SELF-CONSOLIDATING CONCRETE INCORPORATING PALM OIL FUEL ASH AS A SUPPLEMENTARY CEMENTING MATERIAL

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DEPARTMENT OF CIVIL ENGINEERING
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ABSTRACT

This thesis presents the development of self-consolidating concrete (SCC) incorporating palm oil fuel ash (POFA) as a supplementary cementing material (SCM). Different SCC mixtures were produced based on the water/binder (W/B) ratios of 0.40, 0.50 and 0.60. POFA was incorporated in concretes substituting 0%, 5%, 10%, and 15% of normal portland cement by weight. The freshly mixed concretes were tested for filling ability, passing ability, and segregation resistance. The filling ability was determined with respect to slump flow, T_{50cm} spread time, and V-funnel flow time. The passing ability was measured with regard to J-ring flow. The segregation resistance was examined by sieve and column tests. Test results showed that the slump flow and J-ring flow decreased whereas the T_{50}cm spread time and V-funnel flow time increased with higher POFA content. The reduced slump flow and J-ring flow were still in the acceptable range. In addition, the segregation index and segregation factor obtained from sieve and column tests, respectively, decreased with greater POFA content. The hardened concretes were tested for compressive strength, ultrasonic pulse velocity, water absorption, and permeable porosity. The effects of water to binder (W/B) ratio of POFA content on the hardened properties of concrete were observed. The correlations of compressive strength with ultrasonic pulse velocity and permeable porosity were also identified. According to test results, the compressive strength and ultrasonic pulse velocity decreased while the water absorption and permeable porosity increased with higher W/B ratio. POFA was not effective in improving the hardened properties of concretes produced with the W/B ratios of 0.50 and 0.60. However, significant improvement was observed when POFA was used in concrete with the W/B ratio of 0.40. The optimum POFA content was 5% in the context of present study.

ABSTRAK

Tesis ini mempersembahkan pembangunan konkrit rata sendiri (KRT) dengan mengabungkan abu kelapa sawit (AKS) sebagai bahan tambah dalam sement. Pelbagai campuran KRT telah dihasilkan berdasarkan nisbah air/siment (A/S) 0.40, 0.50, dan 0.60. AKS telah dimasukkan kedalam konkrit 0%, 5%, 10% dan 15% daripada siment Portland berdasarkan berat. Konkrit segar telah diuji untuk kebolehan memenuhi, kebolehan melepasi dan rentangan kepada pengasingan. Kebolehan memenuhi telah ditentukan dengan aliran jatuh, T_{50cm} masa merebak, dan masa corong-V. Kebolehan melepasi diuji dengan aliran gegelung-J. Rintangan kepada pengasingan diuji dengan ujian penapis dan tiang. Keputusan ujian aliran jatuh dan aliran gegelung-J menurun manakala T_{50}cm masa merebak dan masa corong-V meningkat dengan kandungan AKS meningkat. Penurunan aliran jatuh dan aliran gegelung-J masih dalam lingkungan yang boleh diterima. Manakala indek pengasingan dan factor pengasingan yang didapati daripada ujian penapisan dan ujian tiang, berkurangan dengan kandungan AKS yang tinggi. Konkrit terkeras pula diuji dengan kekuatan mampatan, denyutan ultrasonik, penyerapan air, dan ketelapan. Kesan daripada nisbah A/S dan kandungan AKS pada sifat konkrit diperhatikan. Petalian antara kekuatan mampatan dengan denyutan ultrasonic dan ketelapan juga dikenal pasti. Berdasarkan kepada keputusan ujian, kekuatanmampatan dan denyutan ultrasonic menurun manakala penyerapan air dan ketelapan meningkat dengan peningkatan nisbah A/S. AKS tidak berkesan dalam memperbaiki sifat konkrit terkeras yang di hasilkan dengan nisbah A/S 0.05 dan 0.06. walaubagaimanapun peningkatan ketara telah dilihat apabila AKS digunakanpada concrete dengannisbah A/S 0.40. kandungan optima AKS adalah 5% berdasarkan kajian yang dijalankan.

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Mohd Hafizan Bin Md.Isa

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CHAPTER 1

INTRODUCTION

1.1. General

Self-consolidating concrete (SCC) is a special concrete that spreads by its own weight to each and every corner of a formwork without segregation and without the need for mechanical vibration. It possesses excellent filling ability, passing ability, and good segregation resistance. Therefore, SCC is a good choice for applications where placing and consolidation of normal concrete are difficult due to the complex shape of formwork and congested reinforcement. Good consolidation of fresh concrete is required for obtaining good hardened properties and durability. By using SCC, the placement and consolidation of concrete in highly congested structural members can be improved.

The SCC technology was first developed in Japan in the late 1980's (Ozawa *et al.*, 1989). Thereafter, SCC had been a topic of research and development in many countries of Asian, Europe, and North America. However, SCC requires some special ingredients such as high-range water reducer (HRWR), supplementary cementing material (SCM), and viscosity-modifying admixture. SCM is most often used with HRWR to improve the filling ability, passing ability, and segregation resistance of SCC. In addition, the use of SCM in SCC contributes to enhance the quality of hardened concrete with respect to strength and durability (Tay & Show, 1995, Tangchirapat *et al.*, 2007). The incorporation of SCM also decreases bleeding, improves workability, and reduces the heat of hydration (Hussin & Awal, 1998). The well-known industrial SCMs such as silica fume, ground granulated blast-furnace slag, and fly ash have been used successfully to produce SCC (Bouzoubaâ & Lachemi, 2001; Khayat, 2000; Okamura & Ozawa, 1994). Several researchers also developed SCC with rice husk ash, which is obtained from the agricultural waste generated in the rice milling industry (Ahmadi *et al*., 2007; Safiuddin, 2008). In comparison, the use of palm oil fuel ash (POFA) obtained from the agricultural waste of palm oil industry is limited.

The oil palm was first introduced in Malaysia in1870 as an ornamental plant, it is now a leading agricultural crop in Malaysia. The plantation agriculture has been the backbone of the Malaysian economy since the turn of the 20th century. The oil palm production is a major agricultural industry in Malaysia. However, this industry generates some agricultural wastes. There are the residues left after the palm fruit bunches are pressed at oil mills, and the oil is extracted. The empty fruit bunches (EFB) are burnt in the boilers to generate steam and electricity for the mills. EFB is a suitable raw material for generating steam and electricity for the mills because it is produced in large quantities in localized areas. Generally, after combustion about 5% palm oil fuel ash (POFA) by weight of solid wastes is produced (Sata *et al*., 2007). In practice, the POFA produced in Malaysian palm oil mills is dumped as a waste without any profitable return. It is considered as a nuisance to the environment and disposed without being put to any other use as compared to other palm oil by-products. Since the production of palm oil is increasing continuously in Malaysia, more ash will be produced and the failure to find any solution in making use of this by-product will create a severe environmental problem due to uncontrolled disposal. As a solution to the disposal problem of the ash derived from oil-palm shell, fibres and bunches, several research studies have been carried out to examine the feasibility of using POFA as an SCM (Tangchirapat *et al*., 2007; Tay & show, 1995; Chindaprasirt *et al*., 2007; Sata *et al*., 2007). The research findings showed that POFA can be used as an SCM to produce concretes.

1.2. Research Objectives

The objectives of the research were decided based on the gap in the current state of knowledge on SCC. The main objective of the proposed research was to develop SCC incorporating POFA as an SCM. The sub-objectives were as follows:

a. Investigation on the effect of POFA on the fresh properties (filling ability, passing ability, and segregation resistance) of SCC.
b. Investigation on the effect of POFA on the strength (compressive strength) of SCC.
c. Investigation on the effect of POFA on the durability properties (water absorption, permeable porosity, etc.) of SCC.
d. Non-destructive evaluation of the physical quality of SCC including POFA based on the ultrasonic pulse velocity of concrete.

1.3. Organization of Thesis

The structure of this thesis mainly consists of six chapters, a list of references, and several appendices. Each chapter covered different components of the research. The summary of each chapter is given below:

Chapter 1 is the introduction; it explains the purpose and basic ideas of the study. In this chapter, the scope of the thesis is briefly presented.

Chapter 2 is the literature review; it presents a background of SCC, describes the various constituent materials of SCC, and identifies several research needs.

Chapter 3 gives the research objectives and an overview of the methodology.

Chapter 4 gives the experimental investigation; it explains the selection of material and the experimental methods that have been used in this study.

Chapter 5 presents and discusses the test results. The discussion is made based on the analysis of all the data obtained from the experiments.

Chapter 6 provides the conclusions that had been made from the test results and discussion; some recommendations are also given to improve the methodology and for relevant future research.

CHAPTER 2

LITERATURE REVIEW

2.1. Self-Consolidating Concrete

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

2.1.1 Definition

Self-consolidating concrete (SCC) is defined as a highly workable concrete that flows easily within the formwork and therefore can be consolidated under its own weight without the need of any means of external compaction (Khayat, 1999). It has substantial commercial benefits because of ease of placement in complex forms with congested reinforcement. However, SCC must require excellent filling ability, good passing ability, and adequate segregation resistance.

2.1.2 Characteristics

SCC differs from conventional concrete with respect to its material components, mixture proportions and performance in the fresh and hardened states. SCC requires several special ingredients such as high-range water reducer (HRWR), supplementary cementing material (SCM) and viscosity-modifying admixture (VMA). SCC includes a much higher quantity of binder, lower water content, a greater fine aggregate content, and a lesser amount of coarse aggregate than ordinary concrete. HRWR is essential to achieve the required filling ability and passing ability of concrete (Safiuddin, 2008). In addition, a properly selected

SCM improves filling ability and passing ability, while maintaining adequate segregation resistance, depending on the mixture proportions of concrete (Safiuddin *et al*., 2012). When SCC suffers from segregation due to low viscosity, a suitable VMA can also be used to improve the segregation resistance of concrete (EFNARC, 2002).

The workability characteristics of SCC are significantly different than those of normal concrete. The flowing ability (filling ability and passing ability) of SCC are much better than those of normal concrete due to self-compact ability. However, SCC is more prone to segregation than normal concrete due to high fluidity (EFNARC, 2002). Furthermore, the performance of hardened SCC is better than normal vibrated concrete because of higher degree of compaction, lower water/binder (W/B) ratio, and greater hydration in the presence of HRWR and SCM.

2.1.3. Advantages

SCC had been a topic of research and development in many countries of Asia, Europe and North America. There are many advantages of using SCC. Some of the advantages are as follows:

- Reduction in the construction time and labour cost
- Elimination of the need for vibration equipment
- Reduction in the noise pollution and provision of better working environment
- Improvement of the placement of concrete in highly congested structural members
- Ease in the constructability of intricate concrete structures.
- Improved concrete placement operations and increased construction ability
- Longer life of the formwork due to the elimination of vibration equipment

- Saving of a large quantity of concrete due to the reduced section of structural components.
- Good finishing without any surface pores and improved aesthetical appearance of concrete.
- Placement of a large amount of reinforcement in small sections.

2.2. Background of Self-Consolidating Concrete

Japan had started producing and using SCC commercially in the early 1990's. The concept of SCC was proposed in 1986 by Professor Okamura (Okamura & Ouchi, 2003). The first prototype of SCC was developed in Japan in 1988 by Professor Ozawa (Ozawa *et al.*, 1989). Since that discovery, most of the large construction in Japan used SCC (Okamura & Ouchi, 2003). Later the concept of SCC spread to the other countries of Asia as well as to Europe and North/South America. "Rational Production and Improved Working Environment through Using Self-compacting Concrete" had been formed in 1996 in several European countries. This project was aimed at investigating the significance of published achievements in SCC and to expand potential applications of SCC.

2.3. Materials Aspects for Self-Consolidating Concrete

Self-consolidating has the same basic materials as conventional concrete such as cement, aggregates and water. In addition, SCM, HRWR and VMA are used for producing SCC. SCM significantly improves the hardened properties. HRWR is essential in order to get the targeted workability properties of fresh SCC. VMA is suggested for use to improve the segregation resistance of SCC.

2.3.1. Coarse aggregate

The aggregates retained on the 4.75 mm (No.4) sieve are defined as coarse aggregates (ASTM C 125, 2002). Coarse aggregates significantly influence the performance of SCC by affecting the flowing ability, segregation resistance, and strength of concrete (Noguchi *et al*. 1999; Okamura & Ozawa, 1995, Xie *et al*., 2002). The spacing of reinforcement plays the important role in determining the maximum aggregate size in any given SCC application. However, the smaller the maximum coarse aggregate size, the easier it is to successfully make SCC and the more spherical the aggregate particles the better their filling and passing ability and the less likely they are to blockage (NCMA, 2007). The shape and particle size distributions of coarse aggregate contribute to produce the optimum mixture with the least particle interference, enhance the flowing ability, and reduce the tendency of segregation in fresh concrete (Neville, 1996). The spherical aggregate particles reduce the internal friction, cause less blocking, and thus give a better flow in fresh concrete. However, the interlocking of the angular particle in crushed aggregates tends to improve the strength although it reduces the flowing ability of SCC (Al-Mishhadani & Al-Rubaie, 2009).

2.3.2. Fine aggregate

Sand is the most commonly used fine aggregate for concrete. Fine aggregates pass the 4.75 mm (No. 4) sieve but are retained on the 75 µm (No. 200) sieve (ASTM C 125, 2002). The influence of fine aggregates on the fresh properties of the SCC is significantly greater than that of coarse aggregate (SCCEPG, 2005). They increase the flowing ability and segregation resistance when used at a suitable amount (Okamura & Ozawa, 1995; Su *et al*., 2002). All types of concreting sand, either crushed or rounded are suitable for producing

SCC. However, the sharp and angular fine aggregates are not beneficial to the flowing ability of SCC, since they increase the viscosity of mortar phase (Westerholm, 2006). This condition can be minimized using increased HRWR dosage and reduced fine aggregate content.

2.3.3. High-range water reducer

High-range water reducer is an essential component of SCC. There are mainly four categories of HRWR (Neville, 1996). They are sulfonated melamine-formaldehyde condensates, sulfonated naphthalene-formaldehyde condensates, modified lignosulfonates, and carboxylated acrylic ester copolymers or polycarboxylates (Chandra and Bjornstorm, 2002).

High-range water reducer improves the flowing ability (filling ability and passing ability) of SCC. The addition of HRWR breaks the cement flakes, releases the entrapped water and causes a better dispersion of cement particles, thereby producing the cement paste of higher fluidity. Figure2.1 shows the mode of action of the newest generation of polycarboxylate-based HRWR containing polyethyleneoxide (PEO) graft chains (PEO side**).** This type of HRWR works based on the sterichindrance effects that result in the particle separation due to movement of long molecules. The water reductions up to 40% are possible when a polycarboxylate-based HRWR is used in concrete (Moser, 2002).

The traditional HRWR such as sulphonatednaphtalene works by inter-particle repulsion and produces a water reduction up to 20% (Moser, 2002). The mode of action of the traditional HRWR is shown in Figure 2.2.

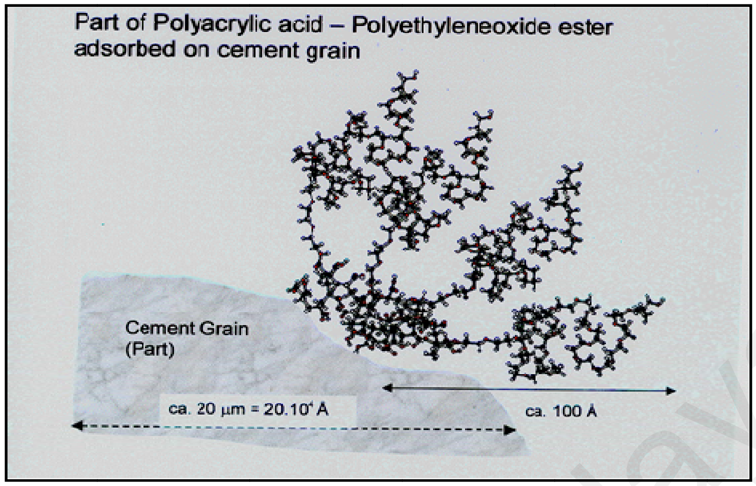


Figure 2.1: Mode of Action for Polycarboxylate-based HRWR (Moser, 2002)

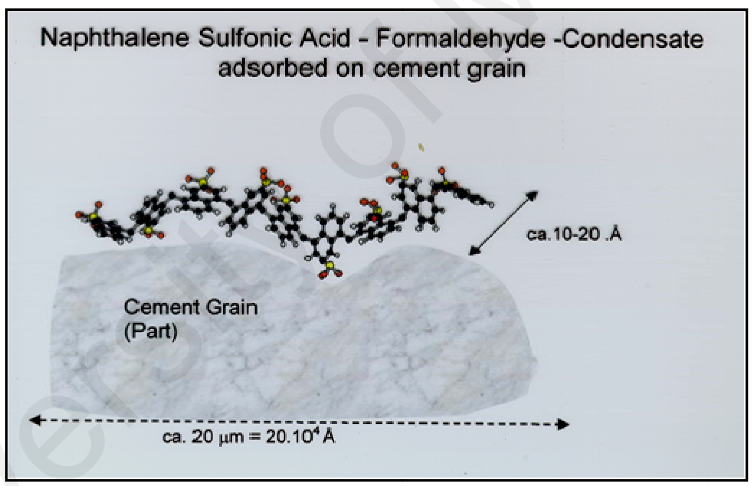


Figure 2.2: Mode of Action for Naphthalene-based HRWR (Moser, 2002)

2.3.4. Viscosity-enhancing admixture

Viscosity-modifying admixture (VMA) is commonly used in SCC as a chemical admixture, which helps to improve the viscosity and cohesion in fresh SCC. There is a new generation of admixture that functions simultaneously as HRWR and VMA.VMA reduces the bleeding, surface settlement and aggregate sedimentation, and gives more uniform and stable fresh concrete (Khayat & Guizani, 1997). VMA plays the same function as the fine particles. It lowers the coarse aggregate segregation and minimizes bleeding by thickening the paste and retaining the water.

2.3.5. Supplementary cementing materials

Industrial and agricultural wastes such as ground granulated blast-furnace slag, fly ash, rice husk ash and POFA are used in concrete as an SCM. Supplementary cementing materials possess cementitious or both cementitious and pozzolanic properties. According to ACI Committee 232 (2003), a pozzolan (poozolanic SCM) is defined as "a siliceous or siliceous and aluminious material which in itself possesses little or no cementitious value but in the presence of moisture, chemically reacts with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties". Pozzolan is a natural or artificial material containing silica in a reactive form apozzolanic SCM reacts with calcium hydroxide liberated during cement hydration (pozzolanic reaction), and thus produces a product with cementitious properties. Most supplementary cementing materials used in concrete are pozzolanic in nature. The pozzolanic activity of an SCM depends on its physical characteristics and silica content. The silica has to be amorphous for high pozzolanic activity because the crystalline silica has low reactivity. Firas *et al*., (2000) commented that the reactivity of a pozzolanic material depends on its particle size and surface area as well as on its mineralogical composition. Hence, the SCMs containing larger proportions of amorphous silico-aluminates, and having particles of smaller mean diameter and higher specific surface area exhibit greater pozzilanic activity.

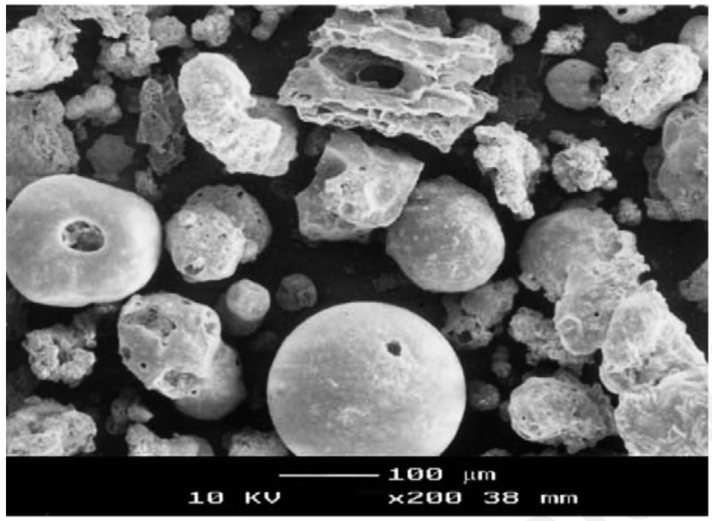
The use of SCM in concrete contributes to enhance the quality of concrete with respect to strength and durability (Tay & Show, 1995; Tangchirapat *et al*., 2007). Incorporation of SCM also decreases bleeding, improves workability, and reduces heat of hydration (Hussin & Awal, 1998). Ground granulated blast-furnace slag, fly ash, rice husk ash, silica fume, and volcanic ash are known to significantly enhance the concrete strength due to their pozzolanic effect. The presence of SCM contributes in producing additional hydration products to fill-up the voids in bulk cement paste. When an SCM is added, calcium hydroxide ($Ca(OH)_2$) is transformed into additional calcium silicate hydrate (C-S-H) gel and large pores are changed into finer pores. It therefore forms a basis for improvement of strength and durability of concrete.

