DURABILITY CHARACTERISTICS OF SELF-CONSOLIDATING HIGH STRENGTH CONCRETE CONTAINING GROUND PALM OIL FUEL ASH AS A PARTIAL CEMENT REPLACEMENT

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DISSERTATION SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ENGINEERING SCIENCE

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ABSTRACT

Palm oil fuel ash (POFA) is considered as a waste material, and it is dumped into landfills without any commercial return or cycling which considered as a costly practice. Previous studies have shown that POFA is a pozzolanic material and can be used as a partial cement replacement in concrete. However, there is a little information regarding the use of POFA as a cement replacement for producing self-consolidating high-strength concrete (SCHSC) as well as there is not any report in the case of durability properties of this type of concrete. In this study POFA has been used as a partial cement replacement to produce SCHSC. Samples were made by replacing Type I Portland cement with various proportions (0%, 10%, 15%, and 20%) of POFA. Fresh properties such as filling ability, passing ability, and segregation resistance were examined to fulfil the requirements of self-compacting concrete according to EFNARC standard. The hardened properties and durability characteristics, such as compressive strength, drying shrinkage strain, rapid chloride permeability, initial surface absorption, acid attack, sulphate attack, and water absorption tests have been studied. Test results showed that SCHSC integrated with POFA can be produced with no adverse effects on the fresh properties. Incorporating ground POFA caused a reduction in the drying shrinkage strain of all the mixes containing POFA compared to concrete made with OPC. SCHSC containing ground POFA showed a significant reduction in the initial surface absorption, and 20% cement replacement level with the POFA exhibited the lowest initial surface absorption compared to all mixes. Integration of ground POFA as a partial cement replacement increases the resistance of SCHSC towards rapid chloride permeability, acid attack, and sulphate attack. 20% cement replacement showed the highest resistant toward chemicals attack.

Conclusively, incorporating POFA as a partial cement replacement in SCHSC does not cause adverse effects on the fresh properties and significantly improved durability characteristics of SCHSC concrete.

ABSTRAK

Abu bahan api kelapa sawit (POFA) dianggap sebagai satu bahan buangan dan banyak dibuang di tapak pelupusan tanpa sebarang pulangan komersial atau kitar semula, dan ini adalah satu praktis yang merugikan. Kajian sebelum ini telah menunjukkan bahawa POFA adalah sejenis bahan pozzolan dan boleh digunakan sebagai bahan ganti simen dalam konkrit. Bagaimanapun, terdapat sedikit maklumat mengenai penggunaan POFA sebagai bahan ganti simen untuk menghasilkan konkrit mampat sendiri berkekuatan tinggi (SCHSC) dan tiada kajian mengenai ketahanan konkrit jenis ini. Dalam kajian ini POFA telah digunakan sebagai bahan ganti simen untuk menghasilkan SCHSC. Sampel telah dihasilkan dengan menggantikan simen Portland Typo I dengan pebagai komposisi POFA (0%, 10%, 15%, dan 20%). Sifat segar seperti kebolehan mengisi, melepasi dan ketahanan segregasi telah dikaji untuk memenuhi keperluan konkrit mampat sendiri mengikut EFNARC. Sifat-sifat keras dan sifat-sifat ketahanan seperti kekuatan mampatan, pengecutan ketika kering, ketelapan klorida, penyerapan permukaan pada awal, serangan asid, serangan sulfat dan kajian penyerapan air telah dijalankan. Kajian menunjukkan bahawa SCHSC dengan POFA boleh dihasilkan tanpa sebarang kesan buruk terhadap sifat segar konkrit. Menggabungkan POFA hancur menyebabkan pengurangan terhadap pengecutan ketika kering dalam semua komposisi POFA berbanding dengan OPC. SCHSC dengan POFA menunjukkan pengurangan pada penyerapan permukaan pada awal dan pada 20% POFA menunjukkan penyerapan permukaan awal yang palng kecil berbanding komposisi lain. Integrasi POFA sebagai bahan ganti simen meningkatkan ketahanan terhadap klorida, asid dan sulfat. 20% POFA menunjukkan ketahanan yang paling tinggi.

Sebagai kesimpulan, POFA sebagai bahan ganti simen dalam SCHSC tidak menyebabkan kesan buruk ke atas sifat-sifat segar dan dapat meningkatkan ketahanan untuk SCHSC konkrit.

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List of Symbols and Abbreviations

SCHSC	Self-consolidating high strength concrete
POFA	Palm oil fuel ash
GPOFA	Ground Palm oil fuel ash
OPC	Ordinary Portland cement
RHA	Rice husk ash
SF	Silica fume
FA	Fly ash
SCC	Self-consolidating concrete
HSC	High strength concrete
SCM	supplementary cementitious material
C-S-H	Calcium- silicate-hydrate
MPOB	Malaysian palm oil board
F.A	Fine aggregate
C.A	Coarse aggregate
Ca(OH)2	Calcium hydroxide
SiO_2	Silicon dioxide
Al_2O_3	Aluminum trioxide
Fe_2O_3	Iron oxide
CaO	Calcium oxide
MgO	Magnesium oxide
Na_2O	Sodium oxide
K_2O	Potassium oxide
SO_3	Sulfur trioxide
ASTM	American Standard Test Method

CHAPTER 1

INTRODUCTION

1.1 General

Concrete is the most widely used construction material in the world after water (Gambhir, 2004). Presently, cement-based materials are among the most important construction materials and it is also expected to dominate in the future as well. However, the demand for better-quality concrete with excellent durability characteristics has increased. In addition, it is not easy to fill and place the fresh concrete into the congested reinforcement and complicated shapes with proper placement and compaction using typical vibration technique. One of the means to ease the placement of concrete is by using self-consolidating concrete (SCC); this novel concrete flows and consolidates through congested reinforcement, fills all area of the formwork under the influence of its self-weight without additional external vibration energy (Khayat, 1999). Besides that, high strength concrete (HSC) is a concrete that is developed to provide high strength and enhanced durability (Shannag, 2000). In order to utilize both features and relevance of SCC and HSC, a new type of mix has been designed known as self-consolidating high strength concrete (SCHSC) (Sabet et al., 2013; Safiuddin et al.,2013; Xie et al. 2000). SCHSC shows good fresh properties concrete and exhibits high strength and excellent durability characteristics (Sabet et al., 2013; Safiuddin et al., 2008; Tangchirapat et al., 2009).

The production of SCHSC provides many advantages, such as saving in the construction time and labour cost, elimination for the need of vibrating equipment, improvement in concrete placement in highly congested structural elements, facilitation of the construction ability of intricate concrete structures, decrease in noise pollution, and creation of better working environment. Thus, SCHSC is very attractive for construction industry. However, SCHSC with high fluidity and high strength requires high cement content and costly chemical admixtures to reduce the water to binder ratio (Safiuddin & Jumaat, 2011), which will increase the cost of SCHSC compared to conventional concrete. Other problems relating to high powder content include an increase in hydration heat and high autogenous shrinkage. In addition, high powder content can cause segregation, and high cement content will lead to increased amounts of carbon dioxide (CO_2) emissions, which can have a serious environmental impact Sabet et al. (2013).

The incorporation of supplementary cementitious materials (SCMs) such as fly ash (FA), rice husk ash (RHA), silica fume (SF), and palm oil fuel ash (POFA) in concrete has many advantages, for example conservation of energy and materials, cost efficiency; in addition, reduced heat of hydration & autogenous shrinkage, improved concrete durability, jobsite productivity, and overall sustainable construction are some other salient features of the SCMs (Hossain & Lachemi, 2009; Sabet et al., 2013). Furthermore, from an environmental point of view, the incorporation of SCMs will lead to sustainable construction by saving energy and resources as it could substantially reduce the greenhouse gases emissions and energy use due to the reduced consumption of cement in concrete (Cheerarot et al.,2004; Dinakar et al., 2008; Elahi et al.,2010).

1.2 Palm Oil Fuel Ash (POFA) as a supplementary cementitious material

Thousands of tons of POFA are produced every year from palm oil mills operation in Malaysia and Thailand. The POFA is considered as a waste material and disposed into landfills. In 2012, Malaysia had over 5.08 million hectares of oil palm plantation producing about 18.8 million crude palm oil, and contributed about 40 % of the world's total palm oil production and 44 % of world exports (Aljuboori, 2012). This generated large amount (70 million ton) of biomass residue (Lam et al., 2009). Palm oil fuel ash (POFA) is considered as an agro-waste generated in the palm oil mills by the burning of palm oil residues, such as palm fibres and shells at temperature of about 800–1000 ^{o}C to generate steam for electricity in biomass thermal power for the use of palm oil mill. The POFA generated in the palm oil mills is dumped into the open fields without any commercial return nor recycled. It constitutes a nuisance to the environment owing to its disposal in open areas (Awal & Hussin, 1999; Chindaprasirt et al., 2007; Chindaprasirt et al., 2008; Safiuddin & Jumaat, 2011; Sata et al., 2004). POFA includes large amounts of silica (44% - 66%) and has recently been recognized as a pozzolanic material; in addition, several researches have been carried out to study the feasibility of using this ash as a SCM (Abdullah et al., 2006; Safiuddin et al., 2013; Sata et al., 2004; Tangchirapat et al., 2007).

