.357	16.465	16.401	16.489	0.0386	0.0314	0.0350
	21	16.357	16.491	16.401	16.528	0.0479	0.0454	0.0466
	28	16.357	16.507	16.401	16.556	0.0536	0.0554	0.0545
C40	0	16.13	0	16.208	0	0.0000	0.0000	0.0000
	1	16.13	16.115	16.208	16.201	-0.0054	-0.0025	-0.0039
	3	16.13	16.109	16.208	16.192	-0.0075	-0.0057	-0.0066
	7	16.13	16.138	16.208	16.217	0.0029	0.0032	0.0030
	10	16.13	16.197	16.208	16.271	0.0239	0.0225	0.0232
	14	16.13	16.254	16.208	16.301	0.0443	0.0332	0.0388
	21	16.13	16.289	16.208	16.372	0.0568	0.0586	0.0577
	28	16.13	16.32	16.208	16.389	0.0679	0.0646	0.0663
C60	0	16.226	0	16.51	0	0.0000	0.0000	0.0000
	1	16.226	16.221	16.51	16.512	-0.0018	0.0007	-0.0005
	3	16.226	16.216	16.51	16.521	-0.0036	0.0039	0.0002
	7	16.226	16.235	16.51	16.598	0.0032	0.0314	0.0173
	10	16.226	16.294	16.51	16.615	0.0243	0.0375	0.0309
	14	16.226	16.328	16.51	16.674	0.0364	0.0586	0.0475
	21	16.226	16.401	16.51	16.724	0.0625	0.0764	0.0695
	28	16.226	16.478	16.51	16.771	0.0900	0.0932	0.0916

C80	0	15.455	0	14.647	0	0.0000	0.0000	0.0000
	1	15.455	15.442	14.647	14.641	-0.0046	-0.0021	-0.0034
	3	15.455	15.451	14.647	14.643	-0.0014	-0.0014	-0.0014
	7	15.455	15.468	14.647	14.685	0.0046	0.0136	0.0091
	10	15.455	15.504	14.647	14.734	0.0175	0.0311	0.0243
	14	15.455	15.545	14.647	14.801	0.0321	0.0550	0.0436
	21	15.455	15.693	14.647	14.896	0.0850	0.0889	0.0870
	28	15.455	15.745	14.647	14.945	0.1036	0.1064	0.1050
C100	0	16.515	0	16.054	0	0.0000	0.0000	0.0000
	1	16.515	16.512	16.054	16.052	-0.0011	-0.0007	-0.0009
	3	16.515	16.518	16.054	16.099	0.0011	0.0161	0.0086
	7	16.515	16.591	16.054	16.191	0.0271	0.0489	0.0380
	10	16.515	16.658	16.054	16.235	0.0511	0.0646	0.0579
	14	16.515	16.768	16.054	16.412	0.0904	0.1279	0.1091
	21	16.515	16.928	16.054	16.501	0.1475	0.1596	0.1536
	28	16.515	17.041	16.054	16.564	0.1879	0.1821	0.1850

APPENDIX – C: CONCRETE TESTING

Table C-1: Workability and bleeding results

Mix ID	Slump (mm)	Bleeding			
		V (ml)	A (mm^2)	t (min)	V/At
Control	140	15	49107.1	45	6.788E-06
B40	125	7	49107.1	60	2.376E-06
A40	120	2	49107.1	15	2.715E-06
C20	140	20	49107.1	90	4.525E-06
C40	120	10	49107.1	60	3.394E-06
C60	80	0	49107.1	60	0

Table C-2: Compressive strength results of concrete

Mix ID	Compressive strength (Mpa)							
	7 days				28 days			
	S1	S2	S3	Ave.	S1	S2	S3	Ave.
Control	42	40	39	40	47	47	45	46
A40	40	39	41	40	48	52	50	50
B40	43	45	44	44	51	49	51	50
C20	39	41	39	40	49	49	47	48
C40	39	40	42	40	49	48	50	49
C60	42	43	41	42	51	50	50	50

Table C-3: Drying Shrinkage test results of concrete

MIX ID	Days	Zero Reading 1	Final Reading 1	Zero reading 2	Final Reading 2	Shrinkage micro strain 1 (10-6)	Shrinkage micro strain 2 (10-6)	Ave. Shrinkage (micro strain)
Control	0	2.971	0.000	7.282	0.000	0	0	0
	7	2.971	2.945	7.282	7.231	93	182	138
	14	2.971	2.892	7.282	7.212	282	250	266
	21	2.971	2.861	7.282	7.198	393	300	346
	28	2.971	2.847	7.282	7.179	443	368	405
	56	2.971	2.841	7.282	7.173	464	389	427
A4O	0	2.742	0	2.55	0	0	0	0
	7	2.742	2.668	2.55	2.478	264	257	261
	14	2.742	2.627	2.55	2.442	411	386	398
	21	2.742	2.612	2.55	2.419	464	468	466

	28	2.742	2.602	2.55	2.411	500	496	498
	56	2.742	2.595	2.55	2.409	525	504	514
B40	0	-1.995		-2.208	0	0	0	0
	7	-1.995	-2.042	-2.208	-2.251	168	154	161
	14	-1.995	-2.075	-2.208	-2.296	286	314	300
	21	-1.995	-2.108	-2.208	-2.322	404	407	405
	28	-1.995	-2.114	-2.208	-2.335	425	454	439
	56	-1.995	-2.118	-2.208	-2.338	439	464	452
C20	0	-2.412		-2.290		0	0	0
	7	-2.412	-2.442	-2.290	-2.323	107	118	113
	14	-2.412	-2.477	-2.290	-2.353	232	225	229
	21	-2.412	-2.499	-2.290	-2.382	311	329	320
	28	-2.412	-2.514	-2.290	-2.403	364	404	384
	56	-2.412	-2.518	-2.290	-2.409	379	425	402
C40	0	-3.022	0	-2.898	0	0	0	0
	7	-3.022	-3.061	-2.898	-2.927	139	104	121
	14	-3.022	-3.105	-2.898	-2.964	296	236	266
	21	-3.022	-3.124	-2.898	-3.015	364	418	391
	28	-3.022	-3.145	-2.898	-3.024	439	450	445
	56	-3.022	-3.151	-2.898	-3.026	461	457	459
C60	0	-1.354		-0.766	0	-4836	0	0
	7	-1.354	-1.421	-0.766	-0.81	239	157	198
	14	-1.354	-1.487	-0.766	-0.833	475	239	357
	21	-1.354	-1.493	-0.766	-0.886	496	429	463
	28	-1.354	-1.5	-0.766	-0.9	521	479	500
	56	-1.354	-1.503	-0.766	-0.908	532	507	520

Table C-4: Splitting tensile strength test results of concrete

Mix ID	Sample ID	Load (kN)	Strength (MPa)	Average (MPa)
Control	1	293.32	4.15	4.14
	2	291.41	4.12	
A40	1	316.43	4.48	4.51
	2	321.31	4.55	
B40	1	321.75	4.55	4.44
	2	305.49	4.32	
C40	1	298.86	4.23	4.26
	2	303.34	4.29	
C20	1	289.15	4.09	4.15
	2	297.49	4.21	
C60	1	310.20	4.39	4.44
	2	317.25	4.49	