2.3.5.1. Palm oil fuel ash

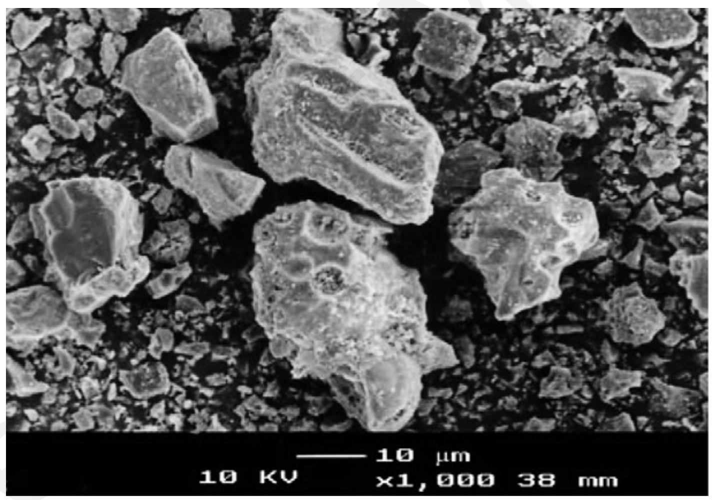
Palm oil fuel ash (POFA) is obtained as an agro-waste from palm oil industry. In palm oil mills, the palm fruit bunches are pressed to extract the oil. The empty fruit bunches (EFB) are burnt in the boilers to generate steam and electricity for the mills. EFB are a suitable raw material for generating steam and electricity for the mills because they are produced in large quantities in localized areas. Generally, about 5% POFA by weight of solid wastes is produced after combustion of EFB (Sata *et al*., 2007). In practice, the POFA produced in Malaysian palm oil mills is dumped as a waste without any profitable return. It is considered as a nuisance to the environment. Since the production of palm oil is increasing continuously in Malaysia, more POFA will be produced and the failure to find any solution in utilizing this waste will create a severe environmental problem due to uncontrolled disposal. As a solution to this problem, several research studies were carried out to examine the feasibility of using POFA as an SCM (Tangchirapat *et al*., 2007; Tay & show, 1995; Chindaprasirt *et al*., 2007; Sata *et al*., 2007). The research findings showed that the properly processed POFA can be used as an SCM to produce concrete. It is found that the incorporation of POFA as an SCM can improve many properties of hardened concrete. This is because the reaction of SiO_2 from POFA and calcium hydroxide from cement hydration (pozzolanic reaction) produces additional calcium silicate hydrate that contributes to improvement in the strength and durability of concrete.

The physical properties of POFA largely depend on burning condition relating to the operating system in palm oil mill. POFA generally is greyish in color that becomes darker due to unburnt carbon content. However, the ash can also be whitish in the absence of unburnt carbon due to complete combustion of the fuel (Awal & Hussin, 1997). The particle shape and size of POFA depend on grinding condition. The scanning electron microscopy (SEM) analysis shows that the size and shape of ground and unground POFA are significantly different. Ground POFA consists mainly of fine irregular-shaped particles as shown in Figure 2.3(b) whereas unground POFA particle is mostly large and spherical, and possesses a porous texture as shown in Figure 2.3(a).

Tay (1990) used unground POFA as an SCM and discovered that POFA should not be used as cement replacement for more than 10% by weight due to its low pozzolanic property. However, Tonnayopas *et al*. (2006), Chindaprasirt *et al*. (2007), Hussin and Ishida (1999), and Hussin and Awal (1998) used ground POFA in their research works and found that it can be used up to 30% as cement replacement. The POFA fineness is one of the contributing factors for pozzolanic reaction in concrete. Some researchers had been grinding the POFA to reduce the particle size by using Los Angeles abrasion machine. There are two different methods for grinding POFA, one of which is by using steel ball (Sata *et al*., 2007; Tangchirapat *et al*., 2007) and the other is by using mild steel bar (Abdullah *et al*., 2006; Awal & Hussin, 1999). But whatever methods are used, the purpose is to reduce the particle size of POFA so that it becomes finer than OPC.



(a) Original/unground palm oil fuel ash



(b) Ground palm oil fuel ash

Figure 2.3: Scanning electron microscopy (SEM): (a) unground POFA (b) Ground POFA (Jaturapitakkul *et al*., 2007)

The ground POFA has also greater microfilling ability than the unground POFA. The ground POFA is finer than cement and therefore it contributes to increase the strength due to its microfilling ability. The particle size distribution of POFA (original/unground and ground) and OPC are shown in Figure 2.4. The original POFA is larger than OPC, but ground POFA is smaller than OPC. According to Tangchirapat et al. (2007), the finer the POFA, the greater is the strength development.

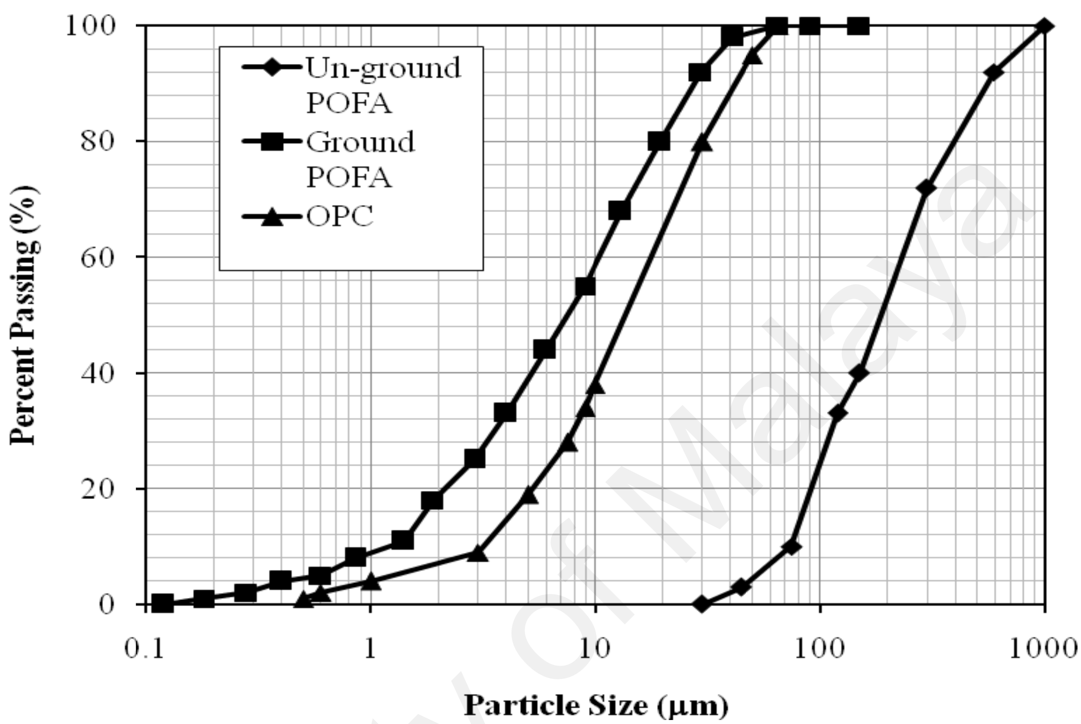


Figure 2.4: Particle size distribution of OPC and POFA (adapted from Tangchirapat *et al.*, 2007)

The published literature shows that the fresh and hardened properties as well as the durability of concrete are improved in the presence of POFA. For example, POFA provided significant improvements in workability, compressive and splitting tensile strengths, and durability of normal and high strength concretes (Hussin and Awal, 1998; Tay & show, 1995; Chindaprasirt *et al.*, 2007; Sata *et al.*, 2007; Tangchirapat *et al*., 2007). The compressive strength of the concrete containing POFA was higher than that of OPC concrete. This is mostly attributed to the good pozzolanic properties of POFA. In a study by Tonnayopas *et al*. (1990), the chemical analysis of the POFA was carried out in accordance with ASTM C 311 (2002). The result indicated that POFA has a good pozzolanic activity.

The partial replacement of cement or the substitution of any other SCM by POFA reduces the cost of concrete production. Also, the use of POFA lowers the demand for cement in construction industry, and thus reduces the cost of cement production and lessens the environmental pollution caused by cement factories. Hence, POFA not only improves concrete properties and durability, but also provides substantial economic and environmental benefits.

2.4. Mixture Design for Self-Consolidating Concrete

In Japan, the most widely used mixture design for SCC was proposed by Okamura and Ozawa (1995). Limiting the coarse aggregate to 50% of the solid volume and the fine aggregate to 40% of the mortar volume, SCC can be achieved by adjusting the W/B ratio and HRWR dosage. Figure 2.5 shows the Okamura and Ozawa's mixture design. Okamura and Ozawa's mixture design method has also been used in many countries of Europe with some modifications (EFNARC, 2002; SCCEPG, 2005).

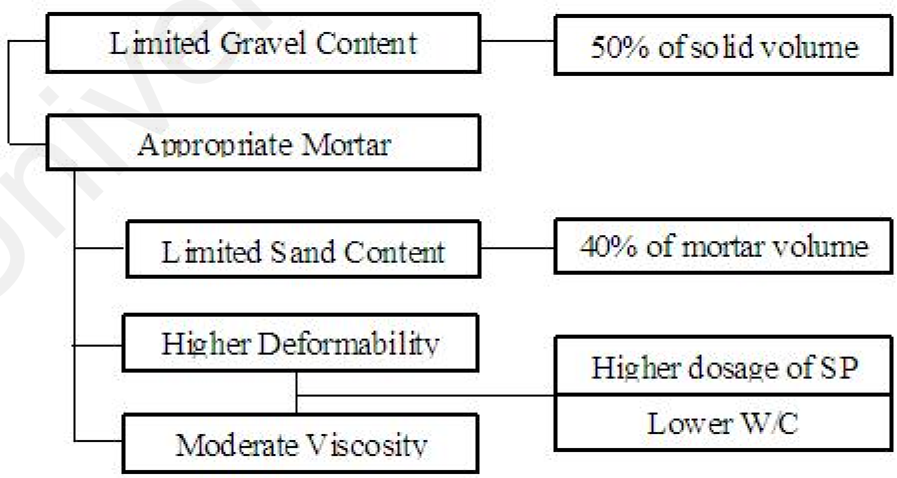


Figure 2.5: Okamura and Ozawa's mixture design (Okamura and Ozawa, 1995)

Saak et al. (2001) has developed a mixture design method by using the concept of rheological self-flow zone (SFZ). In Taiwan, Su *et al*., (2001) has developed a mixture design methodology based on the concept of aggregate packing factor. By using this method, the amount of SCM and the dosage of HRWR that need to be used in the mixture can be determined even though they may need to be adjusted by trial mixtures. The other design method that incorporates VMA is proposed by the Japan society of Civil Engineer (JSCE). The proportions of different constituent materials as specified for the SCC mixtures with and without VMA are shown in Table 2.1.

Table 2.1 JSCE recommendation (Uomoto & Ozawa, 1999)

Mix property	SCC without VMA	SCC with VMA
Coarse aggregate content(maximum size 20 or 25 mm)	0.30 ~ 0.32 m^3/m^3	0.30 ~ 0.32 m^3/m^3
Water content	155 ~ 175 kg/m^3	≤ 180kg/m^3
Water/powder ratio	28 ~ 37 % by weight	Depend on the type and content of VMA
Powder content	0.16 ~ 0.19 m^3/m^3	
Air content	4.5%	4.5%

The International Center for Aggregates Research (ICAR) (Koehler and Fowler, 2006) in Texas, USA had also developed a mixture proportioning procedure for SCC. This mixture design procedure is based on the assumption that SCC has a suspension of aggregate in paste. Aggregate content, paste volume, and paste composition are altered so it can satisfy the criteria of filling ability, passing ability and segregation resistance.

2.5. Testing of Self-ConsolidatingConcrete

Testing of SCC includes the testing of both fresh and hardened concretes. The testing of hardened concretes includes both destructive and non-destructive tests. Among various destructive tests, the compression test is of great importance. The non-destructive testing includes tests for ultrasonic pulse velocity, porosity, absorption, permeability, etc.

The test methods used for ordinary concrete can also be employed for SCC to determine hardened properties. For testing the fresh properties of SCC, the test methods of ordinary concrete are not suitable due to dissimilar workability characteristics. However, several tests have been developed to evaluate the performance of fresh SCC. ASTM has standardized the slump flow test (ASTM C 1611/C 1611M, 2009), though V-funnel flow test has been used to determine the filling ability of SCC (EFNARC, 2002). ASTM has also standardized the J-ring to measure the passing ability of SCC (ASTM C 1621/C 1621M, 2009). The segregation resistance is mostly being measured by standard No. 4 sieve (EFNARC, 2002; Nagataki & Fujiwara, 1995) and column apparatus (Assaad *et al*., 2004; Sonebi, 2004). The ASTM has also standardized a column apparatus for testing the segregation resistance of SCC (ASTM C 1610/C 1610M, 2009).

2.6. Key Fresh Properties of Self-Consolidating Concrete

The key fresh properties of SCC are the three basic characteristics: filing ability, passing ability and segregation resistance. They are briefly discussed below.

Filling ability – the property that determines how fast SCC flows under its own weight and completely fills intricate spaces with obstacles, such as reinforcement, without losing its stability.

Passing ability – the property that defines the ability of SCC to pass through congested reinforcement without the application of external energy.

Stability – the ability of SCC to remain homogenous by resisting segregation, bleeding, and air popping (when the concrete is air-entrained) during transport and placement, and after placement.

2.6.1. Filling ability

Filling ability is defined as the ability of the concrete to spread by its own weight to each and every corner of a formwork. The filling ability is the main parameter for SCC. In order to obtain adequate filling ability, it is important to minimize the friction between the solid particles of the mixture. A reduction in the coarse aggregate content and an increase in the paste volume are required to achieve the desired filling ability (Khayat, 1999). Another way to achieve the target filling ability is by incorporating a suitable SCM, while adding a proper dosage of HRWR. Polycarboxylate based HRWR is commonly used in SCC mixture.

The higher HRWR dosage and greater mortar volume will reduce the yield strength and provide higher slump flow of concrete (Safiuddin, 2008). In general, a lower yield strength decreases the segregation index of concrete. Rols et al. 1997, Lachemi et al. 2003 also had been reported that the slump flow spread or horizontal spread of concrete will be influence the segregation index of the concrete.

Three classes of filling ability can be selected for SCC based on the slump flow requirement (SCCEPG, 2005).The typical slump flow values range from 550 to 850 mm although the values up to ±50 mm than this range have been used for many applications. The levels of filling ability are explained in Table 2.2.

Table 2.2: Levels of filling ability (SCCEPG, 2005)

Level	Slump flow (mm)	Description
Level 1	550 – 650	Suitable for concrete structure that are unreinforced or slightly reinforced for example housing slab, it also can be used for tunnel linings that been cast by a pump injection system and for a small section such as piles and deep foundation.
Level 2	660 – 750	Suitable for many normal applications such as walls, columns
Level 3	760 – 850	Suitable for very congested structure and complex shape typically used for vertical applications with a small maximum size of aggregates.

2.6.2. Passing ability

Passing ability is defined as the ability of fresh SCC to flow through tight openings, such as space between steel reinforce bars, under its own weight (EFNARC, 2002). Passing ability is influenced by the filling ability and the maximum aggregate size. The low maximum size of coarse aggregate should be used to improve the passing ability of SCC. Two levels of passing ability can be classified for SCC depending on the type or purpose of use (SCCEPG, 2005).

Table 2.3: Levels of passing ability (SCCEPG, 2005)

Level	Description	Example
Level 1	• Structures with a gap of 80 mm to 100 mm	Housing, vertical structures
Level 2	• Structures with a gap of 60 mm to 80 mm	Civil engineering structures

2.6.3. Segregation resistance

The segregation resistance of SCC refers to its ability to remain uniform throughout the process of transportation and placing. Adequate cohesiveness can be obtained by incorporating a viscosity-modifying admixture (VMA) along with HRWR to control bleeding, segregation, and surface settlement (Khayat, 1999). Another approach to obtain a good segregation resistance in SCC is by reducing the W/B ratio with increased amount of cementing materials.

Segregation resistance becomes an important parameter for the SCC with a higher slump-flow class and/or the lower viscosity class, or if the placing conditions promotes segregation. Two level of segregation resistance are shown in Table 2.4.

Table 2.4: Levels of segregation resistance (SCCEPG, 2005)

Level	Description
Level 1	• Generally applicable for thin slabs and for vertical applications with a flow distance of less than 5 m and a confinement gap greater than 80 mm
Level 2	• Vertical applications if the flow distance is more than 5 m with a confinement gap greater than 80 mm in order to take care of segregation during flow • Tall vertical applications with a confinement gap of less than 80 mm if the flow distance is less than 5 m but if the flow is more than 5 m a target SR value of less than 10% is recommended • A target value may be specified if the strength and quality of the top surface is particularly critical

2.7. Key Hardened Properties of Self-Consolidating Concrete

Compressive strength, ultrasonic pulse velocity, porosity and absorption are some of the key hardened properties of SCC. They are briefly discussed below.

2.7.1. Compressive strength

Compressive strength is the most important mechanical property of concrete. SCC usually provides a slightly higher compressive strength than the traditional vibrated concrete when both concretes are produced using the same W/B ratio. This is because SCC achieves more compact ability than ordinary concrete due to very high workability. In addition, the binder content of SCC for a given W/B ratio is generally higher than that of a traditional mix for the same application.

2.7.2. Ultrasonic pulse velocity (UPV)

Ultrasonic pulse velocity (UPV) is the traversed distance of the pulse or sonic wave per unit transit time. This is obtained from the path length and transit time. This method is commonly used to predict the quality of concrete in place. The UPV method is also known as the transit time method, as it uses a detector to determine the time of flight that is attained from an ultrasonic pulse to pass through an identified thickness of solid material. Direct and indirect ultrasonic transmissions are the two methods commonly used to assess the properties of concrete. Direct transmission is defined as the propagation of ultrasonic stress waves along a straight-line path between the opposite surfaces of a specimen. This test is appropriate for use in laboratory work. On the other hand, the access to opposite surfaces of a component may not be available in the field. In these cases, indirect test method can be used. This test is defined as the propagation of ultrasonic stress waves between points that are located on the same surface of the material.

Ultrasonic pulse velocity is related to the quality of concrete. High UPV value indicates that the concrete is in good quality, in general. Based on Neville's classification (Neville, 1996), when the pulse velocities of the concrete obtained are in excess of 4.5

km/s, they could be conceived as of ‘excellent’ quality and below 2.14 km/s reveals ‘very poor’ condition of concrete.

2.7.3. Porosity

Porosity is a fraction of total concrete volume that is occupied by the pores in bulk cement paste, interfacial transition zone and aggregates. The porosity of concrete can be characterized into two forms – total and capillary or suction porosity. The total porosity is mainly comprised of air voids and capillary pores. In contrast, the network of open pores mainly constitutes the capillary porosity of concrete (Safiuddin, 2008).

Porosity has a major effect on the strength and transport properties of concrete. The porosity including a greater amount of connected pores produces more effect on the transport properties. It is the interconnectivity of pores, rather than total porosity that determines a concrete’s permeability. A concrete with a high proportion of disconnected pores may be less permeable than a concrete with a much smaller proportion of connected or continuous pores. Hence, the porosity of concrete should be determined properly in order to predict the durability and serviceability of concrete structures.

Due to good consolidation, the higher degree of packing is achieved in SCC. The greater hydration due to deflocculation and dispersion of cement particles in the presence of HRWR and the micro-filling and pozzolanic effects of SCM contribute to forming the refined pore structure in concrete. As a result, an SCC generally has a lower porosity than ordinary or conventional concrete when prepared with the same W/B ratio.

2.7.4. Absorption

Absorption occurs when a liquid penetrates and gets into the open pores of the concrete. Water had been used to determine the water absorption of concrete. It can be determined by using a simple method by measuring the concrete weight before and after immersion in water. Upon immersion in water, the water will fill the open pores and will increase the concrete weight. The water absorption of concrete is influenced by the porosity. Tay and Show (1995) concluded that higher unground POFA increases the water absorption; this is because the concrete with higher unground POFA contains higher porosity. But by using ground POFA, the water absorption can be decreased due to micro-filling ability and pozzolanic activity leading to a pore refinement.

2.8. Research Needs

POFA can be used in concrete with good improvement in fresh and hardened properties. Since the cost involved in using POFA is almost zero, the partial replacement of cement or the substitution of any other SCM by POFA will reduce the cost of concrete production. Also, the use of POFA will lower the demand for cement in construction industry, and thus will reduce the cost of cement production and lessen the environmental pollution caused by cement factories. Hence, POFA not only will improve concrete properties and durability, but also will provide substantial economic and environmental benefits. The use of POFA in SCC will therefore be a novel approach in the context of Malaysia. In this context, the following research needs have been identified for further investigation to encourage the use of POFA in SCC:

- Proper classification of POFA as an SCM for concrete.
- Investigation on the potential use of POFA to produce self-consolidating concretes.

- Investigation of the effects of POFA on the rheological properties (yield stress and plastic viscosity) of concrete.
- Investigation of the effects of POFA on the workability characteristics of highly flowing or self-consolidating concrete.
- Investigation of the effects of POFA on the physical properties (porosity, ultrasonic pulse velocity, etc.) of concrete.
- Investigation of the effects of POFA on the mechanical properties (compressive strength) and transport or durability-related properties (water absorption, permeability, etc.) of concrete.

CHAPTER 3

EXPERIMENTAL INVESTIGATION

3.1. Introduction

The aim of the experimental investigation was to examine the suitability of component materials and to observe the performance of various fresh and harden self-consolidating concretes (SCC). The concretes contained OPC as the main cementing material and palm POFA as an SCM. This chapter discusses different tests for constituent material properties, and fresh and hardened properties of SCC.

3.2. Methodology

Various SCCs were produced through selection and testing of materials, preparation and testing of fresh concretes and preparation and testing of hardened concretes. The overall methodology is shown in the flowchart given in Figure 3.1.The following systematic procedure was followed to carry out the research on SCCs incorporating POFA:

Step 1: The physical and chemical properties of the concrete constituents such as OPC, POFA, fine aggregate, coarse aggregates and HRWR were studied. In addition, various microanalysis studies, such as scanning electron microscopy (SEM), particle size distribution, X–ray fluorescence (XRF), and nitrogen adsorption (BET) test were conducted on OPC and POFA.

Step 2: The mixture proportions were calculated based on the guidelines given in EFNARC and DOE mix design methods.

Step 3: A number of SCC mixtures with different dosages of HRWR were prepared on trial basis to obtain the proper dosage of HRWR for the concrete mixtures.

Step 4: The fresh concretes were tested for filling ability, passing ability, and segregation resistance. The slump flow, T_{50cm} slump flow spread time, and V-funnel flow tests were conducted to measure the filling ability of concrete. The J-ring test was conducted to measure the passing ability of concrete. Moreover, the column and sieve stability tests were carried out to measure the segregation resistance of concrete.

