CHAPTER 1
INTRODUCTION

1.1 General

Concrete is a composite material which consists of a binding medium (a combination of Portland cement and water) which are embedded by particles of relatively inert mineral filler (the aggregate). Concrete performance is largely influenced by the properties of the cement paste, and satisfactory quality of the mineral aggregates. Nevertheless, the strength and porosity of the paste are dependent entirely upon the water-cement ratio. In the past, compressive strength has been used as a basis for selecting a water-cement ratio for a particular job (Troxell & Davis, 1956).

This very versatile building material has been used widely for structural and non-structural applications for years. All because of its nature; the ability to resist water, low initial cost, easy to handle, does not require much maintenance works and universally applicable. Concrete is by far the most economical construction material that has ever been developed. Also, it is generally accepted that there seems to be no better place than the concrete industry for the disposal of millions of tons of siliceous by-products, e.g., fly ash, blast-furnace slag, rice husk ash and condensed silica fume. The use of these by-products or also known as pozzolanic materials is generally accompanied by a significant improvement in concrete quality. Substantial research and development activities have been undertaken in the area of concrete engineering and technology to investigate the material properties, structural behavior and applications.

This has resulted in new generations of concrete being improvised and developed in order to meet the increasing demand for superior workability, mechanical and durability properties. More than 30 years ago, high-strength concrete (HSC) and high-performance

concrete (HPC) appeared as new development on the market of concrete structures in order to meet the industry needs. This high strength and high performance concrete have been used in many countries all over the world. In Malaysia for example, the Petronas Twin Towers was built using high strength concrete technology.

The superior mechanical properties and durability in this new type of technology are achieved by modifying the microstructure and the porosity of the matrix (Larrard & Sendran, 1994). However, this modification of the microstructure leads to a significant increase in the brittleness and in the volume changes which occur during the hardening of the materials (Larrard & Sendran, 1994). These could affect the beneficial and superior properties demonstrated by them. Nevertheless, these effects can be reduced to a large extent by incorporating short discontinuous fibers into the concrete mixes, which results in a material known as fiber reinforced concrete (FRC).

More recently, in mid 1990's a new generation of high-strength concrete, the ultra-high performance concrete (UHPC) also known as reactive powder concrete (RPC) has developed. This type of concrete consists of high cement and mineral admixtures content, very low water-binder ratios which is made possible by the utilization of the new generation of hyper-plasticizers, and the incorporation of steel fiber reinforcement in large quantities. Besides its ultra-high-strength properties, UHPC also exhibits excellent durability and ductility. Unlike general understanding on conventional concrete and HPC, UHPC contains no coarse aggregates in its mix; instead, it comprises of powdery fine sand or quartz sand with particle sizes of 0.600 mm or lower (Moranville, 1992). The first version of this revolutionary material was introduced by French researchers, Richard and Cheyrezy (1995). They have produced concrete-mortar

with compressive strengths ranging between 200 and 800 MPa and fracture energies range between 1200 and 40 000 J/m^2.

In combination with sufficiently high fiber content it is now possible to design extremely slender concrete structures. Light-weight girders with wide spans, bridges and shells constructed with precast UHPC elements are ideal applications, broadening the range of existing concrete applications by far. With a few projects to its name mainly in the construction of footbridges and highway bridges, RPC has proven itself as an innovative construction material, not just a laboratory material. The first application of this material was built in Canada in 1997, the 60m span Sherbrooke footbridge (Graybeal & Tanesi, 2007).

1.2 Problem Statement

Ultra-high performance concrete has rapidly gained broad acceptance in the construction industry world widely. It could be used successfully in many structural as well as non-structural applications. However, comprehensive research is necessary to fill the existing knowledge gaps and to link different issues for the prospect of UHPC in different sectors of construction. Based on the literature review, the following research needs have been identified in the field of UHPC:

a. Potential for the use of locally available materials to reduce production cost.
b. Investigation of the effect of curing methods to develop green concrete.
c. Investigation of the effect of cement and silica fume content on the fresh and hardened properties, and durability of concrete.
d. Assessment of the physical quality of concrete by different non-destructive test methods.

1.3 Objectives of Study

The main objective of the study was to develop UHPC with targeted strength of 120 MPa at 28 days, and to investigate their performance in fresh and hardened states. The sub-objectives of the study were as follows:

a. To determine the feasibility of incorporating silica fume to produce ultra-high performance concrete of grade 120 N/mm^2 at 28 days. The workability of the mix is required to fall within the range of 150-300 mm.
b. To study the mechanical properties of UHPC for short-term duration, i.e. 28-day and 56-day age.
c. To investigate the effect of silica fume content on various properties of fresh and hardened UHPCs.

1.4 Scope of Work

This investigation is to develop ultra-high performance concrete and to study the mechanical properties of UHPC. All mixes were based on the Sherbrooke mix design method with water to binder ratio of 0.22. The investigation was divided into four phases. Table 1.1 shows the phases involved and its descriptions.

The initial phase, Phase 1, was conducted by examining the physical and chemical properties of OPC and silica fume. This was done by various tests such as fineness, specific gravity, chemical composition and microstructural examination. The physical tests for fine aggregates were also carried out in this phase. The physical tests were; the sieve analysis, specific gravity and water absorption.

Table 1.1: Phases of work and its description

Phase	Descriptions of work involved
1	Physical properties test and chemical composition of OPC and densified silica fume Physical tests on fine aggregates
2	Preliminary test – trial mixes to determine the optimum mix
3	Mechanical Property tests
4	Durability tests

Preliminary test on the trial mixes were done in phase II, to determine the optimum mix proportions to achieve the required strength and workability. A series of 'SF addition' and 'SF replacement' mixtures were cast to evaluate the effects of silica fume content on properties of fresh and hardened concrete. SF was 'added' or 'replaced' at 10%, 20% and 30% of the cement content. The selected figures were decided from the optimum results of preliminary works or trial mixes. The property of fresh concrete investigated was workability to produce slump flow in the range of 150-250mm diameter. Compressive strength of the concrete samples was tested at 1, 4, 7, and 28 days under elevated curing (Voo & Foster, 2003).

In phase III, further investigations were done based on the preceding phase. Optimum mixes were selected to study the mechanical properties of concrete such as compressive strength, splitting tensile strength, flexural strength, and static modulus of elasticity. A non-destructive test, the rebound hammer was also carried out. For comparison, specimens with additional of steel fiber were also cast and tested. The specimens were subjected to elevated curing (for compressive strength), water curing and air-drying and tested at 1, 7, 28 and 56 days. Lastly, Phase IV was carried out to study the durability of the concrete. The initial surface absorption test (ISAT) was chosen as the durability test. The test was carried out at 7, 28, 56 days. The specimens were exposed to two curing regimes; air drying after demoulding at 1 day, as well as water curing up to 7 days before testing.

CHAPTER 2
LITERATURE REVIEW

2.1 General

Ultra-high Performance Concrete (UHPC) is relatively a new building material in the construction industry. This chapter presents a background and review of UHPC. It begins with the definition and briefly describes the characteristics, advantages and applications of UHPC. Also this chapter highlights fresh and hardened properties, and describes the curing and testing issues of UHPC.

2.2 Ultra-high Performance Concrete

The development of UHPC has implied significant changes in the conceptual approach and construction methods for concrete structures, and opened opportunities for new designs. The definition, characteristics, advantages, applications and economy of UHPC are briefly discussed below.

2.2.1 Definition

Ultra-high performance concrete (UHPC) is a special type of concrete that exhibits superior mechanical and durability properties. This type of concrete consists of high amount of cement, high silica fume content and using fine aggregate only. UHPC also consists of small steel fibers that provide additional strength and polycarboxylate ether based superplasticizer for its low water-binder ratio (Blais & Couture (1999), Bonneau et al. (2000), Collepardi (1998)).

2.2.2 Characteristics

Ultra-high Performance Concrete (UHPC) is a new family of concretes and it differs from traditional normal strength concrete (NSC) and high performance concrete (HPC) with respect to its performance in fresh and hardened states that are mainly driven by special material components and mixture proportions. While considered a relatively new material, UHPC consists mostly of Portland cement, silica fume, water, quartz sand, steel fibers and superplasticizer. The combination of these components creates a dense packing matrix that improves rheological and mechanical properties, and also reduces permeability (Fehling, Bunje & Schmidt, 2004). A breakdown of the first mixture constituents of reactive powder concrete (RPC) also known as UHPC is shown in Table 2.1 (Richard & Cheyrezy, 1995).

Table 2.1 : Basic composition of Reactive Powder Concrete

Material	Amount (kg/m^3)
Portland Cement	955
Fine Sand	1,051
Silica Fume	229
Superplasticizer	13
Steel Fibers	191
Total Water	153

2.2.3 Advantages

UHPC offers many advantages that could lead to various types of applications. Some of these are as follows (Ashida et al (2008), Dehn (2004), FHWA (2006), Fehling et al (2004), Sakurada et al (2008), Schachinger et al. (2004), Voo (2010), Voo & Poon (2011), Ziad et al. (2004)).

a. Results in greater mechanical and durability properties due to optimization of the design mix.

b. Suitable to be used in conducive environment due to its high durability properties.
c. Realization of the construction of complicated structures design due to the easement in casting and molding of the complex architectural forms.
d. Saves a large quantity of concrete due to the reduced section of structural components.
e. Eases concrete placement operations, and thus increases construction ability.
f. Confers high early strength, allows a quicker reuse of formwork, and thus enhances the production rate.
g. Suitable for precast industry, thus supporting the local construction industry by promoting the industrialized building system (IBS).
h. Requires fewer laborers for transport and placement of concrete, and therefore becomes more economical.
i. Provides good finishing due to the ultra-packed nature of the concrete matrix while improving the aesthetical appearance of concrete.

2.2.4 Applications and Design Recommendations of UHPC

The applications of UHPC are considerably new to the construction industry. Nevertheless, this new type of concrete gives new perspectives for engineers and architects with its superior mechanical properties and durability. To date, this versatile material has been applied successfully in artwork, acoustical panels, precast elements, pedestrian bridges, and highway bridges.

Even though the utilization of UHPC in Malaysia is relatively new and limited, its international roots have led to many different applications used in other parts of Asia, U.S., Canada, Europe, and Australia. While many of the applications have been related

to the transportation industry, more and more uses for this innovative material are being discovered to not only reap the benefits of its strength, but also UHPC's durability. Several applications of UHPC are mentioned in Table 2.2

Table 2.2: Applications of ultra-high performance concrete (Blais & Couture (1999), Jungwirth& Muttoni (2004), Jayakumar (2004), Voo(2010), Voo & Poon (2011), Yazici et al. 2010, Zhang et al. (2008)

Structure	Year	Location	Application
Sherbrooke pedestrian bridge	1997	Canada	Prestressed bridge
Sakata-Mirai Footbridge	2002	Japan	Prestressed bridge
Bourg Les Valence Bridge	2001	France	Precast bridge decks
Cattenom Power Plant	1997	France	Prestressed beams
Toll barrier at Millau	2004	France	Slender Prestressed shell structure
The Footbridge of Peace in Seoul	2002	South Korea	Prestressed bridge
Wilson Hall	2008	Malaysia	Acoustic panel wall
Kg. Linsum Motorway Bridge	2011	Malaysia	Prestressed bridge

2.2.5 Cost Impact of UHPC in Construction Industry.

The overall material cost of UHPC is higher than the ordinary concrete and the cost involved in quality control is also high in case of UHPC due to instability problems. However, the increased cost for materials and quality control can be compensated through concrete quantity savings and productivity improvement. UHPC is generally much stronger than ordinary concrete. Therefore, the structural components will be made of thinner sections, and therefore savings can be attained due to less amount of concrete used.

The productivity improvement also reduces the cost involved in formwork. Moreover, UHPC offers better mechanical and durability performance and greater service life than ordinary concrete, hence can be acceptable over the increased initial cost. If the cost analysis is conducted based on the lifecycle costing, the cost-effectiveness of UHPC in

construction industry will be apparent. Indirect benefits can also be gained through the durability improvement leading to savings on maintenance.

The improved durability of UHPC may lead to lower repair costs for bridges and structures and less down time due to repair construction. UHPC bridges or structures constructed in aggressive environments may remain structurally safe for generations. Also, bridges and buildings that were all but thought impossible may now be realized. Additionally, longer lasting structures minimize the impact on the environment. Cement production is a leading contributor to industrial process-related emission sources (Hanle et al., 2004). While UHPC requires higher cement quantities than normal concretes, the amount of cement used in the lifetime of a UHPC structure may be far less than the amount used for several lifetimes of a NSC or HSC structure. Similarly, UHPC requires much less maintenance than its concrete counterparts and in turn fewer materials are required for repair or rehabilitation.

2.3 Background of UHPC

The development of UHPC is the extension of the development in high performance concrete (HPC) whereby the UHPC materials have benefited from both improved aggregate gradations and the use of a high-range water reducer, or superplasticizer. UHPC was first developed as a reactive powder concrete (RPC) with compressive strengths ranging from 200 to 800 MPa. These high strengths were the products of improving homogeneity by eliminating coarse aggregates, optimizing the granular mixture, and improving microstructure of cement paste by heat treatment application (Moranville, 1992). In the early 1990's two separate French contractors, Eiffage Group and Boygues Construction, with the help of Sika Corporation and Lafarge Corporation, respectively, developed two different UHPC's which exhibit similar properties

(Resplendino, 2004) Eiffage Group with Sika Corporation created BSI® which is noted as being coarser than other UHPCs (Resplendino, 2004) and the partnership between Boygues and Lafarge produced Ductal® (Resplendino & Petitjean, 2003).

2.4 Types of UHPC

There are many types of UHPC materials which have been produced so far, several that have already been developed include Ductal®, BSI®, and CEMENTEC (Resplendino and Petitjean, 2003) which are marketed by Lafarge, Eiffage Group, and Laboratoire of Central des Ponts et Chausses of France, respectively. Our country also has developed the UHPC material called Ultra-High Performance 'ductile' Concrete (UHPdC), which is produced and marketed by Dura Technology Sdn Bhd. While the various UHPC materials differ slightly in composition, and many new UHPC materials are in the process of being developed, a basic understanding of UHPC material behavior and its potential implementation remains a priority.

2.5 Microstructure of UHPC

Portland cement is the primary binder used in UHPC, but at a much higher proportion rate than in NSC or even HPC. UHPC also developed through reduction of the water-to-cementitious material, lowering the ratio of calcium oxide to silicon dioxide, $CaO\text{-}SiO_2$ by introducing the silica components and incorporation of steel fiber reinforcement. The very low water to cementitious materials ratio, $W/B < 0.25$ prevents all the cement from hydrating. After thermal treatment, unhydrated cement grains exist in the matrix (Richard & Cheyrezy, 1995) and act as particle packing material. Cement with high proportions of tricalcium aluminate (CA_3) and tricalcium silicate (C_3S), and a lower Blaine fineness are desirable for UHPC, as the CA_3 and C_3S contribute to high early strength, and the lower Blaine fineness reduces the water demand (Safiuddin, 2008).

Despite the large amount of particles left unhydrated, RPC with a water-to-cementitious material ratio of 0.20 would reach discontinuous capillary porosity when 26% hydration of cement has occurred (Bonneau et al., 2000).

Both the ground quartz and quartz sand (with diameter dimension between 150 and 600 micrometres) contribute to the optimized packing. Additionally, the most permeable portion of a concrete tends to be the interfacial transition zone (ITZ) between coarse aggregates and the cement matrix (Mehta & Aïtcin, 1990) and therefore, the elimination of coarse aggregates aids in improving the durability of UHPC. The ITZ zone is the area where the cement grains have difficulty growing due to the present of a large surface which impedes crystal growth and the area around any inclusion in the cementitious matrix. The interfacial transition zone mainly consists of a water film, a calcium hydroxide layer on the aggregate side, and a porous paste matrix layer between calcium hydroxide layer and bulk paste matrix (Safiuddin, 2008). Silica fume is the smallest component in UHPC and with a diameter of 0.2 μm helps fill this region.

The addition of silica fume fulfills several roles including particle packing, increasing flowability due to spherical nature, and pozzalonic reactivity (reaction with the weaker hydration product calcium-hydroxide) leading to the production of additional calcium-silicates (Richard & Cheyrezy, 1996). Because of its nature, this highly pozzolanic material assists in increased strength and reduced permeability. Reduction of the ITZ zone increases the tensile strength and decreases the porosity of the cementitious matrix (Safiuddin, 2008). By reducing the amount of water necessary to produce a fluid mix, and therefore permeability, the polycarboxylate superplasticizer also contributes to improving workability and durability.

Basically, the incorporation of non-continuous steel fibers to UHPC is to improve the ductility and tensile strength of the concrete. The addition of steel fibers also aids in preventing the propagation of microcracks and macrocracks and thus limits crack width and permeability. This is the largest particle in the mix and is added at two percent by volume to the mix. Because of its size relative to the other constituents, it reinforces the concrete on the micro level (Graybeal, 2005).

2.6 Material Aspects for Ultra-high Performance Concrete

UHPC consists of cement, fine aggregates, water, silica fume, steel fiber and chemical admixture. The most common chemical admixture used for UHPC is superplasticizer. The production of UHPC involves more stringent control on the selection of constituent materials than ordinary concrete to meet the requirements for fresh and hardened properties and durability. The suitable properties of the constituent materials are the defining factors to achieve the expected benefits from UHPC. Indeed, the constituent materials play important roles when they are combined in concrete. The following sections briefly illustrate the component materials of UHPC emphasizing their properties.

2.6.1 Aggregate

One of the basic principles in producing UHPC is through improving the homogeneity of concrete by eliminating the coarse aggregate. As proposed by (Richard and Cheyrezy, 1995) the homogeneity of RPC is improved by using a powder concrete in which aggregates and traditional sand are replaced by ground quartz less than 300 microns in size. However, the usage of very fine aggregate could lead to the increment of cement factor up to 900-1000kg/m^3 which could increase the drying shrinkage and creep of the concrete (Collepardi et al., 1997).

In order to study the influence of the coarse aggregate in UHPC, an investigation has been conducted by Collepardi et al. on modified RPC. The research (Collepardi et al., 1997) reported that the replacement of the fine ground quartz sand by an equal volume of well graded natural aggregate with maximum size of 8 mm did not change the compressive strength of RPC at the same water-cement ratio. However, the flexural strength was lower when graded coarse aggregate replaced all the very fine sand. This effect could be explained in terms of a better homogeneity when only very fine sand is present. Another investigation has been carried out by (Kang et al., 2008) to study the influence of the coarse aggregate to the compressive strength of UHPC. Fine aggregate used was below 5mm instead of coarse aggregates in order to ensure the homogeneity of concrete and improve the strengths. The researchers concluded that the compressive strengths were at its highest when coarse aggregate and very fine sand were combined and the ratio of aggregate to cement was 1:1. This shows that combining aggregates of different sizes were more advantageous to increase strengths than using aggregate of unified size.

2.6.2 Portland Cement

Portland cement is widely used to produce various types of concrete. It is hydraulic cement, which is produced by pulverizing clinker consisting of calcium silicates, and usually containing calcium sulfate as an addition (ASTM C150, 2004). Portland cement is also a key component of UHPC. It is used in combination with silica fume to produce UHPC. After reacting with water, portland cement also reduces the porosity and results in a packed concrete mass leading to low transport properties and good durability (Neville, 1995).

2.6.2.1 Physical Properties

The physical properties of cement significantly influence the performance of concrete. This is also true for UHPC. Lump-free fresh cement should be used in UHPC. The cement should possess carefully controlled fineness, and should produce low or moderate heat of hydration to control the volume changes in concrete (Safiuddin, 2008). ASTM C 150 (2004) has specified the physical property requirements for various Portland cements, which are also useful to choose the proper cement for UHPC.

2.6.2.2 Chemical Composition

The chemical analysis of portland cement has revealed that it mostly consists of various oxide compounds. The major oxide compounds are lime, silica, alumina, and iron. In addition, two minor oxides namely sodium and potassium oxides are of some importance, particularly with regard to alkali-aggregate reactions in concrete. In addition, magnesia and sulfuric anhydrite can be present, although they are not beneficial constituents of cement. The typical chemical composition of portland cement is shown in Table 2.3. ASTM C 150 (2004) has specified the chemical requirements for different types of portland cement. These requirements are also beneficial for selecting the appropriate cement for UHPC.

Table 2.3: Typical chemical composition of portland cement (Neville, 1995)

Chemical Name	Composition	Mass content (%)
Calcium oxide (lime)	CaO	58 – 66
Silicon dioxide (silica)	SiO2	18 – 26
Aluminum oxide (alumina)	Al2O3	4 – 12
Ferrous and ferric oxides (iron oxides)	Fe2O3 and FeO	1 – 6
Magnesium oxide (magnesia)	MgO	1 – 3
Sulfur trioxide (sulfuric anhydrite)	SO3	0.5 – 2.5
Alkaline oxides (alkalis)	Na2O and K2O	≤ 1.0

2.6.3 Silica Fume

ACI 116R-00 (2004) defines silica fume as "very fine non-crystalline silica produced in electric arc furnaces as a by-product of elemental silicon or alloys containing silicon". It is usually a grey colored powder. Silica fume is usually categorized as a supplementary cementitious material. This term refers to materials that are used in concrete in addition to Portland cement.

2.6.3.1 Physical Properties

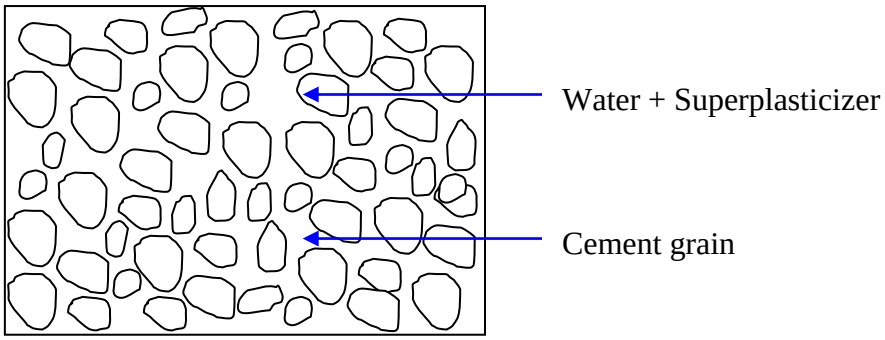
Silica fume particles are extremely small, with more than 95% of the particles being less than 0.1 μm (Neville, 1995). The bulk density or unit weight of the as-produced silica fume is usually very low; Table 2.4 shows the primary physical properties of silica fume. Silica fume has a specific gravity of about 2.2, which is lighter than Portland cement, which has a specific gravity of 3.15.

Table 2.4: Physical properties of silica fume (Scancem Materials, 2009)

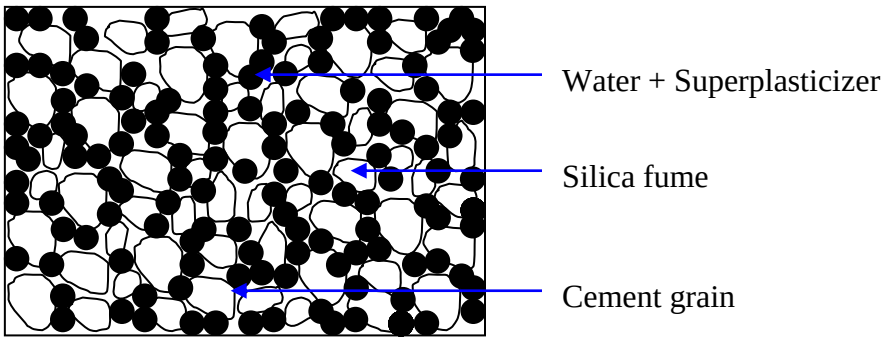
Particle size (typical):	< 0.1 μm
Bulk density:	
(as-produced):	200 to 300 kg/m^3
(densified):	500 to 700 kg/ m^3
Specific gravity:	2.2
Specific surface:	20,000m^2/kg

2.6.3.2 Roles in Concrete

Because of its extreme fineness and high silica content, Silica Fume is a highly effective pozzolanic material (Neville, 1995). Naturally, the silica fume mainly serves in concrete as a microfiller, pozzolan, and viscosity modifier. The silica fume particles can fill the voids between the larger cement grains because of their smaller size, as shown in Figure 2.1. In the presence of water, the silica fume actively reacts with $Ca(OH)_2$ liberated during cement hydration (pozzolanic reaction) and produces additional calcium silicate hydrate (CSH), as shown in Equation 2.1 and Equation 2.2.