1.3 Problem Statement

Despite the advantages of SCHSC as described in previous section, Generally, SCHSC requires higher amount of binder content with lower amount of water and coarse aggregate than conventional concrete. In addition, expensive superplasticizer is needed to obtain flowable concrete. The higher content of cement will increase the cost of SCHSC compared to normal concrete and lead to increase amount of carbon dioxide (CO_2) emissions which can have a serious impact on environmental effect. Also, other problems relating to high cement content is the increase of hydration heat and high autogenous shrinkage. SCMs such as silica fume (SF) and rice husk ash (RHA) have been used with concrete. But these SCMs are costly especially silica fume which pricey than cement. However, POFA is an agro-waste material which is available at minimal cost and can be utilized as cement replacement material.

1.4 Research aims and objectives

The main objective of this study is to investigate the effectiveness of POFA as a cement replacement in a development of durable self-consolidating high strength concrete. The sub-objectives of the study are as follows:

1. To study the effect of POFA as a cement replacement on the fresh properties of SCHSC.
2. To study the effect of POFA as cement replacement on the compressive strength of SCHSC at early and later ages.
3. To investigate the effect of POFA on the permeability of SCHSC in terms of initial surface absorption (ISAT), rapid chloride permeability test (RCPT), and water absorption.
4. To investigate drying shrinkage strain of SCHSC containing POFA.
5. To study the effect of acid and sulphate environments on the properties of SCHSC containing POFA.

1.5 Research Significance

The significance of this research is to utilize of POFA up to 20% as a cement replacement to produce durable SCHSC. Another substantial contribution is the investigation on its durability characteristics such as the resistance to chemical attacks, ions permeability, drying shrinkage, water absorption, and initial surface absorption. The use of POFA will lead to reduction in cement usage as well as the cost of SCHSC. In addition, it will be helpful for the environment by reducing the emission of carbon dioxide and the volume of waste dumped in landfills.

1.6 Organization of the Thesis

The present thesis consists of five chapters and they were organized as follows:

The second chapter is the literature review that starts with Supplementary Cementing Materials, Palm oil fuel ash, Pozzolana, Pozzolanic Reaction, Palm oil fuel ash characteristics, and self-consolidating concrete. This chapter also describes the key fresh, hardened, and durability of concrete including SCMs.

The third chapter presents the methodology and procedure for producing self-consolidating high strength concrete and its mix design.

The fourth chapter presents the result and discussion of experimental investigation of the research.

The fifth chapter includes the conclusions based on the research findings. This chapter also gives recommendations for future studies.

CHAPTER 2

LITERATURE REVIEW

2.1 Supplementary cementitious materials

Supplementary cementitious materials (SCMs) such as fly ash, silica fume, and ground granulated blast-furnace slag can be incorporated with concrete to enhance its properties (Malhotra, 1989). SCMs chemically react with calcium hydroxide (free lime) $Ca(OH)_2$ which was produced from the hydration of cement to form secondary calcium silicate hydrate gel (C-S-H) (Malhotra, 1989).

SCMs may be obtained from natural materials such as limestone powder, volcanic tuffs, pumicite and calcined clay and artificial materials like silica fume, fly ash and rice husk ash. Those SCM can be mixed with blended concrete to reduce cement content, improve flowing ability and segregation resistance, increase strength, and enhance durability of concrete through hydraulic or pozzolanic activity (Al-Amoudi et al., 2007; Safiuddin & Zain, 2006). According to Tangchirapat et al. (2009), he showed that palm oil fuel ash (POFA) can be used as a supplementary cementitious material to produce high strength concrete.

2.2 Pozzolana

According to ASTM C 618 (2004) pozzolan can be difined as a “siliceous or siliceous aluminous materials which in itself possesses little or no cementitious characteristics but when grinded to finer particles and in the presence of water, chemically reacts with $Ca(OH)_2$ to produce compounds which have cementitious properties. Pozzolans are usually used as an addition or cement replacement materials to Portland cement concrete mixtures to enhance concrete properties such as compressive strength and durability characteristics. Also in some cases, pozzolans used to reduce the cost of concrete (ASTM, 2005; Owaid et al., 2012).

Pozzolans can be categorized into natural and artificial pozzolans. Natural pozzolans can be obtained from volcanic tuffs while the artificial pozzolans can be obtained from fly ash, silica fume, and ground granulated blast-furnace slag. These materials contain a certain percentage of vitreous silica and by using them in the concrete mix, they may enhance the properties of hardened concrete through pozzolanic reaction (Gambhir, 2004; Owaid et al., 2012).

POFA is a new type of agricultural by-product ash that has been proven to possesses pozzolanic characteristics and suitable to be used in concrete as cement replacement by a certain percentage without giving a detrimental effect to the strength of the hardened concrete (Sumadi & Hussin, 1995; Tay & Show, 1995).

2.2.1 Pozzolanic Reaction

Pozzolan materials are highly vitreous and independently show little cementitious properties. However, in the presence of $Ca(OH)_2$, and moisture show better cementitious characteristics towards the later age strength development (more than 28 days). The pozzolanic reaction usually slower than the other reactions that happen during hydration of cement, and thus the early age strength of concrete made with pozzolans may not be as high as concrete made with purely Portland cement; conversely, some highly reactive pozzolans, like high reactivity metakaolin and silica fume can be used to make concrete with high strength at the early age (Kosmatka et al., 2002; Mohammed Owaid et al., 2012).

Pozzolanic reaction happens when a pozzolan material which do not possess cementitious properties in itself reacts in the presence of water with lime $Ca(OH)_2$ at normal temperature to produce compounds of low solubility having cementitious properties (Gambhir, 2004).

During the hydration reaction of cement with water, calcium hydroxide $Ca(OH)_2$ is produced. Pozzolanic reaction takes place and reacts with $Ca(OH)_2$ to form secondary gel of calcium-silicate-hydrate as follow:

First phase of reaction

$C_3S + C_2S + H_2O \rightarrow \text{primary C-S-H} + Ca(OH)_2$ (Equation 2.1)

Second phase of reaction

$Ca(OH)_2 + \text{pozzolanic materials} \rightarrow \text{additional C-S-H}$ (Equation 2.2)

Producing $Ca(OH)_2$ from the first reaction can be considered as the weakest product from hydration of portland cement in terms of mechanical properties and durability. Calcium hydroxide can be easily leached out and it is highly susceptible to chemical attacks. Therefore, a pozzolanic reaction enhances the quality of the cement paste and, consequently, the quality of concrete (Lothenbach et al., 2011). These cementitious materials which participate in the hydration reaction significantly increase the strength, permeability, and improve durability characteristics of the concrete.

The chemical reaction of cement with POFA takes place in two phases. In first phase, the hydration reaction of C_2S or C_3S of cement and water and produces primary C-S-H gel plus $Ca(OH)_2$. The reaction is as follows:

$$C_3S + C_2S + H_2O \rightarrow \text{primary C-S-H} + Ca(OH)_2 \qquad \text{(Equation 2.3)}$$

In second phase, the $Ca(OH)_2$ reacts with the silica (SiO_2) of POFA and water to produce secondary C-S-H, which is credited to enhance the strength and durability of concrete. The reaction is as follows:

$$Ca(OH)_2 + POFA(SiO_2) + H_2O \rightarrow \text{secondary C-S-H} \qquad \text{(Equation 2.4)}$$

POFA is generally used as an SCM like fly ash. According to ASTM C 618-08a (2008), the specified minimum strength activity index of fly ash is 75%. This requirement can also be applied for POFA to be a pozzolanic SCM. The strength activity index used to determine natural pozzolan results are in an acceptable level of strength development when used with hydraulic cement in concrete. SAI of POFA greatly depends on its silica content, particle size distribution, and surface area. It can be improved significantly by increasing the fineness of POFA through grinding process (Ismail et al., 2010). Therefore, ground POFA possesses a good strength activity index (78.6−115) (Safiuddin et al., 2011).

2.3 Palm oil fuel ash and its characteristics

Palm oil fuel ash (POFA) is an agro-waste by-product generated from palm oil mills. It is produced from the burning of palm oil plant residues. The palm-oil factories developed rapidly in the 1980s (Tay, 1990). Recently, there are more than five million hectares of palm oil plantation in Malaysia (Aljuboori, 2012). According to Malaysian palm oil board (MPOB) statistics, the total solid waste generated from the palm oil industry has amounted more than 18.8 million tons per year. After extraction of palm oil from the palm oil fruit, both palm oil shell and palm oil husk are combusted as fuel in the steam boiler of the palm oil mills. After extraction of the oil from the fresh palm oil fruit, both palm oil husk and palm oil shell are burnt at a temperature 800 to 1000^0C as fuel in palm oil mill plants to produce steam electricity for the mill operations. After combustion of palm oil shell and fibres generally, about 5% palm oil fuel ash (POFA) by mass of wastes is generated (Sata et al., 2004). The colour of the produced POFA varies from whitish grey to darker shade; it depends on the carbon percentage in it and the burning temperature. In other words, the physical properties of POFA are very much affected by the operating system in palm oil mills.