Step 5: Iteration was made by changing the mixture proportions and re-testing the fresh concretes to achieve the required fresh properties of SCC.

Step 6: After achieving the targeted fresh properties, the fresh concretes were cast in the specified metal molds. Then the hardened concrete samples were de-molded and curedin water.

Step 7: The hardened concretes were tested to determine compressive strength, ultrasonic pulse velocity, water absorption, and permeable porosity.

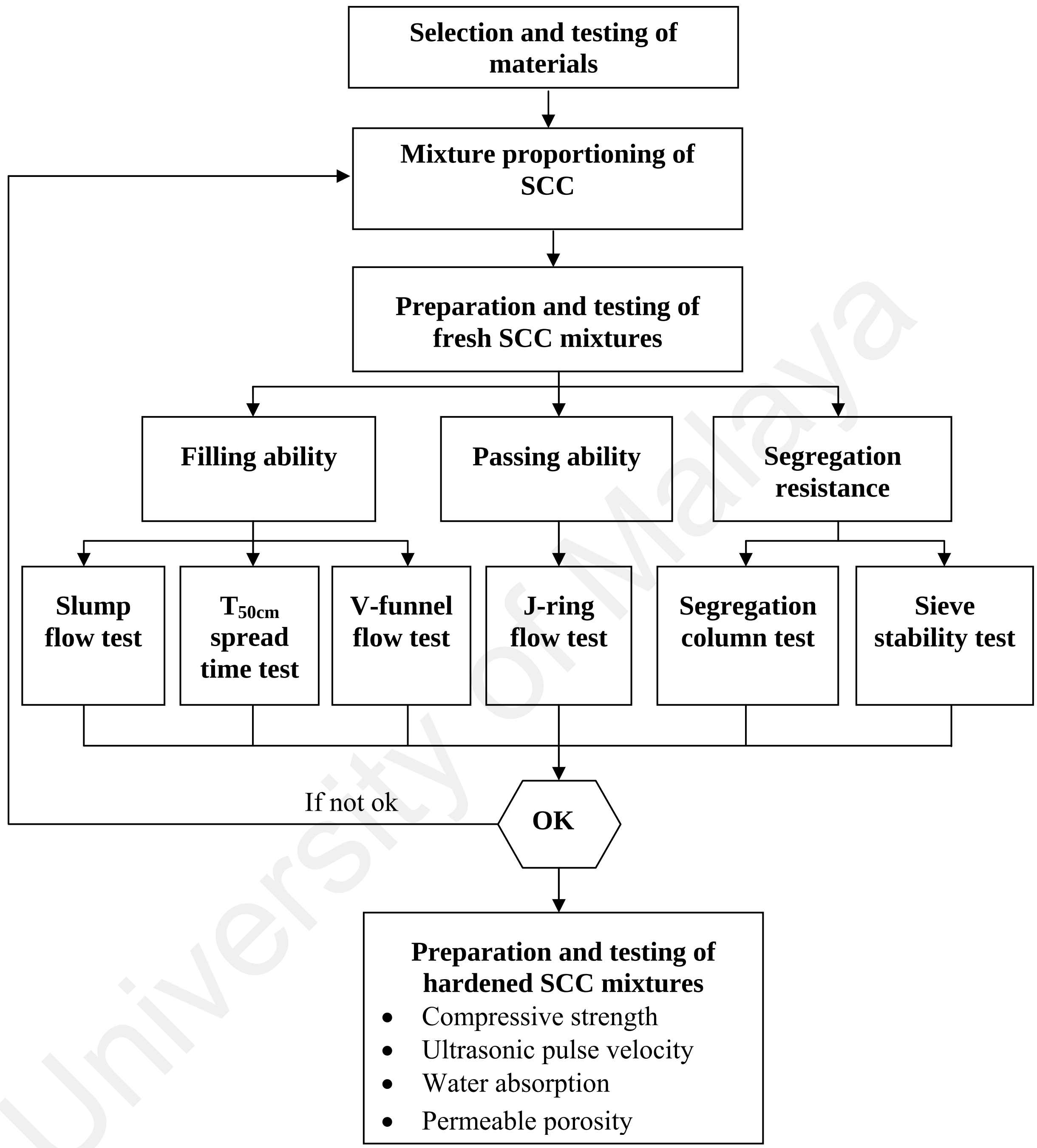


Figure 3.1: Overall research program

3.3. Materials

Normal (ASTM Type I) portland cement, crushed granite stone, mining sand, POFA, tap water, modified polycarboxylate based high-range water reducer (HRWR) were used in the present study to produce SCC.

3.3.1. Ordinary portland cement

Ordinary portland cement (OPC) of ‘Cap Buaya’ brand from Tasek cement Sdn. Bhd (Figure 3.2) was used. The OPC complied with the Type I portland cement as in ASTM C 150 (2004) specifications. OPC is supplied by Lafarge Cement Sdn. Bhd. and certified to MS 522 (2003). The same batch of OPC is used throughout the study to obtain consistent results. The OPC was stored in an airtight steel drum in order to maintain its quality and to exclude moisture at all times. Basically, the portland cement consists of lime, silica, alumina and iron oxide. Four compounds are regarded as the major constituents of cement, which are tricalciumsilicate (C_3S), dicalciumsilicate (C_2S), tricalciumaluminate (C_3A) and tetracalciumaluminoferrite (C_4AF). The composition of OPC is given in Table 3.1. This table shows the oxide composition limits of OPC.

Figure 3.2: Ordinary portland cement (OPC)

Table 3.1: Composition of ordinary portland cement

Oxide	Content (%)
Calcium oxide (CaO)	60 – 67
Silicon dioxide (SiO_2)	17 – 25
Aluminium oxide (Al_2O_3)	3 – 8
Ferric oxide (Fe_2O_3)	0.5 – 6.0
Magnesium oxide (MgO)	0.5 – 4.0
Alkali, Sodium oxide (Na_2O)	0.3 – 1.2
Sulphur Trioxide (SO_3)	2.0 – 3.5

3.3.2. Palm oil fuel ash

POFA was collected from an oil mill located in Sungai Buloh, Selangor. POFA was used as an SCM. The sample was in powder form with a grey colour. The raw POFA (Figure 3.3) collected from the mill was sieved through 400 µm sieve to remove foreign materials. Then the raw POFA was ground in Los Angeles abrasion machine (Figure 3.4) to obtain the required level of fineness. Forty mild steelrods of 10 mm diameter and 500 mm length were placed into the rotating drum to grind approximately 4 kg of raw POFA per batch. The ground POFA (Figure 3.5) was then stored in an airtight container.

3.3.3. Aggregates

Coarse aggregate used during the experiment was crushed granite stone with the maximum size of 20 mm. It was angular in shape and had a rough surface texture. In this study, coarse aggregate obtained from a quarry at Selangor region was used. The crushed granite was kept inside the laboratory which is sheltered from rain or other humid source. Thus it was ensured that the moisture content does not vary in each casting. To get coarse aggregate with the maximum size of 20 mm, a 20 mm sieve (Figure 3.6 (a)) was used to remove the unwanted materials such as leaves, branches of tree and large size of aggregate. Then, it was dried in the open air for not less than 24 hours. It was to prevent the moisture content in the aggregate affecting the concrete production.

Several tests were done to determine the properties of coarse aggregate. They were sieve analysis, specific gravity, and water absorption.

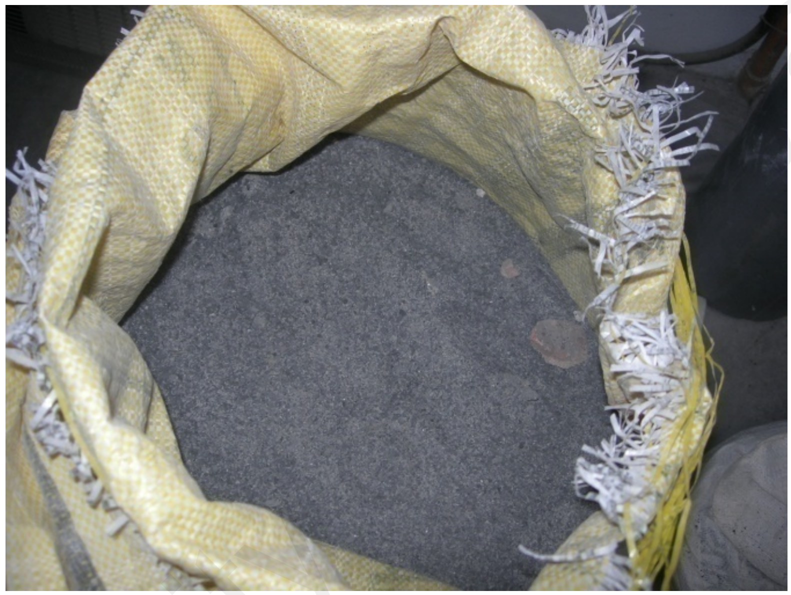


Figure 3.3: Raw palm oil fuel ash

Figure 3.4: Los Angeles grinding machine

Figure 3.5: Ground palm oil fuel ash

The fine aggregate used in the experiment was the mining sand. The sand was stored in a shaded area and sheltered from rainwater to ensure that the sand had no surface moisture. After sieving to get the maximum size of 4.75 mm (Figure 3.6 (b)), the fine aggregate was dried at room temperature.

Several tests were conducted to determine the properties of fine aggregate which include specific gravity, water absorption, and sieve analysis.

(a)

(b)

Figure 3.6: (a) Coarse aggregate with 20 mm sieve; (b) Fine aggregate with 5 mm sieve

3.3.4. High-range water reducer

High-range water reducer (HRWR) or superplasticizer (SP) was used in this study as a chemical admixture to produce SCC mixtures. The chemical admixture used was Sika viscocrete-2088 (Figure 4.7), which is a modified polycarboxylate-based HRWR. It is available in brown colour and meets the requirements of ASTM C 494/C 494M (2004) Type A and F. The relative density, solid content and pH of HRWR were 1.06 kg/l, 13.5% and 6.5, respectively.

The normally recommended dosage rate is 0.5 to 2.0 % of binder. The SP was diluted into water before mixing with the concrete. To ensure proper handling and storage of materials, the SP was stored in a cool and dry area with temperature range of 5–30^{0}C.

Figure 4.6: High-range water reducer (Sika viscocrete-2088)

3.3.5. Water

The normal tap water was used as the mixing water for preparing the concretes. It is important to ensure that the water used for mixing is free from components or particles that may adversely affect the workability, strength, and quality of the concrete. The tap water was also used for curing of the concrete. The water in a curing tank was renewed every month to ensure that the curing water is clean and does not have excessive dirt. The ambient temperature of the water was approximately $24 \pm 1^{o}C$.

3.4. Preparation of Fresh Concretes

3.4.1. Batching procedure

Fresh concretes were prepared based on the adjusted mixture proportions. The constituent materials were batched by weight and mixed in a pan-type mixer. The batch volume was calculated taking the quantity of fresh concrete at least 15% more than the required in order to compensate the loss during mixing, sampling, testing of fresh concrete, and moulding of test specimens.

3.4.2. Mixing method

The fresh concretes were prepared using a pan-type mixer. At first, fine and coarse aggregates were mixed for 1 minute with the first one-third of the mixing water. Then the binding materials (cement alone or cement with POFA) were added with the second one-third of the mixing water including the one-third of HRWR, and the mixing was continued for 2 minutes. Later, the concrete materials were mixed for 2 more minutes with the addition of the two-third HRWR dispensed in the remaining one-third of the mixing water. The total mixing time for all concrete mixtures was 5 minutes.

3.5. Testing for Materials Properties

3.5.1. Testing for cementitous materials

Cementitous materials were tested for specific surface area, wet sieve fineness, and specific gravity. Other tests such as particle size distribution, scanning electron microscopy, and chemical analysis by X-ray fluorescence (XRF) method were also conducted to determine the physical/chemical properties of OPC and POFA.

Table 3.2: Physical tests for cementitous materials

Type of Test	Method
Specific Surface Area	Blaine air permeability and nitrogen absorption (BET) tests were conducted for both OPC and POFA. The Blaine test was carried out according to ASTM C 204 (1996)
Wet Sieve Fineness	POFA and OPC were tested to determine the percentage retained on 45 micron sieve in accordance with BS 3892: Part 1: 1982
Specific Gravity	Both OPC and POFA were tested to determine their specific gravity according to BS 1377: Part 2: 1990

3.5.1.1. Surface fineness

Since the sieve test gives no information on the size of grains smaller than 45 µm sieve, the surface fineness tests (Blaine and nitrogen adsorption (BET) tests) were carried out for determination of the specific surface area cementitious materials. The Blaine air test is a method for determining the fineness of cement or other materials based on the air permeability of a sample prepared under specific condition. The apparatus used was an air-permeability apparatus for measuring the surface area of ground cement. The Blaine fineness, determined by the Blaine air permeability apparatus and procedure, refers to the fineness of granular materials expressed as a total surface area per unit weight. The Blaine fineness number does not adequately characterize the effect of particle surface characteristics on concrete properties.

This test method covers determination of the fineness of hydraulic cement in terms of specific surface expressed as total surface area in square centimetres per gram, or square meter per kilogram of cement. This test method is known to work well with portland cements. In this method, the specific surface is calculated using Equation 3.1.

Specific Surface, $S = S_2\left(\frac{\sqrt{T_1}}{\sqrt{T_2}}\right)$ Equation 3.1

Where,

S_2 = calibrated specific surface of standard sample (3640 cm^2/g)

T_1= calibrated time interval from second to third mark (92.5s)

T_2= time interval from second to third mark for the test sample

In the determination of the specific surface area, the nitrogen absorption method test (BET) was also applied for both OPC and POFA. This method is suitable to determine the specific surface of pozzolanic materials that possess extremely high surface area, such as silica fume and rice husk ash.

3.5.1.2. Specific gravity

The specific gravity of OPC and POFA was determined according to BS 1377: Part 2: 1990. The specific gravity was calculated using Equation 3.2.

Specific gravity $(G) = \frac{\rho_L(m_2 - m_1)}{(m_4 - m_1) - (m_3 - m_2)}$ Equation 3.2

Where,

G = specific gravity of OPC or POFA

m_1 = mass of bottle, g

m_2 = mass of bottle and OPC or POFA (dry), g

m_3 = mass of bottle, OPC or POFA and kerosene, g

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

ρ_L = density of kerosene, Mg/m^3

3.5.1.3. Wet sieve fineness

This test was performed to determine the particle fineness of OPC and POFA. An oven-dry sample of 600g was used for conducting this test. The sample was washed periodically onto the sieve with the water. The screen was rinsed with a gentle stream of water (gravity flow) to wash the particles through and into the assigned dish and stir gently the immersed sieve. Finally, it was rinsed until no visible fines passed through the screen. Once sieving is complete, the coarser fraction was dried on the surface of the sieve by placing the sieve and sediment in an oven at 80–100°C for 24 hrs. After drying, carefully the dried sediment fraction was transferred from the sieve (using a sieve brush) to a weighing dish to obtain the dry weight of the fraction retained on the sieve. The weight of the POFA fraction passing the sieve was calculated using Equation 3.3.

$$M_{passed} = M_{total} - M_{retained} \qquad \text{Equation 3.3}$$

Where,

M_{total}= mass of total of POFA, g

$M_{retained}$= mass of POFA retained, g

3.5.1.4. Particle size distribution

X-ray powder diffraction (XRD) is a direct method for qualitative and quantitative characterization of a fine-grained material such as cement or raw materials. In crystalline substance, the atoms are arranged in a regular pattern forming crystal lattices. Each crystal lattice of a particular substance has a certain space sets of planes, which are characteristics for that substance. XRD test identifies substances by evaluating the orientation of the sets of planes occurring in the crystal and the distance separating the planes within the sets.

3.5.1.5. Scanning electron microscopy

Scanning electron microscopy (SEM) analyzes the surface of the materials. SEM measures and evaluates surface particle; this system can analyze the solid objects by producing higher resolution images than optical microscopy. It can be used for microstructural characterization of materials. SEM can evaluate a wide range of samples such as polymers, films, coatings, geological and mineral core sample, pharmaceuticals, raw materials, metals, plastics, glass, food, dust, contaminants, unknowns and other products. In this experimental the Production of microstructural images of strongly enlarged images using Phillips SEM EDAX; XL 40; PW6822/10.

3.5.1.6. Chemical analysis

X-ray fluorescence (XRF) analysis was carried out at the NANOCEN, UM. XRF was conducted to determine the chemical compositions of OPC and POFA. Most XRF analyses are carried out using wavelength dispersive system. XRF is based on photoelectric effect, whereby a sample irradiated by a beam of highly energetic photons, which will cause an emission of a characteristic secondary fluorescent radiation or X-ray spectra. Each element has its own set of characteristic emission thus making each element identifiable.

Major elements such as Na, Mg, Al, Si, P, K, Ca, Ti, Mn and Fe were determined using the XRF method. The XRF parameters are listed at Table 3.3 below.

Table 3.3: XRF parameters

Equipment	Bruker S4-Explorer X-ray Fluorescence (1kW)
Software	SPECTRA^{PLUS} V1.64
Preparation Method	By pellet formed
Measurement Method	Fast-VAC08
Analytical Method	Semi-quantitative analysis

3.5.2. Testing of fine and coarse aggregates

Fine and coarse aggregates were tested for sieve analysis, moisture content, water absorption, and specific gravity. The tests conducted are shown in Table 3.4.

Table 3.4: Physical tests for fine and coarse aggregates

Type of Test	**Method**
Sieve Analysis	Coarse aggregate - BS 882: Part 103: 1992 Fine aggregate - BS 882: Part 2: 1992
Moisture Content	As prescribed in BS 812: Part 109: 1990
Water Absorption and Specific Gravity	Fine aggregate - ASTM C 128 Coarse aggregate - ASTM C 127

3.5.2.1. Sieve analysis

Sieve analysis of aggregates was performed by using BS 882: Part 103 (1992) for coarse aggregate and BS 882: Part 2 (1992) for fine aggregate to obtain the particle size distribution, fineness modulus, and grading zone of the fine aggregate.

3.5.2.2. Moisture content

This test was performed to determine the moisture contents of fine and coarse aggregate; for fine aggregate, 500g sand and for coarse aggregate, 1000g crushed granite stone were place in the tray and weighed to an accuracy of 0.1g. After weighing, the sample tray was place in the oven at a temperature of 105º C for 24 hours. After drying, the sample was weighed to determine the dry weight. From the weights obtained and formulas given, the moisture contents of the aggregates were determined. The moisture contents were calculated as follows:

$$\text{Total moisture content (\%)} = \frac{\text{Initial weight} - \text{Dry weight}}{\text{Dry weight}} \qquad \text{Equation 3.4}$$

3.5.2.3. Water absorption and specific gravity

According to ASTM C 127 (2004), specific gravity is the ratio of the mass (or weight in air) of a unit volume of a material to the mass of the same volume of water at stated temperatures. The water absorption is defined as the increase in the weight of aggregate due to access of water into the pores of the material, but not including water adhering to the outside surface of the particles, expressed as a percentage of the dry weight.

In order to determine the specific gravity and water absorption of coarse aggregates, the sample of aggregate was immersed in water for approximately 24 hours to essentially fill the pores. The sample is then removed from the water, surface-dried, and weighed. The sample was then submerged in water and weighed. Finally, the sample is oven-dried (110 ± 5ºC) and weighed. From the weights obtained and formulas given in the ASTM C 127 (2004), the specific gravity and water absorption of the coarse aggregates were determined. The specific gravity and water absorption were calculated as follows:

$$\text{Bulk specific gravity (saturated-surface dry)} = \frac{A}{[A-(B-C)]} \qquad \text{Equation 3.5}$$

$$\text{Water absorption (\%)} = [(A - D)/D] \times 100\ \% \qquad \text{Equation 3.6}$$

Where,

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

B = apparent weight of basket and saturated surface dry sample in water, g

C = apparent weight of empty basket in water, g

D = weight of oven-dried test sample in air, g

3.6. Mixture Proportioning

The mixture proportions of the concretes were determined based on the guidelines given in EFNARC and DOE mix design methods (EFNAC, 2002 and DOE, 1975). In the present study, twelve SCC mixtures (including three control concretes) were produced with relatively high W/B ratios. The W/B ratios of the concretes were 0.40, 0.50 and 0.60. POFA was used in the concretes substituting 0–15% of cement by weight.

The basic mixture proportions of the concretes are shown in Appendix A. The basic mixture proportions were corrected considering the absorption and moisture content of aggregates (fine and coarse aggregates) as well as the water contribution of HRWR. The corrected mixture proportions of the concretes are shown in Table 3.5.For each W/B ratio, the HRWR dosage was kept constant to observe the effects of POFA on the properties of concrete.

Table 3.5: Mixture proportions of the concretes

Mix No.	W/(C+POFA)	Water kg/m³	Cement kg/m³	POFA %	POFA kg/m³	FA kg/m³	CA kg/m³	HRWR ℓ
1	0.4	212.0	513	0	-	820	825	0.185
2	0.4	211.8	487	5	25.63	789	794	0.185
3	0.4	212.1	461	10	51.25	788	793	0.185
4	0.4	212.3	436	15	76.88	787	792	0.185
5	0.5	213.5	410	0	-	871	876	0.160
6	0.5	213.2	390	5	20.50	831	837	0.160
7	0.5	213.4	369	10	41.00	830	836	0.160
8	0.5	213.6	349	15	61.50	829	835	0.160
9	0.6	214.2	342	0	-	904	910	0.154
10	0.6	213.7	325	5	17.08	859	865	0.154
11	0.6	214.0	308	10	34.17	859	864	0.154
12	0.6	214.2	290	15	51.25	858	863	0.154

3.7. Preparation and Testing of Fresh Concretes

The fresh concretes were prepared according to the mix proportions shown in Table 3.5. In all cases, a revolving pan type mixer was used to mix the constituent materials for 5 minutes. At first, fine and coarse aggregates were mixed for 1 minute with the first one-third of the mixing water. Then the binding materials (cement alone or cement with POFA) were added with the second one-third of the mixing water including the one-third of HRWR, and the mixing was continued for 2 minutes. Later, the concrete materials were mixed for 2 more minutes with the addition of the two-third HRWR dispensed in the remaining one-third of the mixing water.