Physical packing in presence of cement alone



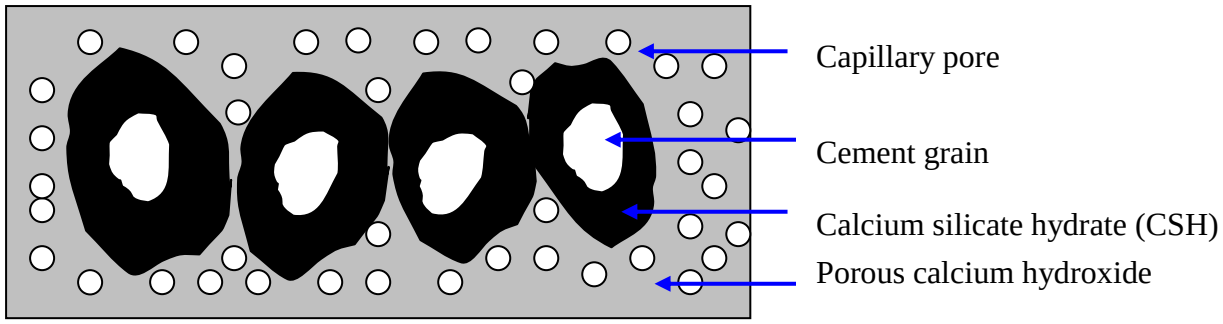
Physical packing in presence of cement and silica fume

Figure 2.1: Microfilling effect of silica fume (Safiuddin, 2008)

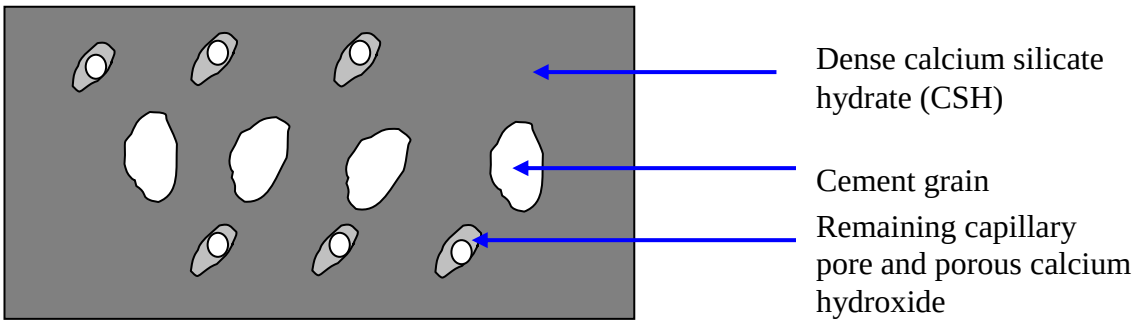
Hydration reaction: C_2S or $C_3S + H_2O \rightarrow$ primary CSH + $Ca(OH)_2$ (2.1)

Pozzolanic reaction: $Ca(OH)_2 + SiO_2 + H_2O \rightarrow$ secondary CSH (2.2)

The pozzolanic reaction product fills the pores existing between cement grains and results in dense calcium silicate hydrate, as shown in Figure 2.2. Both microfilling and pozzolanic effects of silica fume play an important role to refine the pore structure in bulk paste matrix and interfacial transition zone of concrete. The pore refinement occurring due to the secondary reaction between silica fume and $Ca(OH)_2$ makes the microstructure of concrete denser and improves the interfacial bond between aggregates and binder paste. As a result, the strength, transport properties and durability of concrete are improved.



Hydration in the absence of Silica fume



Hydration in the presence of silica fume

Figure 2.2: Pozzolanic effect of silica fume (Safiuddin, 2008)

As studied by Park et al. (2008) in order for silica fume to undergo a pozzolanic reaction, calcium hydroxide is required, which is generated when the cement undergo hydration. The study found that the quantity of calcium hydroxide required for pozzolanic reaction of silica fume was sufficient until the ratio of silica fume reached 0.25. Also stated that the amount of cement decreased when the ratio of silica fume exceeded 0.25, the calcium hydroxide required for pozzolanic reaction was relatively deficient. Therefore it would cause the decrease of the compressive strength. The results show that the increase of compressive strength up to 0.25 of silica fume/cement ratio may somewhat relate to packing effect. The studies suggested that the optimum ratio of silica fume is to be 0.2-0.3.

2.6.4 Superplacticizer

Superplasticizer has a big influence on the fresh and hardened concrete properties and this is even more pronounced in high performance and ultra high performance concrete. Big differences occur mainly in setting time and early strength development, whereas the influence on final strength is not significantly influenced. With the development of superplasticizers based on polycarboxylates, a new field of application could be opened. The main characteristics of the polycarboxylate based superplasticizers are the following (Plank et al., 2009):

- High water reduction (up to 40%)
- High flowability
- Polymer-design allows to control the main characteristics (setting time and workability)
- Blending of different polymers is possible: formulation of customized solutions

Criteria for suitable superplasticizer for UHPC can be determined through two stages; during fresh and hardened state (Plank et al., 2009). The binder content of UHPC is four times higher compared to a standard concrete, which leads to an increased admixture content of up to 15 times. This shows the importance of the right choice of the superplasticizer type. The selection of a suitable superplasticizer is mainly defined by the application. The main focus in the selection of the superplasticizers should be always on the slump life and the early strength of concrete.

Also known as high-range water reducer, superplasticizer has made a breakthrough in concrete industry. It is an essential material component that must be used to produce UHPC. The superplasticizer improves the flowing ability of UHPC by their liquefying and dispersing actions. They reduce the yield stress and plastic viscosity of concrete by their liquefying action (Larrard, 1999), and thus provide a good flowing ability in

UHPC. In addition, superplasticizer deflocculates the cement particles and frees the trapped water by their dispersing action (Aïtcin, 1994) and thus enhances the flowing ability of UHPC. In dispersing action, the inter-particle friction flow resistance is also decreased, and therefore the flowing ability of concrete is improved.

Superplasticizer can either increase the strength by lowering the quantity of mixing water for a given flowing ability, or reduce both cement and water contents to achieve a given strength and flowing ability (Aïtcin, 1995) They contribute to achieving denser packing and lower porosity in concrete by increasing the flowing ability and improving the hydration through greater dispersion of the cement particles, and thus assisting in producing high strength and good durability (Collepardi et al., 1997).. There are mainly four categories of superplasticizer; sulfonated melamine-formaldehyde condensates, sulfonated naphthalene-formaldehyde condensates, modified lignosulfonates, and carboxylated acrylic ester copolymers or polycarboxylates (Neville, 1995).

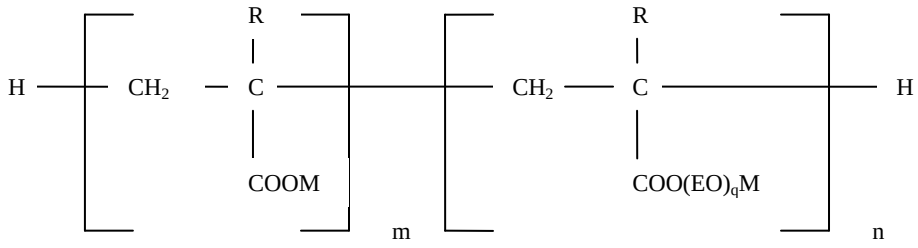
2.6.4.1 Physical Properties

Superplasticizers are generally formulated to produce high plasticity, normal-setting characteristics, and accelerated strengths in concrete. Superplasticizers are usually available in clear to dark brown liquid form but are also obtainable in solid state as a brownish powder. They usually possess a viscosity in the range of 60 to 80 centipoises, and a solid content varying from 22 to 42% by weight (Aïtcin, 1997). Also, the relative density of superplasticizer is near to that of water and hence it can be easily dispersed with water. A particular type of superplasticizer can be used as a singular admixture or as a component in an admixture system, but it must fulfill some physical requirements and should be compatible with cementing materials for good performance in concrete.

he ASTM has specified some physical requirements for superplasticizer (Safiuddin, 2008).

2.6.4.2 Chemical Structure

Polycarboxylate superplasticizers are generally used to produce UHPC. They are produced from the relevant monomers by a free radical mechanism. The molecular structure of polycarboxylate superplasticizer consists of a main chain and a graft chain. The main chain contains carboxylate groups (COO-) while the graft chain comprises ethylene oxide (EO). The chemical structure of polycarboxylate superplasticizers is shown in Figure 2.3.



R = H, CH_3
M= Metal
EO = Ethylene oxide

Figure 2.3: Chemical structure of polycarboxylate superplasticizer (Safiuddin, 2008)

2.6.4.3 Mechanisms of Water Reduction

Superplasticizers prevent the formation of cement-water agglomeration in concrete mixture and disperse the cement particles in aqueous phase, as can be seen from Figures 2.4 and 2.5. Thus, the water demand of concrete mixture is significantly reduced. Superplasticizers can exert the water-reducing action by two mechanisms, known as electrical and steric repulsions.

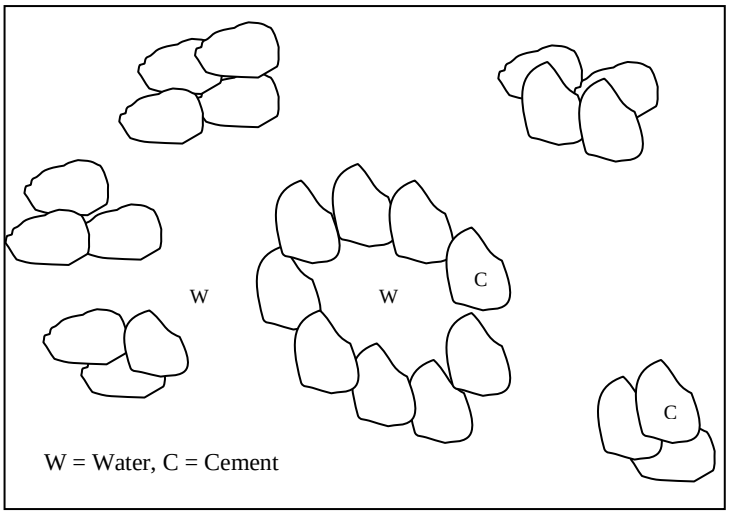


Figure 2.4: Cement-water agglomeration in the absence of Superplasticizer

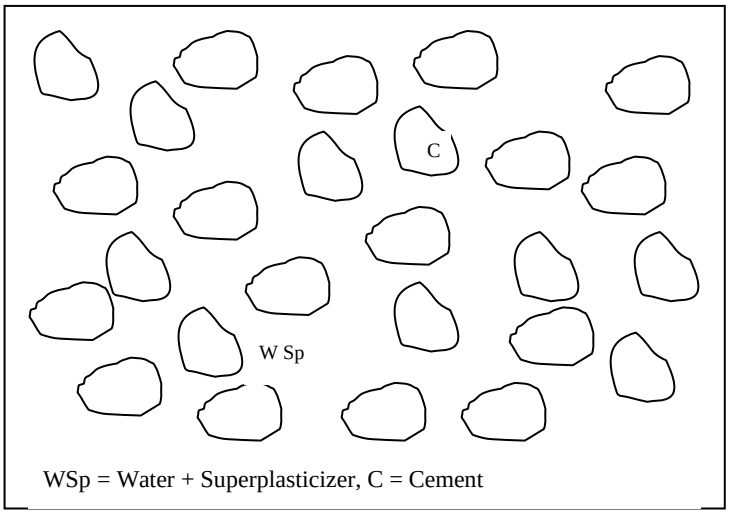


Figure 2.5: Dispersion of cement particles in presence of Superplasticizer

The conventional or first-generation superplasticizer exerts water reducing action by decreasing the surface tension of water and by equidirectional charging of the cement grains. When a superplasticizer is added to concrete, the cement particles are dispersed in the aqueous phase of fresh concrete and therefore the cement-water agglomerates cannot form (Aïtcin, 1998). The dispersion mechanism is driven by the adsorption of the superplasticizer molecules on the cement grains. The adsorbed molecules bring about the repulsion forces between cement particles (electrical repulsion) due to their negative electrical charges. Consequently, flocculation is prevented and the cement

particles are dispersed homogeneously in the fresh concrete (ASTM C 494/C 494M, 2004). This result in an appreciable reduction in the quantity of mixing water, since the water molecules, which were previously entrapped in cement grain flakes, now become free.

The second-generation superplasticizers such as polycarboxylate superplasticizer work by steric hindrance effects (steric repulsion mechanism) to prevent cement-water agglomeration (Safiuddin, 2008). It has unique graft chains (side chains) of polyethelene oxide that extend onto the surface of cement particles (Erdogdu, 2002) .These graft chains move in water and steer the cement grains to disperse evenly in the mixture. Also, the main chains of polycarboxylate superplasticizer spread around the cement grains and prevent them from being in contact with each other. Hence, the cement grains cannot be associated to form cement-water agglomeration, and the water needed for a given flowing ability is greatly reduced.

2.6.5 Steel Fiber

Fiber has been added in cement-based composites since 1960's to enhance concrete properties, particularly tensile strength, abrasion resistance and energy absorbing capacity (Nehdi et al., 1998). The presence of fiber would refrain the growth or propagation of internal cracks and helps to transfer load (Nehdi et al., 2004, Chandra & Björnström, 2002). The specimen with fiber has much higher ductility than the specimen without fiber, for which fiber reinforced concrete also demonstrates a significant increase in energy absorption or toughness (Orgass & Klug, 2004, Nagamoto et al., 2008). However, the properties of fiber reinforced concrete would be affected by the type, volume fraction and aspect ratio of fiber. Lower fiber volume fraction is usually preferred as far as material cost and workability are concerned (Magureanu et

al., 2008). The previous research has suggested that the proper volume fraction of fiber was around 2% in cement-based composites (Lin et al., 2008).

Steel fibers are the most commonly used in fiber reinforced concrete (FRC) and UHPC. The application of short fibers in concrete varies between 0.2 % and 2 % but there have been cases where higher percentages were used. Steel fibers are produced either by cutting wire, by shearing sheets or from a hot-melt extract. It was reported in the previous research that the combination of silica fume with steel fiber would effectively enhance the compressive strength, splitting tensile strength, abrasion resistance and impact resistance and be beneficial for fiber dispersion in cement-based composites (Lin et al., 2008). Silica fume would increase the bonding between fiber and mortar by strengthening the interfacial zone (Nagamoto et al., 2008).

In the study conducted by Song and Hwang, (2004) to investigate high steel-fibre reinforced concrete, it was observed that the addition of steel fibers at 0.5 %, 1.0 % and 1.5 % resulted in progressively improving compressive strength with concrete containing 1.5 % fibers recording the highest improvement of compressive strength at 15.3 %. But the addition of 2.0 % fibers resulted in a slightly lower 12.9 % increase in the compressive strength compared to the control concrete. Meanwhile, the splitting tensile strength and modulus of rupture of the FRC exhibited marked improvements with an enhancement of 98.3 % and 126 % respectively when compared to the control concrete (Song and Hwang, 2004).

Another investigation conducted by Lin et al, (2008) was aimed to evaluate the effect of steel fiber on the mechanical properties of cement-based composites with silica fume. A multiple regression analysis was also performed on the experimental results to quantify

the influence of material variables on the mechanical properties. The findings showed that the addition of steel fiber to silica fume composites achieves a significant increase in tensile strength, toughness and impact resistance and slight improvements in compressive strength and abrasion resistance with an extra average 10% and 9% increase in compressive strength, 68% and 59% increase in splitting tensile strength, 31% and 15% increase in direct tensile strength, 23% and 28% increase in toughness, 18% and 8% reduction in abrasion coefficient, and 118% and 296% increase in impact toughness. The findings also stated that mixture containing 10% silica fume specimens gives higher results compared to concretes containing 5% silica fume.

A study has been conducted by Park et al., (2008) in order to investigate the influence of steel fibers on the compressive strength of UHPC. The researchers has added 2% of steel fibers in volume friction ratio in the UHPC mixtures, and measured the compressive strengths by changing water to cementitious materials ratio. The results showed that the addition of steel fibers has increased compressive strength by 13% irrespective of water-cementitious materials ratio. Also stated that it is possible to manufacture 200 MPa compressive strength UHPC with 2 % steel fibers and 0.20 water-cementitious ratio. Table 2.5 below shows the typical properties of steel fiber in producing UHPC.

Table 2.5: Typical Properties of Steel Fiber in UHPC
(Morin et al., 2001, Mizutani et al., 2008, Lin et al., 2008)

Property	**Specifications**
Density	7860 kg/m3
Tensile Strength	> 2600 MPa
Length	13 mm
Diameter	0.20 mm
Aspect ratio	65

2.6.6 Water

Water readily available is the most important component of UHPC. The hydration of cement can take place only in the presence of water. Adequate water is required for the hydration of cement, leading to the formation of paste to bind the aggregates.

2.6.6.1 Physical Quality

Water intended for use in concrete should be clean, fresh and free from deleterious substances. Water containing harmful substances such as silts, suspended particles, organic matter, oil, or sugar can unfavorably affect the strength and setting properties of cement and disrupt the affinity between aggregate and cement paste (Safiuddin, 2008). Therefore, the suitability of water should be examined before use. As a rule, any water with silt content below 2000 mg/L is suitable for use in concrete (Song & Hwang, 2004). In general, the potable or drinkable water is safe for use in concrete. However, the criterion of potability is not absolute. Water not fit for drinking may also be used satisfactorily in making concrete.

2.6.6.2 Chemical Quality

The mixing water for UHPC should be chemically safe. The pH of mixing water should be in the range of 6.0 to 8.0 (Majuar, 2003). It should not contain high amount of dissolved solids, chlorides, alkalis, carbonates, bicarbonates, sulfates, and other salts, which can interfere with the performance of concrete. Water containing chloride ion, SO_3 ion, and dissolved solids below 500, 1000, and 2000 mg/L, respectively, is generally satisfactory for making concrete (Neville, 1995). Though dissolved solids exceeding 2000 mg/L are not always harmful, they can affect the strength and setting properties of cement adversely. Water, including organic acids, may also adversely affect the hydration of cement. Therefore, when the suitability of water is questionable,

it must be tested before use in concrete. The ASTM (ASTM C 94/C 94M, 2004) has specified some physical and chemical limits to judge the acceptability of questionable mixing water.

2.7 Mixture Design for Ultra-high Performance Concrete

In general, the mixture design of UHPC is different from that of ordinary concrete. Even though compressive strength is the primary criterion for designing ordinary concrete and UHPC, a different design approach is needed. UHPC can be produced by four basic principles (Richard & Cheyrezy, 1995). This type of concrete can be made by the following principles:

- Improving the homogeneity of concrete by replacing the coarse aggregate material with a much finer aggregate material.
- Increasing the dry-compacted density through governing the water-cementitious ratio and adding the silica fume to the mix.
- Improving the microstructure of concrete with thermal application during curing process.
- Enhancing the ductile behaviour of concrete with the addition of steel fibers.

2.7.1 Justification for a Different Method of Mixture Design

The process of mixture design for ordinary concrete is not applicable to UHPC for the following reasons:

- The coarse aggregate content of ordinary concrete is eliminated in the UHPC.
- The approximate water content of concrete mixture does not include the effects of silica fume and superplasticizer, which are usually incorporated in UHPC.
- The fine aggregate content obtained from traditional method is generally much lower than that recommended for UHPC.

- The water-cementitious ratio of UHPC is much lower to the ordinary concrete.
- Established relationships between average and specified compressive strengths of ordinary concrete could be unacceptable for UHPC possessing high strength.
- Traditional curves for the relationship between W/B ratio and compressive strength could be misleading for UHPC that needs a lower W/B ratio.
- None of the traditional curves for W/B ratio and strength relationship accounts for the effect of silica fume and superplasticizer, which are usually used to produce UHPC.

2.7.2 Current Methods of Mixture Design

To date, there are no standard mixture design methods available for designing UHPC. However, there are two design guidelines that provide the necessary information to fully design and calculate a structural member in UHPC. These are the French recommendations for UHPC, established by AFGC/SETRA in France in 2002 (Jungwirth & Muttoni, 2004) and the Japanese recommendations for UHPC (Jungwirth & Muttoni, 2004). On the other hand, typical mixture design approaches are based on the basic principles proposed by Richard and Cheyrezy, (1996) where this methodology fixed the silica fume content, controlled the amount of total water and eliminated the coarse aggregate in which resulting in high content of fine aggregate. Consequently the actual mix proportion is decided through numerous trial mixes.

2.8 Mixing of Ultra-high Performance Concrete

Mixing is a mechanical operation to obtain a uniform mixture of concrete. A conventional mixer can be used in producing UHPC. However, the mixing time for UHPC is longer than that of ordinary concrete due to its higher plastic viscosity at low W/B ratio similar to production of high performance concrete (HPC) and self-

compacting concrete (SCC). The mixing sequence of UHPC can be different from that of ordinary concrete due to the presence of chemical admixture such as superplasticizer. In general, the aggregates are mixed first with a portion of mixing water followed by the addition of cementing materials. Superplasticizer should be added once the aggregates and the cementing materials are wetted out. This will increase the effectiveness of superplasticizer (Habel et al., 2006, Habel & Gauvreau, 2008) and avoid the loss of superplasticizer through absorption by aggregates (Collepardi et al. 1997). Finally steel fiber is added to the concrete mixtures.

2.9 Curing of Ultra-High Performance Concrete

Curing is ideally a process that keeps the concrete element completely saturated or as much saturated as possible until the water-filled spaces are substantially reduced by hydration products (Majuar, 2003). Concrete properties and durability are significantly influenced by curing since it greatly affects the hydration of cement. The hydration of cement virtually ceases when the relative humidity within the capillaries drops below 80% (Neville, 1995).

The lack of moisture in cement paste can also result in autogenous shrinkage due to self-desiccation. This is particularly a concern for the concretes with higher binder content and lower w/b ratio (Neville, 1995). Moreover, the drying of concrete surfaces results in shrinkage cracks that may aggravate the durability problems. Therefore, an efficient curing method is inevitable to prevent the concrete from drying and self-desiccation, and to maintain the relative humidity above 80%. A proper curing of UHPC is crucial to produce greater hydration products, and to reduce the porosity and drying shrinkage cracking of concrete, and thus achieving higher strength and greater resistance to physical or chemical attacks in aggressive environments. If UHPC is not

well cured, particularly at the early age, it will not gain the properties and durability at the desired level due to a lower degree of hydration, and would suffer from irreparable loss. Unlike ordinary concrete, UHPC required elevated curing treatment at the early age as mentioned earlier.

In the previous study several types of curing regimes were implemented to study UHPC characteristics under different curing conditions. The standard curing treatment included steaming the UHPC at 90ºC and 95% relative humidity (RH) for 48 hours (Yazici, 2007). In steaming type method, this procedure included 2 hours of increasing steam and 2 hours of decreasing steam, leaving 44 total hours of constant steaming at 90 ºC and 95 percent RH. This treatment was initiated within 4 hours after demolding, which referred to as steam treatment. The remaining three regimes include untreated, tempered steam treatment, and delayed steam treatment.

The untreated regime allowed the specimens to remain in a standard laboratory environment from demolding until testing. The tempered steam treatment is very similar to the steam treatment, except that the temperature inside the steam chamber was limited to 60 ºC. Finally, the delayed steam treatment is a curing regime wherein the steam treatment described above is followed, but it is not initiated until the 15^{th} day after casting. Until the 15^{th} day, delayed steam specimens are equivalent to untreated specimens. Other than above mentioned, water ponding also can be adopted to cure UHPC with the curing period should be at least 7 days to improve the properties and durability of concrete(Yazici, 2007). This is more crucial for UHPC to reduce its autogenous and drying shrinkages caused by high binder content and low w/b ratio.

2.10 Testing of Ultra-high Performance Concrete

Testing of UHPC includes testing of both fresh and hardened concretes. The testing of fresh concretes usually involves the test for flowing ability. The testing of hardened concretes includes both destructive and non-destructive tests. Among various destructive tests, the compression test is of great importance. The other important destructive tests are flexural (bending), and direct and indirect (splitting) tension tests. The non-destructive testing includes tests for ultrasonic pulse velocity, modulus of elasticity, absorption, permeability, etc.

Most of the test methods available for determining the fresh properties of ordinary concrete are not suitable for UHPC due to different workability characteristics. Only very few standard test methods were established for fresh UHPC. However, the most common and widely used with was slump test, indeed with some modifications to examine the filling ability of UHPC.

In case of hardened UHPC, the test methods used for ordinary concrete can be employed to determine the concrete properties. A higher specified loading rate can be applied to UHPC as compared to ordinary concrete, while conducting the destructive strength test. This is because the strength of UHPC is much higher than that of ordinary concrete.

2.11 Mechanical Properties

Characterization of the mechanical properties is important to the efficient design and use of UHPC. The following sections discuss the basic mechanical properties of UHPC.

2.11.1 Compressive Strength

One of the most noticeable assets of UHPC is its high compressive strength. (Voo and Foster, 2008) demonstrated that UHPC is capable of reaching compressive strengths of more than 150 MPa. This was supported by (Yazici, 2007) and (Habel & Gauvreau, 2008) with research showing a compressive strength of over 150 MPa. The increment in compressive strength, over NSC or HPC, can be attributed to the particle packing and selection of specific constituents, and thermal curing of UHPC. When undergoing a 48 hour thermal treatment of 90°C at 95% relative humidity, UHPC showed an increase of 53 percent over non-thermally cured specimens of the same age (Graybeal, 2005). This creates choices for designers and owners as the increment in compressive strength may allow UHPC to get a foot hold in the long span and low span-to-depth ratio market segments which have been dominated by steel.