Practically, POFA generated in Malaysian palm oil mills is disposed as a waste without any recycle or commercially use (Sumadi & Hussin, 1995). POFA is considered as a disturbance to the environment and dumped without being commercially returned, thus causing environmental problems and human health hazard (Sumadi & Hussin, 1995; Tonnayopas et al., 2006). However several researches were carried out to check the feasibility of using POFA in concrete. It has been found that the properly processed finely POFA can be used as a SCM for producing of concrete (Chindaprasirt et al., 2007; Hussin & Abdul Awal, 1997).

The use of POFA in Malaysia as a SCM for concrete first started in 1990 (Tay, 1990) and he used unground POFA to replace ordinary portland cement (OPC) and found that, it had a low pozzolanic property, and therefore recommended that POFA should not be used with a content higher than 10% of cement by mass of the binder. However, other researchers found that ground POFA can be successfully used as a SCM concrete due to its good pozzolanic property (Chindaprasirt et al., 2007; Hussin & Abdul Awal, 1997).

According to Chindaprasirt et al. (2007) the use of ground POFA in concrete has a good potential for concrete production. They found that the partial replacement of cement by ground POFA resulted in a higher water demand for a given workability of concrete. Moreover, they observed that the compressive strength of concrete with 20% ground POFA was as high as OPC concrete. The strength decreased when the POFA content became higher than 20%. Hence, the optimum percentage of POFA content found by (P Chindaprasirt et al., 2007) was 20%.

Researchers (Sata et al., 2004; Tangchirapat et al., 2009) also stated that the ground POFA can be used to make high strength concrete; thus the use of ground POFA shows higher compressive strength than unground POFA due to significant differences in size of particle and surface fineness. The ground POFA with high fineness and surface area is a pozzolanic material and therefore can be used to make high-strength concrete. Research carried out by (Abdullah et al., 2006) on the use of ground POFA in aerated concrete. They reported that concrete contained ground POFA exhibited similar strength to OPC concrete at 30% cement replacement and the maximum strength obtained at 20 % cement replacement.

2.3.1 Physical characteristics of POFA

The main physical characteristics of POFA are colour, particle shape and size, specific gravity, fineness and strength activity index. POFA collected from palm oil mills contains larger particle of unburnt carbon, palm oil fibres. The physical properties of POFA are greatly influenced by the burning temperature at the palm oil mill (Abdullah et al., 2006). Generally, the color of palm oil fuel ash mainly depends on the content of unburnt carbon in POFA. The lighter the color, the lower the carbon content in the POFA. Unground POFA is light grey in color. This is due to the unburned carbon content produced at low burning temperature. The unburnt carbon content becomes very low when the burning temperature is high (Abdullah et al., 2006; Safiuddin et al., 2011). The color becomes dark grey in case of ground POFA (Safiuddin et al., 2011).

The typical particle size distributions of OPC and POFA are shown in Figure 2.1. The median particle size (d_{50}) of unground POFA varies in the range of 54.3-183 μm, which is larger than that of OPC (10-20 μm). After grinding, the median particle size of POFA can be reduced to 7.2-10.1 μm (Chindaprasirt et al., 2008; Safiuddin et al., 2011; Sata et al., 2004).

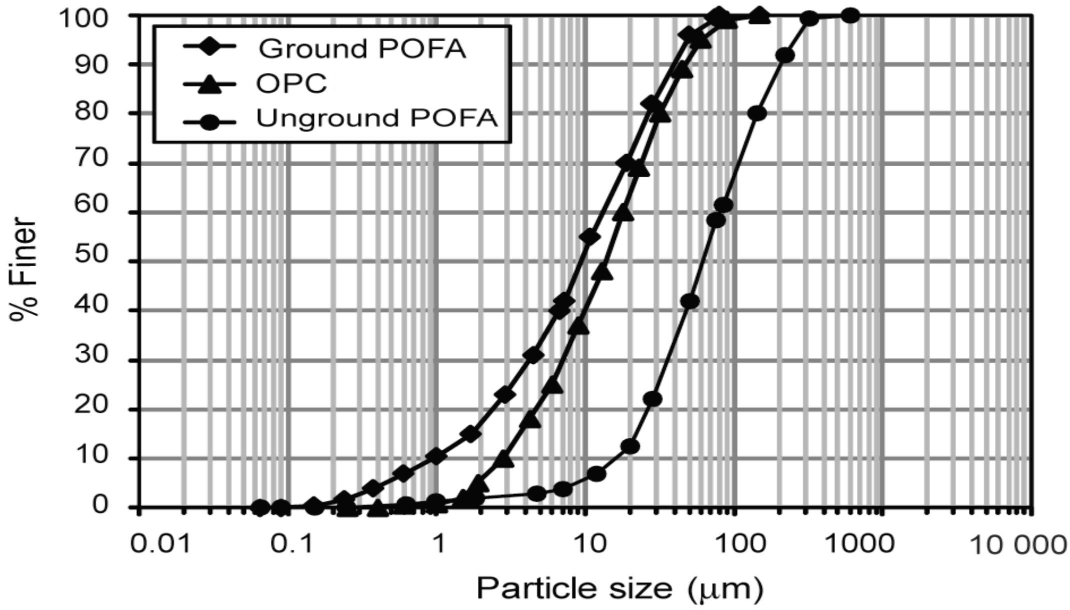

Figure 2.1: Particle size distribution of OPC, ground POFA, and unground POFA (Sata et al., 2004).

The specific gravity of unground POFA generally varies between 1.78-1.97, which is about 40% less than the specific gravity of OPC (Tay, 1990). After the grinding stage, the specific gravity of POFA increases and is found to be in the range of 2.22-2.78 (Safiuddin et al., 2011; Sata et al., 2004; Tangchirapat et al., 2009). This is because the grinding process decreases the porosity with reduced particle size. Fineness is a vital property of cement and SCMs. The fineness of SCM is generally measured with respect to the specific surface area of particles (Safiuddin et al., 2011)

2.3.2 Chemical properties of POFA

The chemical composition can vary depending on the different palm oil mill burning temperature and different sources of materials. The major chemical component of POFA is SiO_2, which varies in the range of 44-66% (Safiuddin et al., 2011). The other pozzolanic components are Al_2O_3 and Fe_2O_3. According to ASTM C 618-08a (2008) the sum of SiO_2, aluminium oxide, (Al_2O_3) and iron oxide (Fe_2O_3) should be 70%. The loss on ignition (LOI) and SO_3 for POFA are in the range of 0.1-21.5% and 0.2-3%, respectively (Safiuddin et al., 2011). In most cases, the LOI was much higher than the specified limit.

Different researchers classified POFA based on its chemical content. Researchers (Sata et al., 2004, 2007; Tangchirapat et al., 2009) found that the chemical composition of POFA satisfies the requirement for Class N pozzolanic materials stated in ASTM C 618-08a (2008), since the sum of SiO_2, Al_2O3 and Fe_2O_3 was close to 70% and SO_3 was not more than 4%, and LOI was close to 10% in their studies.

2.3.3 POFA as a partial cement replacement

In general, pozzolanicity is referred to the ability of any material containing silica to chemically react with $Ca(OH)_2$ to form calcium silicate hydrate. Researchers (Tay, 1990; Hussin & Abdul Awal, 1997) reported that POFA possesses pozzolanic property and can be used as a cementing replacement in concrete. The POFA collected from the mill exhibit in large particle size, naturally porous texture, and possesses low pozzolanic characteristics. However, to improve the pozzalanic properties, POFA should be grinded to increase its fineness (Hussin & Abdul Awal, 1997). Thus, grinded POFA has been recognized as one of the waste ashes which possesses a large amount of silica and has high potential to be used as a cementitious replacement material in concrete (Tangchirapat & Jaturapitakkul, 2010).

Incorporating POFA could produce concrete of higher strength and better durability in comparison with plain concrete (Abdul Awal & Hussin, 1999) up to 30% cement replacement. However, (Tay, 1990) opined that the use of POFA to substitute cement that had low pozzolanic properties should not be used more than 10% by mass of binder.

POFA possesses large amounts of silica and recently has been recognized as a pozzolanic material to be included in concrete and many researches have been conducted to study the feasibility of using this ash as a SCM (Abdullah et al., 2006; Safiuddin et al., 2013; Sata et al., 2004; Tangchirapat et al., 2007). Several resaerches have been carried out to examine the effect of POFA on the durability performance of normal concrete. Researchers (Abdu Awal & Hussin, 1999; P Chindaprasirt et al., 2007; Galau & Ismail, 2010; M. W. Hussin & Abdul Awal, 1996; Tangchirapat et al., 2009) have reported that POFA can be used to improve the durability characteristic of concrete such as resistance to sulphate attack, resistance to acid attack and rapid chloride penetration test.