Immediately after the completion of mixing, the fresh concretes were sampled and tested for filling ability, passing ability, and segregation resistance. Slump flow, T_{50cm} slump flow and V-funnel flow were used to measure the filling ability. The slump flow was determined according to ASTM C 1611 (2009). The T_{50cm} slump flow and V-funnel flow were determined according to EFNARC (2002). The J-ring test was carried out according to ASTM C 1621 (2009) to measure the passing ability. The segregation column and Japanese sieve stability tests were used to measure the segregation resistance. The test methods used are given in Table 3.6.

Table 3.6: Tests for fresh concrete

Types of test	References
Filling ability	
Slump flow	ASTM C 1611/C 1611M,"Standard test method for slump flow of self-consolidating concrete"
T_{50cm} slump flow	EFNARC, "Specifications and guidelines for self-consolidating concrete"
V-funnel flow	EFNARC, "Specifications and guidelines for self-consolidating concrete"
Visual inspection	ASTM C 1611/C 1611M "Standard test method for slump flow of self-consolidating concrete"
Passing ability	
J-ring flow	EFNARC, "Specifications and guidelines for self-consolidating concrete"
Segregation resistance	
Segregation column	Safiuddin (2008)
Japanese sieve stability	Nagataki and Fujiwara (1995)

3.7.1. Slump flow test

This test method was followed to determine the slump flow of self-consolidating concrete.The apparatus includes a cone-shaped metal mould (height: 300 mm, base diameter: 200 mm, top diameter: l00 mm) and a base plate 1000 mm square; the base plate is non-absorbent, smooth and rigid.

The mould was poured with fresh concrete in one layer and without any consolidation. When the filling was completed, the top surface was levelled off and the mould was lifted vertically with no lateral or twisting motion. The fresh concrete was allowed to spread over the base plate until the flow stopped. The diameter of the spread of fresh concrete was measured to the nearest 5 mm. An operational stage of the slump flow test is shown in Figure 3.8. The slump flow was calculated as follows:

$$\text{Slump flow} = (d_1 + d_2)/2 \qquad \text{Equation 3.7}$$

Where,

d_1 = the largest diameter of the circular spread of the concrete

d_2 = the circular spread of the concrete at the angle perpendicular to d_1

3.7.2. T_{50cm} slump flow or spread time test

The T_{50cm} slump flow test is the other method for determining the filling ability of SCC. This test gives the flow time, which is related to the flow rate of SCC as influenced by its viscosity. The apparatus for conducting this test is similar to the slump flow test, but the base plate need to be marked with 500 mm diameter.

The test procedure is similar to the slump flow test. However, the T_{50cm}spread time instead of flow spread is determined in this test. The T_{50cm}spread time is the time required by theSCC to flow to a diameter of 500 mm after the slump cone has been lifted. While performing the slump flow test, the time it takes for the outer edge of the SCC mixture to reach a diameter of 500 mm from the time the mold is first raised is the T_{50cm} spread time.

Figure 3.8: Measurement of slump flow

3.7.3. V-funnel flow test

The v-funnel flow test is used to measure the filling ability of self-consolidating concrete. The apparatus consists of a V-shaped funnel with a height of 425 mm, a top width of 490 mm, a bottom width of 65 mm, and a thickness of 75 mm (Figure 3.9). At the bottom of the V-shape, a rectangular section extends downward by 150 mm. This apparatus also comes along with trowel, bucket, scoop and stopwatch.

About 12 liter of fresh concrete was needed to perform this test; the interior of the V-funnel was initially wetted with water. A bucket was placed underneath the V-funnel. The fresh concrete was placed in the V-funnel without any consolidation, while keeping the trap door closed. Then the door was opened and the concrete was allowed to flow. Simultaneously, a stopwatch was used to record the flow time. An operational stage of the test is shown in Figure 3.10.

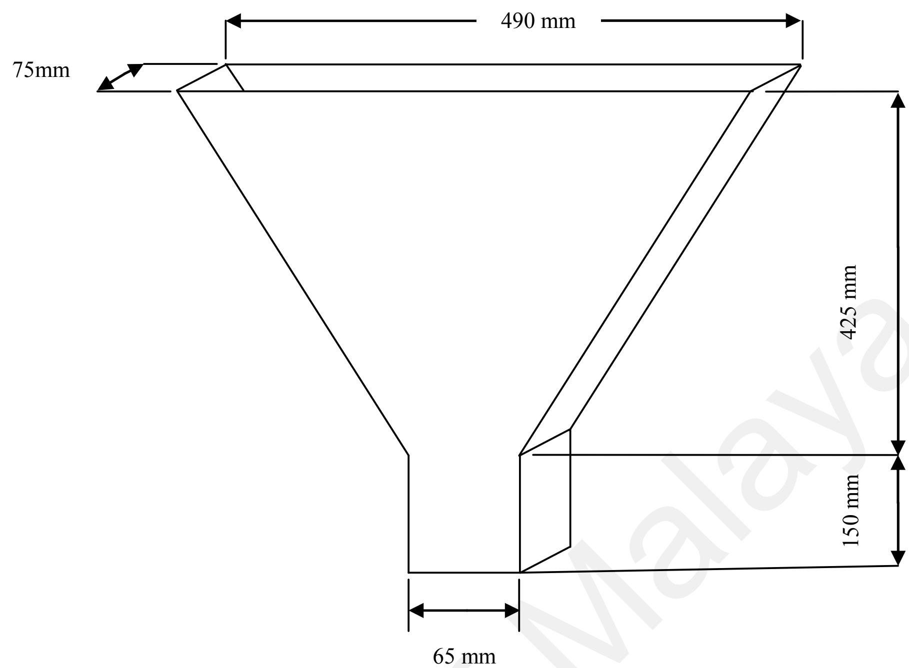


Figure 3.9: Details of V-funnel

Figure 3.10: Testing of V-funnel flow

3.7.4. Slump cone – J-ring flow test

The slump cone-J-ring flow test was used to determine the slump and slump flow with J-ring. The slump and slump flow with J-ring test measure the passing ability of fresh concrete. The details of the J-ring are shown in Figure 3.11.

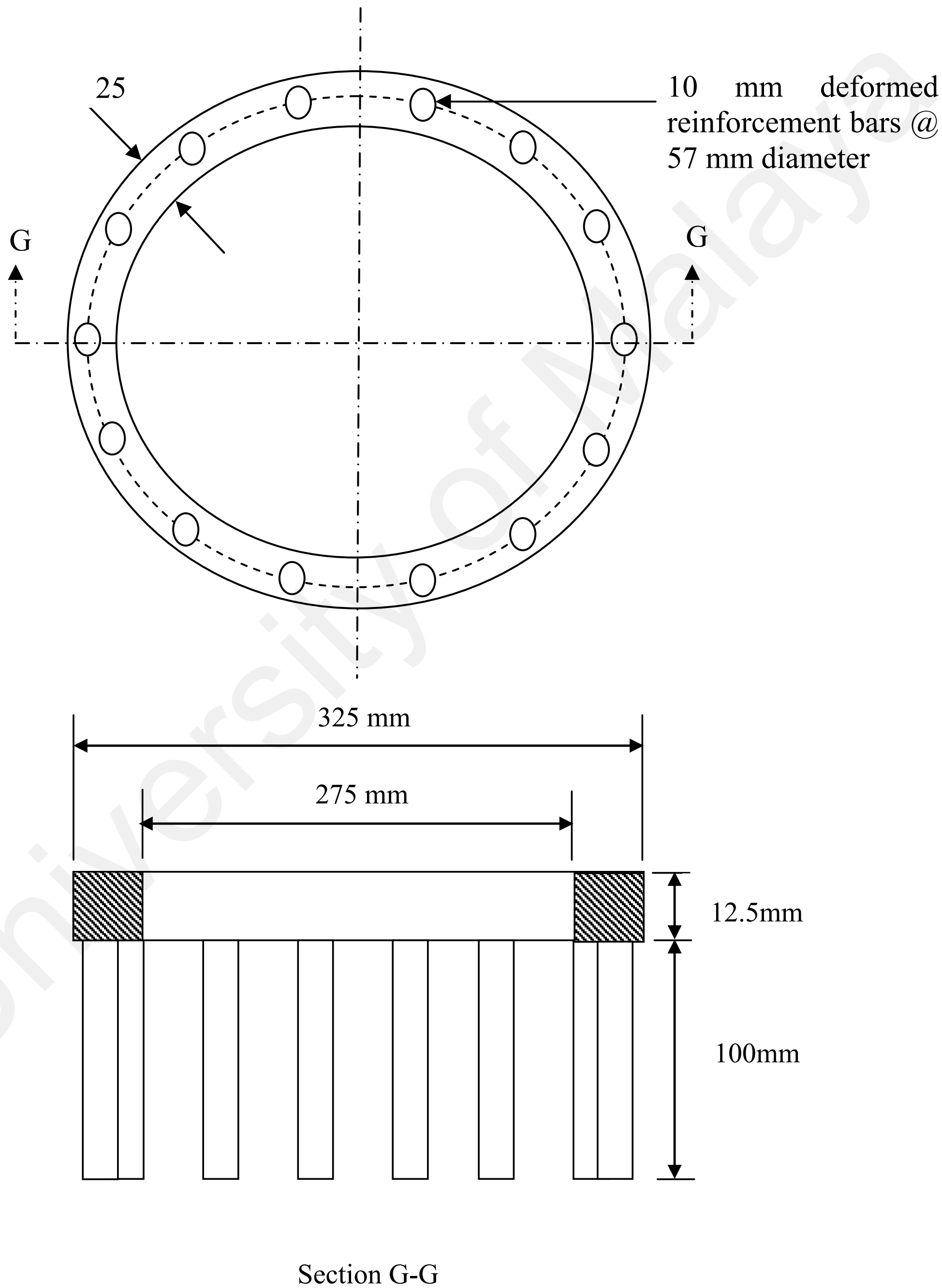


Figure 3.11: Details of the J-ring

The J-ring had an open steel ring, which was built with reinforcing bars. The reinforcing bars were 100 mm long and had a diameter of 10 mm. The spacing of the bar was 57 mm. The slump cone was placed in the center of the J-ring and filled with concrete and leveled with the top of the cone with the trowel, any surplus concrete from around the base of the cone was removed. Then the slump cone was raised vertically and the concrete was allowed to flow out freely and horizontally through the gap between the bars (Figure 3.12). The diameter of the concrete spread was measured.

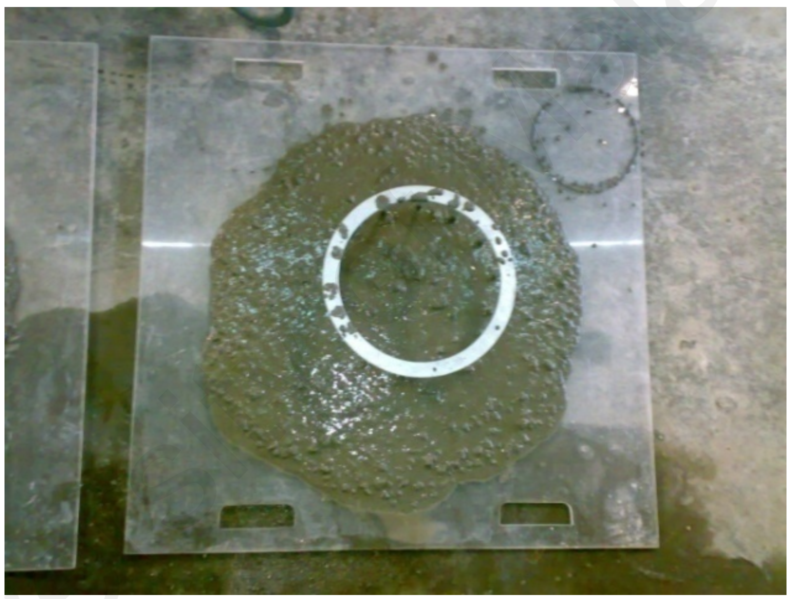


Figure 3.12: Measurement of slump flow with J-ring

3.7.5. Tests for segregation resistance of self-consolidating concretes

3.7.5.1. Segregation column test

The segregation column test was used for measuring the static segregation resistance of a concrete. The column test was executed based on the principle given in ASTM C 1610/C 1610M (2009); however, the simplified segregation column apparatus developed by

Safiuddin (2008) was used in this study. The simplified segregation column apparatus was easy to use in laboratory with a single operator. From this test, the segregation factor was determined based on the mass difference of coarse aggregates in top and bottom sections of the column apparatus to express the segregation resistance of concrete.The simplified column size used in this study was Ø150 × 600 mm columns with 3 sections. The segregation column is shown in Figure 3.13.

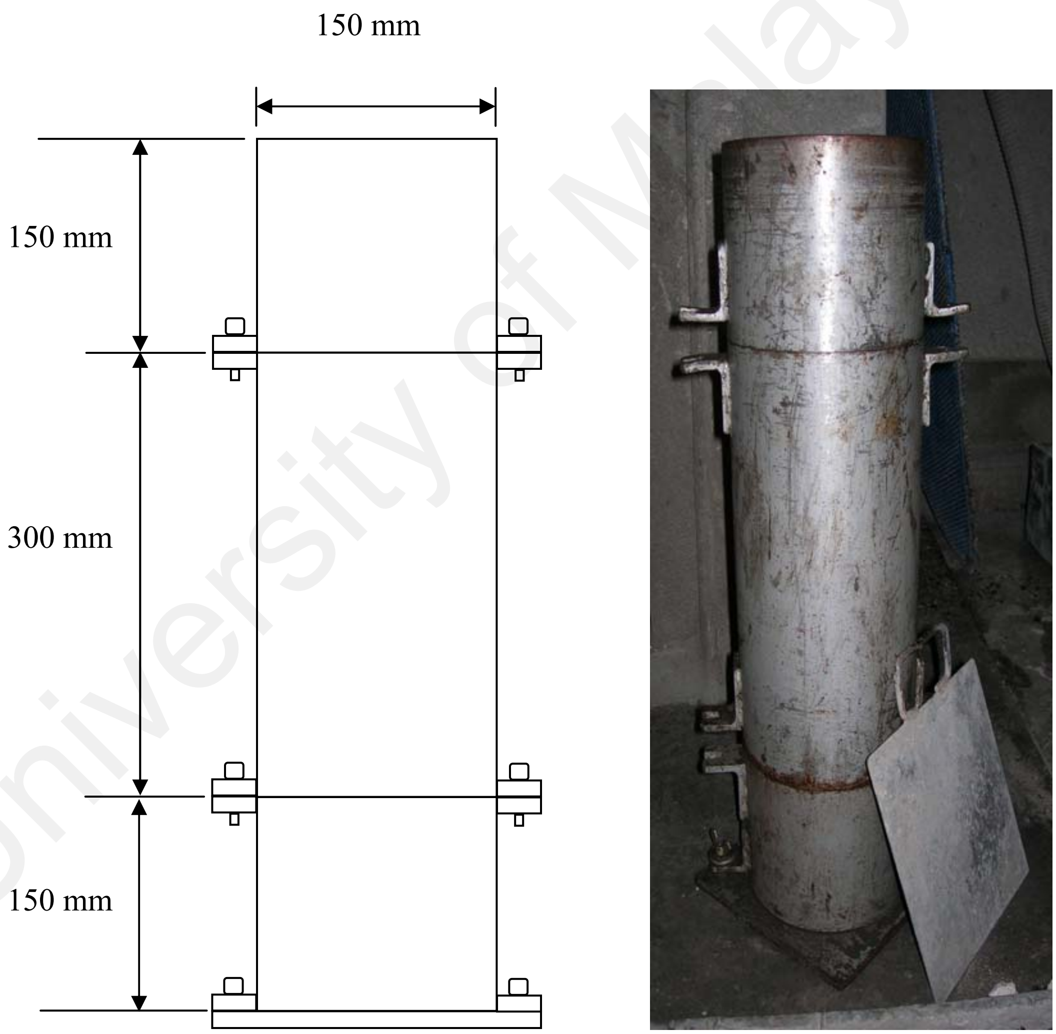


Figure 3.13: Details of the simplified segregation column apparatus

The segregation column was filled with concrete by scooping in one layer, and then the concrete was allowed to rest for 30 minutes. After the rest period, the concretes from upper and bottom parts of the column were separated one at a time by using a steel separator pan. The concrete removed from the column was collected and washed on 4.75 mm standard sieve to separate the coarse aggregates from mortar. The coarse aggregates retained on the sieve were then dried to the saturated surface-dry condition using absorbent cloth, and were weighed thereafter.

The segregation resistance was quantified with respect to segregation factor as follows:

Segregation factor, $SF = [C_B - C_t] / [(C_B + C_t)/2] \times 100\%$ Equation3.8

Where,

C_T = Surface-dry mass of the coarse aggregates in top section, kg

C_B = Surface-dry mass of the coarse aggregates in bottom section, kg

3.7.5.2. Japanese sieve stability test

Nagataki and Fujiwara (1995) developed the Japanese sieve stability test; this test was carried out in accordance with the modified procedure given by Safiuddin (2008) to determine the sieve segregation of concrete. The apparatus used to conduct this test consists of a 4.75 mm standard sieve, a pan, and a 2 liter cylindrical bucket.

Firstly, the sieve and pan were weighed. Then the concrete were poured in a 2 liter cylindrical bucket in one layer without any consolidation. Without delay, the concrete was poured onto the sieve placed over the pan. The sieve and pan that contained the mortar passing through the sieve were weighed. The mortar retained on the pan was also weighed separately. The leftover concrete on 4.75 mm sieve was washed to get the coarse aggregates. The coarse aggregates were surface-dried by absorbent cloth and weighed. From this test, the segregation resistance was determined with respect to segregation index, which was calculated as a ratio of the mortar mass passing the sieve to the mortar mass contained in concrete sample, as follows:

$$\text{Segregation index, } SI = (M_p/M_c) \times 100\% \qquad \text{Equation3.9}$$

Where,

M_p = mass of the mortar that passed the sieve, kg

M_c= mass of the mortar contained in concrete sample, kg

For determining the mass of concrete sample, the mass of the sieve and pan was subtracted from the total weight. The mass of mortar was determined by subtracting the mass of the pan from the mass of pan and mortar. The mass of mortar contained in the concrete was determined by subtracting the weight of coarse aggregate that had been washed and surface-dried from the mass of concrete. The different stages of the sieve stability test are shown in Figure 3.14.

Initial stage of sieve segregation test

Mortar passed through sieve

Coarse aggregate retained on sieve

Figure 3.14: Several operational stages of the sieve stability test

3.8. Testing of Hardened Concretes

The hardened specimens of SCC mixes were tested to determine compressive strength, ultrasonic pulse velocity, water absorption and total porosity. The different test methods used for hardened concretes are shown in Table 3.7.

Table 3.7: Tests for hardened concretes

Type of Test	**Specimens (mm)**	**Age of Test (days)**	**References**
Mechanical properties			
Compressive Strength	100×100×100 mm cubes	3,7,14, 28,56	BS 1881(1983a)
Durability			
Water Absorption	100×100×100 mm cubes	28,56	BS 1881(1983b)
Physical properties			
Ultrasonic pulse velocity	100×100×100 mm cubes	28,56	BS 1881(1986)
Permeable porosity			
i) Cold water saturation	Ø100×50 mm cylinders	28,56	ASTM C 642 (2006)
ii) Boiling water saturation	Ø100×50 mm cylinders	28,56	ASTM C 642 (2006)

3.8.1. Compression test

The compressive strength performance was investigated on cubes (100×100×100 mm) at the ages of 3, 7, 28 and 56 days. The compressive strength test was carried out in accordance with BS 1881(1983a).

The compressive strength-testing machine used throughout this investigation is manufactured by Engineering Laboratory Equipment Limited (ELE) with a maximum capacity of 2000 kN and is shown in Figure 3.15. The specimens were subjected to load at the rate of 2.4kN/s.

On the day of test, the specified test specimens were removed from the curing tank. The surfaces were then wiped dry and loose sand grains were removed before starting the test. The dimensions of the cubes were measured using a vernier calliper and recorded before test. The test was carried out at the ages of 3, 7, 28 and 56 days. The test procedure complied with the standard prescribed by BS 1881(1983b). The cube samples were placed below the center of the upper bearing block of the testing machine. The specimens were tested at the specified loading rate and the load was applied slowly until the specimen failed. The total maximum load as indicated by the testing machine was recorded as the failure load. The compressive strength was calculated by dividing the load at failure by the loaded area of sample (Equation 3.10). The entire procedure was repeated for the other two samples and the compressive strength value was determined as the average of three specimens.

Compressive strength, f_c = Failure load (P)/Loaded area (A) Equation 3.10

Figure 3.15: Compression testing machine for compressive strength test

3.8.2. Test for ultrasonic pulse velocity

The ultrasonic pulse velocity (UPV) test was done to assess the physical quality of concrete. This test was conducted in accordance with BS 1881(1986). The UPV test was conducted on 100 mm cube specimens at 28and 56 days. The objective of this test was to determine the pulse velocity by measuring the time of travel of an ultrasonic pulse passing through the concrete specimen being tested. The apparatus are shown in Figure 3.16. The equipment was calibrated before test by using the calibration cylinder that approximately gives a time interval of 26 μsfor the pulse.