A study was conducted to investigate the mechanical behaviour of thermally treated UHPC at different ages and with different sized specimens (Kollmorgen, 2004). Three cylindrical, two cube, and two prismatic geometries were used to complete the testing. Specimens were cured under ambient conditions for three days before being demolded, then tested or thermally treated. Thermal treatment included a six hour ramp up to 90°C at 100% relative humidity, a 48 hour hold period, and a ramp down over night. Over 240 compressive specimens were tested at various ages and with different geometries. Specimens were tested before thermal treatment (3 days after mixing), and after thermal treatment (7, 14, 28, and 56 days after mixing). The average compressive stress exceeded 58.6 MPa for specimens tested 3 days after casting before thermal treatment and over 193 MPa for all specimens undergoing thermal treatment regardless of age.

2.11.2 Modulus of Elasticity and Poisson's Ratio

The modulus of elasticity is a material dependent property which is often described as a mathematical relationship between stress and strain. The slope of the elastic portion of the stress-strain curve is the modulus of elasticity. The modulus of elasticity is used in design calculations to predict deflection behavior of the element so the design can often satisfy the specified limit states.

2.11.3 Flexural Strength and Flexural Toughness

A research done by (Graybeal, 2005) has used ASTM C 1018 *Standard Test Method of Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading)* to evaluate the first crack strength and flexural toughness of portland cement concrete. Since there are no standards available for UHPC, the author has adapted the ASTM C 1018 in the investigation (Graybeal, 2005). Also stated that the first-crack strength is a useful indicator of the tensile strength of UHPC. However it can overestimate the tensile strength when small scale prisms are utilized. The research stated that flexural toughness is an indication of the energy absorption capabilities and can be calculated as the area under the load deflection curve.

In a study conducted by Cheyrezy et al. (1995) showed that UHPC was capable of reaching a flexural strength as high as 48MPa and had a toughness of 250 times that of normal strength concrete. Perry and Zakariasen, (2004) confirmed Cheyrezy's findings by showed that UHPC had flexural strengths ranging from 34.5-48.3 Mpa. Dugat et al., (1996) reported average modulus of rupture values of 22.0 MPa and an ultimate flexural strength of 31.7 MPa attributed the increase in the flexural behavior of UHPC to the particle packing and the addition of fibers which hold the cement matrix together after cracking has occurred. UHPC exhibits ductility because as the specimen begins to

microcrack the small scale fibers reinforce the matrix causing smaller, less damaging cracks to form.

2.11.4 Ultrasonic Pulse Velocity

The ultrasonic pulse velocity is defined as the traversed distance of the pulse or sonic wave per unit transit time. This is obtained from the path length (length of the interposed concrete specimen) and transit time. The ultrasonic pulse velocity of concrete is mainly influenced by the mixture composition of concrete, moisture and maturity of concrete, curing conditions, and temperature. Generally, a high ultrasonic pulse velocity through concrete indicates that the concrete is of good quality. An ultrasonic pulse velocity above 4575 m/sec states the 'excellent' quality of concrete whereas an ultrasonic pulse velocity below 2135 m/sec reveals the 'very poor' condition of concrete (Safiuddin, 2008).

Ultrasonic pulse velocity can be used to evaluate the physical quality of UHPC. It is also useful to detect the cracks and flaws, and to study the freeze-thaw durability of UHPC. The ultrasonic pulse velocity of UHPC is expected to be much higher than that of ordinary concrete. This is due to the refined pore structure and dense microstructure of UHPC. However, no considerable studies have been conducted on the non-destructive evaluation of UHPC using ultrasonic pulse velocity method.

2.11.5 Absorption

Absorption is a process by which a liquid gets into and tends to fill the open pores in a porous solid body such as a component of concrete (ASTM C 128-93, 2004). The absorption is generally more significant in surface layer than the core of concrete due to strong capillary action. The rate at which a dry concrete surface absorbs a liquid can be

taken as a predictor of the durability of concrete. Water is the most common liquid with which the concrete comes in contact. Hence, water absorption is widely used to indicate the absorptivity of concrete. It can be determined based on the increase in mass of a concrete specimen due to the penetration of water into its open pores.

Water absorption is directly related to concrete's resistance to water penetration, which plays an important role in various deterioration mechanisms and carries many deleterious agents from the surroundings. Like other engineering properties, the water absorption of concrete is directly influenced by the porosity (Dugat et al., 1996). The porosity controls the microstructure and thus the absorption of concrete, depending on the relative quantities of the pores of various types and sizes (Graybeal & Hartmann, 2003). When the porosity decreases, the water absorption is also reduced.

2.11.6 Permeability

Permeability of concrete is defined as the movement of liquid and or gas through a mass of concrete under a constant pressure gradient (Neville, 1995). It is an intrinsic property of concrete that chiefly depends upon the geometric arrangement and characteristics of the constituent materials. The permeability of concrete is mainly controlled by the compactness and porosity of the hydrated paste present in bulk paste matrix and interfacial transition zone.

In the hydrated paste, the capillary and gel pores can be distinguished. The gel pores are very small. Although they constitute a network of open pores, the permeability of this network is very low. Conversely, the capillary pores are relatively large spaces existing between the cement grains. It is the capillary porosity that greatly affects the permeability of concrete (Safiuddin, 2008). The permeability of UHPC is typically

lower than that of ordinary concrete. This is mostly attributed to the superior flow properties, dense microstructure and refined pore structure that develop in the presence of silica fume and superplasticizer at low W/B ratio. Good flow properties result in excellent packing condition due to improved consolidation, and thus contribute to the reduction of the permeability of concrete.

2.12 Thermal Treatment

Owing to the very low water-to-cementitious material ratio in UHPC, the full hydration potentials of the cement and silica fume are never reached (Cheyrezy et al., 1995). However, improved performance has been observed after thermally treating UHPC using combinations of heat, steam, and pressure treatments (Richard & Cheyrezy 1995, Yazici 2007, Habel & Gauvreau, 2008). The thermal treatment appears to allow continued hydration of the portland cement and pozzolanic reaction of the silica fume (Richard & Cheyrezy, 1995). Yazici (2007) noted that after treating UHPC in 90°C water, up to 65% of the cement is hydrated (compared to 48% before treatment). In addition to improving mechanical properties, thermal treatment or elevated curing also improved durability characteristics including increased resistance to chloride penetration and abrasion as has been observed by (Graybeal, 2007). These findings signify that the full assurance of UHPC's benefits are not only realized because of particle packing, but also due to the method of curing.

2.13 Durability Improvements

Concrete durability has become an ever more important aspect in the design of structural concrete. While compressive strength has long been the standard method for determining the quality of a concrete, more and more research is focused on investigating the durability aspects of concretes. Aitcin (1998) defines durability of

concrete as “the resistance of concrete to the attack of physical or chemical aggressive agents”. The American Concrete Institute, or ACI, further details the durability of concrete as that which is able to resist weathering, chemical attack, abrasion, or other processes of deterioration (ACI 201.2R-01, 2004). In general, the durability of a concrete can be summarized as the capability of a concrete to continue performing its designed functions while maintaining its dimensional stability in a given environment.

Concrete can experience deterioration from either physical attacks (abrasion, freezing and thawing, fire, or salt crystallization) or chemical agents (alkali-silica reaction, chloride ingress and corrosion of embedded steel, sulfate attack, or delayed ettringite formation). All of these issues can lead to additional durability problems or adding upon already existing problems. Generally, other than poor material selection leading to internal attack (high chloride content in cement paste or alkali aggregate reaction) or poor construction practices, the main cause of durability failures is high permeability in concrete (Mehta and Monteiro, 1993). On the other hand, UHPC has an extremely low water/cement ratio and a densely packed matrix that may contribute to a very low permeability.

CHAPTER 3

MATERIAL CHARACTERISTICS AND EXPERIMENTAL PROCEDURES

3.1 General

The research program was comprised of experimental investigation. The aim of the experimental investigation was to examine the suitability of component materials in producing 120MPa UHPC at 28 days and to observe the performance of concrete in fresh and hardened states. This chapter discusses the research procedure and provides a flowchart for the overall research program.

3.1.1 Experimental Investigation

The overall experimental investigation is shown in the flowchart given in Figure 3.1. The following procedures were followed to carry out the research on UHPCs containing silica fume:

- Step 1: The constituent materials for UHPCs were selected, collected, and tested for its properties.
- Step 2: The mixture proportions of UHPCs were determined based on the results obtained from the testing of materials, and by fixing the water-binder ratio and estimating the mixing water requirement of concrete.
- Step 3: The preliminary mixture proportions of UHPCs were batched based on the results obtained from the testing of materials and by fixing the water-binder ratio and estimating the mixing water requirement of concrete as well as water correction to the mixtures.
- Step 4: The primary mixtures of UHPCs were batched based on the optimum results obtained from the primary works. The selected mixtures were prepared, batched and cured in different types of curing.

- Step 5: The laboratory tests were carried out to determine the hardened properties of UHPCs on compressive strength, flexural strength, splitting tensile strength, modulus of elasticity, ultrasonic pulse velocity, surface hardness, and initial surface absorption.

3.2 Materials Used

3.2.1 Cement

The type of cement used in the study was Type I ordinary Portland cement (OPC) conforms to the ASTM C150 (2004). The cement was supplied by YTL Cement Sdn Bhd with the branding named 'Orang Kuat'. The cement was kept in airtight steel drum to protect it from moisture. Table 2.3 shows typical composition of OPC. From table, it can been seen that four compounds are regarded as major constituents of cement are Tricalcium Silicate (C_3S), Dicalcium Silicate (C_2S), Tricalcium Aluminate (C_3A) and Tetracalcium Aluminoferrite (C_4AF).

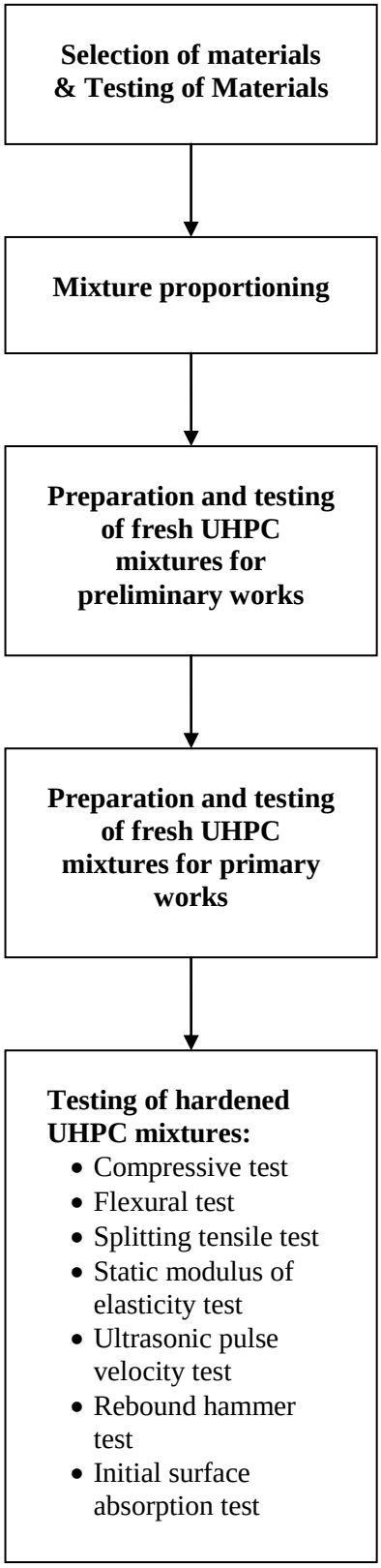


Figure 3.1: Overall research program

3.2.2 Silica Fume

Silica fume is a by-product in the production of elemental silicon or alloys containing silicon and also known as condensed silica fume or microsilica (ACI 116R-00 (2004), Cement and Concrete Terminology). This pozzolanic material was used in this investigation as an additive or partial replacement of OPC in concrete. Table 3.1 shows the typical chemical and physical data of silica fume as compared to OPC. Silica fume contains higher silicon dioxide (SiO_2) than OPC and other cementitious pozzolanic materials, whereby SiO_2 will react with calcium hydroxide to produce more aggregate binding CSH. Throughout the investigations, it was supplied by Scancem Material Sdn Bhd and comes in dark grey colour powdered form. The material was kept in an airtight steel drum to prevent from moisture.

Table 3.1: Comparison of Chemical and Physical Composition for OPC and Silica Fume
(Scancem Materials, 2009)

Oxide	Unit	OPC	Silica Fume
Silicon dioxide (SiO_2)	%	17-25	90 - 98
Aluminum trioxide (Al_2O_3)	%	2-8	0.4 – 0.9
Ferric oxide (Fe_2O_3)	%	0-6	1 - 2
Calcium oxide (CaO)	%	60-67	0.2 – 0.7
Other/s	%	1-8	2 - 3
Specific Gravity	Kg/m^3	3150	2200
Bulk Density	Kg/m^3	1400	900 - 1000
Surface Area	m^2 /kg	200-500	20,000

3.2.3 Aggregate

The properties and performance of concrete depend to a large extent on the characteristics and properties of aggregate used. Aggregate with good gradation is an important factor in producing workable concrete. The sieve test was conducted according to BS 812: Section 103.1 (1991) to determine the particle size distribution in a sample of aggregate to be used in the study. The type of selected aggregate used was silica sand, supplied in 50 kg bag by L & T Mineral Sdn. Bhd. Table 3.2 shows the Sieve test results of used aggregates. The maximum size was 2mm and the Fineness

Modulus obtained was 3.20. This type of aggregates used falls in Zone III category, as shown in Figure 3.2 the gradation chart for fine aggregate (IS 383, 1970).

Table 3.2: Sieve analysis for fine aggregate (BS 812:Section 103.1, 1991)

Sieve Analysis (fine aggregate)							
Sieve size		**Weight of sieve**	**Weight of sieve + aggregate retained**	**Weight of aggregate retained**	**Percentage retained**	**Cumulative Percentage retained**	**Cumulative percentage passing**
Inch/No.	**mm**	**(g)**	**(g)**	**(g)**	**(%)**	**(%)**	**(%)**
	9.5	467.00	467.00	0.00	0.00	0.00	100
3/16”	4.75	408.00	408.00	0.00	0.00	0.00	100.00
7	2.36	375.50	375.50	0.00	0.00	0.00	100.00
14	1.18	343.00	442.00	99.00	19.80	19.80	80.20
25	0.60	316.50	366.50	50.00	10.00	29.80	70.20
52	0.30	289.00	501.60	212.60	42.52	72.32	27.68
No.100	0.15	274.50	405.70	131.20	26.24	98.56	1.44
No. 200	0.075	275.00	281.50	6.50	1.30	99.86	0.14
Pan		240.50	241.20	0.70	0.14	100.00	0.00
Total			3022.00	500.00	100.00		
fineness modulus of fine aggregate							
Fineness modulus (FM)							3.20

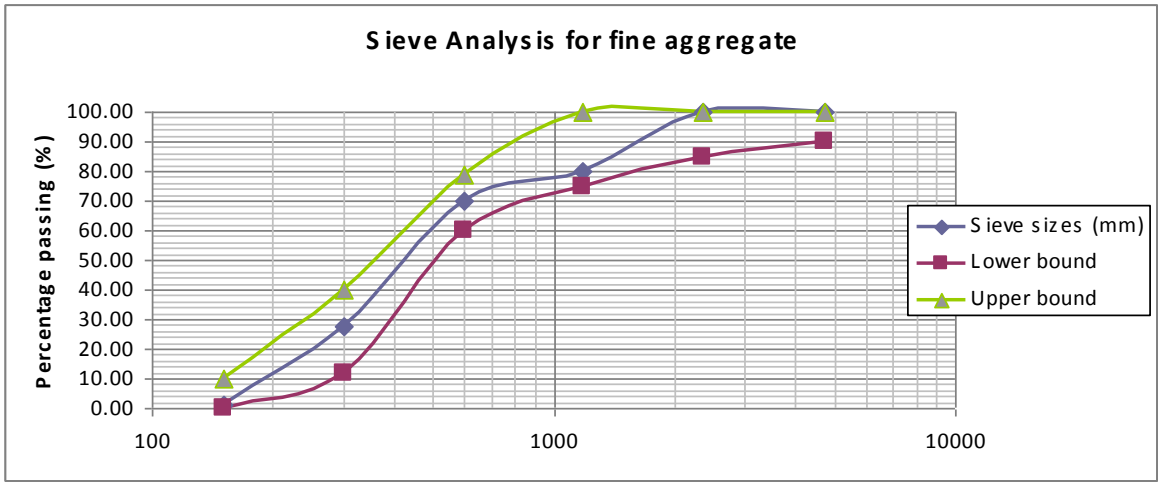


Figure 3.2 Gradation chart for fine aggregate

3.2.4 Superplasticizer

The type of superplasticizer used in this research was Sika Viscocrete-2044 supplied by Sika Kimia Sdn Bhd. It is a third generation superplasticizer with aqueous solution of modified polycarboxylates based. According to ASTM C494 (2005), this type of superplasticizer is categorized as Types F admixtures and chloride free conforms to the

EN 934-2 requirements (Sika Kimia, 2009). The recommended dosage by manufacturer is between 1.0-2.0 % by weight of cement or binder. The superplasticizer has a specific gravity of 1.06 (at 20ºC) and 30 ± 1 % solids content.

3.2.5 Water

Tap water with temperature approximately 27°C ± 1°C was used for mixing and curing procedures. It was visually checked for any dirt and impurities that may be presented. For the curing process, the water was changed once every two months to ensure it is clean from excessive dirt. The water/binder ratio used is fixed at 0.22 %.

3.2.6 Steel Fiber

The purpose of adding steel fibers in this research was to improve the ductility of the concrete produced. The type of steel fibers used in this research was straight and brass coated. The properties of steel fiber used are shown in Table 3.3. This fiber has aspect ratio of 30, with 6mm length and 0.2 mm diameter, as shown in Figure 3.3. Its tensile strength is 2880 MPa. The fiber was imported from China and supplied by Arancia Sdn Bhd.

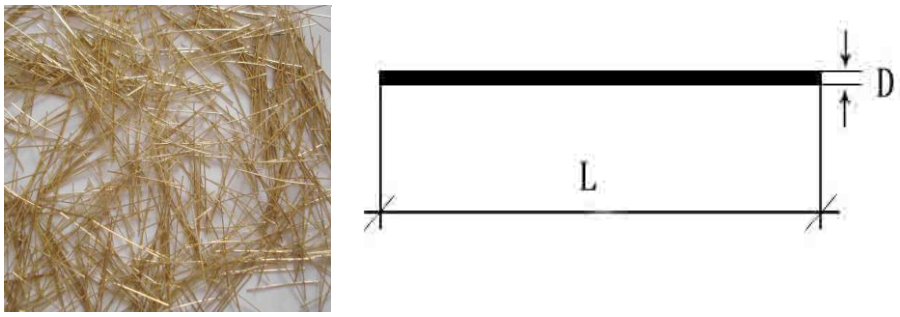


Figure 3.3: Steel fiber diagram and L/d ratio

Table 3.3: Properties of steel fiber used (given by the manufacturer)

Properties	
Diameter	0.2 ± 0.02 mm
Length	6.0 ± 1.0 mm
Aspect ratio (l/d)	30
Tensile strength	2850 MPa

3.3 Testing of Material Used

3.3.1 Specific Gravity Test for Cement and Silica Fume

The specific gravity of cement and silica fume was determined by using the Small Pyknometer Method according to BS 1377: Part 2 (1990). The value of specific gravity was determined using the Equation 3.1.

$$\text{Specific gravity } (G) = \frac{\rho_L (m_2 - m_1)}{(m_4 - m_1) - (m_3 - m_2)} \qquad (3.1)$$

Where

G = Specific gravity of cement or pozzolanic material

m_1 = mass of density bottle, g

m_2 = mass of bottle and cement or pozzolanic material (dry), g

m_3 = mass of bottle, cement or pozzolanic material and kerosene, g

m_4 = mass of bottle when full of kerosene only, g

ρ_L = density of kerosene, Mg/m^3

Since the sieve test gives no information on the size of grains smaller than 45μm sieve, therefore, a test of fineness by determination of the specific surface area expressed as the total surface area in square metres per gram (m^2/g) was conducted. In the determination of the specific surface area, the nitrogen absorption method test (BET) was applied. Other tests were also conducted to determine the properties of OPC and silica fume, namely; particle size distribution, X-ray diffraction (XRD) and X-ray fluorescence (XRF) analysis tests, these tests were carried out at the Centre for Research in Nanotechnology and Catalysis (NANOCEN), UM. XRF was conducted to determine the oxide and element contents of OPC and silica fume particles. XRD was done to determine the state of the used materials, either crystalline or amorphous.

3.3.2 Specific Gravity Test for Fine Aggregates

A reference to BS 812-103.1 (1991) was made in determining the particle size distribution of fine aggregates. The mass of the material retained on the test sieves are taken and recorded. The mass retained on each sieve was calculated as a percentage retained and plotted on the grading curve.

The fineness modulus is computed from the analysis data by adding the cumulative percentage of aggregate retained on each of a specified series of sieves and dividing the sum by 100. The fineness modulus is used as an index of the fineness of an aggregates; the higher the fineness modulus, the coarser the aggregate. In determining the specific gravity and water absorption of the fine aggregates, reference to ASTM C 128-93 (2004) were made. Equations 3.2 and 3.3 were used for specific gravity and water absorption respectively.

$$\text{Bulk specific gravity (saturated-surface dry)} = \frac{A}{[A-(B-C)]} \qquad (3.2)$$

$$\text{Water absorption (\%)} = [(A-D)/D] \text{ x } 100\ \% \qquad (3.3)$$

Where A = Weight of saturated-surface dry test sample in air, g

B = Weight of pycnometer containing sample and water, g

C = Weight of pycnometer with water only, g

D = Weight of oven dried (110 $\pm$ 5ºC) test sample in air, g.

3.4 Optimization of Concrete Mixes

3.4.1 Preliminary Work

This preliminary work is under Phase 2 of the scope of work. The work involved in this phase is described in Table 1.1. The purpose of the trial mixes in the preliminary work

was to determine the optimum mix of concrete containing replacement or additional of silica fume that are able to achieve the target strength of 120 N/mm^2.

Mixture proportioning for all the mixes was based on Sherbrooke Mix Design method (Aïtcin, 1997). Using this method, two series of mixture; 875 kg/m^3 and 900 kg/m^3 of cement were designed with a water binder ratio (w/b) of 0.22. Superplasticizer was added to achieve the workability of fresh concrete of 150-300 mm slump. Although the superplasticizer content was conventionally adjusted to achieve the same workability across all mixtures, it was decided at the designing stage that the superplasticizer content for each mixtures to be fixed at 1% and added up to 2% during the mixing processes to achieve the targeted slump. The effect of partial 'addition' and 'replacement' of cement with SF at 10%, 20% and 30% were then investigated.

The series involved in the preliminary work are described in Table 3.4. The performance of concrete in terms of its compressive strength with partial replacement of silica fume in different percentages by weight of cement was carried out. The optimum mix was chosen based on achieving the targeted compressive strength of 120 N/mm^2.

Table 3.4: The series of mixture cast for the preliminary work

Batch	Mixes		Testing age (days)
		Denoted as:	
1st Series (875kg/m^3 cement content)	100% OPC	CONTROL1	1,3,7,28
	OPC + 10% SF	SF10A	1,3,7,28
	OPC + 20% SF	SF20A	1,3,7,28
	OPC + 30% SF	SF30A	1,3,7,28
	OPC - 10% SF	SF10R	1,3,7,28
	OPC - 20% SF	SF20R	1,3,7,28
	OPC - 30% SF	SF30R	1,3,7,28
2nd Series (900kg/m^3 cement content)	100% OPC	CONTROL2	1,3,7,28
	OPC + 10% SF	SF10A	1,3,7,28
	OPC + 20% SF	SF20A	1,3,7,28
	OPC + 30% SF	SF30A	1,3,7,28
	OPC - 10% SF	SF10R	1,3,7,28
	OPC - 20% SF	SF20R	1,3,7,28
	OPC - 30% SF	SF30R	1,3,7,28

**Note: A and R denote 'addition' and 'replacement' mixes respectively*

3.4.2 Properties of Optimum Mixes

The optimum mixes as derived from the two mix series in Phase 2 were subjected to the mechanical, time dependent and durability tests. The mechanical and time dependent tests are classified as work carried out in Phase 3, while durability tests are classified as work involved in Phase 4. The specimens for the mechanical test were subjected to air drying and water curing for the duration of 56 days, while for time dependent properties, the specimens were either subjected to air drying or water curing condition for 7 days after demoulding at 1 day prior to storing in a room at temperature of about 29 ± 1ºC with relative humidity (RH) of 77 ± 2%.

The time-dependent properties were measured in terms of their dimension and weight change due to air drying or water immersion. For the durability performance, the duration in which the specimens were subjected to air drying and water curing depend on the type of tests. All the test procedures involved in Phase 3 and Phase 4 will be described in the following sections.