According to the research done by Sata et al. (2004), POFA can be classified to be in class N pozzolan since the total sum of SiO_2, Al_2O_3, and Fe_2O_3 is higher than or close to 70%, SO_3 are not exceeding 4% referring to the ASTM C-618. Another study of (Tangchirapat et al., 2009) a grinding process is recommended to improve the reactivity of POFA.

2.4 Factors of POFA that influence concrete performance

2.4.1 Chemical Compositions of POFA

Chemical composition of POFA is important factor which affects the performance of concrete. The silica content is the main component of POFA and it varies in the range of 44% - 66%. Also vary other elements such as Al_2O_3 and Fe_2O_3 which in the range of 1.5% - 11.5%, and 1.5% - 5.5% respectively (Safiuddin et al., 2011). Loss on ignition

(LOI) also one of the elements that will influence the concrete properties and it depends on the burning temperature of POFA. A study carried out on different types of POFA which were collected from different places showed that, the higher the silica content the higher the compressive strength is (Galau & Ismail, 2010). In addition, the higher percentage of LOI lowers the slump and compressive strength of concrete (Chandara et al., 2010).

2.4.2 Fineness of POFA

Studies conducted by researchers (Abdullah et al., 2006; Safiuddin et al., 2013; Sata et al., 2004; Tangchirapat et al., 2007) showed that POFA concrete performance is better than the ordinary portland with medium size (MP) and small size (SP) replacement of POFA. This indicated that the increase of the concrete compressive strength contributed by pozzolanic reaction. They found that with medium size and small size of POFA satisfied the requirement for cementitious material at 28 days. Thus, the POFA replacement has shown great improvement towards concretes compressive strength as the fineness of the POFA increased.

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Fineness is a vital property of cement and SCM. The rate of hydration and pozzolanic reaction depends on the fineness of particles. For the rapid development of strength, a high fineness is necessary (Tangchirapat et al., 2007).

2.4.3 Replacement level of POFA

The different proportion of the POFA replacement is the other main factor that influences the characteristic of the POFA concretes. Studies conducted on POFA utilization in concrete found that only certain percentages of POFA used as a partial cement replacement could increase the strength of concrete to be higher than the plain concrete. According to (Abdul Awal & Hussin, 1999) integration of 30 % POFA would produce concrete of higher strength and better durability in comparison to plain concrete.

Another study (Hussin et al., 2008) found that use of 20 % POFA would produce the highest strength as compared to any other percentage. The variation in the replacement level for achievement for best performing concrete mix varies due to the difference in chemical composition of the POFA used. However both researchers (Abdul Awal & Hussin, 1999; Hussin et al., 2008) reported that substitution more than 30 % of POFA would produce concrete of lower compressive strength in comparison to the concrete made with only OPC.

According to study of (Tangchirapat et al., 2007) which showed decrease in the compressive strength of concrete as the replacement levels of the POFA increased. However, the strength of concrete with 10% and 20% of the replacement levels at later age is higher or comparable to control concrete. As a conclusion, POFA being a pozzolanic material could not be used in very high replacement levels since it would give negative effect towards strength improvement of concrete.

2.5 Self-consolidating concrete

Self-consolidating concrete (SCC) is a one of the most significant advances in concrete technology which is characterized by its high degree of workability. SCC is high flowable concrete and does not need any vibration during casting and placing in the formwork (EFNARC, 2002). SCC also finishes very smoothly, leaving a glassy finish after curing. SCC developed in Japan in the late 1980’s due to Japan’s lacking of skilful labour force (Khayat, 1999). SCC is a special concrete that can flow through congested reinforcement to fill all area of the formwork and gets consolidated without any aid of vibration (Khayat, 1999).

Self-compacting concrete possesses excellent filling ability, passing ability through congested reinforcing bars, and good segregation resistance during and after placement. The concept of SCC first came out in Japan in 1986 to build durable concrete structures and to compensate the growing shortage of skilled labourers (Okamura & Ouchi, 2003). SCC was widely used in large constructions in Japan in the early 1990's (Okamura & Ouchi, 2003).

The mix composition of SCC is different from that of conventional concrete. In order to obtain the high workability of SCC while maintaining cohesiveness, the components of SCC have to be altered. This can be done by using chemical admixture, or material control, or a combination of the two. To achieve SCC with good fresh properties, two admixtures are used; high range water reducers (HRWR) and viscosity modifying admixtures (VMA). A W/B ratio in the range of 0.35–0.50 is generally used to produce SCC (Safiuddin, 2008). SCC also needs a lower amount of coarse aggregate whereas a higher content of fine aggregate (Safiuddin, West, et al., 2012).

In addition, Segregation is normally associated with the cohesiveness of the fresh concrete, which can be improved by including (VMA) along with a HRWR, by decreasing the water content, by increasing the paste volume, or by some combination of these components. HRWR is generally used in SCC to modify its fresh properties, and more specifically to ensure sufficient flowing ability at low W/B ratios. (Safiuddin, 2008).

SCC is different from the conventional concrete because of its special features such as excellent flowing ability, non-segregation, and non-blocking tendency (Ravindrarajah et al., 2003). Due to the highly flowability of SCC, the common used fresh properties tests of the conventional concrete are not applicable to SCC. For this reason, many new fresh properties tests were derived to evaluate the fresh state of SCC. The new fresh properties tests are flowability tests, possibility tests, and resistance to segregation tests (EFNARC, 2002).

2.5.1 Advantages of SCC

SCC provides significant economic, aesthetic and engineering advantages. Some advantages of SCC (EFNARC, 2002; Khayat, 1999; Safiuddin, 2008) are as follows:

- Less labors involved.
- Provides faster construction due to rapid rate of concrete placement.
- Improves quality and durability of concrete.
- Saves concrete due to the reduced cross-section of structural elements.
- Provides the benefits of both SCC and high strength concrete.
- Low noise-level in construction sites.
- Eliminates problems associated with vibration.
- SCC can be cast and placed at a faster rate without vibration.
- Improves the architectural surface finish with little remedial surface work.
- SCC can fill the restricted sections and hard-to-reach areas. Hence, create structural and architectural shapes and surface finishes which are not achievable with conventional concrete.
- Improves the bonds between the concrete and reinforcement due to good compaction.

- Improves the pumpability.
- Reduces noise in the absence of vibrating equipment and thus improves construction environment.
- Increases jobsite safety by eliminating the need for vibration.

2.5.2 Fresh Properties of SCC

2.5.2.1 Workability

According to (EFNARC, 2002) which investigated that the SCC flows alone under its own weight, airs out and consolidates itself thereby without any need of vibration energy and without segregation. As shown in table 2.1, a concrete mix can only be classified as self-consolidating concrete if the requirements for all three characteristics are fulfilled.

- Filling ability: Ability to fill and reach all the corners of a formwork under its self-weight.
- Passing ability: Ability to pass obstacles under its self-weight without hindrance. Examples of Obstacles are congested reinforcement and small openings etc.
- Segregation resistance: Homogeneous composition of concrete mix during and after the process of transport and placing.

Table 2.1: List of test methods for workability properties of SCC (EFNARC, 2002)

	Method	Properties
1	Slump flow by Abrams cone	Filling ability
2	T_{50cm}	Filling ability
3	J-ring	Passing ability
4	V-funnel	Filling ability
5	Time increase, V-funnel at $T_{5minutes}$	Segregation resistance
6	L-box	Passing ability
7	U-box	Passing ability
8	Fill box	Passing ability
9	GTM screen stability test	Segregation resistance
10	Orimet	Filling ability

For the initial mix design of SCC, all three workability requirements need to be checked to ensure that all aspects are fulfilled. These parameters are to be tested and fulfilled at the time of casting and placing. Changes in the workability of SCC during transport should be taken into consideration. Typical acceptance criteria for self- consolidating concrete with a maximum aggregate size up to 20 mm are shown in Table 2.2.

Table 2.2: Acceptance criteria for Self-compacting Concrete (EFNARC, 2002)

No	Method	Unit	Typical range of values	
			Minimum	Maximum
1	Slump flow by Abrams cone	mm	650	800
2	T_{50cm}	sec	2	5
3	J-ring	mm	0	10
4	V-funnel	sec	6	12
5	Time increase, V-funnel at $T_{5minutes}$	sec	0	+3
6	L-box	%	0.8	1.0
7	U-box	mm	0	30
8	Fill box	%	90	100
9	GTM screen stability test	%	0	15
10	Orimet	Sec	0	5

2.6 Properties of hardened concrete and durability characteristics

2.6.1 Compressive strength

The compressive strength is the most important parameter of all the mechanical properties of concrete. Many factors influence the compressive strength measurement such as specimen size, curing conditions, loading rate, etc. Compressive strength is frequently used as the key indicator of concrete quality. It is the ability of concrete to resist axially directed pushing load. Many researches have been conducted to examine the effect of POFA on the compressive strength of concrete.

According to (Tay, 1990; Tay & Show, 1995) they found that the compressive strength of concrete decreases as the POFA content is increased. However, some other researchers found that the concrete made with POFA exhibits a higher compressive strength than OPC concrete. (Hussin & Abdul Awal, 1996; Warid Hussin & Abdul Awal, 1997) revealed that it is possible to use up to 40% ground POFA in concrete without any adverse effect on strength although the maximum strength gain occurs at 30%.