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 digital indicating device. To ensure that the vibration of the transducer was transmitted to the concrete by close contact, adequate grease was applied on the faces of the concrete, and the transducers were pressed hard against the surface. The details of the test method are shown in Figure 3.17. The pulse velocity V (km/s or m/s) was calculated as follows:

$$V = \frac{L}{T} \qquad \text{Equation3.11}$$

Where,

L = path length (0.1 m)

T = time taken by the pulse to traverse that length ($\times 10^{-6}$s)

Figure 3.16: Apparatus for ultrasonic pulse velocity (UPV)

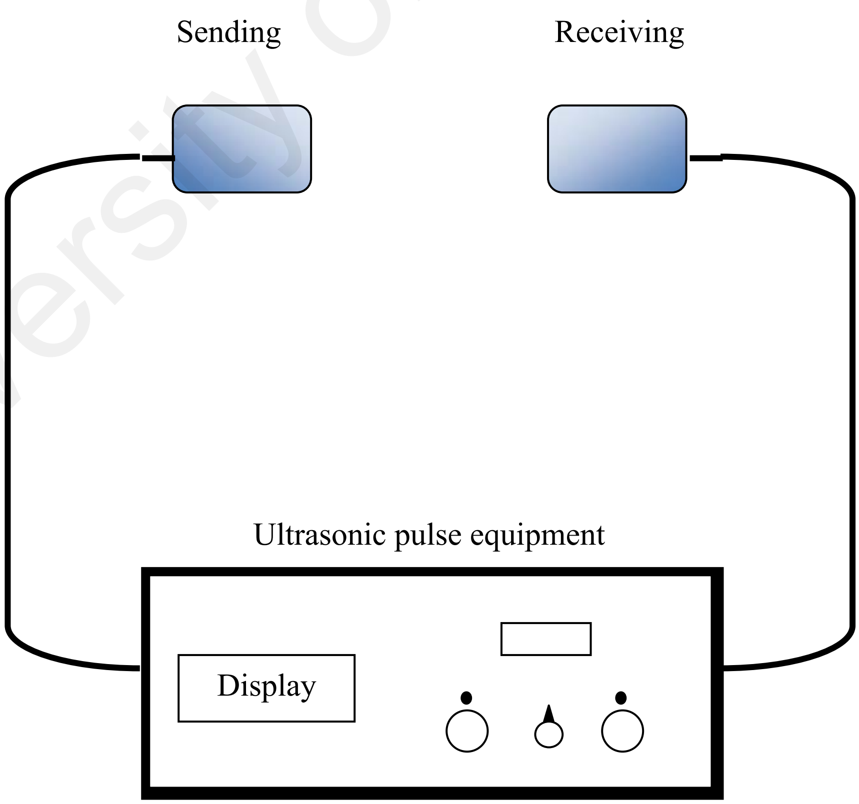


Figure 3.17: Details of ultrasonic pulse velocity (UPV) test

3.8.3. Test for water absorption and permeable porosity

The water absorption of hardened concretes was determined based on the cold water and boiling water saturation techniques. However, the permeable porosity of hardened concretes was determined based on the boiling water saturation technique. The test procedures given in ASTM C 642 (2007) were followed.

The cylinder specimens with the dimensions of Ø100×50 mm were tested for determining the absorption and permeable porosity. The samples were prepared from 100×200 mm cylinder by cutting. A thin layer from both ends was discarded to minimize the end effects. After cutting, the specimens were dried in the oven at 105±5°C (Figure 3.18) for more than 48 h to determine the oven-dry mass. After removing from the oven, the specimens were allowed to cool in desiccators to the room temperature of 20 to 25°C (Figure 3.19) and their oven-dried mass was determined. In order to determine the saturated surface-dry mass in cold-water saturation technique, the specimens were simply immersed in cool water at approximately 21°C for more than 48 h (Figure 3.20). During boiling-water saturation, the specimens were boiled in a water bath for 5 h (Figure 3.21) and then allowed to cool for 14 h by natural loss of heat to a final temperature of 20–25°C. After the periods of boiling and cooling, the wet specimens were placed in a metal wire basket immersed in water tank (Figure 3.22) and their buoyant mass was recorded.

The water absorption was calculated based on the concept of weight gain. The permeable porosity was calculated based on the concept of weight loss because of buoyancy. The following equations have been used to calculate the water absorption and permeable porosity of hardened concretes:

Absorption after immersion, % = $[(B - A)/ A] \times 100$ Equation 3.12

Absorption after immersion and boiling, % = [(C - A)/A] × 100 Equation 3.13

Permeable porosity, % = (C – A)/(C – D) × 100 Equation 3.14

Where,

A=mass of oven-dried sample in air, g

B=mass of surface-dry sample in air after immersion, g

C=mass of surface-dry sample in air after immersion and boiling, g

D=Apparent mass of sample in water after immersion and boiling, g

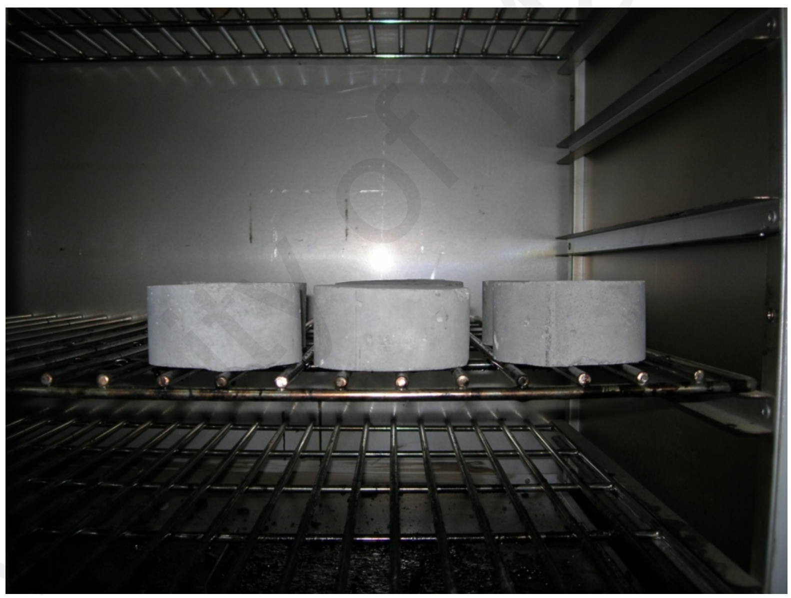


Figure 3.18: Specimens drying in the oven

Figure 3.19: Specimens cooling in desiccators

Figure 3.20: Specimens immersion in cool water

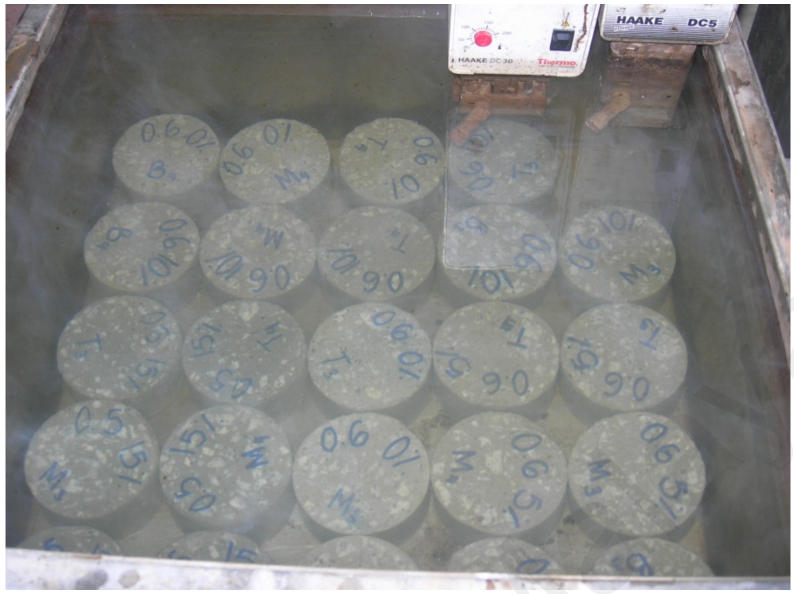


Figure 3.21: Specimens boiling in a water bath

Figure 3.22: Buoyant mass measurement of specimen

CHAPTER 4

RESULTS AND DISCUSSION

4.1. Properties of Concrete Constituent Materials

Normal (ASTM Type I) portland cement (C), crushed granite stone, mining sand, ground POFA, normal tap water (W), and high-ranger water reducer (HRWR) were used in the present study. The constituent materials were tested for the key properties.

4.1.1. Cement

The normal portland cement that been used in this study was collected from Tasek Cement Sdn. Bhd. The cement was tested for sieve fineness by 45-µm sieve, specific gravity, Blaine specific surface area, BET specific surface area, particle size distribution, and chemical composition. The key physical properties of cement are shown in Table 4.1. The specific gravity of ordinary portland cement (OPC) as determined using Eq. 3.1 is 3.12. It has a Blaine specific surface of 364.1 m^2/kg and a BET specific surface area of 3181 m^2/kg. The chemical analysis of cement was conducted using X-ray fluorescence (XRF) and is presented in Table 4.2. This table shows that the cement mainly consists of calcium oxide of 70.428%, silicon dioxide of 15.713% and aluminium oxide of 3.443%. Also, the deleterious chemical components of cement such as MgO and SO_3 were below the maximum allowable limits specified in ASTM C 150.

4.1.2. Palm oil fuel ash

According to ASTM C 618 (2008), the mass of fly ash and natural pozzolan passing 45-µm wet sieve shall be at least 66%. This criterion can also be used for POFA. However, the mass of cement passing the 45-µm sieve was 84% in the present study. To use POFA as a suitable SCM, it was ground to achieve a percent mass passing the 45-µm wet sieve greater than 84%.

Table 4.1: Physical properties of constituent materials

Material	Properties
Crushed granite stone	Maximum size: 20 mm Specific gravity (saturated surface-dry based): 2.53 Water absorption: 0.6 % Fineness modulus: 7.02
Mining sand	Maximum size: 5 mm Specific gravity (saturated surface-dry based): 2.62 Water absorption : 1.11% Fineness modulus: 3.11
Ordinary portland cement	Specific gravity: 3.12 % Passing 45-µm sieve: 84 Specific surface (m^2/kg): 364.1 (Blaine), 3181 (BET)
Palm oil fuel ash (POFA)	Specific gravity: 2.78 % Passing 45-µm sieve: 88.4 Specific surface (m^2/kg): 668.9 (Blaine), 4998 (BET)
High-range water reducer (HRWR)	Specific gravity: 1.06 Solid content: 13.5%

Forty mild steel rods of 10 mm diameter and 400 mm length were placed in the rotating drum to grind approximately 4 kg of raw POFA per batch. The grinding of POFA was carried out for 16 hours to obtain the desired level of fineness (> 84%). The fineness of POFA was checked at 4 hours grinding interval using a 45-µm sieve in accordance with the procedure given in ASTM C 430 (2009). The sieve fineness of POFA for different grinding periods is shown in Figure 4.1. After the completion of the grinding process, the particle characteristics of POFA were examined with a scanning electron microscope. The particles of ground POFA were porous, angular and irregular, as can be seen from Figure 4.2.The particle size distributions are shown in Figure 4.3. The original POFA has larger particles than OPC. But ground POFA has almost the similar particles size as OPC.

Table 4.2: Chemical compositions of cement and POFA

Element	Mass content (%)	
	Cement	POFA
Magnesium oxide (MgO)	2.402	1.211
Aluminium oxide (Al_2O_3)	3.443	3.153
Silicon dioxide (SiO_2)	15.713	79.306
Phosphorus pentoxide (P_2O_5)	0.388	2.322
Sulfur trioxide (SO_3)	3.773	0.451
Potassium oxide (K_2O)	0.265	3.233
Calcium oxide (CaO)	70.428	2.793
Titanium dioxide (TiO_2)	0.110	0.235
Manganese oxide (MnO)	0.086	0.072
Iron oxide (Fe_2O_3)	3.343	7.122
Copper oxide (CuO)	0.011	0.016
Zinc oxide (ZnO)	0.001	0.028
Rubidium oxide (Rb_2O)	0.004	0.012
Zirconium dioxide (ZrO_2)	0.008	0.044
Strontium oxide (SrO)	0.025	---

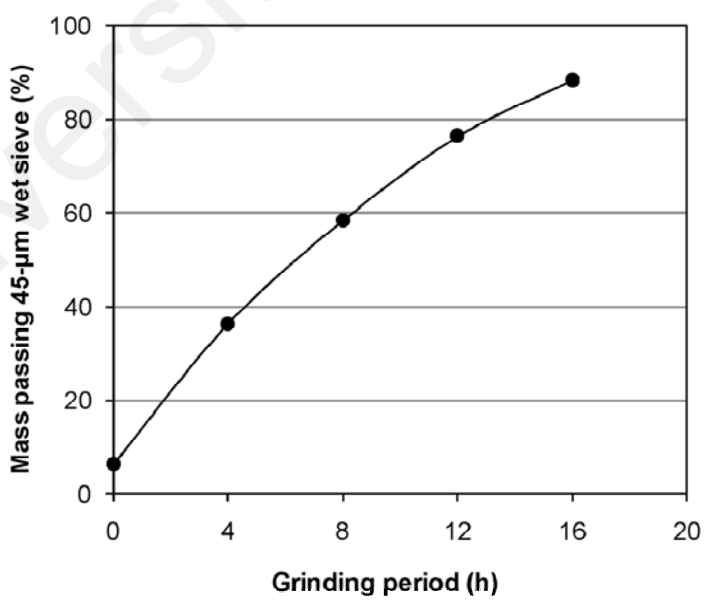


Figure 4.1: Fineness of POFA with different grinding periods

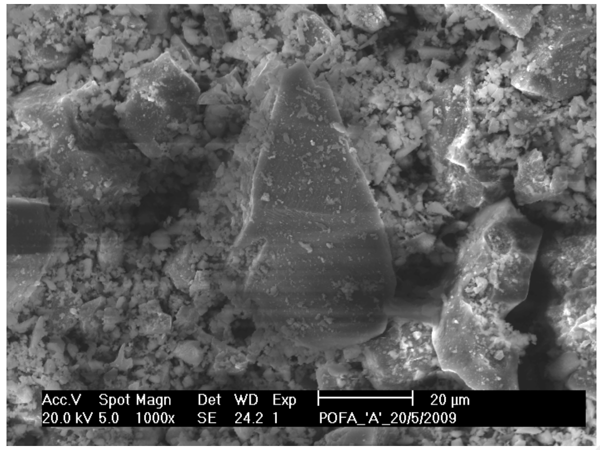


Figure 4.2: Scanning electron micrograph (SEM) of ground POFA

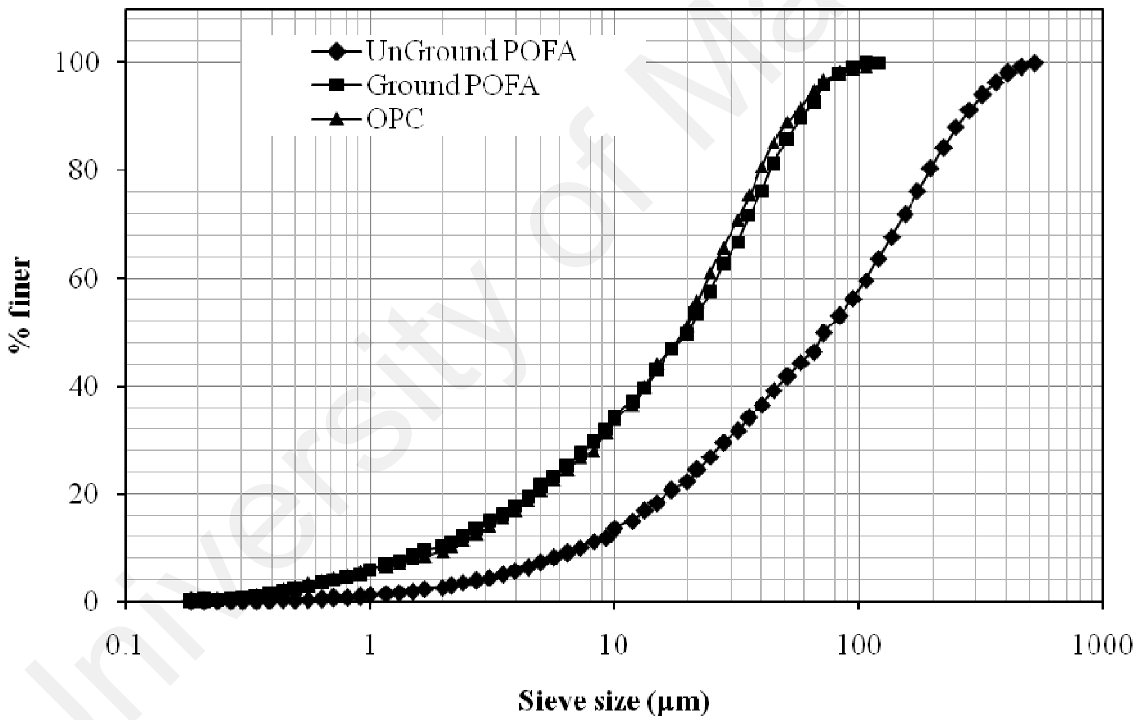


Figure 4.3: Particle size distribution of unground POFA, ground POFA and portland cement

Ground POFA was tested for the chemical composition. X-ray fluorescence (XRF) analysis was carried out to determine the chemical composition of POFA, as shown in Table 4.2. In addition, the cumulative mass content of silicon dioxide (SiO_2), aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3) was 89.6% for the POFA used in the present study. Hence, the POFA was a highly pozzolanic supplementary cementing material in accordance with ASTM C 618.

4.1.3. Fine and coarse aggregates

Various tests were conducted to determine the physical properties of coarse and fine aggregates. They are water absorption and specific gravity (ASTM C 127 (2004) and ASTM C 128 (2004)), moisture content (BS 812 (1990)) and sieve analysis (BS 882 (1985)). The results of the tests are summarized in Table 4.1, and Figure 4.4 presents the grading curve of the fine and coarse aggregates. The results presented in Figure 4.4 show that fine aggregate conformed to zone 1of BS 882 (1973).

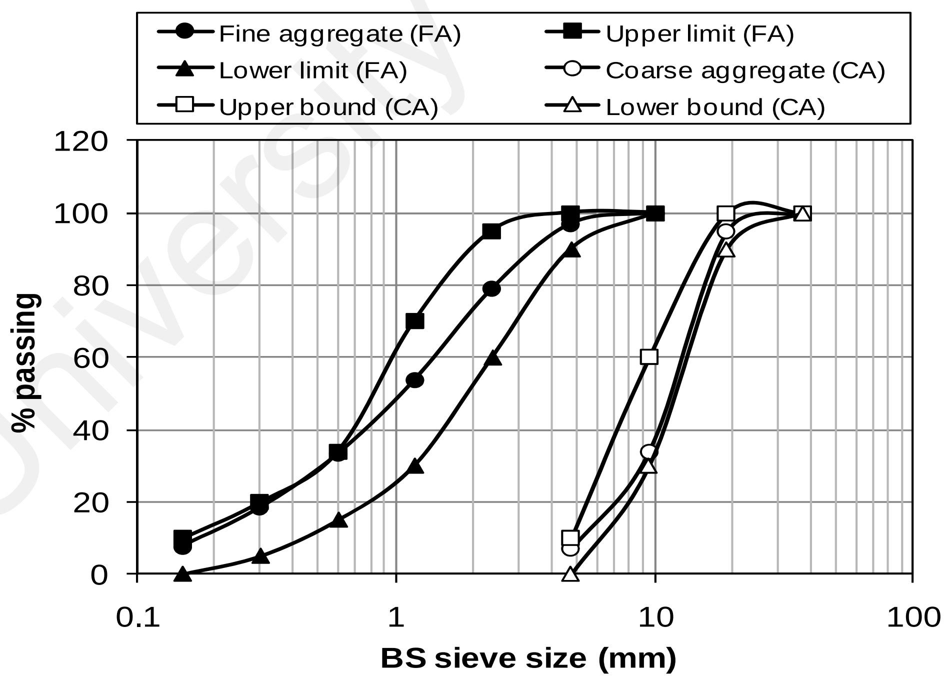


Figure 4.4: Gradation of aggregates

4.2. Properties of Freshly Mixed Self-consolidating Concrete

The test results for the filling ability (slump flow, T_{50cm} spread time, and V-funnel flow time), passing ability (J-ring flow), and segregation resistance (segregation index and segregation factor) of different SCC mixtures are given in Table 4.4. The visual stability index (VSI) values of different SCC mixtures are shown in Table 4.5.

Table 4.4: Fresh properties of various SCCs

Mix. no.	W/B	POFA (% B)	Filling ability			Passing ability	Segregation resistance	
			Slump flow (mm)	T_{50cm} spread time (s)	V-funnel flow time (s)	J-ring flow (mm)	Segre. index (%)	Segre. factor (%)
1	0.40	0	625	2.87	4.86	600	23.4	10.4
2		5	605	2.42	4.96	580	23.9	10.3
3		10	575	4.10	8.32	565	21.7	8.0
4		15	545	5.99	14.07	525	15.8	6.9
5	0.50	0	655	1.10	1.50	650	23.2	25.2
6		5	655	1.13	1.89	645	22.1	23.8
7		10	650	1.43	2.37	630	15.7	15.7
8		15	630	1.81	2.66	610	11.3	10.9
9	0.60	0	650	0.57	1.35	635	21.3	19.1
10		5	640	0.58	1.64	635	20.2	16.1
11		10	610	0.88	1.99	600	14.7	12.7
12		15	600	0.97	2.52	585	10.2	10.8

4.2.1. Filling ability of concretes

The filling ability results of various mixtures were obtained with respect to slump flow, T_{50cm} slump flow time, and V-funnel flow time. They are discussed below.

4.2.1.1. Slump Flow

The slump flow of concrete varied in the range of 545-655 mm (refer to Table 4.4), The required filling ability was achieved for the freshly mixed concretes, except Mix 4 with the W/B ratio of 0.40 and 15% POFA content. The slump flow of this concrete was 545 mm, which is slightly less than the allowable minimum slump flow (550 mm) of SCC. (SCCEPG, 2005).This is because the free water content was reduced due to the greater binder content at a lower W/B ratio (0.40) and thus the dispersion of aggregates decreased. The slump flow of the other concretes varied in the range of 575–655 mm, which indicates good filling ability of SCC (Khayat, 2000; EFNARC, 2002). However, a minimum slump flow of 600 mm is generally recommended for SCC to ensure adequate self-consolidation capacity (Khayat, 2000). In the present study, the slump flow was higher for the 0.50 W/B ratio than 0.60 W/B ratio, as evident from Table 4.4. This is mainly due to the increased paste volume and slightly greater HRWR dosage at 0.6W/B ratio. The increased paste volume and greater HRWR dosage enhanced the dispersion of aggregates with reduced collisions. Despite increased paste volume and greater HRWR dosage, the slump flow at 0.40 W/B ratio was relatively low. This is perhaps due to increased plastic viscosity, as indicated by the flow time results.