3.4.3 Mix Design Method

Mix design to produce UHPC folllows the same approach of ACI 211-1 Standard Practice for Selecting Proportion for Normal Concrete. It is a combination of empirical results and mathematical calculations based on the absolute volume method. All the calculations needed to find the mix proportions are presented in a single sheet. Appendix A and B give the design sheet for selected mixtures, i.e. Control, SF10A, SF20R, and SF30R.

The mix design sheet is divided into two parts. In the part A, the specific properties of the mix are reported. This part of the mix design sheet must be completed before any

calculations can be made. Part B of the mix design sheet is the actual design of the mixture. Detail calculations of the design procedure are also discussed later.

3.4.4 Preparation of Concrete Specimens

In this study, the batching was done by weight and all ingredients of concrete mixes were prepared according to the calculated mix design proportions. In the preliminary work, the specimens were prepared using 100mm cubic steel mould. In determining the mechanical and durability, four types of specimens were prepared using steel moulds with sizes of 100 mm cubes, 100 mm dia. x 200 mm length cylinders, 150 mm dia. x 300 mm length cylinders and 100 x 100 x 500 mm prisms (BS1881: Part 116, 117, 118 & 121, 1983).

Due to the small amount of concrete, about 0.02 m^3, mixing was carried out using a small pan mixer with a capacity of 20 kg fresh concrete. For Phase III and IV, mixing was done using a pan-type mixer with larger capacity, 120 kg of fresh concrete. The mixer was manufactured by ORU Asia-Pacific Pte. Ltd. The mixer was wetted with water before filling any materials inside to prevent the mixing water being absorbed by the side of mixer.

The sequence of mixing can be summarised as follows; fine aggregates and one-third of water were mixed for about 1 minute, followed by cement or blended cement with silica fume, and then adding the liquid superplasticizer and the remaining water. The total mixing time taken was between 30 to 45 minutes. Longer mixing time is required to get the homogenous and workable mix since the particle sizes of the constituents are very small and due to the very low w/b ratio. For mixtures with steel fibers, the fibers were added after concrete getting the homogenous mix, and while the mixing drum was

rotating, steel fibers were added bit by bit slowly to prevent it from pile up which could lead fibers to 'balling'. And mix it for at least 5 minutes. These are to make sure that the fibers were uniformly distributed in the mixtures. Mixing time and rheological properties of fresh UHPC are mainly influenced by the concrete mixer type and the environmental ambient conditions. A 120 kg ORU Asia-Pacific Pte. Ltd. mixer was used successfully to mix the UHPC. However, the inability of this mixer to impart significant energy into the mix resulted in extended mixing times. High temperature in the mix room can result in stiffer UHPC.

The fresh concrete was transported using wheelbarrows and placed into steel moulds using shovels. Prior to casting, the, surface of the moulds were cleaned and the interior faces of the moulds were applied with a thin layer of oil to facilitate the demoulding process. Fresh concrete was placed in the moulds in two layers; each layer compacted before placing the final, and each layer was placed whilst the underlying layer was still plastic or in the fresh state. The specimens were compacted using the vibrating tables. The time of vibration required for sufficient compaction without causing excessive segregation or bleeding could be adjusted using an electronic timer attached to the controller. After the final layer has been compacted, the top was levelled to provide a smooth and flat surface. The specimens were covered with wet gunnysacks to prevent moisture loss and to minimise plastic shrinkage. The specimens were demoulded after 24 hours and labelled using the permanent ink marker.

For curing process, one-third of the specimens were cured in water at 27ºC. The remaining specimens were given the heat treatment in the hot water bath under 45ºC for one hour and 90ºC for 71 hours and also air cured for comparison. Total heat treatment or elevated curing to the specimens was 72 hours or 3 days (Yazici, 2007). The

specimens, which were subjected to heat treatment, were kept in laboratory conditions for air curing until the age of testing.

3.4.5 Size and Curing of Specimens

To study the effect of curing on the compressive strength of concrete mixes, three types of curing, namely, elevated curing, water curing and air-drying were carried out. However, other mechanical properties of concrete were tested only in two types of curing i.e. water and air curing. This is due to unavoidable constraint, the size of water bath.

For elevated curing regime the specimens were given heat treatment in hot water bath under 45ºC for one hour, 90ºC for minimum 48 hours and cooling it in 45ºC in one hour. The specimens were then left to cool down naturally in the water before removing it to air curing until the testing age. For water and air curing, it was conducted in accordance to BS 1881: Part 111 (1983). For air-drying condition, the samples were left inside the laboratory after demoulding at 1 day, until age of test. Details of curing methods for different types of tests that were used in this research are presented in Table 3.5.

Table 3.5: Details of curing methods for different types of test

Phase	Type of test	Size of specimen	No of samples	Types of curing	Age of test (day)
I	Compressive strength	100 mm cube	3	Water curing/Elevated curing	1, 3, 7 and 28
II	Compressive strength	100 mm cube	3	Water curing/air-drying/Elevated curing	1,3,7, 28 and 56
	Static modulus of elasticity	150 mm dia. x 300 mm cylinder	2	Water curing/air-drying	7, 28, and 56
	Splitting tensile strength	150 mm dia. x 300 mm cylinder	3	Water curing/air-drying	7, 28, and 56
	Modulus of rupture	100 x 100 x 500 mm	3	Water curing/air-drying	7, 28, and 56
	Rebound hammer	100 mm cube	3	Water curing/air-drying	7, 28, and 56
	Ultrasonic pulse velocity	100 mm cube	3	Water curing/air-drying	7, 28, and 56
	Initial surface absorption	150 mm cube	3	Water curing/air-drying	7, 28, and 56

3.5 Testing of Concrete

3.5.1 Properties of Fresh Concrete

The objective of determining the properties of fresh concrete is to investigate the effects of silica fume on the uniformity and workability characteristics of concrete. Immediately after discharging, the slump test was conducted to measure the workability of concrete in the fresh state.

3.5.1.1 Slump Flow Test

As mentioned earlier, determination of slump flow was carried out to measure the workability of concrete in fresh state. Although this test is not a direct measurement of workability, it is used extensively in measuring consistency and detecting variations in the uniformity of a mixture. Similar in form to the slump apparatus used in ASTM C 143 (2004), the mini-slump cone has a 50-mm top diameter and a 100-mm bottom

diameter. The height of the cone is 150-mm. The apparatus includes a cone-shaped metal mould. The mould was dampened with water and placed on a flat, moist and non-absorbent rigid surface, which was then filled with two equal layers of fresh concrete. Each layer was tamped 10 times and the strokes were distributed uniformly over the cross section of each layer. When the filling was completed, the top surface was leveled. The slump was measured by taking average diameter of two values.

3.5.2 Test for Hardened Concrete

3.5.2.1 Compressive Strength of Concrete Cubes

The effect of silica fume on the physical properties of hardened concrete was investigated by conducting the compressive strength test on the specimens according to BS1881: Part 116 (1983). The compressive strength tests were conducted at the ages of 1, 7, 28, and 56 days under three different curing types, which was water or also called normal curing, elevated curing and air-drying curing regimes.

The compressive testing machine used throughout this investigation was manufactured by *Engineering Laboratory Equipment Limited (ELE)* with a maximum capacity of 2000 kN and is shown in Figure 3.4. The specimens were subjected to loading at the rate of 2.4kN/s or 0.3 N/mm^2.s. The average compressive strength of three samples was calculated. The sample was placed with the flat smooth surface of specimen in contact with the platens of the testing machine and loaded at the rate of 2.4 kN/s until failure. Figure 3.3 (a) shows the specimen being tested using the ELE Machine. The compressive strength was calculated by dividing the load at failure by surface area of sample.

3.5.2.2 Static Modulus of Elasticity

This test was conducted according to BS 1881: Part 121 (1983) on cylindrical specimens (150 mm dia. x 300 mm length) at 7, 28, and 56 days. The test specimens, with the strain measuring apparatus attached axially, was placed centrally in the ELE compression testing machine. A basic stress (σ_b) of 0.5 N/mm^2 was applied and the strain gauge reading was recorded. The stress was steadily increased at a constant rate of 0.6 N/mm^2.s^{-1} until an upper loading stress equaled to one-third of cylinder compressive strength reading (σ_a) was reached and the strain gauge reading was taken. Figures 3.4 (f) shows the specimen being tested using the ELE machine.

The static modulus of elasticity in compression E_c (N/mm^2) is calculated as follows:

$$E_c = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{\sigma_a - \sigma_b}{\varepsilon_a - \varepsilon_b} \qquad (3.4)$$

Where

σ_a = upper loading (σ_a = 0.8 f_{cu}/3) (kN/mm^2)

σ_b = basic stress (0.5 N/mm^2)

ε_a = strain under upper loading stress

ε_b = strain under basic stress

3.5.2.3 Splitting Tensile Test

The splitting tensile strength test was carried out on cylindrical specimens (150 mm dia. x 300 mm length) according to BS 1881: Part 117 (1983). The specimens were tested at 7, 28, 56 days. Figures 3.4 (d) & (e) showed the sample was prepared and being tested using the ELE machine. The specimen was positioned in the centering jig with packing strips placed along the top and bottom. Hardboard packing strips made of plywood of 15 mm width by 4 mm thick were used to prevent local failure. Load was applied and increased continuously at a rate of 1.767 kN/s or 0.025 N/ (mm^2.s^{-1}) until failure.

The splitting tensile strength f_{sp} (N/mm^2) is calculated as follows:

$$f_{sp} = \frac{2F}{\pi \times L \times d} \tag{3.5}$$

Where

F = maximum load (N)

L = length of specimen (mm)

d = diameter of specimen (mm)

3.5.2.4 Flexural Tensile Strength Test / Modulus of Rupture Test

The flexural tensile strength test was carried out on 100 x 100 x 500 mm prism specimens according to BS 1881: Part 118 (1983) at 7, 28, and 56 days. The flexural strength was determined by means of a constant moment in the central zone of the specimen using a two-point loading, using the EL 33-6090 flexural testing machine. Load was then applied steadily and continuously at a rate of 0.067 kN/s or 0.06 $\pm$ 0.04 N/(mm^2.s^{-1}) until failure. Figures 3.4 (b) & (c) show the specimen before and after tested using ELE machine. The flexural tensile strength, also known as the modulus of rupture f_r (N/mm^2) can be calculated as follows:

$$f_r = \frac{F \times L}{b \times d^2} \tag{3.6}$$

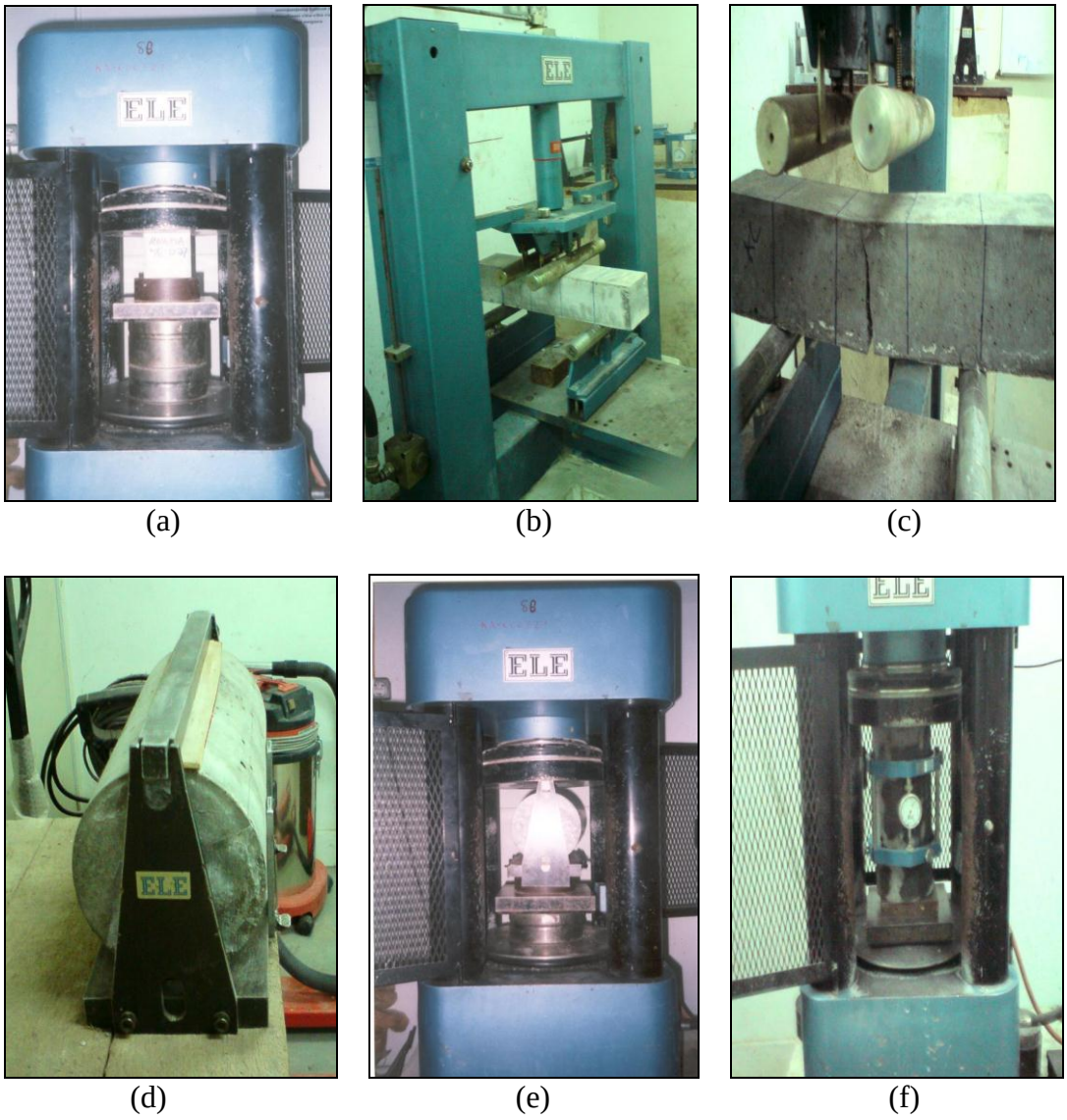
Where

F = breaking load (N)

L = distance between the supporting rollers (mm)

b = width of cross section (mm)

d = depth of cross section (mm)



(a) (b) (c)

(d) (e) (f)

Figure 3.4: Equipments for testing hardened properties of UHPC (a) Compression strength test, (b) & (c) Before and after failure of Modulus of rupture test, (d) & (e) Tensile splitting strength test, (f) Static modulus of elasticity test

3.5.3 Non-destructive Tests (NDT)

Non-destructive test (NDT) is an experimental technique used in science and industry to evaluate the properties of a material, component or system without causing damage. In this research work, the following tests have been chosen i.e. rebound hammer and ultrasonic pulse velocity (UPV). These tests were conducted to measure the surface hardness and elastic modulus of the specimens.

3.5.3.1 Rebound Hammer Test

The rebound hammer test was conducted in accordance to BS 1881: Part 202 (1986) on 100 mm cubes specimen at 7, 28, 56 days using a standard rebound hammer, before carrying out compression test on the specimen . Figure 3.5 shows how the rebound hammer test was carried out. The specimen was placed in the same machine as used in compression test and a constant compressive load was applied to the specimen to prevent any lateral and vertical movement. The rebound hammer was pressed horizontally against the surface and a rider along a graduated scale on the rebound hammer indicates the rebound number. By referring to the manufacture's calibrated chart, the estimated surface strength could be obtained from the observed rebound number.

Figure 3.5: Rebound hammer test

3.5.3.2 Ultrasonic Pulse Velocity Test (UPV)

This test was conducted in accordance to BS 1881: Part 203 (1986). The UPV test was conducted on 100 mm cube specimens (Figure 3.6) at 7, 28 and 56 days. The objective of this test is to determine the velocity of longitudinal waves through the specimen, determined by time taken by a pulse to travel the length of specimen.

Figure 3.6: Ultrasonic pulse velocity (UPV) test

A pulse of longitudinal vibrations was produced by an electro-acoustical transducer, held in contact with the surface of the specimen. After traversing a known path length of the specimen (i.e. 100 mm), the pulse was converted into an electrical signal by a second transducer. The time interval for the pulse to travel between the two transducers was measured by the time of the digital indicating device. To ensure that the vibration of the transducer was transmitted to the concrete by close contact, grease was applied on the faces of the concrete and the transducers were pressed hard against the surface. The equipment was calibrated before usage using the calibration cylinder and time interval for the pulse to travel is approximately 26 μs.

The pulse velocity V (km/s or m/s) is given by

$$V = \frac{L}{T} \tag{3.7}$$

Where

L = path length 100 mm

T = time taken by the pulse to traverse that length (ms)

3.5.4 Durability Test

3.5.4.1 Initial Surface Absorption Test (ISAT)

The ISAT was conducted according to BS 1881: Part 5 (1970). The test is time dependent and comparative, indicating the ability of concrete to resist absorption of water. The principle of this test is to determine the time taken for a quantity of water to flow through a calibrated glass tube onto a fixed area of the concrete surface. The limitation of the test is the viscosity of water that may affect the rate of flow through the tube when considering very porous concrete, resulting in high flow rates. The apparatus consist of a capillary tube diameter with a bore of 1.9 mm and length of 240 mm, test caps with minimum area of 5000 mm^2, rubber seal and support board.

The set-up for the ISAT apparatus is shown in Figures 3.7 (a) & (b). Prior to testing, specimens were oven dried at 105 ± 5°C for 72 hours and allowed to cool in desiccators for 1 day. The valve connected to the test cap was opened and filled up with distilled or de-ionized water. It is essential that the water level in the reservoir was maintained at 200mm from the top surface of the concrete. The measurement was recorded at intervals of 10 minutes, 30 minutes, 1 hour and 2 hours after the beginning of the test. At each interval, the reservoir valve was shut and the water flowed through the capillary. The time in units of seconds for the meniscus to travel 86 divisions was recorded. After each interval, the reservoir valve was opened and the water level was maintained at 200 mm above the concrete.

The divisions on the scale are marked to indicate the rate of flow of water into the concrete at the rate of $ml/m^2.s$ based on test duration of 1 minute. Therefore, the data

obtained for each interval namely, 10 minutes, 30 minutes, 60 minutes and 120 minutes from the start of the experiment is calculated as equation below:

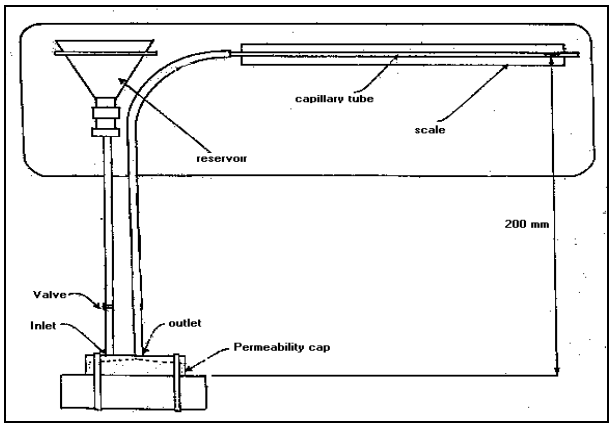
$$ISA = \frac{60}{t} \times div \times 0.01 \qquad (3.8)$$

Where,

t = time period in seconds (sec)

div = number of scale divisions during period of t

ISA = flow in millimeter/meter^2/second (ml/m^2/sec)



(a)

(b)

Figure 3.7 (a) & (b): Experimental set-up for Initial Surface Absorption Test

CHAPTER 4
RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter reports on the properties of materials used in this study, i.e. cement, silica fume, fine aggregate, superplasticizer, and steel fiber. This chapter also reports on the results obtained from the preliminary work as well as the fresh and mechanical properties of hardened concrete of selected mixes. Four selected mixes were determined from the preliminary work. Based on achieving the targeted strength of 120 N/mm^2 from the trial mixes, silica fume content were chosen at 10% additional, 20% and 30% replacement of cement content.

Four mixes of concrete were involved; denoted as Control for the reference mix, 10% OPC additional denoted as SF10A, and 20% and 30% replacement of OPC are SF20R and SF30R respectively. The tests conducted on the workability for fresh concrete was the slump flow test. For hardened concrete test, tests involved were the destructive mechanical and non-destructive tests. The destructive mechanical tests conducted comprise of the compression, modulus of rupture, tensile splitting, and static modulus of elasticity, whilst the non-destructive mechanical tests were ultrasonic pulse velocity (UPV), and rebound hammer. For the durability of concrete, test involved was initial surface absorption test (ISAT).

4.2 Properties of Material

4.2.1 Cement

The specific gravity of ordinary Portland cement (OPC) was 3.14. It was determined using Equation 3.1. The specific surface of used cement was 336 m^2/kg. The chemical analysis of cement was conducted using X-ray fluorescence (XRF), the results is

presented in Table 4.1. It shows that the cement consists of calcium oxide (69.43%), silicon dioxide (16.50%), aluminium trioxide (3.65%) and ferric oxide (3.63%). The loss on ignition (LOI) and other oxide contents are about 1.53% and 6.79% respectively.

Table 4.1: Chemical composition of OPC and SF

Oxide (%)	OPC*	SF*
Silicon dioxide (SiO_2)	16.5	90.63
Aluminum trioxide (Al_2O_3)	3.65	0.55
Ferric oxide (Fe_2O_3)	3.63	0.46
Calcium oxide (CaO)	69.43	0.83
Magnesium oxide (MgO)	1.29	0.92
Potassium oxide (K_2O)	0.49	3.17
Phosphorus oxide (P_2O_5)	0.42	0.80
Sulfur trioxide (SO_3)	4.23	1.07
Sodium oxide (Na_2O)	0.17	0.27
Titanium oxide (TiO_2)	0.20	0.01
Manganese oxide (MnO)	0.04	0.09
Loss on ignition (L.O.I)	1.53	4.81

** Tested at Nanocen, UM*

4.2.2 Silica Fume

The specific gravity of silica fume (SF) was 2.25. It was determined using Equation 3.1. By using nitrogen absorption method test (BET), the specific surface of silica fume was determined as 17280 m^2/kg. Table 4.1 also shows the results of chemical analysis of silica fume that was conducted using X-ray fluorescence (XRF). It shows that SF consists of very high amount of silicon dioxide, more than the OPC, 90.63%.

4.2.3 Fine Aggregate

The used fine aggregate was mining sand. Sieve analysis test was conducted in accordance to BS 812-103.1(1991). The result obtained conforms to Zone III (IS 383, (1970)) with fineness modulus of 3.20. The specific gravity and water absorption were determined using Equation 3.2 and 3.3, with reference to ASTM C 128-93 (2004). The results were 2.65 and 0.59% respectively.

4.2.4 Superplasticizer

In this study, third generation superplasticizer, Sika Viscocrete-2044 was used, with specific gravity of 1.06 (at 20ºC) and 30 ± 1 % solids content. This type of superplasticizer is suitable for the production of concrete mixes with very high water reduction. This type of superplasticizer is chosen for the concretes require excellent flow ability and high early strength development.

4.2.5 Steel Fiber

There are various types of sizes and shapes of fibers that are available for production of concretes. However for the purpose of the present study, the only type of steel fiber used was; straight and brass coated steel fiber. The size of this micro steel fiber was 6 ±1 mm lengths with 0.2 ± 0.02 mm diameter. Its tensile strength and aspect ratio were 2880 MPa and 30 respectively.

4.3 Preliminary Results

This section reports on the results obtained from the preliminary work to develop UHPC with compressive strength of 120 N/mm^2 at 28 day. The design mix proportions of the concrete specimen were based on absolute volumetric method. The mixes were designed with water-to-binder ratio of 0.22. The slump flows were between 150 mm to 250 mm and cement content of 875 kg/m^3 and 900 kg/m^3. All mixes were added with a minimum of 1% polycarboxylate ether based superplasticiser. In this phase of work, all specimens were subjected to elevated curing in order to accelerate the hydration process and to obtain the optimum results for the early strength of concrete.

4.3.1 Compressive Strength

The objective of this test is to obtain appropriate mixes to achieve the targeted strength. The results are tabulated in Table 4.2 and illustrated in Figures 4.1 and 4.2. Table 4.2 shows that the highest results were obtained from mixtures with 900kg/m^3 of cement content. It also shows that SF10A with 900 kg/m^3 cement content can achieve the targeted strength of 120 N/mm^2 at 28 days. However, in the graph it can be seen that reduction of strength at 7 days has occurred. This is due to higher temperature during placing and setting (Neville, 1997). Also stated by Neville (1997), the explanation is that a rapid initial hydration appears to form products of a poorer physical structure, more porous, and the proportion of the pores will always remain unfilled which will lead to a lower strength compared with a less porous, slowly hydrating cement paste in which a high gel/space ratio will eventually be reached.

From the graphs, it can be concluded that UHPC can be used in the precast concrete industry as the minimum 12 hours strength for every mix was more than 15 MPa which make it possible to demould in less than 24 hours, thus reducing the production cost and duration. With these findings, four optimum mixes from 900 kg/m^3 of cement content has been selected for further investigations. The mixtures are SF10A, SF20R, SF30R and Control_2 for comparison.