Compressive strength for unground POFA decrease as the POFA content increase. (Tangchirapat et al., 2007) reported that the decrease in the compressive strength of concretes containing a high amount of unground POFA was due to the large POFA particles sizes with high porosity. The porous POFA particles increase the demand for water, and thus lead to lower the compressive strength.

(Tangchirapat et al., 2009) found that the concrete containing 10−30% ground POFA exhibits a higher compressive strength than plain concrete at 28 days. Also, (Sata et al., 2007) observed that the concrete with 10−20% ground POFA provides a greater strength than OPC concrete. In addition, POFA concrete compressive strength is influenced by the level of replacement and fineness of the POFA (Tangchirapat et al., 2007).

2.7 Concrete Durability

Durability of concrete is referred to its ability to resist chemical attack, weathering action, abrasion, or any other process of deterioration. Concrete is a porous material which allows water to penetrate into its interior parts. Concrete is considered as durable when it remains its original form, quality, and serviceability when exposed to its environment (ACI Committee, 201, 1990). Many field and laboratory studies have been conducted on concrete durability, and it has been concluded that the deterioration of concrete is not due to any single reason, but arises from the combined causes of a number of potentially aggressive agencies.

2.7.1 Drying shrinkage

Drying shrinkage is defined as the contracting of a hardened concrete mixture due to the evaporation of water. It occurs when concrete hardens and dries out at the early age. It creates potential flow channels in the form of micro-cracks (Safiuddin et al., 2008).This shrinkage could lead to increase in tensile stress, which may cause cracking, and external deflection, even before applying any type of load on the concrete. All types of concrete are subjected to drying shrinkage as time passes. Drying shrinkage can occur in many structural elements such as beams, slabs, columns, bearing walls, prestressed members, tanks, and foundations. Hence, the change in concrete volume is very important and critical to the engineer in the design of a structure.

According to (Tay, 1990) the drying shrinkage of concrete with unground POFA increases slightly after 28 days if the ash content is increased. It was also found that the drying shrinkage of concrete with 10% POFA is comparable to that of OPC concrete. Moreover, (Hussin & Ishida, 1999) produced concretes with 10–40% ground POFA and found that 40% POFA exhibits the highest shrinkage, while 20% and 30% POFA show a similar drying shrinkage developed in OPC concrete. (Tangchirapat et al., 2009) observed that high strength concrete with ground POFA produced lower drying shrinkage than OPC concrete for any amount of POFA. The lower value of drying shrinkage in high strength POFA concrete is due to the densification of pore structure. The incorporation of ground POFA decreases the pore sizes in concrete due to pore refinement (Haque & Kayali, 1998). The transformation of large pores into fine pores decreases the loss of water from concrete surface and thus reduces the drying shrinkage of concrete (Safiuddin et al., 2011).

2.7.2 Initial surface absorption test

Initial Surface Absorption Test (ISAT) is defined as the rate of flow of water into the hardened concrete surface per unit area at a specified interval from the beginning of the test at a fixed head distance and temperature (Malhotra & Carino, 2004). Explanation of the ISAT test is given in BS 1881: Part 5 as shown in Figure 2.2, which measures the surface water absorption in this method, a reservoir with a minimum surface area of 5000 mm^2 is placed to the specimen surface and completely filled with water. The flow rate at which water is entered into the concrete under a pressure head of 200 mm is taken by movement along a capillary glass tube connected to the reservoir. When water comes into contact with dry surface concrete, it is absorbed by capillary action at a high flow rate in the beginning but the flow rate will decrease as the concrete surface becomes saturated.

Research carried out by Al-Oraimi et.al (2007) on surface absorption of high strength concrete containing silica fume, he found that the flow of water reduced as the percentage replacement of silica fume was increased. This is due to the fact that the silica fume acts as a micro filler and its extreme fineness allows it to fill the gaps between cement particles, which greatly decreases the permeability of the concrete. Johari et al., (2012) showed that the integration of the ultrafine POFA in concrete reduces the ISAT values in comparison to the plain concrete. This is can be attributed to satisfactory micro filling ability of POFA which lead for more pores refinement.

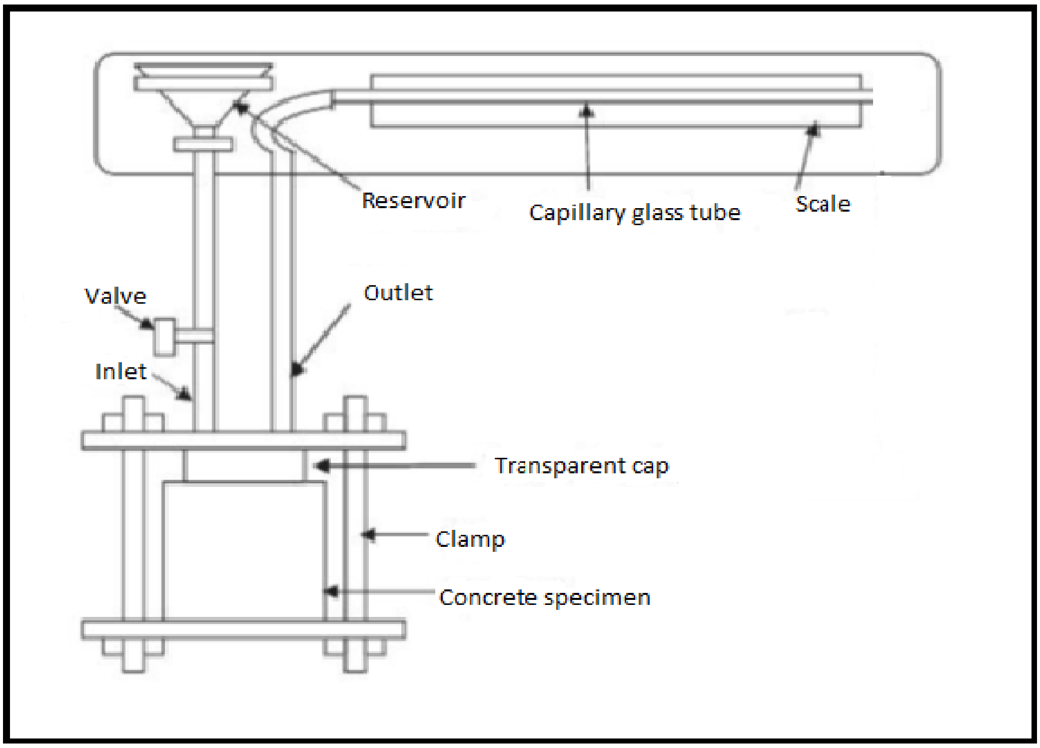

Figure 2.2: Initial surface absorption test

2.7.3 Chemical Attacks

The chemical attacks on concrete may cause expansion and decomposition of the cement paste components leading to destructive deterioration of concrete. Concrete will perform satisfactorily when exposed to different atmospheric conditions, to most waters and soils containing aggressive chemicals, and too many other kinds of chemical exposure. However, there are some chemical environments that will cause damages to concrete and shorten its useful life unless specific measures are taken (ACI Committee 201, 1990).

The durability of concrete towards chemical attack could be enhanced through formation of dense and well compacted concrete, use of an appropriate water cement ratio, use of properly graded aggregates selected for strength and durability, also integrating pozzolanic ash as partial cement replacement material (ACI Committee 201, 1990).

2.7.3.1 Sulphate Attack

The deterioration of cement based materials attacked by sulphate has been known as one of the significant durability issues. Different types of sulphate such as sulphate s of sodium, potassium, calcium, or magnesium, that can attack concrete, are found in soil or dissolved in water nearby to concrete. Sulphate salts in solution penetrate into the concrete and attack the cementing materials (ACI Committee 201, 1990).

Sulphate attack can be external attack or internal attack. The external sulphate attack is a chemical breakdown mechanism where sulphate ions enter into the concrete and attack compounds of the cement paste. Such attack can happen when concrete is adjacent to sulphate include water e.g. seawater, swamp water, ground water or sewage water. The excessive formation of gypsum and ettringite due to the external sulphate attack may result concrete to crack and loss its strength. Also the internal attack is attributed to a soluble source being integrated with the concrete at the time of concrete mixing, such as gypsum in the aggregate, excess of added gypsum in the cement (Winter, 2012).

Irassar (2009) reported that the external sulphate attack to cementitious material is a complex process that includes the penetration of sulphate ions into the pores by means of different mechanisms of transportation and the interaction of aggressive sulphate solution with some components produced from cement hydration to form expansive compounds (ettringite and gypsum) that lead to softening of concrete, cracking, and reduction in its strength.

Sulphate attack on hardened concrete involves primary and secondary chemical reactions, some of which are interrelated. Soluble sulphate of calcium, sodium, magnesium and ammonium present in soil and ground water are harmful to concrete since these elements can lead to swelling and consequently cracking of concrete. The degree of deterioration, however, depends on the intensity of the attack as well as on the characteristics of the concrete. According to Baghabra et al. (1995), Ekolu et al. (2006), Naik et al. (2006) and Taylor (1997) when a cementitious material is exposed to a sulphate environment, the sulphate attack takes place as a sequence of the following Mechanisms:

(a) The first phase is the reaction between sulphate ions and calcium hydroxide $Ca(OH)_2$ which produced from cement hydration to yield calcium sulphate (gypsum). The formation of gypsum can cause softening and loss of concrete strength (ACI Committee 201, 1990).