The slump flow decreased linearly with the increased POFA content at all W/B ratios, as can be seen from Figure 4.5. This is mostly because of a lesser amount of available free water in the presence of POFA. The POFA particles were more porous and possessed a greater specific surface than cement (Table 4.2). The porous POFA particles confined a portion of mixing water due to greater specific surface area, and thus reduced the quantity of free water in concrete mixtures. Therefore, the water needed for the lubrication action of binder paste became lower in POFA concrete. Consequently, the concrete slump flow was reduced. In addition, the angularity and irregularity of POFA particles contributed to decrease the slump flow of concrete.

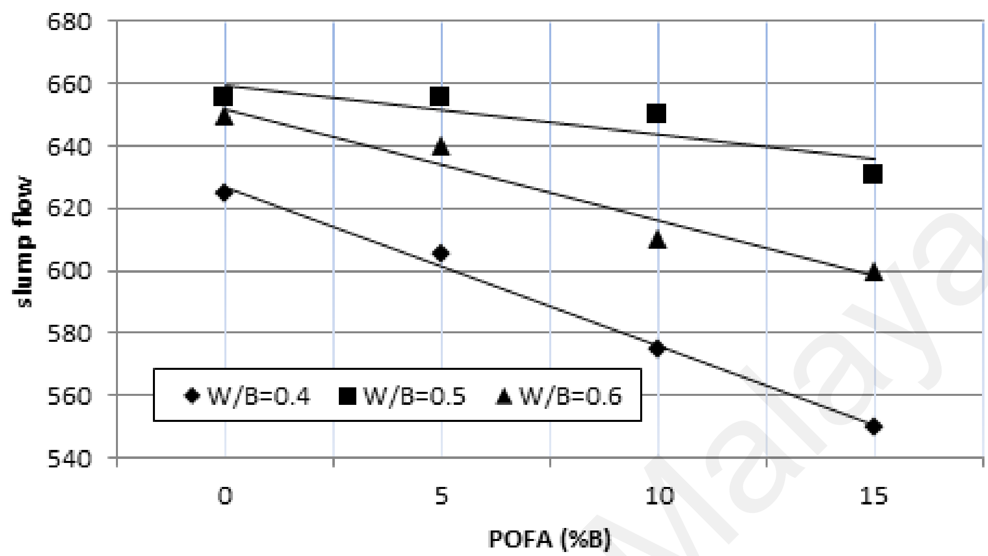


Figure 4.5: The effect of POFA on slump flow

4.2.1.2. *T_{50cm} slump flow or spread time*

The T_{50cm} spread time varied from 0.57 s to 5.99 s for different SCC mixtures (Table 4.4). The T_{50cm} spread time < 2 s for 0.50 and 0.60 W/B ratios indicates that the plastic viscosity of concretes was comparatively low (SCCEPG, 2005). The lower values of T_{50cm} spread time were obtained in the present study due to the use of relatively high W/B ratios. However, the T_{50cm} spread times at 0.40 W/B ratio were significantly higher than those at 0.5 and 0.60 W/B ratio, as evident from Table 4.4. It suggests that the SCC mixtures with 0.40 W/B ratio had a greater plastic viscosity than the SCC mixtures with 0.5 and 0.60 W/B ratios. This is because the free water content was reduced due to the greater binder content at 0.40 W/B ratio. Moreover, for all W/B ratios, the T_{50cm} spread time increased linearly with higher POFA content, as can be seen from Figure 4.6. The lowest T_{50cm} spread time was obtained for the control concretes (0% POFA). On the contrary, the highest T_{50cm} spread time was achieved for the SCC mixtures with 15% POFA content. The increase in T_{50cm} spread time indicates that the plastic viscosity of the concrete increased with higher POFA content. Indeed, the quantity of free water was reduced due to the greater specific surface of POFA. Therefore, the SCC mixture with greater POFA content experienced a higher flow resistance in T_{50cm}slump flow or spread test. It slowed down the deformation of concrete, and thus a longer time was required for the 50-cm flow spread.

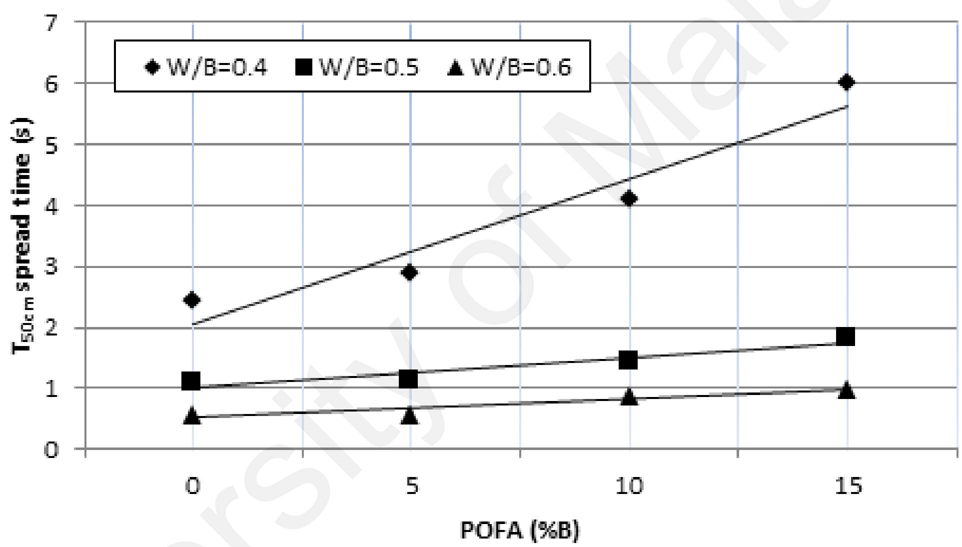


Figure 4.6: The effect of POFA on T_{50cm} spread time

4.2.1.3. V-funnel flow time

The V-funnel flow time for different SCCs varied in the range of 1.35–14.07 s (Table 4.4). The V-funnel flow time < 8 s also indicates that the plastic viscosity of concretes was comparatively low (SCCEPG, 2005). Only two mixes with 10% and 15% POFA at 0.4 W/B ratiohad a V-funnel flow time >8s. Alike T_{50cm} spread times, the V-funnel flow times were lower because of relatively high W/B ratios. However, the V-funnel flow times at

0.40 W/B ratio were higher than those at 0.50 and 0.60 W/B ratios, as can be seen from Table 4.4. In addition, the V-funnel flow time increased linearly with higher POFA content at both W/B ratios, as evident from Figure 4.7. The lowest V-funnel flow time was obtained for the control concretes (0% POFA). In contrast, the SCC mixtures with 15% POFA provided the highest V-funnel flow time. The higher V-funnel flow times at a lower W/B ratio (0.40) and greater POFA content indicated an increased plastic viscosity of the concrete. This is due to the same reason as discussed in the case of T_{50cm} spread time.

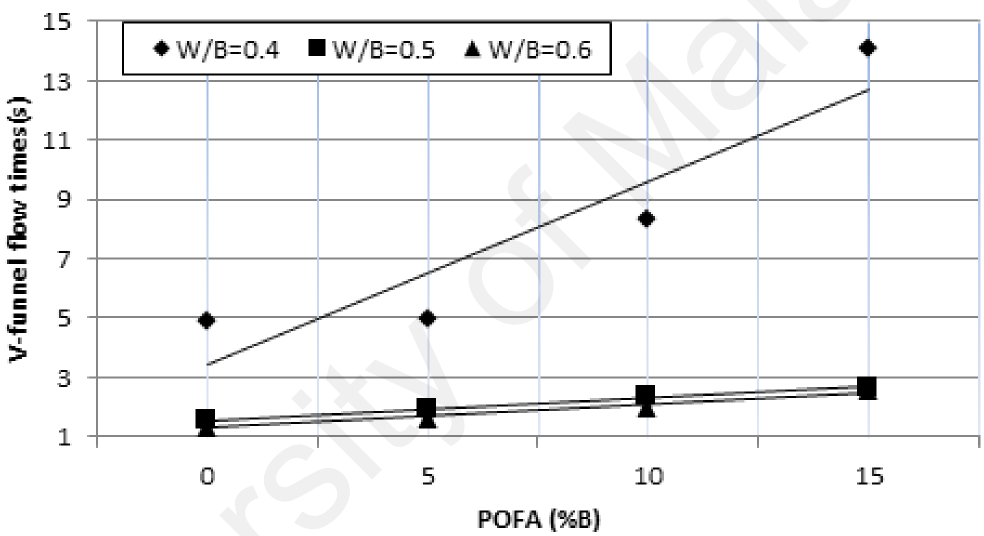


Figure 4.7: The effect of POFA on V-funnel flow

4.2.2. Passing ability of concretes

4.2.2.1. J-ring flow

The J-ring flow (slump flow in the presence of a J-ring) varied in the range of 525–650 mm (see Table 4.4). The difference between slump flow and J-ring flow was 5–20 mm, which indicates the excellent passing ability. According to ASTM C 1621/C 1621M (2009), no visible blocking occurs when the difference between slump flow and J-ring flow is 0-25 mm. In the present study, the J-ring flow at 0.50 W/B ratio was higher than that at 0.60 W/B ratio (refer to Table 4.4). However, the J-ring flow at 0.40 W/B ratio was significantly lower than that at 0.50 and 0.60 W/B ratios. This is due to the similar reasons as discussed in the case of the slump flow results. Moreover, the J-ring flow decreased linearly with the increased POFA content, as can be seen from Figure 4.8. The lowest J-ring flow was observed for the SCC mixtures with 15% POFA. In contrast, the highest J-ring flow was attained for the SCC mixtures without any POFA (control concretes). This is owing to the same reason as discussed in the case of slump flow.

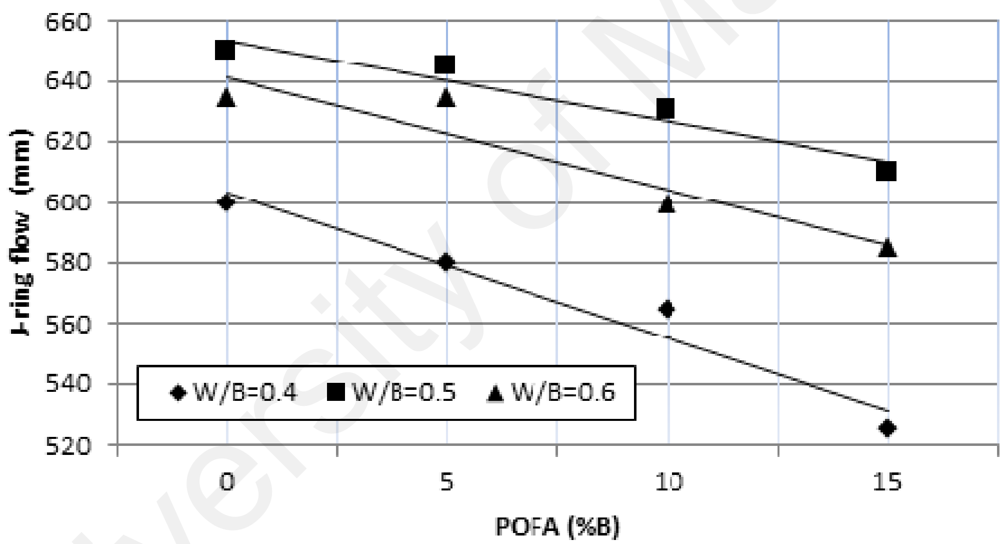


Figure 4.8: The effect of POFA on J-ring flow

4.2.3. Segregation resistance of concretes

4.2.3.1. Visual stability index (VSI)

The VSI values of the concretes were the same for all W/B ratios (see Table 4.5). Hence, the effect of the W/B ratio on the segregation resistance of concrete was not obvious in visual observation. However, the effect of POFA was evident during visual inspection (refer to Table 4.5). The concrete mixture with 15% POFA was highly stable with a VSI value of ‘0’ for no evidence of segregation or bleeding. Besides, the concrete with 10% POFA was stable having a VSI value of ‘1’ for no evidence of segregation but a very slight bleeding. The VSI values of these two concretes suggest that they had a good segregation resistance, which was validated by the sieve and column tests (see Table 4.4).

Table 4.5: Visual stability index (VSI) values of various SCCs

Concrete mix	Visual inspection	VSI value
1, 5, 9 (W/B = 0.40, 0.50, 0.60 POFA = 0%)	Significant bleeding, a slight paste ring but no mortar halo, no aggregate pile in the center of the slump flow patty	2 = Unstable
2, 6, 10 (W/B = 0.40, 0.50, 0.60 POFA = 5%)	Slight bleeding, a very slight paste ring but no mortar halo, no aggregate pile in the center of the slump flow patty	1.5 = Unstable
3, 7, 11 (W/B = 0.40, 0.50, 0.60 POFA = 10%)	Very slight bleeding, no paste ring or mortar halo, no aggregate pile in the center of the slump flow patty	1 = Stable
4, 8, 12 (W/B = 0.40, 0.50, 0.60 POFA = 15%)	No bleeding, no paste ring or mortar halo, no aggregate pile in the center of the slump flow patty	0 = Highly stable

The concrete mixtures with 5% POFA showed slight bleeding and a very slight paste ring. This concrete was rated as ‘unstable’ with a VSI value of ‘1.5’. The worst visual rating was in the concrete with 0% POFA. This concrete was also rated as ‘unstable’ with a VSI value of ‘2’. The unstable nature of the concretes with 0% and 5% POFA suggested that they had a poor segregation resistance, which was confirmed by the sieve and column tests (refer to Table 4.4).

4.2.3.2. Segregation index

The segregation index of different SCC mixtures obtained from the Japanese sieve stability test varied in the range of 10.2–23.9% depending on the POFA content and the W/B ratio (refer to Table 4.4). A lower value of segregation index indicates a higher segregation resistance. The maximum acceptable limit for the segregation index obtained from the Japanese sieve test is 18% (Perez *et al*., 2002). Hence, the SCC mixtures with 0% and 5% POFA at 0.4, 0.5 and 0.6 W/B ratios and the SCC mixture with 15% POFA at 0.4 W/B ratio failed to have the adequate segregation resistance. It is also obvious from Table 4.4 that the segregation index at 0.50 W/B ratio was slightly higher than that at 0.60 W/B ratio. This is because the concrete spread over the sieve was greater, as understood from the increased slump flow. Consequently, more mortar passed through the openings of sieve after separation from coarse aggregates. A higher amount of mortar passed increases the segregation index, since it is measured as the ratio of mortar mass passing the sieve to the mortar content of concrete.

The segregation index of concrete decreased with higher POFA content at all W/B ratios, as evident from Figure 4.9. The highest segregation index was obtained with 0% POFA. In contrast, the lowest segregation index was achieved for 15% POFA. The decrease in the segregation index at higher POFA content was also related to the reduced spread of concrete.

The effects of W/B ratio and POFA content were greatly influenced by the yield strength and plastic viscosity of concrete. The segregation resistance is improved at the higher yield strength and greater plastic viscosity of concrete (Petrou *et al*., 2000; Bonen & shah, 2005). In the present study, the yield strength and plastic viscosity of concrete were not measured directly. However, the yield strength is strongly correlated with the slump flow – the higher the slump flow, the lower is the yield strength (Safiuddin, 2008; Saak *et al.*, 2004). The reduction in slump flow at higher W/B ratio and greater POFA content suggests an increased yield strength, which improves the segregation resistance of concrete and thus gives a lower segregation index. Furthermore, the flow time and plastic viscosity of concrete are well-correlated – the greater the flow time, the higher is the plastic viscosity (Safiuddin *et al.*, 2010). Hence, the flow time results obtained from T_{50}cm spread and V-funnel flow tests indicate that the plastic viscosity of concrete increased with higher POFA content. The increased plastic viscosity worked oppositely to decrease the flow spread on the sieve, and thus reduced the segregation index of POFA concrete.

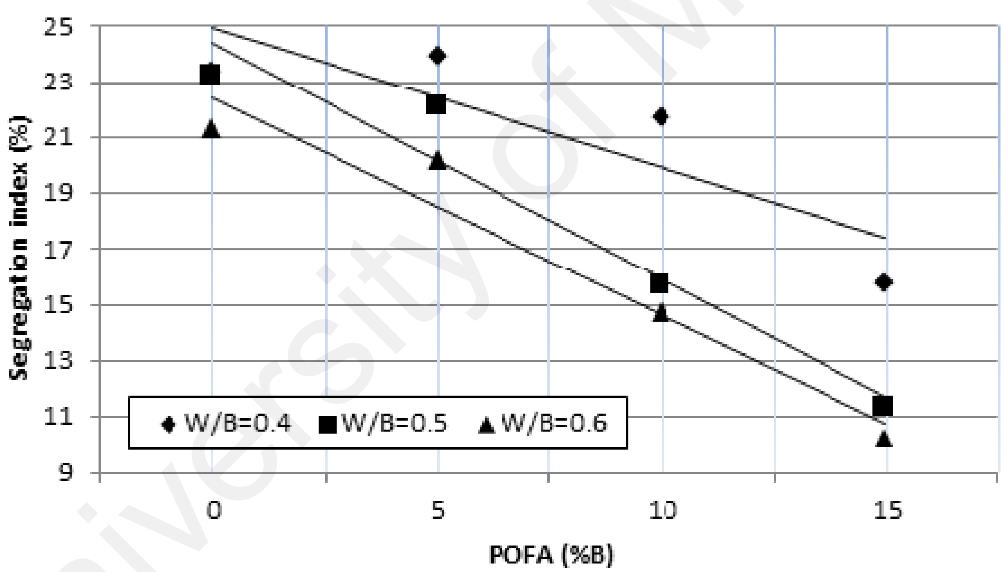


Figure 4.9: The effect of POFA on segregation index

4.2.3.3. Segregation factor

The segregation factor of different SCCs obtained from the column stability test ranged from 10.8%–25.2%(see Table 4.4). A lower value of segregation factor suggests a higher segregation resistance. The maximum acceptable limit for the segregation factor obtainedfrom the column test is 20% (Safiuddin, 2008). Therefore, the SCC mixtures with 0% and 5% POFA contents at 0.50 W/B ratio did not possess adequate segregation resistance, since they provided a segregation factor greater than 20%. All SCC mixtures at 0.40 W/B ratio satisfied the requirement for good segregation resistance. It is also evident from Table 4.4 that the segregation factor at 0.60 W/B ratio was lower than that at 0.50 W/B ratio. This is mostly attributed to the increased yield strength of concrete, as understood based on the slump flow results. The high yield strength decreases the settlement height of aggregates in concrete (Bonen & Shah, 2005; Koehler & Fowler, 2006). Although the plastic viscosity of concrete was lower at 0.60 W/B ratio, as comprehended based on the T_{50}cm spread time and V-funnel flow time results, it was not predominant in increasing the settlement of coarse aggregates. Therefore, the SCC mixtures with 0.60 W/B ratio provided a lower segregation factor. The effect of plastic viscosity was perhaps predominant in reducing the settlement of aggregates in case of the SCC mixtures at 0.40 W/B ratio. Hence, these concretes had relatively low segregation factor, thus indicating good segregation resistance.

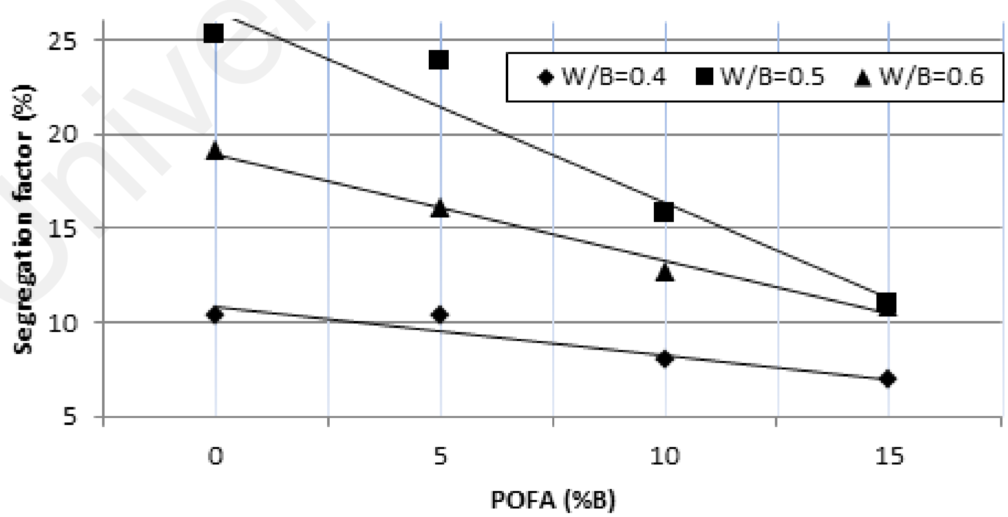


Figure 4.10: The effect of POFA on segregation factor

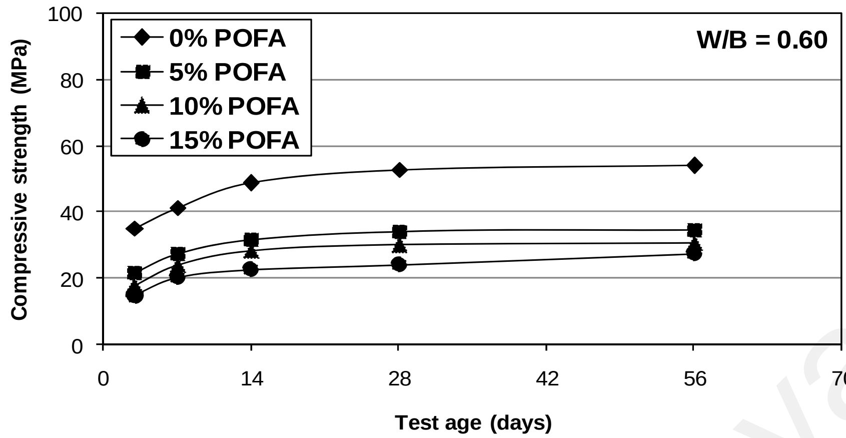
The segregation factor decreased with greater POFA content, as evident from Figure 4.10. For all W/B ratios, the highest segregation factor was obtained at 0% POFA, whereas the lowest segregation factor was achieved at 15% POFA. These test results indicate that the settlement of aggregates was decreased with greater POFA content. This is attributed to the increased yield stress and plastic viscosity of concrete.