Table 4.2: Compressive Strength of Concrete Mixes for Preliminary Works

Mixture	w/b	Total Binder (kg/m^2)	Cement (kg/m^2)	CSF (kg/m^2)	Fine Aggregate (kg/m^2)	Sp (%)	Compressive Strength (N/mm^2)			
							1d	3d	7d	28d
Series_1: OPC 875 kg/m^3										
Control_1	0.22	875.0	875.0	-	1356.0	1.0	37.6	87.8	86.6	63.1
SF10R	0.22	875.0	787.5	87.5	1327.0	1.0	46.2	104.5	95.0	91.3
SF20R	0.22	875.0	700.0	175.0	1298.0	1.0	43.7	109.8	102.6	103.3
SF30R	0.22	875.0	612.5	262.5	1269.0	1.0	47.2	122.7	121.6	120.6
SF10A	0.22	962.5	875.0	87.5	1200.0	1.0	29.6	109.8	95.0	102.6
SF20A	0.22	1050.0	875.0	175.0	1044.0	1.0	46.2	95.0	76.3	103.8
SF30A	0.22	1137.5	875.0	262.5	889.0	1.0	45.9	122.9	120.9	115.3
Series_2: OPC 900 kg/m^3										
Control_2	0.22	900.0	900.0	-	1320.0	1.0	38.4	96.8	96.6	94.3
SF10R	0.22	900.0	810.0	90.0	1290.0	1.0	44.5	112.5	110.4	110.2
SF20R	0.22	900.0	720.0	180.0	1260.0	1.0	51.0	109.5	109.3	108.9
SF30R	0.22	900.0	630.0	270.0	1320.0	1.0	53.1	115.2	114.0	113.4
SF10A	0.22	990.0	900.0	90.0	1160.0	1.0	47.4	118.1	118.6	117.4
SF20A	0.22	1080.0	900.0	180.0	1000.0	1.0	44.7	108.3	107.8	107.0
SF30A	0.22	1170.0	900.0	270.0	840.0	1.0	46.8	105.0	104.2	105.7

Note:
- A and R denote 'addition' and 'replacement' mixes respectively
- Percentage of sp was calculated from the total binder content
-All specimens were cured in elevated curing process

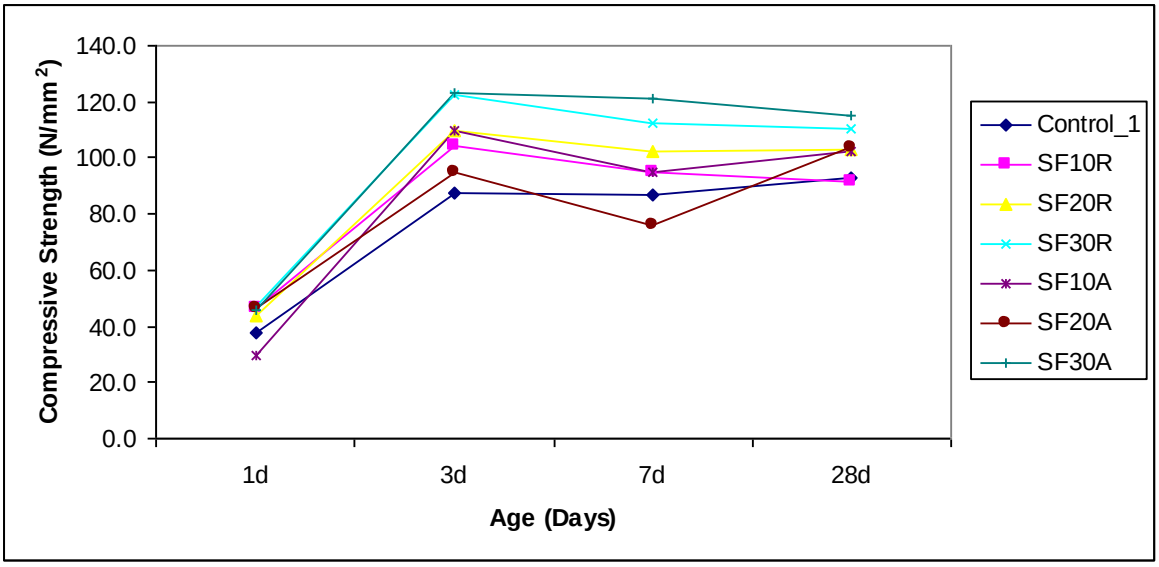


Figure 4.1: Compressive strength development of Series_1 concretes: OPC 875 kg/m^3

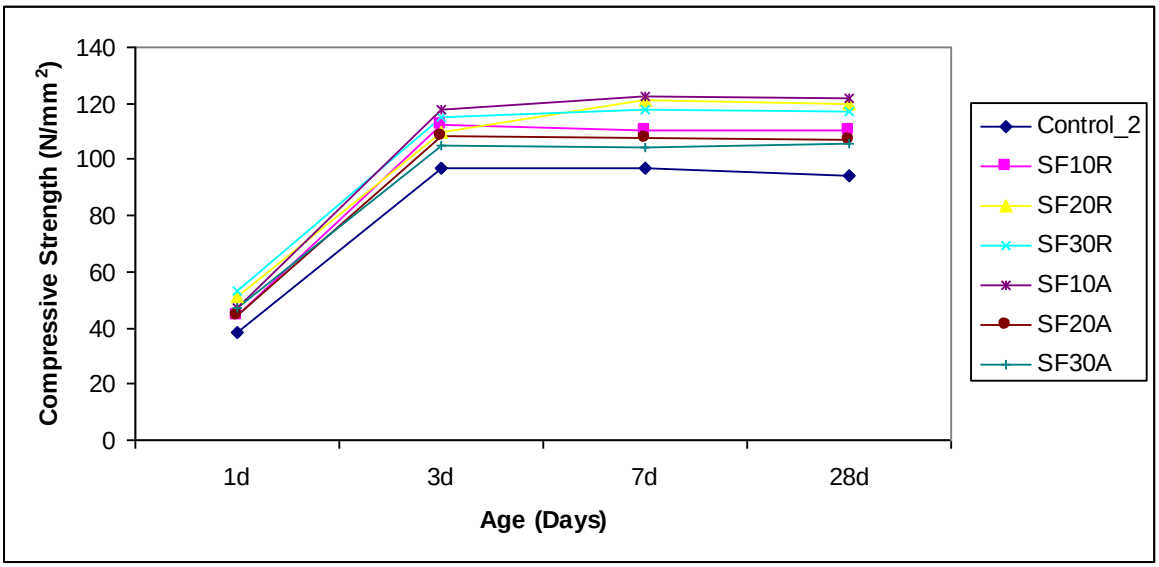


Figure 4.2: Compressive strength development of Series_1 concretes: OPC 900 kg/m^3

4.4 Workability of Fresh Concrete

Workability is the ability to be transported and placed easily, and consolidated without excessive bleeding or segregation. The most popular test that used to control concrete workability is the slump test. The main purpose of this test is to ensure that the designated mixes were able to provide slump flow of 150-250 mm diameter. The measured slump values of all the mixes are shown in Table 4.3.

Table 4.3: Mix proportion and workability of selected mixes

Mixture Designation	w/b	Steel fiber (%)	Sp (%)	Mass per Unit Volume of Materials (kg/m^3)				Slump flow Average Diameter.(mm)	
				Cement	Silica fume	Water	Fine aggregate	Concrete without fiber	Concrete with fiber
Control	0.22	0, 1	1.0	900	-	198	1320	225	210
SF10A	0.22	0, 1	1.0	900	90	218	1160	250	230
SF20R	0.22	0, 1	1.5	720	180	198	1260	200	180
SF30R	0.22	0, 1	2.0	630	270	198	1220	190	150

Note: Percentage of sp was calculated from the total binder content

Table 4.3 shows that the amount of cement and superplasticizer content affected the slump flow of the mixture. In general, superplasticizer dosage for silica fume addition mix was lower than the replacement mixtures. It can be seen that the required amount of superplasticizer to obtain the targeted slump were between 1 - 2 % of the binder content.

From the table, it shows that concrete with the higher silica fume content required more superplasticizer to maintain the workability compared to control and SF10A. This is due to the higher specific surface area and the percentage amount of the silica fume in the mixtures.

In silica fume replacement mixes, the superplasticizer dosage was increased with increasing percentage of silica fume cement replacement. In order to obtain the workability in the required range of 150 – 250 mm slump flow, more superplasticizer dosage were required for SF20R and SF30R compared to Control and SF10A mixes. SF10A gives the highest value for slump test, 250 mm diameter for concrete without fiber and 230 mm diameter for concrete with fiber.

4.4.1 Comparison with Published Data

It is expected that the slump flow decrease with increasing of cement replacement. The results obtained from the present work shows that concrete containing more cement replacement require more water for a given workability. This is due to the absorptive character of silica fume particles. Table 4.4 shows the findings by other researchers such as Cwirzen et al. (2008), Long et al. (2002), and Chan & Chu (2004). From the table, it shows that concrete with the higher silica fume content and lower w/b ratio required more superplasticizer to obtain the said slump. This is due to the higher specific surface area and the percentage amount of the silica fume in the mixtures.

Table 4.4: Comparison on concrete workability with various researchers

Researchers	w/b	Cement	CSF	SP %	Slump Flow,mm
Present Study (2011)	0.22	1	0.10	1.0	230
	0.22	1	0.20	1.5	180
	0.22	1	0.30	2.0	150
Cwirzen et al. (2008)	0.180	1	0.25	5.0	215
	0.180	1	0.25	4.5	170
	0.210	1	0.25	4.0	300
Long et al. (2002)	0.180	1	0.10	2.0	190
	0.167	1	0.20	2.0	185
	0.160	1	0.25	2.0	175
	0.154	1	0.30	2.0	160
Chan and Chu (2002)	N/A	1	0.10	2.0	>300
	N/A	1	0.20	2.0	265
	N/A	1	0.25	2.0	215
	N/A	1	0.30	2.0	180

4.5 Mechanical Properties

Properties of hardened concrete can be characterized in terms of short and long term properties. Compressive strength, modulus of elasticity, tensile strength, shear strength and bond strength are the short term properties. The long term properties consist of creep, shrinkage, fatigue behaviour and durability characteristics such as porosity, permeability, freeze-thaw resistance and abrasion resistance.

Strength of concrete is considered as the most valuable property. Strength of concrete depends on several factors such as properties and proportions of the constituent materials, degree of hydration, rate of loading, method of testing and specimen geometry and size. Usually, it gives an overall picture of the quality of concrete.

4.5.1 Compressive Strength

The compressive strength results of all the specimens cured in water, elevated and air are given in Table 4.5. The temperature of water in the water tank was recorded as 27 ± 0.5ºC while the laboratory temperature was 29 ± 1ºC with 77 ± 2ºC relative humidity (RH). For elevated curing, water bath heat treatment was applied at 90 ºC for a

minimum of 48 hours and air cured until testing. Figures 4.3 and 4.4 show the schematic graphs of various mixes containing different silica fume amount with stated curing process. The figures show compressive strength for mixes without steel fibers, in the legend, w, a, and e denotes water, air and elevated curing method applied for the mixes. Reasons for reduction of strength at 7 days for elevated cured specimens have mentioned in the earlier section. It can be seen steel fiber helps in increasing the compressive strength slightly.

Table 4.5: Compressive strength of cement and silica fume concretes without and with steel fibers

Mixture	w/b	Cement (kg/m^3)	SF (kg/m^3)	Curing Type	Compressive Strength (N/mm^2)							
					concrete without fiber				concrete with fiber			
					1d	7d	28d	56d	1d	7d	28d	56d
Control	0.22	900	-	Water	30.0	93.0	97.2	99.6	39.0	104.5	115.6	117.2
				Air	30.0	80.2	92.1	99.2	39.0	100.1	114.0	116.9
				Elevated	30.0	112.2	110.0	114.0	39.0	111.3	110.0	118.4
SF10A	0.22	900	90	Water	51.0	102.0	118.0	121.9	65.0	101.8	134.3	137.3
				Air	51.0	95.0	103.7	119.8	65.0	96.2	127.0	134.7
				Elevated	51.0	127.0	121.2	128.8	65.0	133.0	131.0	131.0
SF20R	0.22	720	180	Water	50.0	101.0	114.0	106.0	53.0	102.0	114.5	114.9
				Air	50.0	85.0	92.1	99.4	53.0	89.0	103.0	107.3
				Elevated	50.0	111.0	110.3	122.4	53.0	111.0	109.8	111.2
SF30R	0.22	630	270	Water	40.0	89.0	112.0	104.3	46.0	93.5	99.0	104.3
				Air	40.0	80.0	89.0	98.7	46.0	83.3	100.8	109.1
				Elevated	40.0	113.0	111.4	119.0	46.0	108.0	107.2	107.2

Note:
- All mixtures were using 1% Sp initially and added up to 2% of the binder content to get the homogenous mix.
- Steel fibers amount used was 1% for all mixtures with fibers.

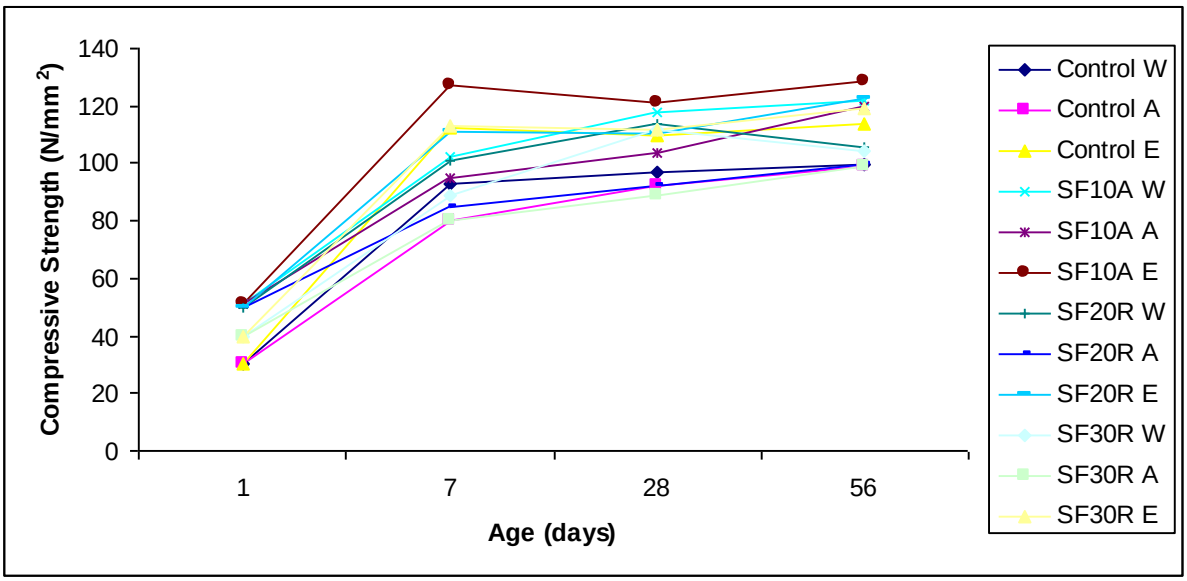


Figure 4.3: Compressive Strength Development for Various Mixes without steel fiber

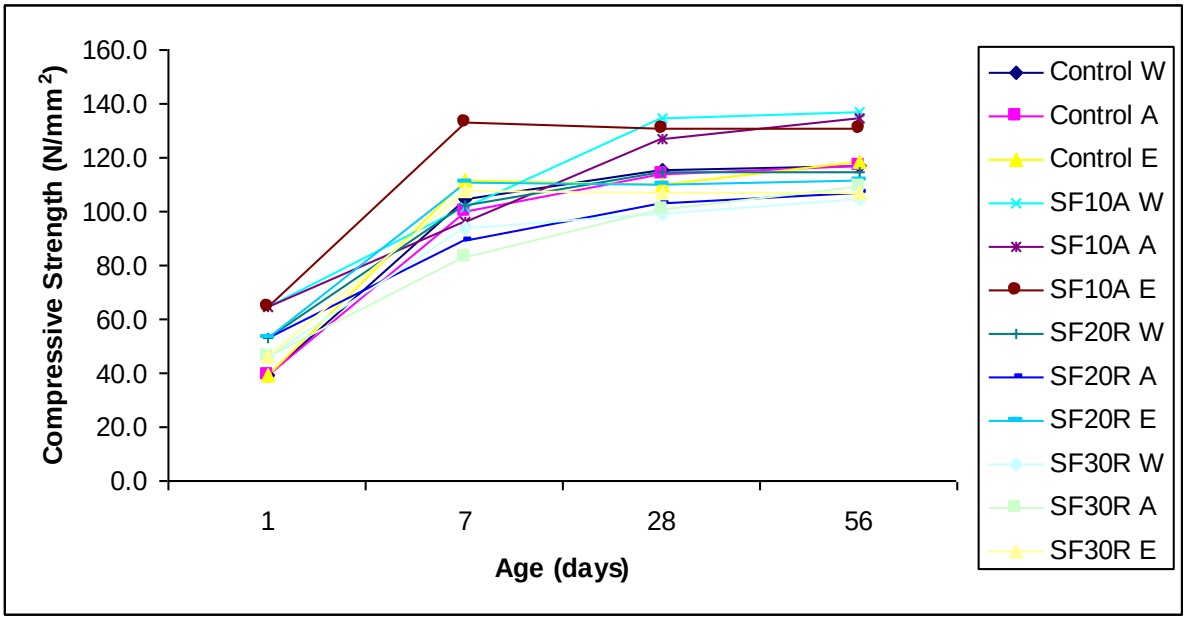


Figure 4.4: Compressive Strength Development for Various Mixes with steel fiber

4.5.2 Effect of Silica Fume on the Compressive Strength

The strength of pozzolanic cement depends very much on the formation of 'cementing agents', and any condition that hasten the formation of dicalcium silicate (C_2S) will give pozzolanic cement of reasonably good strength. Generally, results from Table 4.5 reveal that the compressive strength of concretes increases with age. As compared to the Control mix, almost all additional and replacement of silica fume to the cement content has led to the increment of compressive strength for up to 20%. However, the

percentage increase in strength depends on the amount of cement replacement with silica fume and cement content of the total binder. Regardless of the curing methods applied, an additional of 10% silica fume to concrete mixture gave the highest value of compressive strength of 121 N/mm^2 thus achieving the targeted strength of 120 N/mm^2 at 28 days.

For silica fume replacement mixes, the highest strength was achieved at 20% cement replacement. The targeted strength was still achievable regardless of the curing regime opted. The actual objectives of steel fibers inclusion in concretes are generally to improve the mechanical toughness in tension and durability. However, the use of steel fibers also has led to the improvement of concrete strength by 10 – 15%.

4.5.3 Effect of Curing on the Compressive Strength

Curing is the process in which the concrete is protected from loss of moisture and kept within a reasonable temperature range. Good curing can help mitigate the appearance of unplanned cracking. Sufficiently cured concrete will exhibit greater durability, wear resistance, and gain strength faster. Inadequate curing method will affect the hydration process of concrete thus reduces the concrete strength. As stated by Neville (1995), hydration of cement reduces when the relative humidity within capillaries drops below 80%. The evaporation decreases the relative humidity of concrete by reducing the amount of available moisture, and thereby retards the hydration of cement. In severe cases, the hydration is eventually stopped, affecting the development of sufficient calcium silicate hydrate (CSH) from the reaction of cement compounds and water. CSH is the major strength-providing reaction product of cement hydration.

Table 4.5 shows that different curing types gave different values to the compressive strength of concrete. It shows that all mixes treated with elevated curing gave higher

strength compared to water and air cured specimens. Nevertheless, for elevated curing regime concrete, it attained lower values of up to 4.7% of compressive strength at the age of 28 days as compared to the 7 days age. The reasons are mentioned in the earlier section.

It is also shown in the Table 4.5 that the water cured specimen gave higher compressive strength compared to air dried specimens, thus suggesting that increase in the compressive strength for water cured specimens was due mainly to the densification of the pore structure by the precipitation of the hydrated cement or binder products. This agrees with Mehta and Monteiro (1993) who quoted that a minimum period of 7 days of moist curing is generally recommended for concrete containing normal Portland cement and for concrete containing either a blended Portland cement or a mineral admixture, a longer period of curing would be desirable to ensure the strength contribution from the pozzolanic reaction.

4.5.4 Comparison with Published Data

Table 4.6 compares the results obtained from the present study with published data obtained from other researchers. It can be seen that curing type plays an important role by giving higher values of strength. Elevated curing gives the best results when compared to the other types of curing. This is followed by water curing specimen and air curing specimen. Findings by present study are in agreement with Cwirzen et al. (2008), Yazici et al. (2010) and Collepardi et al. (1997) that water cured specimen gave strength not more than 160 MPa regardless of the mix designed proportions and water-binder ratio. Types of elevated curing also influenced the specimen strength; autoclave and pressure treated specimens can reach up to 200 MPa compressive strength. These show that types of curing influenced the compressive strength. Apart from that, present

study also shows that inclusion of steel fibers also can increase the strength by up to 10%.

Table 4.6: Comparison of compressive strength for UHPC

Researchers	w/b	Cement amount	Silica fume	SP	Curing	Steel fiber	Compressive Strength (N/mm^2)	
							7 days	28 days
Present Study (2011)	0.22	900kg/m^3	0	1%	Water	0	93	97
					Air		80	92
					Elevated		112	110
	0.22	900kg/m^3	0	1%	Water	1%	105	116
					Air		100	114
					Elevated		111	110
	0.22	900kg/m^3	90kg/m^3	1%	Water	0	102	118
					Air		95	104
					Elevated		127	121
	0.22	900kg/m^3	90kg/m^3	1%	Water	1%	102	134
					Air		96	127
					Elevated		133	131
	0.22	720kg/m^3	180kg/m^3	1.5%	Water	0	101	114
					Air		85	92
					Elevated		111	110
	0.22	720kg/m^3	180kg/m^3	1.5%	Water	1%	102	115
					Air		89	103
					Elevated		111	110
	0.22	630kg/m^3	270kg/m^3	2%	Water	0	89	112
					Air		80	89
					Elevated		113	111
	0.22	630kg/m^3	270kg/m^3	2%	Water	1%	94	99
					Air		83	101
					Elevated		108	107
Cwirzen et al.* (2008)	0.18	900kg/m^3	225kg/m^3	4.2%	Elevated	2%	205	202
					Water		128	155
	0.21	900kg/m^3	225kg/m^3	4.5%	Elevated	0	178	172
					Water		121	132
Yazici (2010)	0.13	940kg/m^3	282kg/m^3	61L/m^3	Autoclave	234kg/m^3	-	218
					Water		158	180
					Steam		-	270
Collepardi et al. (1997)	0.17	933kg/m^3	234kg/m^3	12.7kg/ m^3	Pressure	187kg/m^3	-	190-200
					Water		135	160
					Steam		165	168

**Note:*

- Cwirzen et al. presented data in 1 part of cement, the author calculated 1 part of cement is equivalent to 900kg/m^3

4.6 Modulus of Rupture

The flexural strength of a concrete specimen is expressed in terms of the modulus of rupture (MOR), i.e. the maximum stress at rupture where fracture is in the tension surface within the middle third of the span length. This test is normally preferred for quality control of concrete where it is loaded in bending rather than in axial tension. However, due to the equipments' constrain, the opted curing process for this testing were water curing and air drying only.

4.6.1 Effect of Silica Fume on the Modulus of Rupture

The results of the modulus of rupture for the selected mixes under water curing and air drying are shown in Table 4.7. From the table, it shows that the MOR for additional of 10 % silica fume to the mixture gave higher value as compared to the Control mixture for both mixtures with and without the steel fibers. However, for 20-30 % cements replacement with silica fume, the MOR values were lower than the Control specimens.

Table 4.7: Modulus of rupture for selected mixes

Mix	w/b	Cement (kg/m^3)	SF (kg/m^3)	Curing	Modulus of rupture (N/mm^2)					
					without fiber			with fiber		
					7d	28d	56d	7d	28d	56d
Control	0.22	900	-	WC	6.79	12.40	14.70	12.28	13.51	14.90
				AC	6.36	9.30	9.70	7.90	9.66	9.90
SF10A	0.22	900	90	WC	12.30	13.20	14.30	13.80	14.70	14.90
				AC	6.81	7.80	8.30	7.20	8.24	9.40
SF20R	0.22	720	180	WC	6.43	14.10	14.26	12.46	14.41	14.60
				AC	5.59	7.95	8.64	8.83	9.88	10.65
SF30R	0.22	630	270	WC	11.40	11.88	12.90	11.92	12.04	13.42
				AC	5.59	6.83	7.11	7.36	8.76	9.91

Note:
- WC and AC denote 'water curing' and 'air curing' respectively.