$Ca(OH)_2 + SO_4^{-2} \longrightarrow CaSO_4 \cdot 2H_2O$ (gypsum) (Equation 2.5)

(b) In the second phase, sulphate ions react with tricalcium aluminates to form ettringite (calcium aluminate trisulphate 32 hydrate, $CaO \cdot Al_2O_3 \cdot {}_3CaSO_4 \cdot {}_{32}H_2O$). The formation of ettringite results in an increase in solid volume, leading to concrete expansion and cracking (ACI Committee 201 , 1990).

$3CaO.Al_2O_3 + SO_4^{-2} \longrightarrow CaO.Al_2O_3.{}_3CaSO_4.{}_{32}H_2O$ (ettringite). (Equation 2.6)

One of the important factors to prevent sulphate attack on concrete is to reduce the permeability of the concrete by lowering water/cement ratio, well compaction and well curing. Care should be taken to ensure that the concrete is designed and constructed to minimize shrinkage cracking. In terms of cement compositions, tricalcium aluminate (C_3A) compound should be within the limit (<8%) (ACI Committee 201 , 1990; Skalny, 2002). In addition, integration supplementary cementing materials like fly ash, silica fume, blast-furnace slag and other pozzolanic materials would be able to reduce the amount of calcium hydroxide because of the pozzolanic reaction that took place finally increasing the resistance of the concrete to sulphate attack. Many pozzolans have been found that can effectively double the service life of a concrete when exposed to sulphate attack (Harboe, 1982).

Several researches investigated the effect of unground and ground POFA on concrete's resistance to sulphate attack (Chindaprasirt et al., 2007; Hussin & Abdul Awal, 1996; Sata et al., 2004). Studies have been done on lightweight concrete (Hussin et al., 2008), and normal concrete. Hussin & Abdul Awal (1997) confirmed that POFA blended cement concrete performed better than the specimen formed of 100 % OPC. In addition, the ability of pozzolanic material to increase the sulphate resistance of high strength concrete containing POFA was investigated by Tangchirapat et al. (2009). He reported that the inclusion of ground POFA improved the resistance of concrete toward sulphate attack. However, more research is needed to investigate the sulphate resistance of POFA concrete.

2.7.3.2 Acid Attack

Deterioration of concrete can also be caused by acid attack. Portland cement does not have good resistance to acids. This is because concrete contains Portland cement which is highly alkaline in nature. The products of combustion of many fuels include sulfurous gases that combine with moisture to form sulfuric acid. Acid attack is caused by the reaction of an acid and the calcium hydroxide portion of the cement paste which produces a highly soluble calcium salt by product (ACI Committee 201 , 1990). The calcium salts are easily removed from the cement paste thus weakening the paste's structure as a whole. Therefore, exposure to acid environments results in the reduction in the alkalinity of the concrete (Siad et al., 2010).

Many factors influence the decomposition of the concrete in acidic environment. It depends on the porosity of concrete, the solubility of the acid calcium salts, the concentration of the acid, and the fluid penetrates through the concrete. However, degree of protection of concrete can be increased by reduction of water/ cement ratio, inclusion of cementitious materials which lead to lower $Ca(OH)_2$ in concrete (ACI Committee 201 , 1990)

Acids such as hydrochloric acid, nitric acid, and acetic acid are classified as very aggressive acids, whereas phosphoric and carbonic acids categorized as moderate and low acids respectively. Highly acidic environment sometimes exists in industrial and agricultural wastes (ACI Committee 201 , 1990). Any environment with pH less than 12.5 is considered to be harmful to concrete because a reduction of the alkalinity of the pore fluid could eventually cause decomposition of the cementitious products produced from cement hydration.

Research was carried out by (Abdul Awal & Hussin, 1999; Hussin & Awal, 1996) to evaluate the acid resistance of POFA concrete. They determined the weight loss of the concrete containing 30% ground POFA along with non-POFA concrete continuously submerged in 5% hydrochloric acid solution (HCL) to measure the resistance to acid attack. They found that the weight loss of POFA concrete after 1800 hours was less than that of OPC concrete. It was also observed that POFA concrete showed a better surface condition than OPC concrete after exposure to acid solution. (Abdul Awal & Hussin, 1999; Budiea et al., 2010) also reported that concrete containing POFA exhibit higher resistance towards acid attack in comparison plain concrete.

The inclusion of pozzolanic material tends to reduce the amount of calcium hydroxide in the concrete since this free lime has been used for pozzolanic reaction for formation of extra C-S-H gel that makes the blended cement based concrete is more dense than the plain concrete. The high acid resistance of POFA concrete was attributed to the pozzolanic property and low lime content of POFA (Safiuddin et al., 2011). Moreover, secondary hydration product (additional C–S–H gel from pozzolanic reaction) was produced at the expense of $Ca(OH)_2$. As a result, the microstructure of concrete became dense with a reduction in porosity. This led to a reduced penetration of acid solution into the interior part of concrete.

2.7.3.3 Rapid chloride permeability test

The rapid chloride permeability test (RCPT) is defined as the resistance of concrete against penetration of chlorides ions (Chindaprasirt et al., 2008; Whiting, 1981). This method is promoted by the concept of measuring the direct electric current through a Portland cement concrete specimen between a salt solution and a base solution to determine the chloride penetration of concrete (ASTM C1202, 2005).

According to (ASTM C1202, 2005), the test method requires obtaining a 100 mm diameter cylinder. Then around 52 mm specimen is cut from the cylinder. The outer diameter of the cylindrical specimen is coated with epoxy, and after the epoxy is dried, it is placed for 3 hours in a vacuum chamber. The specimen is vacuum saturated for 1 hour and then put in water for 18 hours. One side of the concrete specimen is in contact with a sodium chloride solution 3% (NaCl) and the other side with a sodium hydroxide solution 0.3 M (NaOH). It is then placed in the testing machine. Then, a current of 60 V (DC) is applied and maintained for 6 hours. The total charge passing through in the specimen after 6 hours is measured.

Researchers reported (Abdul Awal & Hussin, 1999; Rukzon & Chindaprasirt, 2009) that the ground POFA can be used to produce concrete possessing a better resistance to chloride penetration than OPC concrete. The depth of penetration of chloride ions into POFA concrete is much lower than that in OPC concrete. This is can be attributed to POFA particles which increase the nucleation sites for the production of hydration products, consume $Ca(OH)_2$, and formation of secondary C-S-H product. The pozzolanic products fill in the pores in bulk binder paste and transition zone. Consequently, POFA decreases the permeability of concrete, and thus improves the resistance to chloride penetration (Safiuddin et al., 2011).

2.7.4 Water Absorption test

Water absorption is the phenomenon in which the water fills up the open pores of concrete. Limited research has been conducted on the water absorption of concrete containing POFA. (Tay, 1990; Tay & Show, 1995) releaved that the water absorption of concrete containing unground POFA is higher than concrete made with OPC. They mentioned that the POFA concrete shows a more porous nature with higher unground POFA content.

It indicates that the concrete with a higher amount of unground POFA content absorbs more water due to a higher porosity (Tay & Show, 1995). But the water absorption of concrete containing ground POFA can be reduced because of its satisfactory micro-filling ability and pozzolanic activity leading to denser structure of concrete (Safiuddin et al., 2011).

Table 2.3: literature summary

Year	**Authors**	**Title**	**Objective**	**Findings**	**Research Gap**
1990	Tay, J.	"Ash from Oil-Palm Waste as a Concrete Material"	The feasibility of using the shell and fiber ash as a construction material	The results show that shell and fiber ash can be blended in small amounts (up to 10%) with cement for concrete making.	- Proper classification of POFA as a SCM for concrete. − Investigation of the effects of POFA on the plastic shrinkage, slump loss, and air content of concrete - Investigation on the use of POFA to produce durable self-consolidating normal strength, high strength and high performance concretes.
1997	A.S.M. ABDUL AWAL and M. WARID HUSSIN	"DURABILITY OF HIGH PERFORMANCE CONCRETE CONTAINING PALM OIL FUEL ASH"	To investigate some durability aspects such as chloride and acid attack.	The findings showed that concrete made with POFA exhibited much better resistance to attack by chloride ions and acid solution.	
2009	Weerachart Tangchirapat, Chai Jaturapitakkul, Prinya	"Use of palm oil fuel ash as a supplementary cementitious material for producing high-strength concrete"	to study the use of ground POFA with high fineness as a pozzolanic material to produce high-strength concrete	Results indicated that ground POFA can be used as a SCM for producing high-strength concrete.	
2010	Md. Safi uddin, Mohd H. Md.Isa, and Mohd Z. Jumaat	"Fresh Properties of Self-consolidating Concrete Incorporating Palm Oil Fuel Ash as a Supplementary Cementing Material"	To investigate the fresh properties of SCC containing (POFA) as a SCM	filling ability and passing ability of SCC decreased whereas its segregation resistance increased with higher POFA content.	
2012	Weerachart Tangchirapat, Supat Khamklai, Chai Jaturapitakkul	"Use of ground palm oil fuel ash to improve strength, sulfate resistance, and water permeability of concrete containing high amount of recycled concrete aggregates"	The use of ground (POFA) with high fineness to improve the mechanical properties and durability of concrete containing high amount of recycled concrete aggregates.	The results showed that ground POFA could improve the compressive strength, reduce the water permeability and decreased the expansion of recycled aggregate concretes.	
2014	Safiuddin, M., Salam, M., and Jumaat, M	"Key fresh properties of self-consolidating high strength POFA concrete"	To determine the key fresh properties of SCHSC containing POFA	The optimum POFA content for filling ability, passing ability, and segregation resistance was 20%.	