The slump flow results indicate that the yield stress of concrete increased with higher POFA content. The increased yield stress decreases the settlement height of coarse aggregates, as discussed earlier regarding the effect of W/B ratio. Moreover, the T_{50}cm spread time and V-funnel flow time results suggest that the plastic viscosity of concrete increased with greater POFA content. The increased plastic viscosity decreases the settlement rate of coarse aggregate, and thus enhances the segregation resistance of concrete (Bonen & Shah, 2005; Saak *et al*., 2001). Therefore, the lower segregation factor was obtained at higher POFA content.

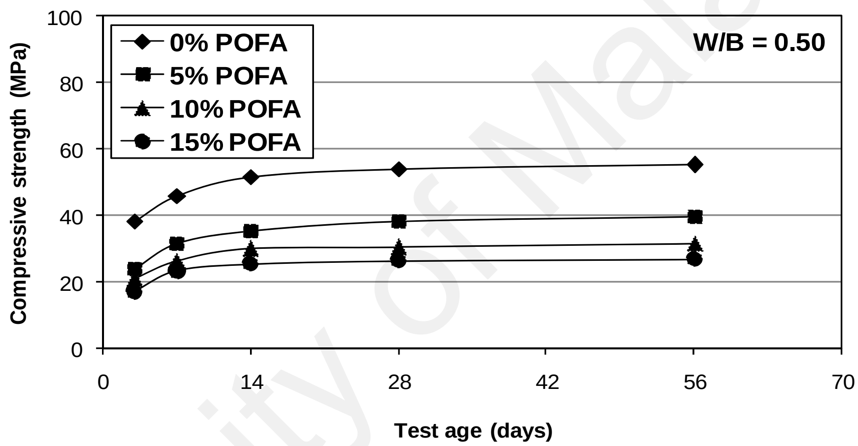
4.3. Properties of Hardened Self-Consolidating Concretes

4.3.1. Compressive strength

The average compressive strengths of the concretes are presented in Figures 4.11(a)–4.11(c). The detailed results are also tabulated in Appendix B. The gain in compressive strength continued to occur until the age of 56 days. The 28-day compressive strength varied from 24.20 to 80.56 MPa while the 56-day compressive strength differed from 27.53 to 85.42 MPa for different concretes depending on the W/B ratio. In general, the 7-day compressive strength was smaller than the 28-day compressive strength. The maximum increase in the 28-day compressive strength was 28.87% as compared to the 7-day compressive strength.



(a)



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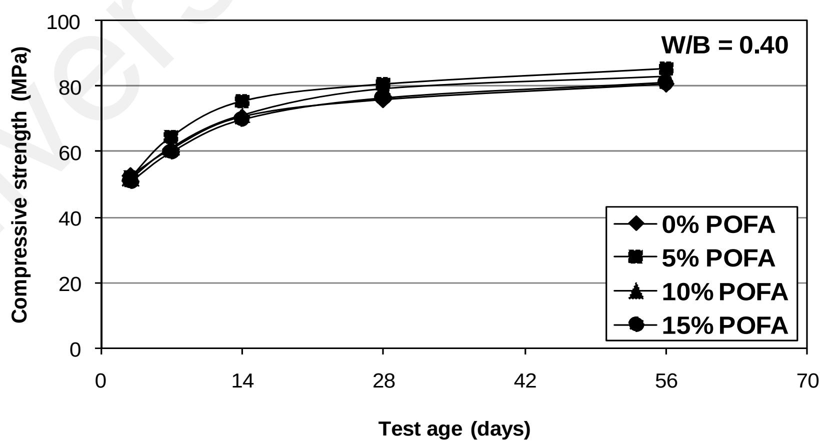


(c)

Figure 4.11: Compressive strength for W/B ratio (a) 0.60, (b) 0.50, and (c) 0.40

The highest compressive strength at all ages was achieved for the SCC mixture with 0.40 W/B ratio and 5% POFA. On the contrary, the SCC mixture with 0.60 W/B ratio and 15% POFA provided the lowest level of compressive strength at all ages.

The compressive strength of the POFA and non-POFA concretes increased with a lower W/B ratio, as can be seen from Figure 4.12. This is attributed to the reduction in concrete porosity (Neville, 1996)**.**In the current study, the permeable porosity of concrete decreased with a lower W/B ratio. The improvement of microstructure of concrete occurs in both bulk paste matrix and interfacial transition zone with a reduced porosity (Zhang *et al*., 1996). As the water content was kept constant, the cement content became higher at a lower W/B ratio (Table 4.3). Due to this increased cement content, the physical packing of aggregates was improved and a greater amount of calcium silicate hydrate (C-S-H) was produced, thus contributing to a higher compressive strength.

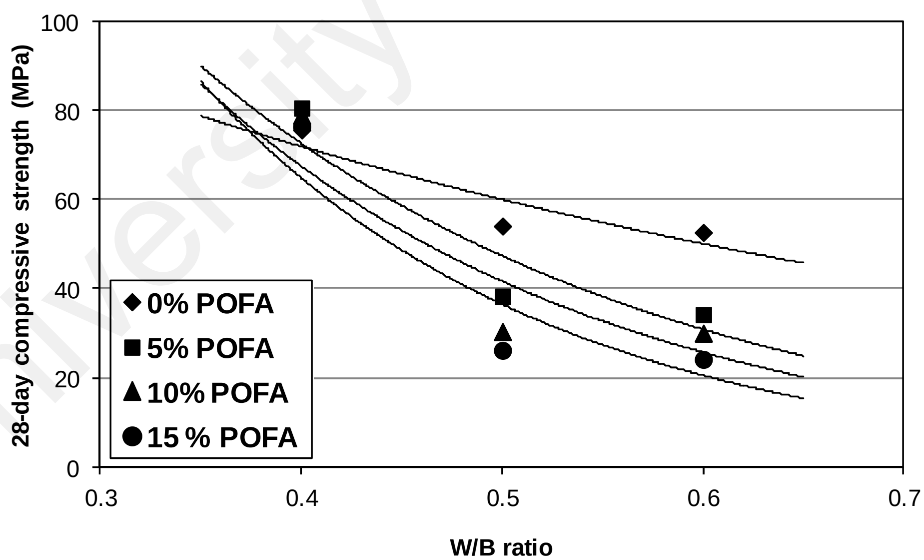


Figure 4.12: Compressive strength for various W/B ratios

POFA decreased the compressive strength at all ages for the concretes produced with higher W/B ratios (0.50 and 0.60), as evident from Figure 4.12 and Figure 4.13. The cement content decreased with the higher W/B ratio, since the water content was the same (Table 4.3). The reduced cement content produces lower C-S-H, and thus decreases the compressive strength of SCC. In addition, the pozzolanic contribution of POFA becomes insignificant at lower cement content. The micro-filling ability of POFA also becomes ineffective due to increased capillary porosity and connectivity of pores at a higher W/B ratio. On the other hand, the higher cement content plus the micro-filling ability and pozzolanic activity of POFA play significant role at a lower W/B ratio to increase the compressive strength of concrete. Therefore, the compressive strength of the SCC mixtures containing 5–15% POFA was higher than that of the control concrete (0% POFA) at the lower W/B ratio of 0.40. The optimum POFA content for the concrete with 0.40 W/B ratio was 5%, which produced the maximum compressive strength (Figure 4.13).

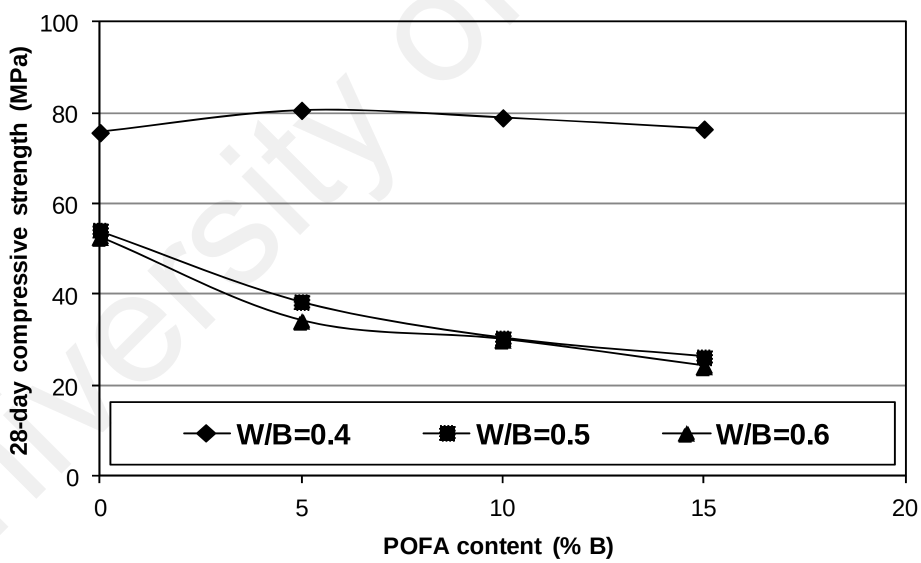


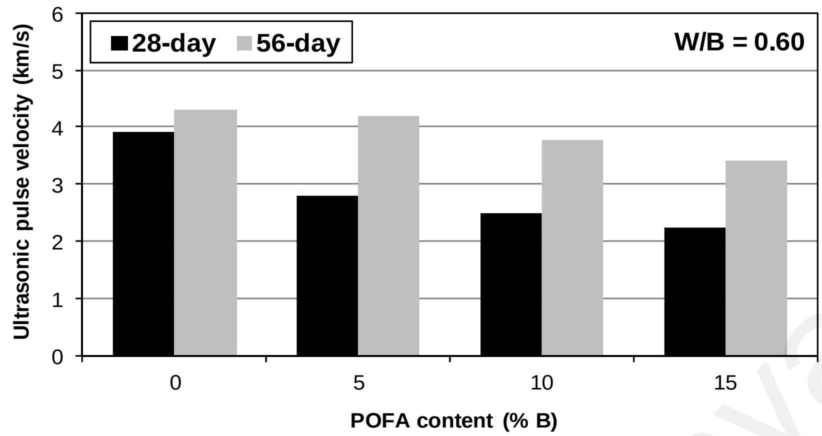
Figure 4.13: Compressive strength for various POFA contents

4.3.2. Ultrasonic pulse velocity (UPV)

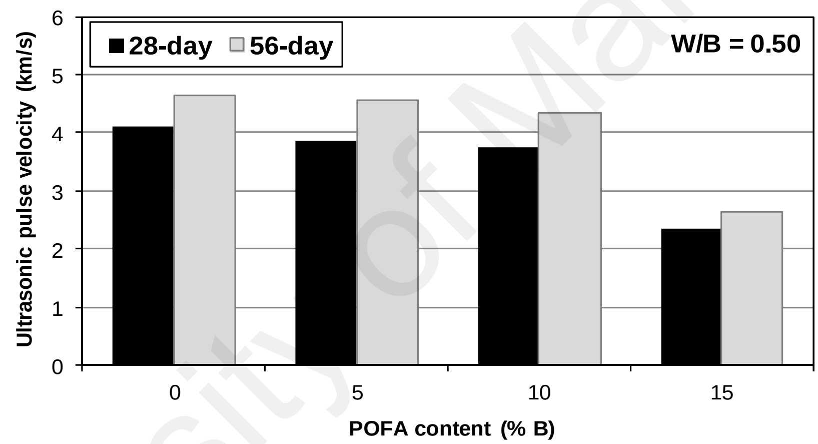
The average test results for the 28-day and 56-day ultrasonic pulse velocity of the concretes are presented in Figures 4.14(a) – 4.14(c).The detailed results are also tabulated in

Appendix B. The ultrasonic pulse velocity varied in the range of 2.24–4.98 km/s. The concretes prepared with the W/B ratio of 0.40 produced the highest level of ultrasonic pulse velocity. These concretes provided an ultrasonic pulse velocity higher than 4.5 km/s that generally represents the excellent quality of concrete (Shetty, 2001).On the contrary, the concretes produced with the W/B ratio of 0.6 provided the lowest level of ultrasonic pulse velocity.

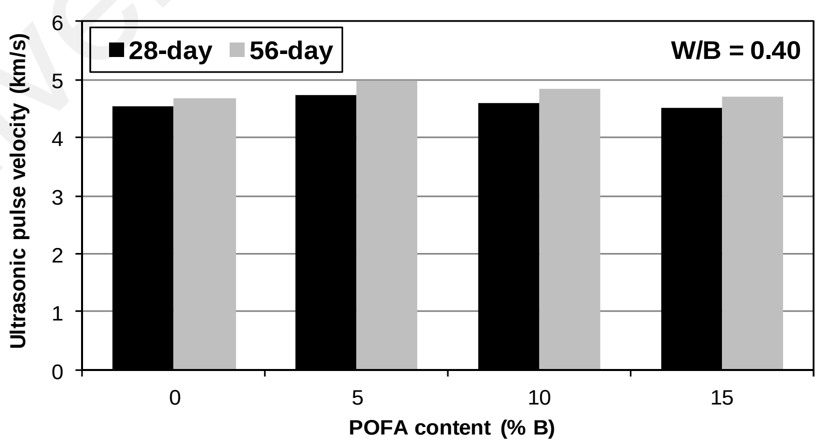
The ultrasonic pulse velocity of the POFA and non-POFA concretes increased with a lower W/B ratio, as evident from Figures 4.14(a)–4.14(c). The presence of POFA was not effective in improving the ultrasonic pulse velocity of the concretes prepared with higher W/B ratios. At the W/B ratios of 0.50 and 0.60, the ultrasonic pulse velocity decreased with higher POFA content, as can be seen from Figure 4.14(b) and Figure 4.14(c). In contrast, POFA had no negative impact when used in the concretes with 0.40 W/B ratios. Indeed, the ultrasonic pulse velocity slightly increased for the concretes with 5 and 10% POFA contents. The maximum ultrasonic pulse velocity was obtained for the concrete including 5% POFA content. The positive and negative effects of POFA on the ultrasonic pulse velocity of concrete were due to the same reasons, as discussed in the case of compressive strength. In addition, the aggregate content decreased for the POFA concretes; the decrease was greater for a higher W/B ratio, as can be seen from Table 4.3. Consequently, the positive effect of POFA on the ultrasonic pulse velocity of concrete can be reduced, as a reduction in aggregate content decreases the ultrasonic pulse velocity of concrete (Shetty, 2001; Naik *et al*., 2004). For the same reason, the increase in ultrasonic pulse velocity at 0.40 W/B ratio was not significant.



(a)



(b)



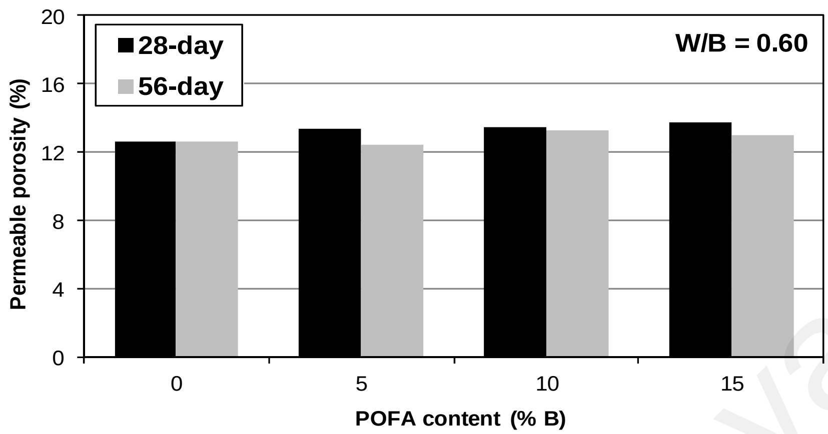
(c)

Figure 4.14: Ultrasonic pulse velocity for W/B ratio (a) 0.6, (b) 0.5, and (c) 0.4

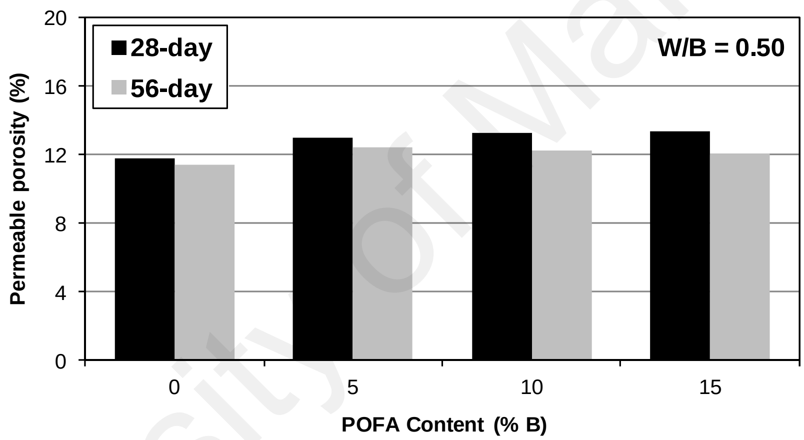
4.3.3. Permeable porosity

The average test results for the 28-day and 56-day permeable porosity of the concretes are shown in Figures 4.15(a) – 4.15(c).The detailed results are also tabulated in Appendix B. The permeable porosity varied in the range of 6.5–13.76%. The overall test results imply that the permeable porosity of the concretes was slightly/relatively low when compared with ordinary or conventional concrete. Safiuddin & Hearn (2005) found that the 28-day permeable porosity of the concretes at the W/B ratios of 0.50 and 0.60, as determined according to the boiling water method, varied in the range of 13.66 to 17.46%. In the present study, the 28-day permeable porosity of POFA and non-POFA concretes at the same W/B ratios (0.50 and 0.60) was 11.71 to 13.76%. Obviously, the microstructure of POFA and non-POFA SCC mixtures was denser than that of ordinary concrete. This is credited to the excellent workability of SCC mixtures that facilitates a high degree of compaction with minimum voids in concrete.

The permeable porosity of the POFA and non-POFA concretes decreased with a lower W/B ratio, as obvious from Figures 4.15(b) and Figure 4.15(c). It was understood that the increased cement content at a lower W/B ratio (0.40) produced a greater amount of hydration products (C-S-H, C-A-H) that filled up more voids present at the bulk cement paste and the transition zone of concrete. Consequently, the microstructure of concrete was improved with reduced permeable porosity. In addition, the physical (microfilling) and chemical (pozzolanic) effects of POFA contributed to decrease the permeable porosity of concrete.



(a)



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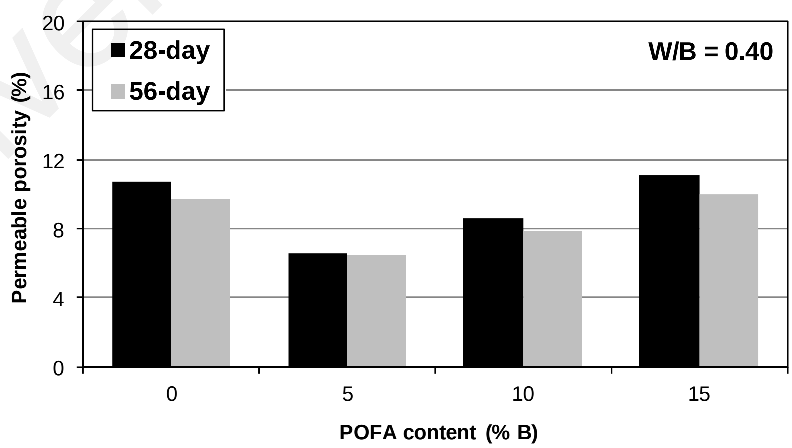


(c)

Figure 4.15: Permeable porosity for W/B ratio (a) 0.6, (b) 0.5,and (c) 0.4

The permeable porosity of the concretes was relatively high at the W/B ratios of 0.50 and 0.60. It is possibly due to the fact that these two W/B ratios were significantly higher than the minimum W/B ratio needed to eliminate the capillary pores (connected permeable pores). When the W/B ratio is more than 0.38, the bulk volume of C–S–H gel is not adequate to fill all water-filled pores and hence some capillary pores can still exist in the binder paste even after complete hydration (Neville, 1996; Demirboğa *et al*., 2004).

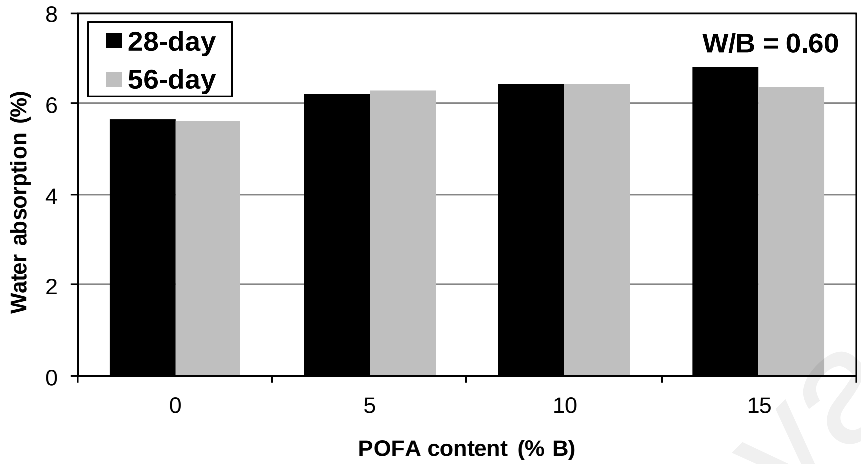
The permeable porosity of the concretes slightly increased in the presence of POFA at higher W/B ratio, as can be seen from Figures 4.15(b) and Figure 4.15(c). This is due to reduced hydration products obtained from a lower cement content, and insignificant pozzolanic activity and micro-filling ability of POFA at a higher W/B ratio. In contrast, the permeable porosity of concrete first decreased for 5 and 10% POFA contents and then increased for 15% POFA content at a lower W/B ratio (0.40), as evident from Figure 4.15(a). This suggests that the micro-filling ability and pozzolanic activity of POFA became effective at the lower W/B ratio of 0.40. However, the reduction in cement content was more at 15% POFA content; this produced a relatively low amount of calcium hydroxide ($Ca(OH)_2$) from cement hydration. Hence, the entire amount of POFA at 15% POFA content perhaps could not react with $Ca(OH)_2$ to maximize the production of secondary hydration product from pozzolanic reaction. The amount of POFA available at 5% POFA content was probably utilized completely to produce the maximum amount of secondary hydration product. Hence, the optimum POFA content was 5%, which produced the minimum permeable porosity.