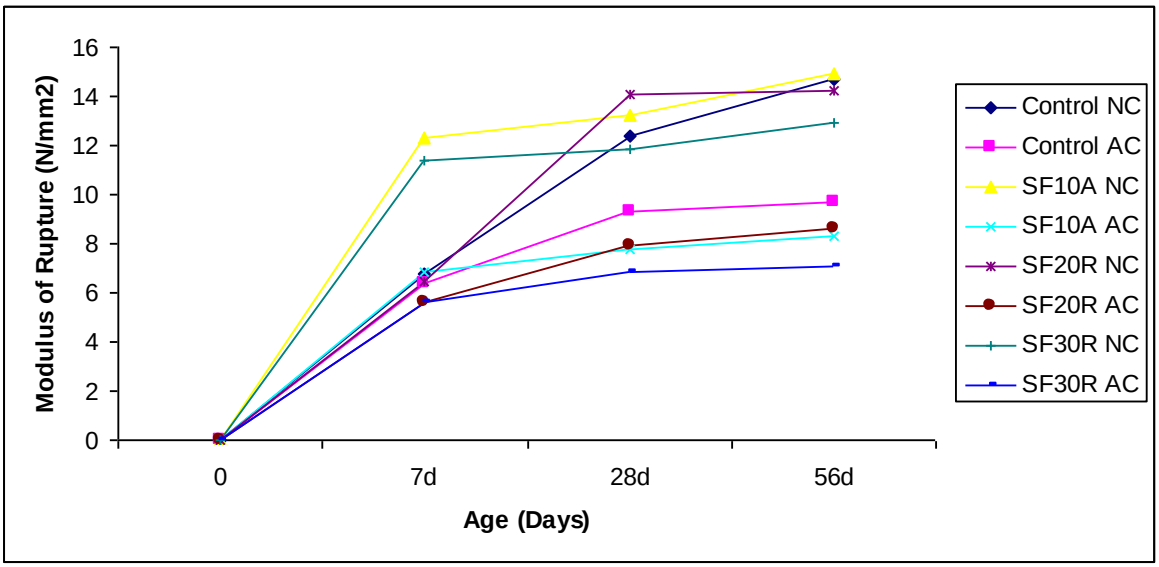


Figure 4.5: Modulus of rupture of Control and SF concretes without steel fibers under water and air curing conditions.

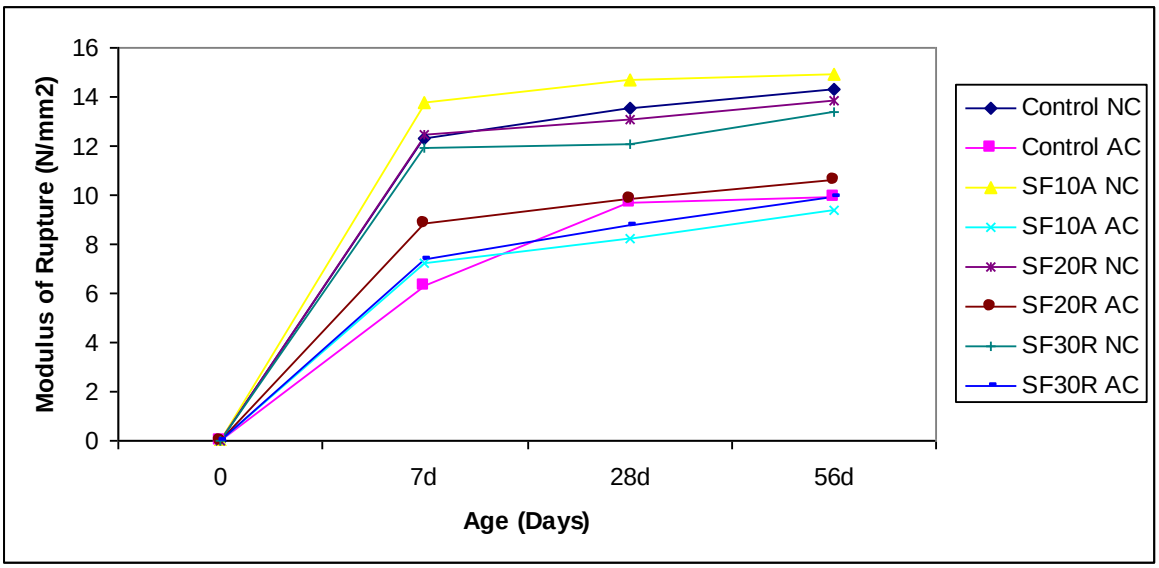


Figure 4.6 Modulus of rupture of Control and SF concretes with steel fibers under water and air curing conditions.

4.6.2 Effect of Curing on the Modulus of Rupture

In order to determine the effect of curing on the MOR, the specimens were placed under two curing conditions, i.e. water curing and air drying. The results of the MOR are tabulated in Table 4.7 and shown graphically in Figures 4.5 and 4.6. From the table and figures, it can be seen clearly that the MOR of the selected concrete mixes cured in water were higher than that under air dried condition. This is because water is needed for hydration process that will precipitate with the voids and micropores resulting in densification of the pore structure. This concluded that for Control and CSF concretes prolong moist curing is necessary to promote the hydration of cement and CSF in terms of strength development as the effects of the pozzolanic reaction is slower.

4.6.3 Effect of Steel Fiber to the Modulus of Rupture

From Table 4.7, it is noticeably that MOR of the mixtures with inclusion of fiber was higher than the mixtures without. However, the difference is small, only about 2-10%. Generally, steel fiber can increase the flexural strength up to 3 times depending on the type and percentage of fibers. This behavior is mainly attributed to the role of steel fiber in releasing fracture energy around crack tips which is required to extent crack growing by transferring stress from one side to another side (Salih et al, 2005). Furthermore, this behavior is also due to the increase in crack resistance of the composite and the ability of fibers to resist forces after the concrete matrix has cracked.

4.6.4 Relationship between Modulus of Rupture and Compressive Strength

The ratio of modulus of rupture and compressive strength (f_r /f_{cu}) of the selected mixes is presented in Table 4.8. By referring to the table, it shows that as the compressive strength of concrete increases, the MOR also increases whereby it is influenced by age, composition of concrete and curing conditions. From the table, it can be seen that the fr

/ fcu ratio increases with age, the values for concretes with fiber gave higher values than concretes without. This behaviour may be attributed to pore and grain size refinement processes, thus strengthen the transition zone and reduces the microcracking in the interface that caused by pozzolanic reaction. It can be seen that concretes with water cured give higher fr/fcu ratio as compared to the air cured due to contribution of water to the hydration of cement thus increasing the concretes strength.

Table 4.8: Ratio of the MOR and compressive strength of Control and SF concretes

Mixture	Curing	Modulus of rupture (N/mm^2)					
		without fiber			with fiber		
		7d	28d	56d	7d	28d	56d
Control	Water	6.8	12.4	14.7	12.3	13.5	14.9
	Air	6.4	9.3	9.7	7.9	9.7	9.9
SF10A	Water	12.3	13.2	14.3	13.8	14.7	14.9
	Air	6.8	7.8	8.3	7.2	8.2	9.4
SF20R	Water	6.4	14.1	14.3	12.5	14.4	14.6
	Air	5.6	8.0	8.6	8.8	9.9	10.7
SF30R	Water	11.4	11.9	12.9	11.9	12.0	13.4
	Air	5.6	6.8	7.1	7.4	8.8	9.9
Compressive Strength (N/mm^2)							
Control	Water	93.0	97.2	99.6	104.5	115.6	117.2
	Air	80.2	92.1	99.2	100.1	114.0	116.9
SF10A	Water	102.0	118.0	121.9	101.8	134.3	137.3
	Air	95.0	103.7	119.8	96.2	127.0	134.7
SF20R	Water	101.0	114.0	106.0	102.0	114.5	114.9
	Air	85.0	92.1	99.4	89.0	103.0	107.3
SF30R	Water	89.0	112.0	104.3	93.5	99.0	104.3
	Air	80.0	89.0	98.7	83.3	100.8	109.1
Modulus of Rupture / Compressive Strength (*fr / fcu*) %							
Control	Water	7.30	12.76	14.76	11.75	11.69	12.71
	Air	7.93	10.10	9.78	7.89	8.47	8.47
SF10A	Water	12.0	11.18	11.73	13.55	10.95	10.85
	Air	7.17	7.52	6.93	7.48	6.49	6.98
SF20R	Water	6.37	12.37	13.45	12.22	12.59	12.71
	Air	6.58	8.63	8.69	9.92	9.59	9.93
SF30R	Water	12.81	10.61	12.37	12.75	12.16	12.87
	Air	6.99	7.67	7.20	8.84	8.69	9.08

4.6.5 Comparison with Published Data

It can be seen in Table 4.9 that the present study shows that the values of MOR are higher for water cured concretes as compared to the air cured. The results are improved with steel fibers inclusion in the concrete. Results obtained by Cwirzen et al. (2008) agreed with the present study results; for 0.21 water-binder ratio, water cured specimen the MOR value were about 12 N/mm^2 for 28 days. However, other researchers, Yazici (2010), Hong et al. (2010) and Collepardi et al. (1997) to name a few, obtained better MOR values for different curing method and different mix designed. The highest MOR value was obtained by Yazici (2010) with MOR value was 29.6 N/mm^2 for 28 days age. The curing method opted was autoclave.

4.7 Tensile Splitting Strength

The tensile splitting strength is defined as the maximum tensile stress at failure as calculated from the theory of elasticity. According to Neville (1995), the strength determined in the splitting test is believed to be close to the direct tensile strength of concrete, being 5 to 12% higher. The tensile strength of the four selected concrete mixes under water curing and air drying condition are tabulated in Table 4.10.

4.7.1 Effect of Silica Fume on the Splitting Tensile Strength

From Table 4.10, it shows that the strengths are increased with age. The highest splitting tensile strength was for concrete with 20% silica fume, SF20R, exhibiting 6.55N/mm^2 at 28 days. This is followed by 10% silica fume addition, SF10A of 6.10 N/mm^2 at 28 days and 6.90 N/mm^2 at 56 days. Furthermore, the tensile splitting strength is improved when steel fiber is included in the concrete mixtures. These are shown in the Figures 4.7 and 4.8.

Table 4.9: Comparison of modulus of rupture with published data

Researchers	w/b	Cement amount	SF	SP	Curing	Steel fiber	Modulus of rupture (N/mm^2)	
							7 days	28 days
Present Study (2011)	0.22	900 kg/m^3	0	1%	Water	0	6.79	12.40
					Air		6.36	9.30
	0.22	900 kg/m^3	0	1%	Water	1%	12.28	13.51
					Air		7.90	9.66
	0.22	900 kg/m^3	90kg/m^3	1%	Water	0	13.80	14.70
					Air		6.81	7.80
	0.22	900 kg/m^3	90kg/m^3	1%	Water	1%	12.30	13.20
					Air		7.20	8.24
	0.22	720 kg/m^3	180kg/m^3	1.5%	Water	0	6.43	14.10
					Air		5.59	7.95
	0.22	720 kg/m^3	180kg/m^3	1.5%	Water	1%	12.46	14.41
					Air		8.83	9.88
	0.22	630 kg/m^3	270kg/m^3	2%	Water	0	11.40	11.88
					Air		5.59	6.83
	0.22	630 kg/m^3	270kg/m^3	2%	Water	1%	11.92	12.04
					Air		7.36	8.76
Cwirzen et al.* (2008)	0.18	900kg/m^3	225kg/m^3	4.2%	Elevated	0.2	-	26
					Water		-	26
	0.21	900kg/m^3	225kg/m^3	45%	Elevated	0	-	13
					Water		-	12
Yazici et al. (2010)	0.13	940kg/m^3	282kg/m^3	61L/m^3	Autoclave	234kg/m^3	-	29.6
					Water		23.6	29.3
					Steam		-	26.7
Hong et al. (2010)*	0.20	900kg/m^3	225kg/m^3	1.8%	Elevated	2%	25.18	28.76
Collepardi et al. (1997)	0.18	934kg/m^3	234kg/m^3	12.7kg/m^3	Pressure	187kg/m^3	19.1	20.1
					Water		19.6	20.5
					Steam		18.5	20.2
	0.20	758kg/m^3	190kg/m^3	12.9kg/m^3	Pressure	189kg/m^3	18.6	17.9
					Water		13.8	16.1
					Steam		18.1	18.0

**Note:*

- Cwirzen et al. and Hone et al. presented data in 1 part of cement, the author calculated 1 part of cement is equivalent to 900kg/m^3

Table 4.10: Tensile splitting strength of concretes under water curing and air drying conditions

Mix	Splitting Tensile Strength (N/mm^2)					
	without fiber				with fiber	
	7d	28d	56d		7d	28d	56d
Water Curing						
Control	4.91	5.04	5.42		7.73	7.94	8.41
SF10A	5.50	6.10	6.90		6.73	7.61	8.45
SF20R	5.58	6.55	7.67		6.07	7.77	8.49
SF30R	4.50	5.02	6.13		5.92	7.40	7.70
Air Curing						
Control	4.51	4.42	5.12		7.24	7.65	8.22
SF10A	4.20	5.10	5.80		6.32	7.39	8.07
SF20R	3.94	4.07	5.20		5.55	6.94	7.98
SF30R	3.72	3.89	4.20		5.69	7.20	7.40

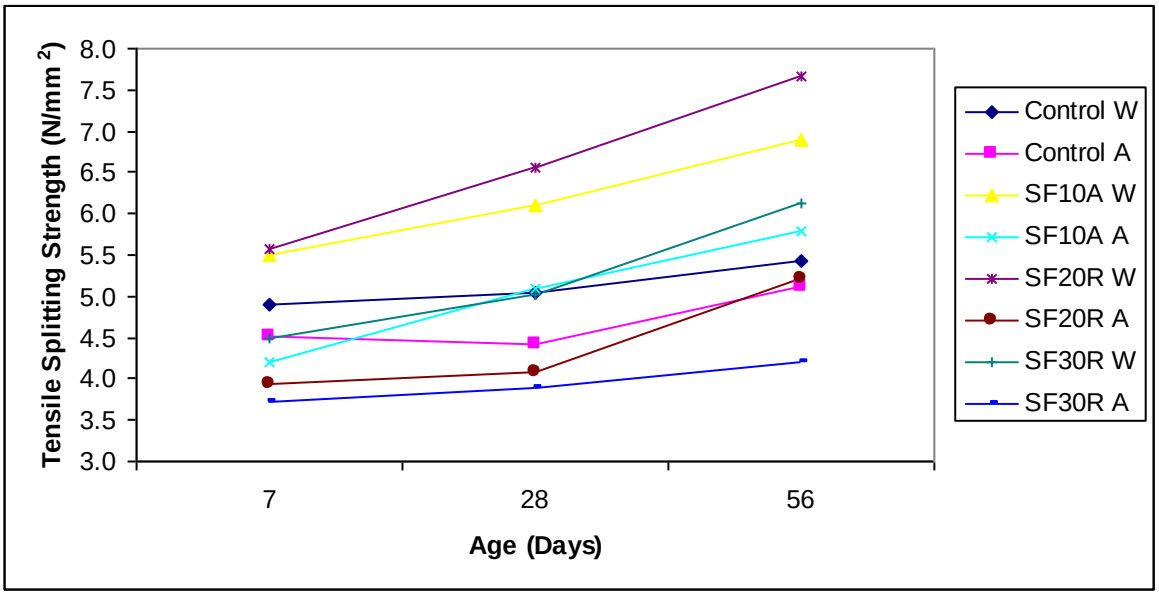


Figure 4.7: Tensile splitting strength of concretes under water and air curing conditions

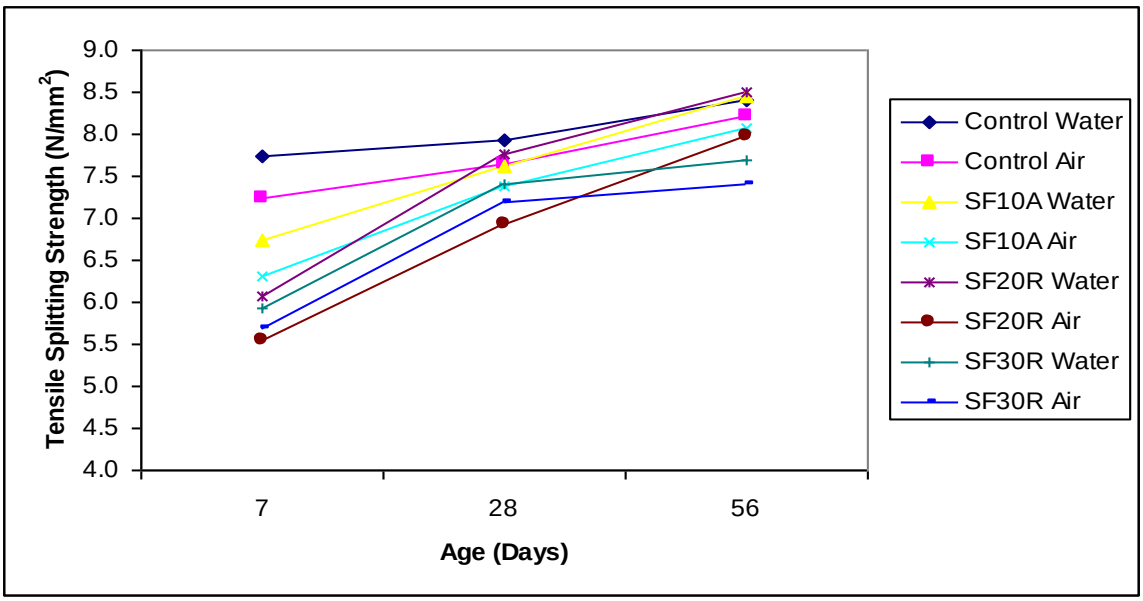


Figure 4.8: Tensile splitting strength of steel fiber concretes under air and water curing conditions

4.7.2 Effect of Curing and Steel Fiber on the Splitting Tensile Strength

It can be seen from the Table 4.10 that type of curing opted can influence the tensile splitting strength. Water cured specimens give higher values compared to air cured specimens. This is due to water contribution in cement hydration process, higher cement hydrated gives higher concretes strength. From the table also can be seen that concretes with fibers inclusion give higher results. This behavior is attributed to the mechanism of steel fibers in arresting crack progression, where the addition of fibers in the mixtures leads to increase in crack arrestors point, thereby, increasing the tensile strength.

4.7.3 Relationship between Splitting Tensile Strength and Compressive Strength

The relationship between indirect splitting tensile strength and compressive strength is shown in Table 4.11. It shows that the tensile strength and compressive strength increase with age. Curing condition also affected the ratio. Air cured specimens gave lower values compared to the water cured concretes. It is noticeably that concretes with the steel fibers inclusion gave higher value of tensile strength thus gives higher ratio of tensile strength-compressive strength. Control mixture with steel fiber gives highest

value of f_{ct}/f_{cu}, 6.78% and 7.18% for 28 and 56 days respectively. However, as a comparison with modulus of rupture-compressive strength, fr/fcu ratio gives higher values for Control mixtures with fiber of 11.69% and 12.71%, for 28 and 56 days respectively. As stated by Neville (1995), the expression of MOR is based on the elastic beam theory, in which the stress-strain relation is assumed to be linear, however, the shape of the actual stress block under loads nearing failure is parabolic, and thus the MOR overestimates the tensile strength of concrete. Neville (1995) also stated that the correct value of tensile strength was presented by Raphael (Neville, 1995) of about ¾ of the theoretical modulus of rupture.

Table 4.11: Ratio of tensile splitting strength to compressive strength for concretes

Mixture	w/b	Cement (kg/m^3)	SF (kg/m^3)	Curing	Splitting Tensile Strength (N/mm^2)						
					without fiber				with fiber		
					7d	28d	56d		7d	28d	56d
Control	0.22	900	-	Water	4.91	5.04	5.42		7.73	7.94	8.41
				Air	4.51	4.42	5.12		7.24	7.65	8.22
SF10A	0.22	900	90	Water	5.50	6.10	6.90		6.73	7.61	8.45
				Air	4.20	5.10	5.80		6.32	7.39	8.07
SF20R	0.22	720	180	Water	5.58	6.55	7.67		6.07	7.77	8.49
				Air	3.94	4.07	5.20		5.55	6.94	7.98
SF30R	0.22	630	270	Water	4.50	5.02	6.13		5.92	7.40	7.70
				Air	3.72	3.89	4.20		5.69	7.20	7.40
					Compressive Strength (N/mm^2)						
Control	0.22	900	-	Water	93.0	97.2	99.6		104.5	115.6	117.2
				Air	80.2	92.1	99.2		100.1	114.0	116.9
SF10A	0.22	900	90	Water	102.0	118.0	121.9		101.8	134.3	137.3
				Air	95.0	103.7	119.8		96.2	127.0	134.7
SF20R	0.22	720	180	Water	101.0	114.0	106.0		102.0	114.5	114.9
				Air	85.0	92.1	99.4		89.0	103.0	107.3
SF30R	0.22	630	270	Water	89.0	112.0	104.3		93.5	99.0	104.3
				Air	80.0	89.0	98.7		83.3	100.8	109.1
					Splitting Tensile Strength / Compressive Strength (*fct / fcu*) %						
Control	0.22	900	-	Water	5.28	5.19	5.44		7.40	6.87	7.18
				Air	5.62	4.80	5.16		7.23	6.71	7.03
SF10A	0.22	900	90	Water	5.39	5.17	5.66		6.61	5.67	6.15
				Air	4.42	4.92	4.84		6.57	5.82	5.99
SF20R	0.22	720	180	Water	5.52	5.75	7.24		5.95	6.79	7.39
				Air	4.64	4.42	5.23		6.24	6.74	7.44
SF30R	0.22	630	270	Water	5.06	4.48	5.88		6.33	7.47	7.38
				Air	4.65	4.37	4.26		6.83	7.14	6.78

4.7.4 Relationship between Splitting Tensile Strength and Modulus of Rupture

The value of tensile strength is about one-third of the theoretical modulus of rupture (Neville, 1995) the overestimation of the MOR value are due to the flexural formula assumes a linear stress-strain relationship in concrete throughout the cross section of the beam and in tensile splitting tests resulted from localized effect as the load is applied on the specimen as line load on the cylinder surface. Meanwhile, in the flexure test only small volume of concrete near the bottom of the specimen is subjected to high stress. Table 4.12 shows the relationship between modulus of rupture and tensile splitting strength of the present study. The results obtained show a ratio of 39.5% to 91.7%. Concretes with steel fibers gave higher ratio as compared to concretes without.

4.7.5 Comparison with Published Data

Very limited research data are available on splittting tensile strength. Graybeal (2006) has reported that for steam-based curing regime specimen gave values between 11-12.4 MPa and > 9.0 MPa for untreated group of specimen at the age of 28 days. Research findings by Voo (2010) were between 5-10 MPa for DURA-UHPdC at 28 days.

4.8 Static Modulus of Elasticity

Modulus of elasticity is one of the most important properties in concrete. It is closely related to the properties of cement paste and the stiffness of the selected aggregates. Other factors that can affect the modulus of elasticity of concrete are method of curing, chemical admixture, supplementary cementitious materials, specimen size and age of the concrete. Static test on the specimens was performed in order to determine the elastic behaviour of concretes.

Table 4.12: Ratio of tensile splitting strength to modulus of rupture

Mixture	Curing	Splitting Tensile Strength, f_{ct} (N/mm^2)					
		without fiber			with fiber		
		7d	28d	56d	7d	28d	56d
Control	Water	4.91	5.04	5.42	7.73	7.94	8.41
	Air	4.51	4.42	5.12	7.24	7.65	8.22
SF10A	Water	5.50	6.10	6.90	6.73	7.61	8.45
	Air	4.20	5.10	5.80	6.32	7.39	8.07
SF20R	Water	5.58	6.55	7.67	6.07	7.77	8.49
	Air	3.94	4.07	5.20	5.55	6.94	7.98
SF30R	Water	4.50	5.02	6.13	5.92	7.40	7.70
	Air	3.72	3.89	4.20	5.69	7.20	7.40
Modulus of rupture, f_r (N/mm^2)							
Control	Water	6.79	12.40	14.70	12.28	13.51	14.90
	Air	6.36	9.30	9.70	7.90	9.66	9.90
SF10A	Water	12.3	13.2	14.3	13.8	14.7	14.9
	Air	6.81	7.80	8.30	7.20	8.24	9.40
SF20R	Water	6.43	14.10	14.26	12.46	14.41	14.60
	Air	5.59	7.95	8.64	8.83	9.88	10.65
SF30R	Water	11.40	11.88	12.90	11.92	12.04	13.42
	Air	5.59	6.83	7.11	7.36	8.76	9.91
Splitting Tensile Strength / Modulus of rupture (f_{ct} / f_r) %							
Control	Water	72.31	40.65	36.87	62.95	58.77	56.44
	Air	70.91	47.53	52.78	91.65	79.19	83.03
SF10A	Water	44.72	46.21	48.25	48.77	51.77	56.71
	Air	61.67	65.38	69.88	87.78	89.68	85.85
SF20R	Water	86.78	46.45	53.79	48.72	53.92	58.15
	Air	70.48	51.19	60.19	62.85	70.24	74.93
SF30R	Water	39.47	42.26	47.52	49.66	61.46	57.38
	Air	66.55	56.95	59.07	77.31	82.19	74.67

Table 4.13: Development of static modulus of elasticity

Mix	Curing	Static modulus of elasticity (kN/mm^2)					
		without fiber			with fiber		
		7d	28d	56d	7d	28d	56d
Control	Water	29.81	34.56	39.67	42.76	43.47	46.64
	Air	30.33	33.28	38.51	38.65	41.74	44.32
SF10A	Water	40.40	41.38	43.11	40.78	49.89	53.25
	Air	31.65	37.63	38.01	39.42	43.43	47.58
SF20R	Water	41.74	44.26	45.94	37.04	47.58	58.50
	Air	36.86	36.6	40.88	40.22	40.84	45.70
SF30R	Water	32.78	36.06	36.47	34.60	40.32	47.50
	Air	31.08	29.55	33.24	35.33	36.40	42.60

4.8.1 Effect of Silica Fume on Static Modulus of Elasticity

From the Table 4.13 shown, it is clearly seen that the static modulus of elasticity of plain opc concrete was lower than concretes with silica fume. The value of modulus of elasticity at 28 days for the control concrete is 34.56 kN/^{mm2} and the values for silica fume concretes are in the range of 36 - 44.3 kN/mm^2 at the same age.