CHAPTER 3 MATERIALS AND METHODS

3.1 Introduction

This chapter explains the materials which have been used and the tests procedures for conducting different experimental investigations. At the beginning, the collection of palm oil fuel ash and its preparation are discussed. The selection and testing of constituent materials and the mix design of different self-consolidating high-strength concretes (SCHSCs) are presented in this chapter. In addition, fresh properties tests, compressive strength, and durability characteristics tests are presented and discussed in this chapter.

3.2 Materials

3.2.1 Palm oil fuel ash collection and preparation

The original POFA was collected from a local palm oil mill in Selangor, Malaysia as shown in Figure 3.1. First, original POFA was dried in an oven for 24 hours to remove moisture. Then the dry POFA was sieved by using of a 300 µm sieve to remove larger size particles. Due to smaller size of POFA has better reactivity, a Los Angeles abrasion machine was used to grind and achieve a finer POFA as shown in Figure 3.2

Figure 3.1: Original palm oil fuel ash

Figure 3.2: Ground palm oil fuel ash

3.2.2 Cement

Ordinary Portland cement (OPC) was used in all mixes as shown in Figure 3.3. The storage condition was maintained under control during the use of OPC. Some physical properties as well as chemical compositions of the cement are given in chapter 4.

Figure 3.3: Portland cement

3.2.3 Aggregate

Local mining sand with a fineness modulus of 2.88, specific gravity of 2.56, and water absorption of 1.13% was used as a fine aggregate. Crushed limestone with a maximum size of 12.5 mm, specific gravity of 2.62, water absorption of 0.44%, and fineness modulus of 6.3 was used as coarse aggregate, as shown in Table 2.

3.2.4 Super plasticizer

Aqueous solution of modified polycarboxylate copolymers (Sika ViscoCrete-1600) was used in this research. It is specially designed for producing high flowable concrete with exceptional flow retention and workability properties. It meets the requirements for superplasticisers according to ASTM C494-86 Type G and BS 5075: Part 3. It has a density of 1.09 ±0.02 kg/m^3, and the recommended dosage is between 0.5 – 2.0 % by weight of cement.

3.3 Mix Design

Ground POFA was used to partially replace Type I Portland cement at proportions of 10%, 15%, and 20% by weight of binder. The targeted compressive strength of concrete incorporating ground POGA was at least 60 MPa at 28 days curing. All mix proportions of SCHSCs had the same binder content of 480 kg/ m^3 and water content was estimated based on ACI 211.4R guideline. Several mixes proportions have been carried out to achieve the requirement of SCHSC. The primary mix proportion has been carried out at W/C ratio 0.38 as shown in Table 3.1. It was visually noted that there was segregation, bleeding due to higher water content and superplasticizer. Then the primary mix has been adjusted and w/c ratio was reduced to 0.35 and the superplasticiser was used in different percentages in order to obtain the fresh properties of SCHSC.

Table 3:1 Primary mix proportion of SCHSCs

Mix No.	W/C ratio	Cement (Kg/m^3)	POFA (Kg/m^3)	F.A (Kg/m^3)	C.A (Kg/m^3)	Water (Kg/m^3)	S.P (% B)	Remark
SCHSC0	0.38	480	0	925	758.2	182.4	1.8	bleeding
SCHSC10	0.38	432	48	923	752	182.4	1.8	Segregation and bleeding
SCHSC15	0.38	408	72	924	752	182.4	1.8	Segregation and bleeding
SCHSC20	0.38	384	96	924	752	182.4	1.8	Segregation and bleeding

Table 3.2: Adujsted Mix proportions of SCHSCs

Mix No.	W/C ratio	Cement (Kg/m^3)	POFA (Kg/m^3)	F.A (Kg/m^3)	C.A (Kg/m^3)	Water (Kg/m^3)	S.P (% B)
SCHSC0	0.35	480	0	925	758.2	168	1.3
SCHSC10	0.35	432	48	923	752	168	1.4
SCHSC15	0.35	408	72	948	772	168	1.5
SCHSC20	0.35	384	96	944	772	168	1.8

3.4 Research Procedure

The experimental investigation for various SCHSCs was comprised of selection and testing of materials, preparation and testing of fresh and hardened concretes. Figure 3.4 shows the research procedure.

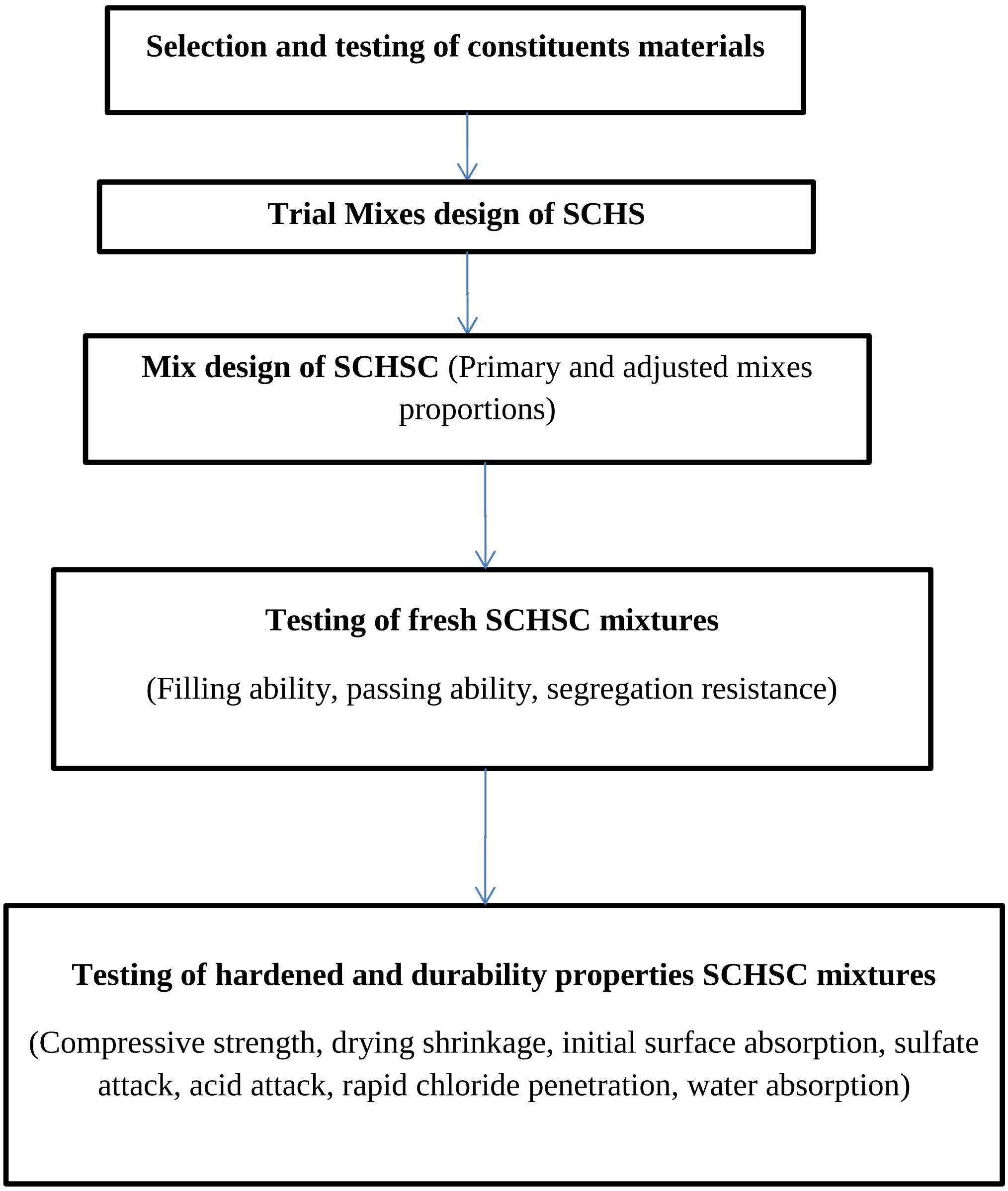

Figure 3.4: Research procedure chart

3.5 Specimen preparation and testing methods

3.5.1 Fresh Properties

First, the coarse and fine aggregates were mixed. Then, initially, 10% of water was added. Subsequently, the cement and POFA were added to the mixture. About 50% of water was added to the mixture to obtain homogeneity and then the superplasticizer was dissolved into the remaining 40% of water. Then, they were added to the mixture and the mixing was continued to obtain a homogeneous mix. Generally, the mixing process needs to be longer than for conventional concrete mixes. Soon after mixing, the mix was subjected to a slump flow test and T_{50cm} test as shown in Figure 3.5. If the mix passed both the tests, it was then subjected to V-funnel, J-ring, L-box, and segregation tests. All fresh properties were conducted according to EFNARC 2002.