4.3.4. Water absorption

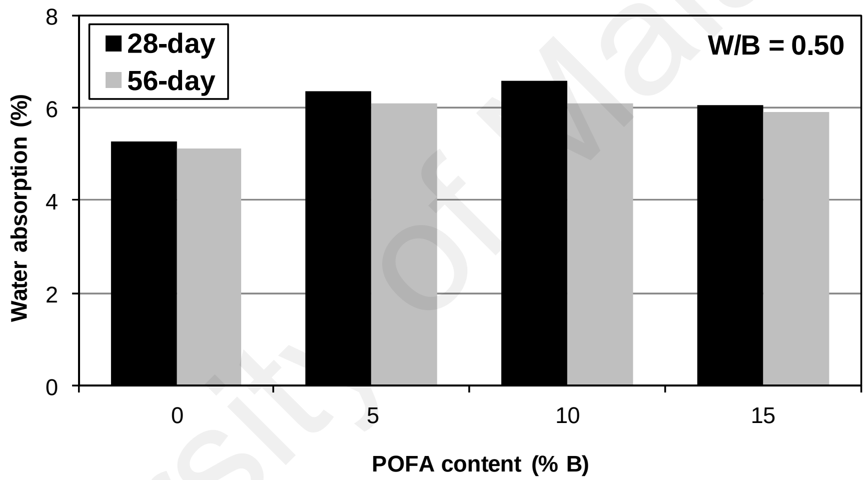
The average test results for the water absorption of the POFA and non-POFA concretes at 28 and 56 days obtained based on the boiling water saturation technique are presented in Figures 4.16(a)–4.16(c).The detailed results for both cold-water and boiling water saturation techniques are tabulated in Appendix B. The boiling water based water absorption varied in the range of 2.83–6.81%, which is relatively low. In case of high quality concrete, the water absorption is generally less than 5% (Kosmatka *et al*., 2002).

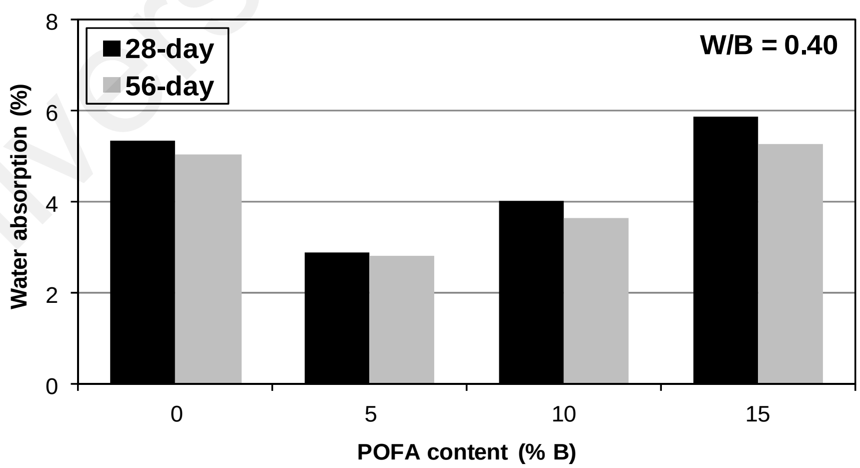
The low range of water absorption was obtained due to the relatively low permeable porosity of the concretes. Furthermore, the water absorption of the concretes was relatively low when compared with the water absorption of ordinary concretes. Safiuddin *et al.* (2011) found that the 28-day water absorption of the concretes at the W/B ratios of 0.50 and 0.60, as determined based on the boiling water method, varied in the range of 5.94 to 7.63%. In the present study, the 28-day boiling water based water absorption of the concretes at the same W/B ratios ranged from 5.27 to 6.81%. Obviously, the SCC mixtures produced in this study provided lower water absorption. This is due to the similar reasons as discussed in the case of permeable porosity.

The boiling water based water absorption of the non-POFA concretes slightly decreased at a higher W/B ratio, as obvious from Figures 4.16(a)–4.16(c). The highest level of water absorption was noticed for the concretes prepared with the W/B ratio of 0.60. On the contrary, the lowest level of water absorption was achieved for the concrete produced with the W/B ratio of 0.40. These results were consistent with the permeable porosity of concrete presented in Figure 4.15(a) – Figure 4.15(c). The water absorption increased for a higher W/B ratio, and decreased for a lower W/B ratio. Similar results were also observed for cold-water saturation technique.



(a)





(c)

Figure 4.16: Water absorption for W/B ratio (a) 0.6, (b) 0.5, and (c) 0.4

The boiling water based water absorption of the concretes increased with greater POFA content when used at higher W/B ratios (0.50 and 0.60), as evident from Figure 4.16(b) and Figure 4.16(c). In contrast, the water absorption decreased for 5 and 10% POFA contents when used in the concrete with 0.40 W/B ratio. The lowest level of water absorption was attained for the concrete with 0.40 W/B ratio and 5% POFA content that provided 45% and 50% lower water absorption at 28 and 56 days, respectively, as compared to the control concretes. This reduction in water absorption is primarily credited to the reduced porosity of concrete at 5% POFA content (Figure 4.15(a)). It should also be mentioned that the water absorption of the concrete with 0.40 W/B ratio and 15% POFA content slightly increased as compared to the control concrete (Figure 4.16(a)).A similar result was also observed for cold-water saturation technique. This is due to the reason that the permeable porosity of concrete increased for 15% POFA content (Figure 4.15(a)).

4.3.5. Correlation between compressive strength and ultrasonic pulse velocity

The correlation between the compressive strength and ultrasonic pulse velocity of self-consolidating POFA concrete is shown in Figure 4.17. In this study, the ultrasonic pulse velocity varied from 2.24 km/s to 4.73 km/s whereas the compressive strength ranged from 24.2 MPa to 80.56 MPa. They varied identically with the W/B ratio and POFA content of concrete. Therefore, a strong positive linear relationship with the correlation coefficient of +0.9252 was noticed for compressive strength and ultrasonic pulse velocity (Figure 4.17). A similar correlation was observed by Demirboğa *et al*. (2004) or the concretes including fly ash and blast-furnace slag, and by Safiuddin (2008) for the concretes incorporating rice husk ash.

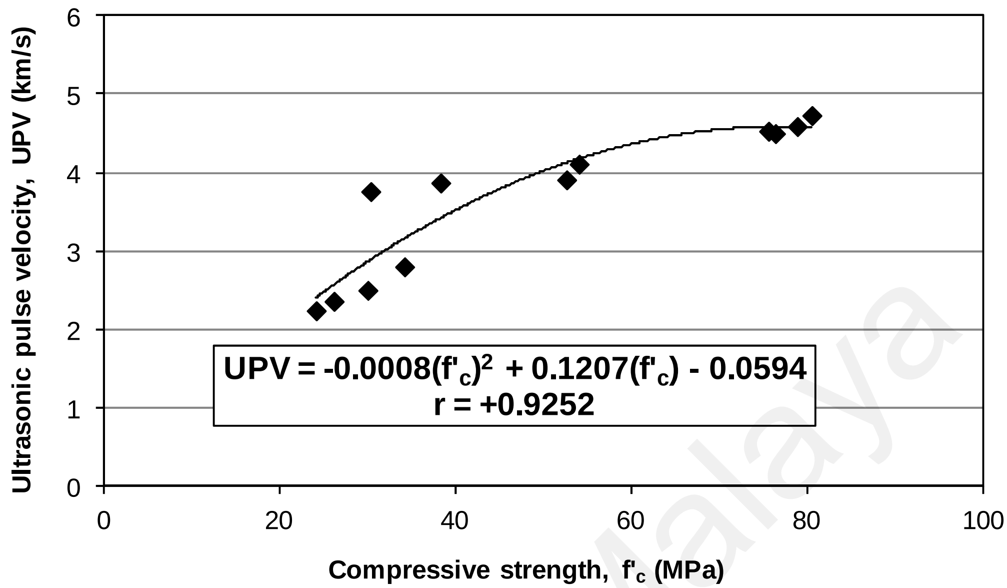


Figure 4.17:Correlation between compressive strength and ultrasonic pulse velocity

4.3.6. Correlation between compressive strength and permeable porosity

The compressive strength and porosity of self-consolidating POFA concrete were strongly correlated, as evident from Figure 4.18. The porosity differed from 6.6% to 13.76% for the concretes whose compressive strength ranged from 24.2 MPa to 80.56 MPa. The compressive strength increased with the decreased porosity of concrete. Also, the compressive strength and porosity varied oppositely with the W/B ratio and the POFA content of concrete. Therefore, a strong negative linear relationship with the correlation coefficient of –0.9094 was observed between compressive strength and porosity. A similar relationship was also reported by the other researchers (Safiuddin, 2008; Al-Amoudi *et al*., 1996; Lian *et al*., 2011) for the concretes including fly ash, silica fume, and rice husk ash.

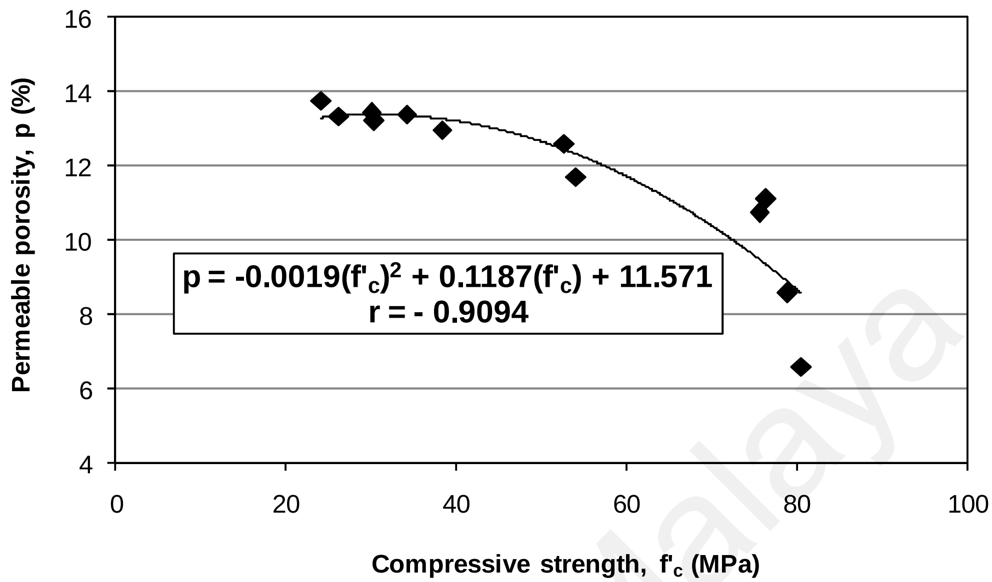


Figure 4.18: Correlation between compressive strength and permeable porosity

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1. General

This chapter lists the conclusions on the research findings and gives a number of recommendations for future research.

5.2. Conclusions

The overall outcomes of the present study reveal that the SCC with reasonably good filling ability and passing ability can be produced at relatively high W/B ratios with and without SCM. However, the SCC mixture at higher W/B ratios is susceptible to segregation, which can be improved by using POFA as an SCM.POFA also improved the hardened properties of concrete when used for a lower W/B ratio. Based on the experimental results for various self-consolidating POFA concretes produced in the present study, the following conclusions can be drawn.

5.2.1. Conclusions on fresh properties of concretes

1. The required filling ability for self-consolidating concrete was achieved for all concretes except Mix 4. The passing ability was reasonably good for all concretes. However, the demand for HRWR was increased with lower W/B ratio and higher POFA content due to the increased surface area of binder. Therefore, the filling ability and passing ability were decreased at lower W/B ratio and higher POFA content.

2. The slump flow and J-ring flow were higher at the lower W/B ratio. This is because the increased paste volume at a lower W/B ratio with higher binder content enhanced the dispersion of aggregates, thus producing a greater concrete spread.
3. The T_{50cm} spread time and V-funnel flow time increased at the lower W/B ratio. This is because the lower W/B ratio provided a higher binder content, which reduces the amount of free water in concrete and thus causes a greater resistance to flow.
4. The slump flow and J-ring flow of concrete decreased, whereas T_{50cm} spread time and V-funnel flow time increased with a greater amount of POFA. This is due to a lesser quantity of available free water in the presence of POFA, which confines some mixing water because of high specific surface area.
5. The segregation index and segregation factor were lower at higher W/B ratio. This is mainly credited to the increased yield strength of concrete, as exhibited by the results of slump flow.
6. The segregation resistance of concrete improved in the presence of POFA. Hence, both segregation index and segregation factor decreased with higher POFA content. This is due to increased yield strength and plastic viscosity of concrete, as indicated by the results of slump flow and T_{50cm} spread time or V-funnel flow time, respectively.
7. It is possible to produce SCC with adequate filling ability, passing ability and segregation resistance by incorporating POFA as an SCM. At least, 10-15% POFA shall be used in SCC to improve its segregation resistance.

5.2.2. Conclusions on hardened properties of concretes

1. The hardened properties of concrete were improved with lower W/B ratio due to the improved physical packing produced by a greater amount of hydration products resulting from higher binder content. In particular, the permeable porosity of the concretes decreased with lower W/B ratio. The reduction in permeable porosity increased the compressive strength and ultrasonic pulse velocity, and decreased the water absorption of concrete.
2. The hardened properties of concrete were not improved with the increased content of POFA at higher W/B ratios (0.50 and 0.60). However, the excellent hardened properties were achieved at 5% POFA, when used in the concrete with a lower W/B ratio (0.40). The higher cement content at a lower W/B ratio produced more hydration products, thus increased the compressive strength of concrete. In addition, the micro-filling ability and pozzolanic activity of POFA improved the compressive strength of SCC. Hence, 5% POFA was the optimum POFA content for SCC in the context of the present study.
3. The compressive strength and ultrasonic pulse velocity were strongly correlated with a positive relationship, which possessed the correlation coefficient of +0.9252; such strong positive relationship was obtained because both compressive strength and ultrasonic pulse velocity varied identically with the W/B ratio and POFA content of concrete.
4. The compressive strength and permeable porosity were strongly correlated with a negative relationship; the coefficient of correlation was -0.9094. Such strong negative relationship was observed since the compressive strength, and permeable

porosity varied oppositely with the W/B ratio and POFA content of concrete, and the compressive strength increased with the decreased porosity of concrete.

5. It is possible to produce SCC with good hardened properties by incorporating POFA as an SCM. POFA shall be used in SCC as a 5–15% replacement of cement by weight.

5.3. Recommendations

Further investigation on the potential utilization of POFA in concrete is required. The following recommendations for future study are given.

1. The effect of POFA from different palm-oil mills should be investigated with respect to fresh and hardened properties and durability.
2. The effect of POFA on mechanical properties such as tensile, flexural and bond strengths of concrete should be investigated.
3. The effect different levels of POFA fineness on the fresh and hardened properties of SCC should be investigated.
4. The effect of different curing methods on the hardened properties of SCC should be studied.
5. The influence of POFA on the durability properties of SCC such as resistance to chemical attack should be examined.
6. A study should be carried out to observe the effect of the combination of POFA and other supplementary cementing materials on the fresh and hardened properties, and durability of SCC.

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APPENDIX A

Primary Mixture Proportionsof Concretes

Mix no.	w/b ratio	CA (kg/m^3)	FA (kg/m^3)	C (kg/m^3)	POFA (% B)	POFA (kg/m^3)	W (kg/m^3)	HRWR (l/m^3)
1	0.4	829.0	829.0	513.0	0	0	205.0	0.185
2	0.4	798.0	798.0	487.0	5	25.6	205.0	0.185
3	0.4	796.0	796.0	461.0	10	51.3	205.0	0.185
4	0.4	795.0	795.0	436.0	15	76.9	205.0	0.185
5	0.5	880.0	880.0	410.0	0	0	205.0	0.160
6	0.5	840.0	840.0	390.0	5	20.5	205.0	0.160
7	0.5	839.0	839.0	369.0	10	41	205.0	0.160
8	0.5	838.0	838.0	349.0	15	61.5	205.0	0.160
9	0.6	914.0	914.0	342.0	0	0	205.0	0.154
10	0.6	869.0	869.0	325.0	5	17.1	205.0	0.154
11	0.6	868.0	868.0	308.0	10	34.2	205.0	0.154
12	0.6	867.0	867.0	290.0	15	51.3	205.0	0.154

APPENDIX B

Properties of Hardened Concretes

Compressive Strength of Different SCCs

Mix no.	W/B Ratio	POFA content %	Compressive strength (N/mm^2)				
			3d	7d	14d	28d	56d
1	0.4	0%	52.32	60.84	70.6	75.64	80.33
2	0.4	5%	52.27	64.51	75.38	80.56	85.42
3	0.4	10%	51.6	61.23	71.08	78.91	83.01
4	0.4	15%	50.8	59.67	69.84	76.42	80.87
5	0.5	0%	38.16	45.85	51.69	54.10	55.31
6	0.5	5%	23.72	31.45	35.23	38.36	39.81
7	0.5	10%	20.92	26.36	29.89	30.40	31.52
8	0.5	15%	17.15	23.33	25.36	26.23	26.85
9	0.6	0%	35.00	41.23	48.67	52.67	53.84
10	0.6	5%	21.78	27.58	31.59	34.25	34.54
11	0.6	10%	17.99	24.15	28.46	30.07	30.73
12	0.6	15%	14.73	20.42	22.59	24.20	27.53

Ultrasonic Pulse Velocity (UPV) of Different SCCs

POFA (%)	0.4(W/B)		0.5(W/B)		0.6(W/B)	
	28 day	56 day	28 day	56 day	28 day	56 day
0%	75.64(4.40)	80.33(4.67)	4.11	4.65	3.91	4.3
5%	80.56(4.69)	85.42(4.98)	3.87	4.57	2.8	4.19
10%	78.91(4.59)	83.01(4.83)	3.76	4.34	2.5	3.77
15%	76.42(4.48)	80.87(4.71)	2.36	2.64	2.24	3.41

Permeable Porosityof Different SCCs

Mix No.	W/B ratio	POFA contents %	Permeable porosity (%)	
			28 day	56 day
1	0.4	0%	10.72	9.73
2		5%	6.60	6.50
3		10%	8.57	7.84
4		15%	11.10	10.02
5	0.5	0%	11.71	11.34
6		5%	12.95	12.40
7		10%	13.20	12.23
8		15%	13.33	12.04
9	0.6	0%	12.61	12.56
10		5%	13.37	12.43
11		10%	13.41	13.25
12		15%	13.76	12.96

Water Absorption of Different SCCs

Mix no.	W/B ratio	POFA	ASTM saturation technique	Absorption	
				28 day	56 day
1	0.4	0%	CWS	4.95	4.72
			BWS	5.35	5.06
2		5%	CWS	2.96	2.78
			BWS	2.91	2.83
3		10%	CWS	3.95	3.55
			BWS	4.05	3.66
4		15%	CWS	5.29	4.78
			BWS	5.90	5.28
5	0.5	0%	CWS	5.12	4.99
			BWS	5.27	5.11
6		5%	CWS	6.06	5.93
			BWS	6.34	6.09
7		10%	CWS	6.15	5.83
			BWS	6.57	6.08
8		15%	CWS	5.9	5.73
			BWS	6.06	5.9
9	0.6	0%	CWS	5.58	5.55
			BWS	5.65	5.62
10		5%	CWS	6.12	6.19
			BWS	6.21	6.27
11		10%	CWS	6.29	6.28
			BWS	6.45	6.42
12		15%	CWS	6.55	6.26
			BWS	6.81	6.37

APPENDIX C

Publications

1. Safiuddin, Md.,Rahman, M.M., Salam, M.A., **Md.Isa, M.H.**, and Jumaat, M.Z., "Properties of self-consolidating POFA concrete", *Advanced Science Letters*, 2012. **(In-press). ISSN: 1936-6612; E-ISSN: 1936-7137**. **(Indexed in ISI Web of Science)**.
2. Safiuddin, Md.,**Md.Isa, M.H.,** and Jumaat, M.Z., "Fresh properties of self-consolidating concrete incorporating palm oil fuel ash as a supplementary cementing material", *Chiang Mai Journal of Science*, Vol. 38, No. 3, 2011, pp. 389-404. **ISSN: 0125-2526**. **(Indexed in ISI Web of Science)**.
3. **Md.Isa, M.H.**, Safiuddin, Md., and Jumaat, M.Z., "Key properties of fresh self-consolidating concrete incorporating palm oil fuel ash as a supplementary cementing material", *The Fifth Civil Engineering Conference in the Asian Region and Australasian Structural Engineering Conference*, Sydney Convention and Exhibition Centre, Australia, August 8-12, 2010.**(Abstract only)**.
4. Safiuddin, Md.,Jumaat, M.Z., Salam, M.A., and **Md.Isa, M.H.**, "Elegant use of palm oil fuel ash", *News from Bangladesh*, October 18, 2010. http://bangladesh-web.com. **ISSN: 1563-9304**. (**Web Portal**).
5. Safiuddin, Md.,Jumaat, M.Z., Salam, M.A., and **Md.Isa, M.H.**, "Best use of palm oil fuel ash", *The Independent*, October 01, 2010. http://theindependentbd.com. (**The Online Daily**).