Referring to Table 4.13, the values of static modulus of elasticity for concretes cured in water are higher than concretes cured in air. The range of values for concretes cured in the water and air at 28 days are between 34 – 44 kN/mm^2 at 28 days and 29 – 37 kN/mm^2 respectively. At the age of 56 days, the value is between 36 – 46 kN/mm^2 for water cured and 29 – 38 kN/mm^2 for air cured specimens. This shows that specimens placed in water prior to testing gave higher modulus compared to air dried specimens. It is important to provide proper curing for the concretes.

Concretes being saturated with water give higher modulus of elasticity because it experiences less strain for a given stress, meanwhile air cured concretes show higher strain for a given stress due to less gel water and inter-crystal adsorbed water, which is due to Van der Waals force of attraction in the hydration process (Long et al., 2002).

4.8.2 Effect of Steel Fiber on Static Modulus of Elasticity

From the Table 4.13 shown, it can be seen that static modulus of concretes with inclusion of steel fibers is higher than concretes without fibers addition. The value of static modulus also increased with the increment amount of silica fume in concretes. This can be seen clearly in Figures 4.9 and 4.10. Inclusion of fibers increased the stiffness of the overall concrete

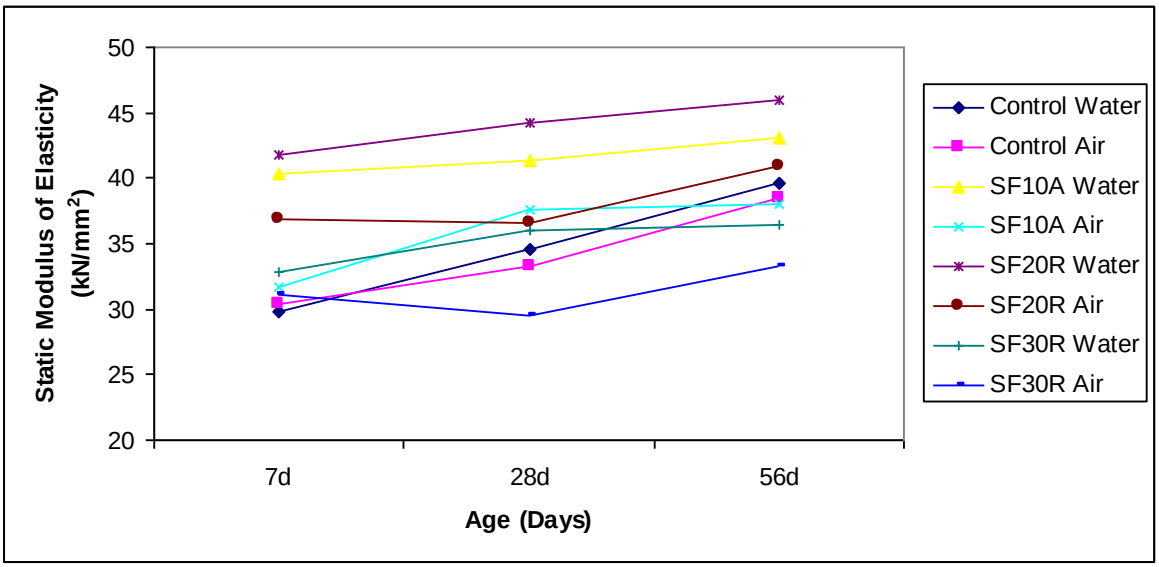


Figure 4.9: Effect of curing on static modulus of elasticity of concretes

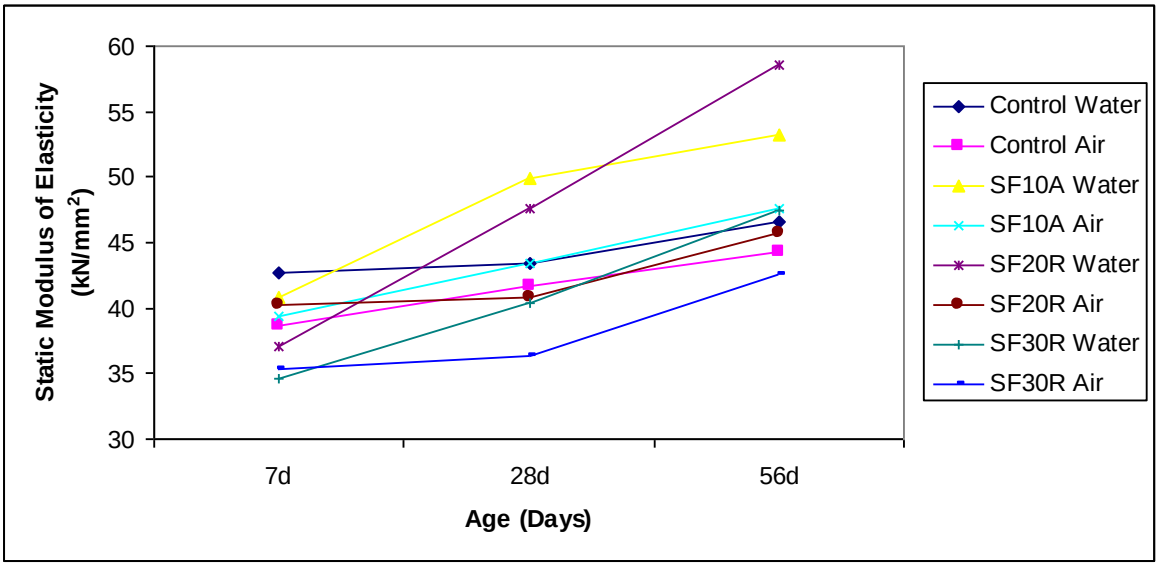


Figure 4.10: Curing effect on static modulus of elasticity of steel fiber concretes

4.8.3 Comparison with Published Data

Table 4.14 shows the results obtained by present study and published data by other researchers. Present results show the findings of modulus of elasticity are in concurrent with other researchers' observations, concretes without fiber and fibers at the age of 28 days are 34 – 44 kN/mm^2 and 40 – 49 kN/ mm^2 respectively. Cwirzen et al. (2008) reported that modulus of elasticity obtained was 45 – 49 kN/mm^2 and Hong et al. (2010) obtained 46 kN/mm^2. Results found by present research are in agreement with other researchers' even though the mix proportions and curing methods are different.

Table 4.14: Comparison of static modulus of elasticity with published data

Researchers	w/b	Cement amount	Silica fume	SP	Curing	Steel fiber	Static modulus of elasticity (kN/mm^2)	
							7 days	28 days
Present Study (2011)	0.22	900kg/m^3	0	1%	Water	0	29.81	34.56
					Air		30.33	33.28
	0.22	900kg/m^3	0	1%	Water	1%	42.76	43.47
					Air		38.65	41.74
	0.22	900kg/m^3	90kg/m^3	1%	Water	0	40.40	41.38
					Air		31.65	37.63
	0.22	900kg/m^3	90kg/m^3	1%	Water	1%	40.78	49.89
					Air		39.42	43.43
	0.22	720kg/m^3	180kg/m^3	1.5%	Water	0	41.74	44.26
					Air		36.86	36.60
	0.22	720kg/m^3	180kg/m^3	1.5%	Water	1%	37.04	47.58
					Air		40.22	40.84
	0.22	630kg/m^3	270kg/m^3	2%	Water	0	32.78	36.06
					Air		31.08	29.55
	0.22	630kg/m^3	270kg/m^3	2%	Water	1%	34.60	40.32
					Air		35.33	36.40
Cwirzen et al. (2008)	0.18	900kg/m^3	225kg/m^3	4.2%	Elevated	2%	-	45.32
					Water		-	45.32
	0.21	900g/m^3	225kg/m^3	4.5%	Elevated	0	-	49.55
					Water		-	48.43
Hong et al. (2010)	0.20	900kg/m^3	225kg/m^3	2%	Elevated	2%	42.33	46.04

Note:
- Cwirzen et al. and Hone et al. presented data in 1 part of cement, the author calculated 1 part of cement is equivalent to 900kg/m^3

4.9 Non-Destructive Tests

In general, the aim of NDT is to evaluate the properties of concrete in place such as the compressive strength. It is vital in the inspection of alteration, repair and new construction. Researchers are exploring the performance of non-destructive testing methods. Establishment of an experimental relation between the in place and laboratory compressive strengths is essential to evaluate the strength of concrete. The precision of relationship to forecast its strength depends on the degree of correlation between compressive strength of concrete and the quality measured by the in-place test. On the other hand, it should be kept in mind that the relationship is only to producing predicted strength not as a measured strength. In this study, two NDT methods such as ultrasonic pulse velocity and rebound hammer were used to forecast the strength of UHPC.

4.9.1 Ultrasonic Pulse Velocity (UPV)

This test is defined as the propagation of ultrasonic stress waves between points that are located on the same surface of the material. The UPV method is also known as the transit time method i.e. it uses a detector to determine the time of flight that attained from an ultrasonic pulse to pass through an identified thickness of solid material.

Table 4.15 shows the tabulated results of UPV prior to water and air curing conditions for the selected OPC and silica fume concretes. The test is conducted on 100mm cube specimens at the age of 7, 28 and 56 days for concretes with and without steel fibers.

Table 4.15: Ultrasonic wave velocities for UHPC cubes with and without fibers

Mix	w/b	Cement (kg/m^3)	SF (kg/m^3)	Curing	UPV (km/s)					
					without fiber			with fiber		
					7d	28d	56d	7d	28d	56d
Control	0.22	900	-	Water	4.02	4.17	4.26	4.10	4.18	4.31
				Air	3.85	3.98	4.05	4.05	4.13	4.24
SF10A	0.22	900	90	Water	4.17	4.26	4.31	4.15	4.27	4.37
				Air	4.00	4.07	4.18	4.15	4.24	4.37
SF20R	0.22	720	180	Water	4.07	4.12	4.22	4.03	4.07	4.26
				Air	3.98	4.02	4.24	3.86	3.83	3.89
SF30R	0.22	630	270	Water	3.83	3.97	4.03	4.39	4.44	4.57
				Air	3.77	3.90	4.00	3.86	3.91	4.02

4.9.1.1 Effect of Silica Fume on UPV

From the table 4.15 above, it shows that all concrete mixes produce UPV range of between 3.97 – 4.44 km/sec and 3.90 – 4.24 km/sec at 28 days, under water curing and air drying respectively. According to BS EN 12504-4 (2004) and Neville (1995), concrete with pulse velocity of between 3.5 – 4.5 km/sec can be categorized as good or even excellent concrete and concrete with pulse velocity $\geq$ 4.5 km/sec can be classified as excellent concrete, from the table, it is proven that the studied UHPC is an excellent concrete. Also concluded that the values of UPV increases with age.

Total amount of binder also affected the UPV values. From the Table 4.15, it shows that 10% additional of silica fume improve the UPV values from the Control concrete. This is due to the improvement of its physical structure which increased the strength of

concrete, which results in an increase in the pulse velocity value. Nonetheless, 20% - 30% silica fume replacement of cement decreases the UPV values as compared to the Control concrete. This is due to the decrement of total binder content in which lessen the density of concrete. Whereas, an additional of 10% silica fume in the concrete mixture has resulted the highest UPV values of 4.26 and 4.31 km/s for concretes without steel fiber and 4.13 and 4.37 km/s for concrete with steel fiber at 28 and 56 days respectively.

4.9.1.2 Effect of Curing on UPV

Table 4.15 generally shows that the UPV of water cured specimens is higher compared to air dried specimens. These are presented in Figures 4.11 and 4.12 for concrete with and without steel fibers respectively. This behaviour is due to the facts that the pulse travels faster through a water-filled void than through an air-filled one (Neville, 1995).

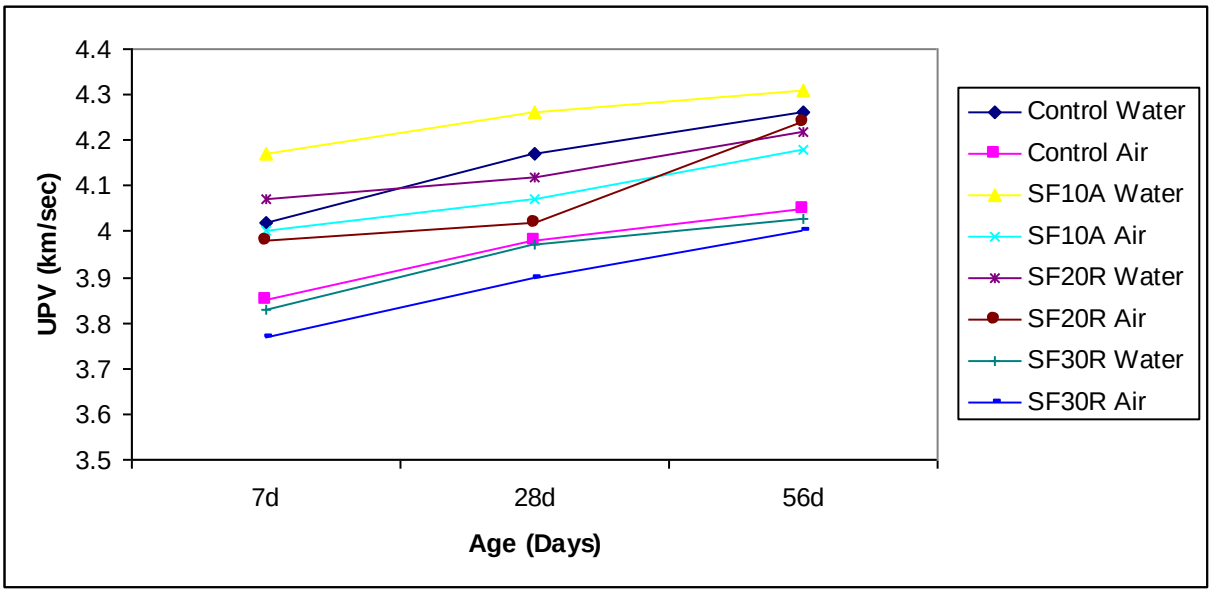


Figure 4.11: Pulse velocity of selected concretes without steel fibers

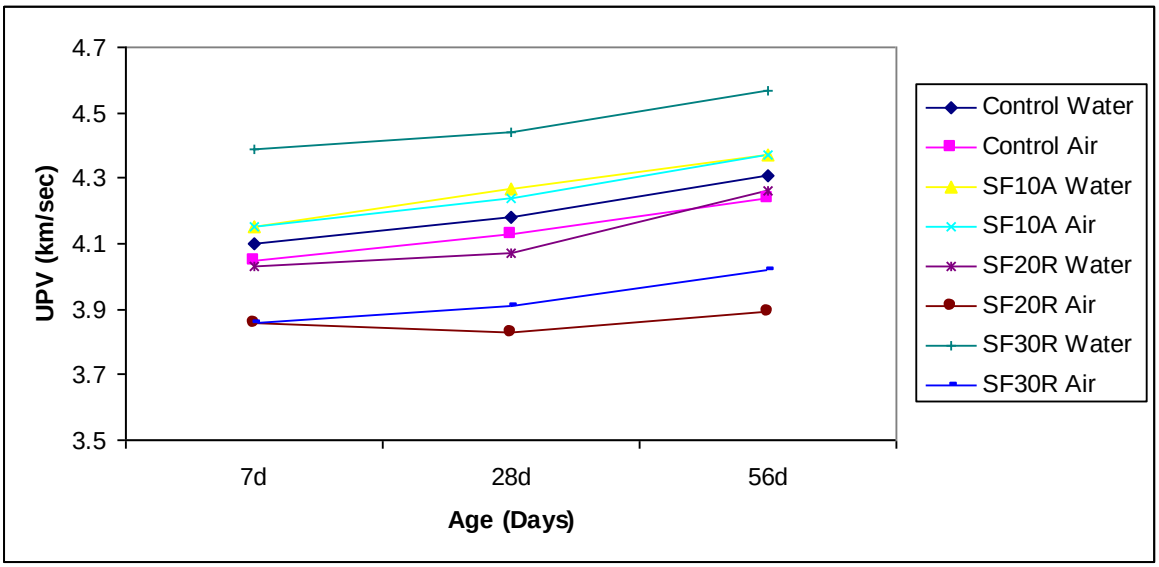


Figure 4.12: Pulse velocity of selected concretes with steel fibers

4.9.1.3 Effect of Steel Fiber on UPV

From figures 4.11 and 4.12, it can be noted that concretes with steel fibers inclusion give higher UPV values. This is due to the densification of concrete density as mentioned by Neville (1995). However, there is no physical relation between the value of the ultrasonic pulse velocity and the strength of concrete.

4.9.1.4 Comparison with Published Data

Graybeal and Tanesi (2007) has reported that RPC cubes were used to determine the basic wave propagation characteristic of RPC. Cube with and without 2% of steel fibers were cast and cured under ambient air and steam cured for 48 hours. The findings show that specimen without fibers and elevated cured has consistently higher velocities than air-cured specimens with fibers. This increased wave velocity is primarily related to the curing conditions of the cube. The steam curing used results in a higher modulus material than air-curing. The author also reported that specimens containing fibers have a higher velocity than those without fibers if the curing conditions are identical. The results of the present study are with agreement with results obtained by Graybeal (2005) that higher velocity is obtained for concretes with fiber than concretes without.

4.9.2 Rebound Hammer

The rebound hammer test conducted on the specimen measures the properties of the surface zone of the tested specimen. There are many application of rebound hammer to predict the concrete strength, for instance to forecast the uniformity of concrete within structures. The results obtained from the test are presented in Table 4.16.

4.9.2.1 Effect of Silica Fume on Surface Hardness

The rebound numbers for the concretes are tabulated in Table 4.16. It shows that the value of rebound numbers increases with age. Samples with the inclusion of steel fibers also gave higher strength when compared to the plain concrete.

4.9.2.2 Effect of Curing on Rebound Number

Table 4.16 shows that elevated curing samples gave higher value at 7 days, however, the values were more or less the same with water cured samples at the later age, 28 days and 56 days. These shows that heat treatment given has accelerated the hydration process thus increase the strength of concrete at early age. This has resulted in high values of RN at early age. From the table, the estimated strength of concrete at 28 days are 14-28 N/mm^2 and 20-34 N/mm^2 for concretes without and with steel fibers respectively. The estimated results obtained were much lower when compared with the actual compressive strength as shown in Table 4.2. From the results, it can be concluded that rebound hammer test is not suitable to use in assessing and predicting the hardness of UHPC.

4.9.2.3 Comparison with Published Data

The present study shows that the values of the rebound number are influenced by the curing method; the rebound number is highest for elevated cured specimens and lowest

values for air dried specimens. However, no available data can be obtained for UHPC concrete to compare with the present study as mentioned earlier that this type of test is not suitable to predict and assess UHPC.

Table 4.16: Rebound hammer test for selected mixes

Mix	Sample without fiber						Sample with fiber					
	7d		28d		56d		7d		28d		56d	
	RN	Est st (N/mm^2)	RN	Est st (N/mm^2)	RN	Est st (N/mm^2)	RN	Est st (N/mm^2)	RN	Est st (N/mm^2)	RN	Est st (N/mm^2)
Water Curing												
Control	29.5	23.0	31.5	25.5	32.5	27.0	33.0	28.0	35.0	32.0	35.0	32.0
SF10A	31.0	25.0	32.0	26.0	34.0	30.0	34.0	30.0	33.0	28.0	37.0	35.0
SF20R	32.0	26.0	30.0	24.0	34.0	30.0	34.0	30.0	36.0	33.0	36.0	33.0
SF30R	26.5	18.5	32.0	26.0	32.5	27.0	29.0	22.0	31.0	25.0	35.5	32.5
Air Curing												
Control	28.0	20.0	23.5	13.5	30.0	24.0	26.0	18.0	28.0	20.0	31.0	25.0
SF10A	30.0	24.0	29.0	22.0	35.0	32.0	31.0	25.0	33.0	28.0	35.0	32.0
SF20R	30.0	24.0	32.0	26.0	35.0	32.0	27.0	19.0	30.0	24.0	32.0	26.0
SF30R	29.0	22.0	33.0	28.0	32.0	26.0	26.0	18.0	31.0	25.0	33.0	28.0
Elevated Curing												
Control	32.0	26.0	31.5	25.5	34.5	31.0	32.0	26.0	34.0	30.0	34.0	30.0
SF10A	32.0	26.0	32.0	26.0	35.5	32.5	37.0	35.0	36.0	33.0	34.0	30.0
SF20R	33.0	28.0	32.0	26.0	34.5	31.0	31.0	25.0	36.5	34.0	34.5	31.0
SF30R	31.0	25.0	32.5	27.0	33.5	29.0	32.0	26.0	35.5	32.5	31.0	25.0

Note:
- Est st denotes 'estimated strength'

4.10 Initial Surface Water Absorption

The hydraulic permeability absorption is a liquid transport mechanism due to capillary suction in pores of concrete. Initial surface absorption test (ISAT) has been recognized as one of the methods to measure water permeability of concrete by British Standard (BS 1881: Part 5 (1970). Irrespective of curing, grade or mix proportions, ISAT could be used to accurately assess durability of concrete.

4.10.1 Effect of Silica Fume on Initial Surface Water Absorption of Concrete

The initial surface absorption test is prescribed in BS 1881: Part 5: 1970, the rate of absorption of water by the surface zone of concrete is determined during a prescribed

period, ranging between 10 minutes and 1 hour. The rate of initial surface absorption is expressed in milliliters per square meter per second. According to Neville (1995), initial absorption after 10 minutes greater than 0.50 ml/m^2 per second would be considered high, and smaller than 0.25 ml/m^2 per second, low. Also stated that initial surface absorption values after 2 hours are, greater than 0.15 ml/m^2 per second and smaller than 0.07 ml/m^2 per second are high and low respectively (Neville, 1995).

The results of ISAT performed on 150 mm cube are tabulated in Table 4.17 below. It can be seen that specimens subjected to water curing gave lower ISA value than the air-dried at all ages. The results also show that the ISA value decreased with the increasing age. The flow values taken at 120-minutes reading for the water cured control concrete at 7, 28 and 56 days were 0.018, 0.015, 0.011 ml/m^2 per second, and for SF10A the flow values were 0.016, 0.011, and 0.010 ml/m^2 per second. On the other hand, the flow values for SF20R and SF30R concretes were 0.016, 0.013, and 0.009 ml/m^2 per second and 0.017, 0.014 and 0.006 ml/m^2 per second respectively. All values were less than 0.25 ml/m^2 per second at 10 minutes reading and less than 0.07 ml/m^2 per second at 2 hours reading. It can be concluded that UHPC gives low values of initial surface absorption, indicating that UHPC is very low permeability concrete.

The results of the test are clearly presented in Figures 4.13 and 4.14. The figures show that incorporation of silica fume resulted in reduction in absorption characteristics. The possible reason for this is due to the filler effect of silica fume, which substantially reduce the large pores size to finer pores, thus reduced the permeability of the cementitious systems. From the figures it also show that an addition of steel fibers to concrete mixtures improve the durability of concrete by decreasing the absorption ability of concretes.

4.10.2 Effect of Curing and Steel Fibers on Initial Surface Water Absorption

The ISA values are shown in Table 4.17. Figure 4.13 shows the ISA values of the selected concretes cured under two curing conditions taken at 120-minutes after the start of the test. Meanwhile Figure 4.14 shows the ISA values for concretes incorporating steel fibers with the same curing methods opted; water and air drying conditions. From the figures, it is clearly seen that air dried specimens resulted in higher ISA values compared to water cured specimens. This shows that water absorption is lowered if curing is sufficient. Therefore, it is suggested that water curing and prolonged duration of curing should be carried out to reduce the absorption characteristic of the concrete. From the figures it show that inclusion of steel fibers reduce the ISA values for every mixes.

4.10.3 Comparison with Published Data

The present study shows that all values were less than 0.25 ml/m^2 per second at 10 minutes reading and less than 0.07 ml/m^2 per second at 2 hours reading, referring to Figures 4.13 and 4.14. As reported by Voo (2010) the ISAT for DURA UHPdC concrete is less than 0.02 for 10-minutes reading and <0.01 for 120-minutes reading. The results obtained in the present study are with agreement with the reported results.

Table 4.17: Initial surface absorption test for selected concrete mixes

Mix	Curing	Flow (ml/m^2.sec.)							
		without fiber				with fiber			
		10 min	30 min	60 min	120 min	10 min	30 min	60 min	120 min
7 days									
Control	Water	0.053	0.043	0.020	0.018	0.048	0.037	0.018	0.011
	Air	0.082	0.064	0.048	0.034	0.052	0.047	0.031	0.029
SF10A	Water	0.075	0.053	0.026	0.016	0.032	0.024	0.014	0.01
	Air	0.082	0.06	0.043	0.023	0.061	0.039	0.034	0.021
SF20R	Water	0.041	0.039	0.027	0.016	0.034	0.021	0.013	0.008
	Air	0.056	0.043	0.039	0.028	0.039	0.025	0.017	0.016
SF30R	Water	0.054	0.046	0.033	0.017	0.027	0.014	0.009	0.007
	Air	0.061	0.049	0.038	0.019	0.033	0.02	0.013	0.008
28 days									
Control	Water	0.033	0.031	0.022	0.015	0.032	0.018	0.012	0.006
	Air	0.071	0.054	0.038	0.021	0.037	0.038	0.027	0.022
SF10A	Water	0.034	0.026	0.017	0.011	0.031	0.021	0.012	0.009
	Air	0.039	0.036	0.027	0.015	0.038	0.033	0.027	0.011
SF20R	Water	0.039	0.037	0.023	0.013	0.025	0.01	0.006	0.005
	Air	0.049	0.041	0.029	0.016	0.036	0.033	0.022	0.012
SF30R	Water	0.046	0.041	0.027	0.014	0.021	0.013	0.008	0.005
	Air	0.049	0.047	0.035	0.015	0.027	0.017	0.008	0.006
56 days									
Control	Water	0.026	0.025	0.019	0.011	0.023	0.011	0.007	0.004
	Air	0.042	0.039	0.023	0.016	0.027	0.01	0.006	0.005
SF10A	Water	0.031	0.025	0.013	0.010	0.024	0.016	0.011	0.008
	Air	0.037	0.034	0.026	0.014	0.035	0.03	0.018	0.01
SF20R	Water	0.035	0.029	0.021	0.009	0.02	0.012	0.006	0.003
	Air	0.039	0.031	0.025	0.012	0.028	0.021	0.018	0.014
SF30R	Water	0.021	0.02	0.017	0.006	0.016	0.01	0.007	0.006
	Air	0.03	0.025	0.017	0.011	0.019	0.012	0.011	0.008

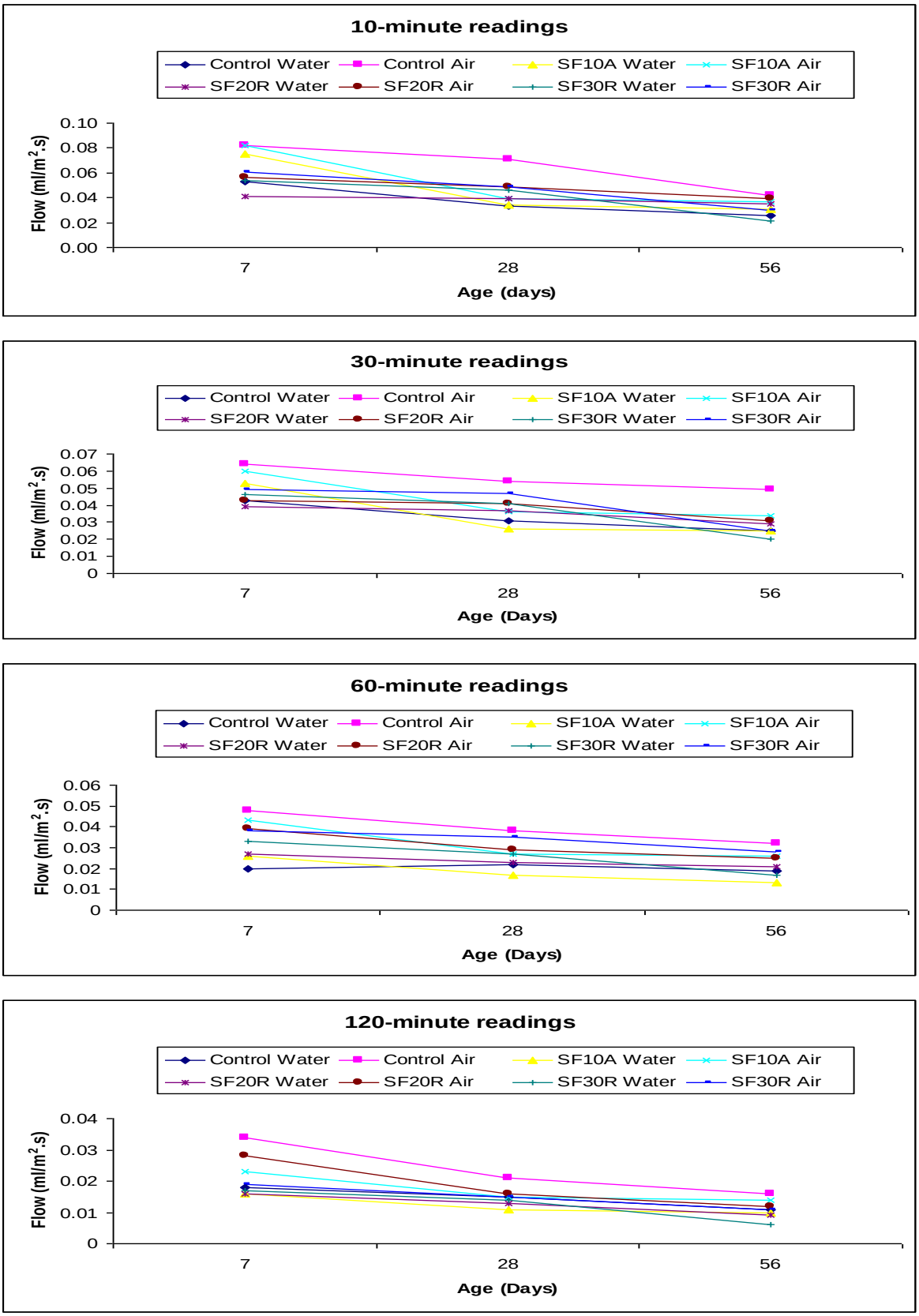
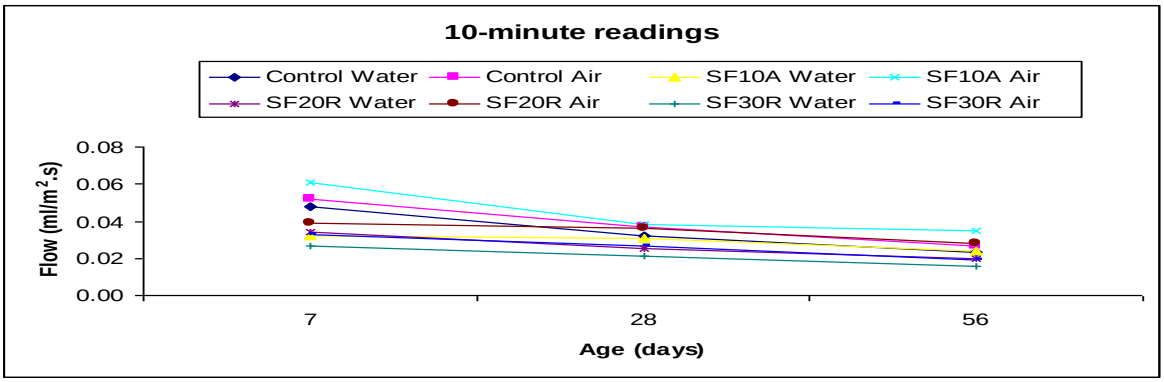
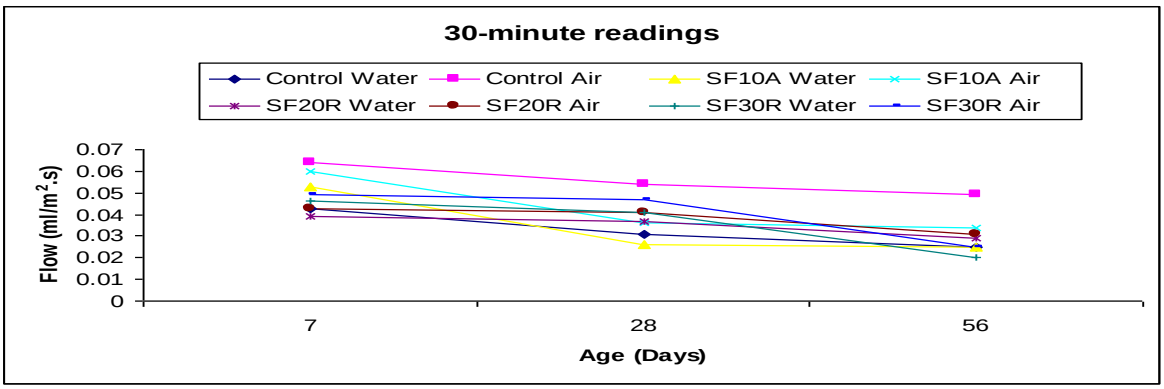
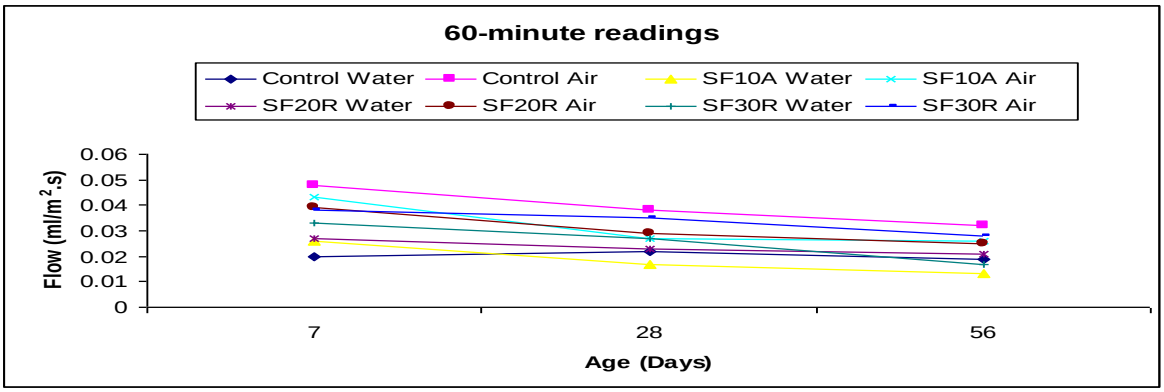


Figure 4.13: ISA of concretes cured in water and air for a period of 7, 28 and 56 days







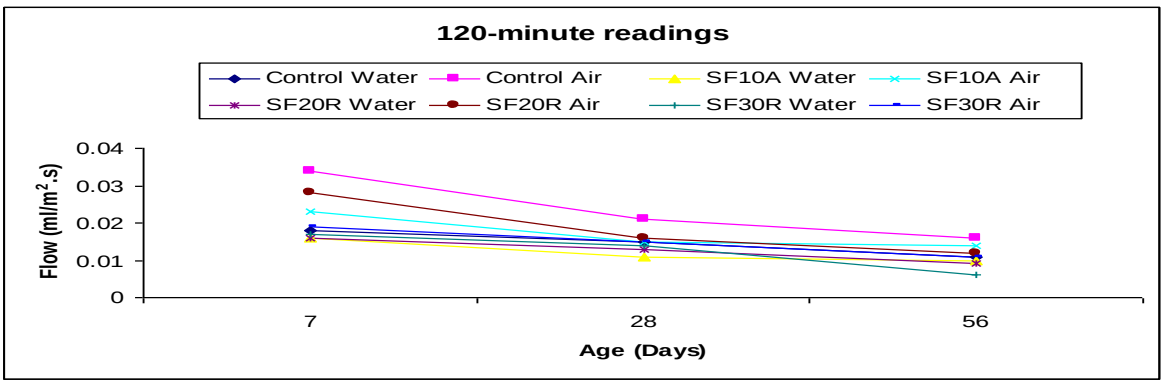


Figure 4.14: ISA of concrete with steel fiber inclusion cured in water and air for a period of 7, 28 and 56 daysk

CHAPTER 5
CONCLUSIONS AND FUTURE RESEARCH

5.1 Introduction

UHPC is a new type of concrete that exhibits properties of enhanced strength, durability, and long-term stability. The objective of this research is to develop UHPC by using locally available silica fume with the targeted compressive strength of 120 MPa at 28 days. The experimental phase of this research focused on determining the economical design mixes in achieving the targeted strength as well as to study the behavior of UHPC. The tests determined the compressive and tensile behaviors, and the durability of UHPC. The analytical phase of this research combined, analyzed, and elaborated on the results from the experimental phase. The conclusions of this study are presented in section 5.2. A brief recommendation of potential future research topics follows in section 5.3.

5.2 Conclusions

The following conclusions are based on the research presented in this report.

1. The main objective to produce UHPC of 120 MPa compressive strength at 28 days has been achieved, using cement content of 900 kg/m^3 with the addition of 10% of silica fume of total cement content with and without steel fibers inclusion.
2. Mix design method can be used to produce both steel-fiber-reinforcement and non-steel-fiber-reinforcement UHPCs with and without silica fume providing a slump flow ranging from 150 to 250 mm, and a compressive strength in the range of 100 to 120 MPa.
3. The mixing time and rheological properties of fresh UHPC are mainly influenced by the concrete mixer type and the environmental ambient

conditions. A 120 kg ORU Asia-Pacific Pte. Ltd. mixer was used successfully to mix the UHPC. However, the inability of this mixer to impart significant energy into the mix resulted in extended mixing times. High temperature in the mix room can result in stiffer UHPC.

4. Irrespective to the method of curing and the percentage of binder content, the workability of concrete, ranged between 150 to 250 mm can be obtained by using superplasticizer of about 2% of the binder content.
5. Elevated curing of UHPC tends to enhance its compressive strength at earlier stage when compared to water and air curing. In general terms, elevated curing increases UHPC's compressive strength by 3-27% and 4-32% for concrete without and with steel fibers respectively at 7 days. However, for elevated curing, the compressive strength decreases by 1-5% for concrete with and without fibers at 28days due to accelerated hydration process at the early age.
6. Curing conditions of UHPC can affect the final properties of concrete. For elevated-treated concrete cubes, the compressive strength at 28-days indicated that the strength values were 5% lower than water cured specimens. These strength differences are likely caused by the accelerated hydration process of concrete for high-temperature curing treatment applied. However, the elevated-treated cubes gave higher results at the earlier age i.e. 7-day as compared to water-treated and air-treated concrete cubes for up to 30 percent. These make it possible and are suitable to use this type of concrete in the pre-cast industry, also known as IBS in Malaysia..
7. The hardened properties of UHPC were improved with lower W/B ratio due to higher binder content, which produced greater hydration products and thus resulted in enhanced paste densification.

8. UHPC exhibits very high compressive strengths, regardless the curing treatment applied. The targeted strength and objective were achieved with SF10A, containing 10% silica fume 'addition' and 900kg/m^3 cement content. The average 28-days compressive strengths of SF10A for elevated, water, and untreated UHPC were found to be 121, 118 and 104 MPa respectively.
9. The highest modulus of rupture of UHPC was obtained from the 20 percent cement replacement mix. Under water curing, its modulus of rupture was 14.1 N/mm^2 and 14.4 N/mm^2 at 28 days for UHPC without steel fibers and UHPC with fibers inclusion respectively. The modulus of rupture to the compressive strength ratio of UHPC was in the range of 6-15%.
10. Regardless of curing conditions, the tensile splitting strength of 28-day UHPC ranged between 4.1-6.6 N/mm^2 and 6.9-7.9 N/mm^2 for non-fibers concrete and fibers inclusion concrete respectively. The ratio of tensile splitting strength to the compressive strength of modified UHPC was in the range of 4.2-7.5%.
11. The modulus of elasticity of UHPC at 28-day exhibits the results in the range of 29.6 kN/mm^2 and 37.6 29.6 kN/mm^2, irrespective of curing regime. Results for modified steel fiber UHPC were in the range of 36.4 N/mm2 and 49.9 N/mm2.
12. In the UPV test conducted, results show that the UPV of water cured specimens is higher compared to air dried specimens. This behaviour is due to the facts that the pulse travels faster through a water-filled void than through an air-filled one. The findings also in agreement with other researchers' data that steel fiber inclusion give better results for UHPCs.
13. Results for rebound hammer test obtained were much lower when compared with the actual compressive strength. From the data obtained it can be

concluded that rebound hammer test is not suitable to use in assessing and predicting the surface hardness of UHPC.

14. Specimens subjected to water curing gave lower ISA values than the air-dried at all ages. At 28 days, ISA values after 2 hours from the started test were between 0.011-0.015 and 0.015-0.021 ml/m^2 per second for water-cured and air-dried specimens respectively. For steel fibers specimens, the values were between 0.005-0.009 and 0.006-0.022 ml/m^2 per second for water-cured and air-dried specimens respectively.
15. UHPC is suitable to be used in precast industry, as the minimum 12hrs strength for every mix was more than 15MPa which make it possible to demould in less than 24hrs, thus reducing the production cost and duration. This is supporting the Governments initiatives in promoting IBS usage in the local construction industry.

5.3 Recommendations for Future Research

There are several aspects that were not investigated in the present study. The following recommendations are given for future research:

a. Hardened properties of UHPC for long term or longer data up to 365 days should be carried out
b. The effects of silica fume on the fresh and hardened properties of UHPC should be investigated for different types, sizes and percentage of steel fibres.
c. The effects of various curing conditions on the hardened properties of UHPC, including drying and autogenous shrinkages, should be examined.
d. The durability performance of UHPC such as resistances to corrosion, alkali-aggregate reaction and sulfate attack, and the effects of silica fume should be investigated.

e. The combined effects of silica fume and other supplementary cementing materials such as rice husk ash (RHA) and fly ash (FA) on the fresh and hardened properties and durability of UHPC should be investigated.

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APPENDIX A

MIX DESIGN CALCULATION SHEET & PROCEDURES

Mix: **Control (OPC-900kg/m3)**
Date:

Part A: Properties of Materials

Material	Gsp	%
Cement	3.14	100
Silica Fume	2.25	0

Aggregate	Gssd	Wtot (%)	Wabs (%)	Wc (%)
coarse	0	0	0	0
fine (standard sand)	2.65	0.04	0.59	-0.55

Gsp	solids content (%)	M sol (kg/m^3)	V liq (l/m^3)	V w (l/m^3)	V sol (l/m^3)
1.06	30	8.8	28	-20	47.9

Part B: Design

W/B:	0.22
binder content (kg/m3)	875
sand (of binder vol)	1.1
SP dosage (%)	1
vol of concrete batch	0.1265

Materials	content (kg/m3)	Volume (l/m^3)	Water Correction (l/m^3)	Composition (kg)	
				Per m3	Actual mix
Water	192.5	192.5		220.4	27.88
Cement	875	278.7		875	110.69
silica fume	0	0.0		0	0.00
coarse agg	0	0.0	0.0	0.0	0.00
sand (std sand)	1356	471.0	7.5	1348.5	170.59
air	1	10.0	-	-	-
Superplasticizer (%)	1	47.9	20	27.5	3.48 L
Total		**1000.1**	**27.87**	**2443.9**	**312.64**

sand	(kg)
70% 600micron	119.41
30% 2mm	51.18

Mix: **SF10A**
Date:

Part A: Properties of Materials

Material	Gsp	%

Cement	3.14	100
Silica Fume	2.25	10

Aggregate	Gssd	Wtot (%)	Wabs (%)	Wc (%)
coarse	0	0	0	0
fine (standard sand)	2.65	0.04	0.59	-0.55

Gsp	solids content (%)	M sol (kg/m^3)	V liq (l/m^3)	V w (l/m^3)	V sol (l/m^3)
1.06	30	10.9	34	-25	59.7

Part B: Design

W/B:	0.22
binder content (kg/m3)	990
sand (of binder vol)	1.1
SP dosage (%)	1
vol of concrete batch	0.1265

Materials	content (kg/m3)	Volume (l/m^3)	Water Correction (l/m^3)	Composition (kg)	
				Per m3	Actual mix
Water	239.58	239.6		272.4	34.46
Cement	990	315.3		990	125.24
silica fume	99	44.0		99	12.52
coarse agg	0	0.0	0.0	0.0	0.00
sand (std sand)	1356	331.5	7.5	1348.5	170.59
air	1	10.0	-	-	-
Superplasticizer (%)	1	59.7	25	34.2	4.33 L
Total		**1000.0**	**32.87**	**2710.0**	**347.15**

sand	(kg)
70% 600micron	119.41
30% 2mm	51.18

Mix: **SF20R**
Date:

Part A: Properties of Materials

Material	Gsp	%
Cement	3.14	80
Silica Fume	2.25	20

Aggregate	Gssd	Wtot (%)	Wabs (%)	Wc (%)
coarse	0	0	0	0
fine (standard sand)	2.65	0.04	0.59	-0.55

Gsp	solids content (%)	M sol (kg/m^3)	V liq (l/m^3)	V w (l/m^3)	V sol (l/m^3)
1.06	30	9.0	28	-21	49.3

Part B: Design

W/B:	0.22
binder content (kg/m3)	900
sand (of binder vol)	1.1
SP dosage (%)	1
vol of concrete batch	0.1265

Materials	content (kg/m3)	Volume (l/m^3)	Water Correction (l/m^3)	Composition (kg)	
				Per m3	Actual mix
Water	198	198.0		226.5	28.65
Cement	720	229.3		720	91.08
silica fume	180	80.0		180	22.77
coarse agg	0	0.0	0.0	0.0	0.00
sand (std sand)	1356	433.4	7.5	1348.5	170.59
air	1	10.0	-	-	-
Superplasticizer (%)	1	49.3	21	28.3	3.58 L
Total		**1000.0**	**28.46**	**2475.0**	**316.67**

sand	(kg)
70% 600micron	119.41
30% 2mm	51.18

Mix: **SF30R**
Date:

Part A: Properties of Materials

Material	Gsp	%
Cement	3.14	70
Silica Fume	2.25	30

Aggregate	Gssd	Wtot (%)	Wabs (%)	Wc (%)
coarse	0	0	0	0
fine (standard sand)	2.65	0.04	0.59	-0.55

Gsp	solids content (%)	M sol (kg/m^3)	V liq (l/m^3)	V w (l/m^3)	V sol (l/m^3)
1.06	30	9.0	28	-21	49.3

Part B: Design

W/B:	0.22
binder content (kg/m3)	900
sand (of binder vol)	1.1
SP dosage (%)	1
vol of concrete batch	0.1265

Materials	**content (kg/m3)**	**Volume (l/m^3)**	**Water Correction (l/m^3)**	**Composition (kg)**	
				Per m3	**Actual mix**
Water	198	198.0		226.5	28.65
Cement	630	200.6		630	79.70
silica fume	270	120.0		270	34.16
coarse agg	0	0.0	0.0	0.0	0.00
sand (std sand)	1356	422.1	7.5	1348.5	170.59
air	1	10.0	-	-	-
Superplasticizer (%)	1	49.3	21	28.3	3.58 L
Total		**1000.0**	**28.46**	**2475.0**	**316.67**

sand	(kg)
70% 600micron	119.41
30% 2mm	51.18

Step	Process
Part A: Properties of materials	
1	Enter specific gravity values for cement, RHA, silica fume and aggregate
2	Enter percentages of binders.
3	Enter moisture content Wtot and water absorption Wabs of aggregate.
4	Calculate SSD water correction for aggregates, Wc = Wtot - Wabs.
5	Enter specific gravity and solids content of superplasticizer (from manufacturer).
6	Calculate Msol, Vliq, Vw and Vsol using the equations below:

$$Msol = d \times \frac{B}{100}$$

$$Vliq = \frac{Msol}{s \times G\,\mathrm{sup}} \times 100$$

$$Vw = Vliq \times G\,\mathrm{sup} \times \frac{(100 - s)}{100}$$

$$Vsol = Vliq - Vw$$

d = superplasticizer dosage (%)

B = total binder material (kg/m^3)

s = solids content of superplasticizer (%)

Part B: Design	
7	Enter W/B ratio, total binder per m^3 concrete, superplasticizer dosage and volume of concrete batch
8	Enter the water content, cement, RHA, silica fume content based on W/B ratio
9	Enter the fine aggregate content, air (assumed), and superplasticizer content.
10	Calculate the volumes of each material by dividing its mass to its specific gravity.
11	Calculate the total volume for all materials per m^3 concrete and check that it is equal to 1000l/m^3. If not, adjust the aggregate content until the absolute valome criterion is satisfied.
12	Calculate the water corrections for aggregates by multipling the aggregate content with Wc.
13	Enter the water correction for superplasticizer (Vw). A negative sign is given because of the additional water brought into the mixture by the liquid superplasticizer
14	Calculate the adjusted water dosage.
15	Calculate the mass of materials in the actual mix with the actual volume of the concrete batch.