Fresh concrete was investigated with respect to filling ability, passing ability, and segregation resistance according to EFNARC (2002). Filling ability was examined with respect to slump flow, $T_{50\ cm,}$ and V-funnel. The slump flow was used to evaluate the ability of fresh concrete to flow free horizontally without objections as shown in Figure 3.5, in the same time $T_{50\ cm}$ was recorded. In addition, V-funnel test was conducted to check the flowability of concrete and assess the inter-particle friction as shown in Figure 3.6.

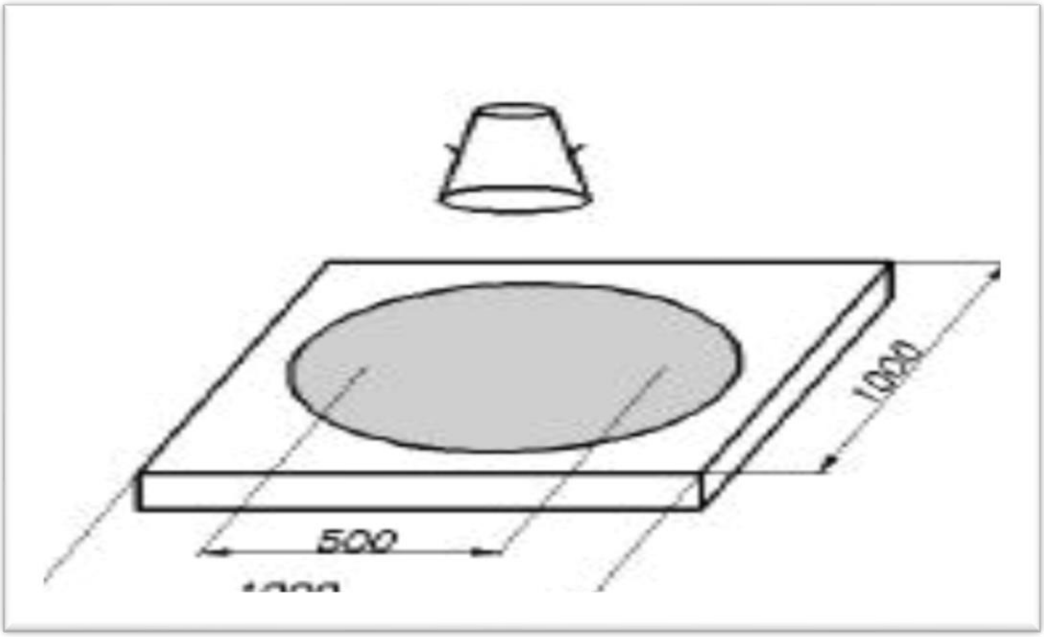

Figure 3.5: Slump flow table

Figure 3.6: V-funnel test equipment

Passing ability of fresh concrete was checked to ensure that the concrete can pass through congested reinforcement and small openings without any vibration. J-ring and

L-box were used to assess the passing ability of fresh concrete as explained in Figure 3.7 and 3.8, respectively.

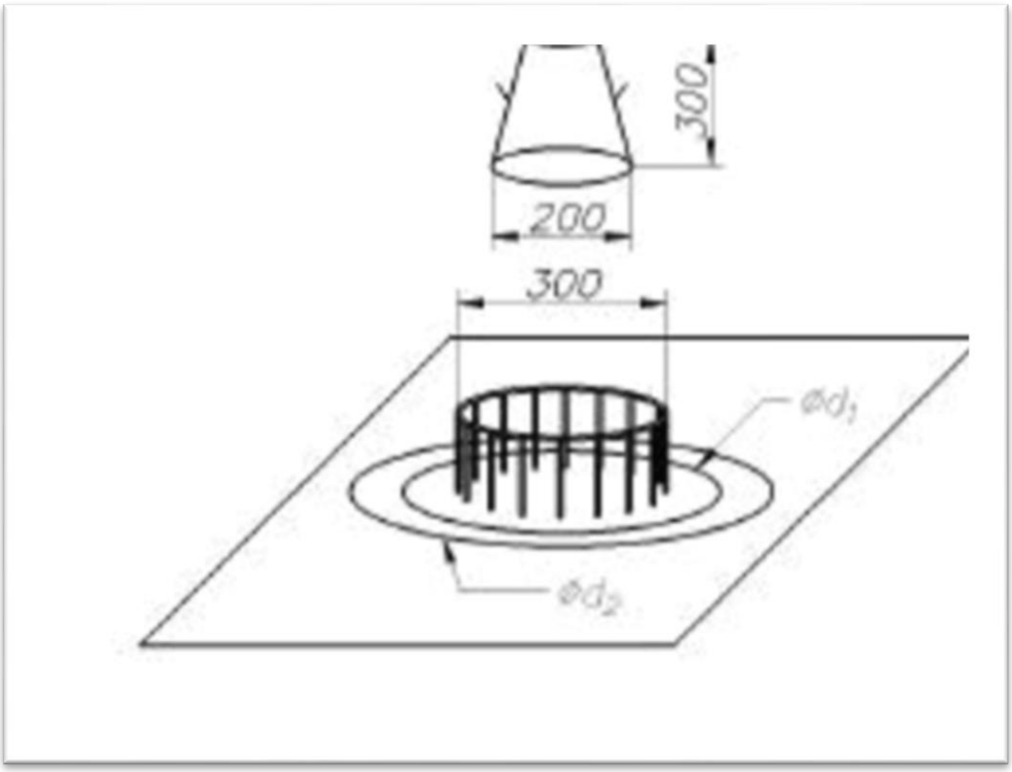

Figure 3.7: J-ring test equipment.

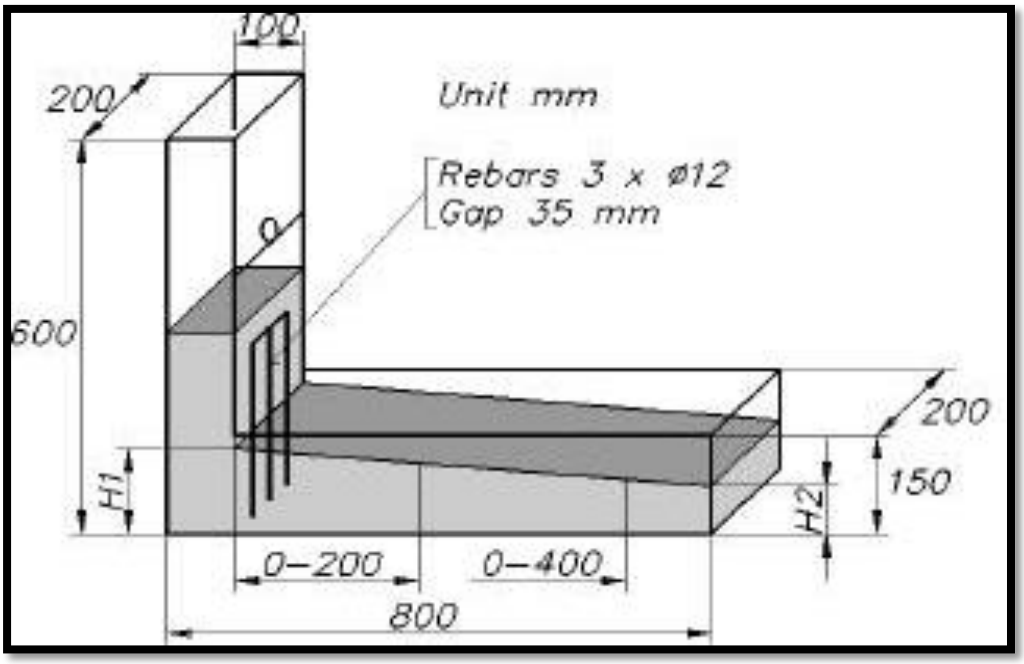

Figure 3.8: L-box test equipment

Segregation resistance of SCC was assessed with respect to GTM screen stability test method to ensure that concrete remain cohesive and stable during the process of casting.

3.5.2 Hardened properties and durability characteristics

3.5.2.1 Compressive strength

Compressive strength of hardened concrete was checked according to BS EN 12390-3:2002. The 100×100×100 mm^3 cubes concrete specimens were tested at the ages of 3, 7, 28, 56, and 90 days using a compression testing machine of 3000 KN capacity as shown in Figure 3.9.

Figure 3.9: Compressive strength testing machine

3.5.2.2 Drying shrinkage

Prismatic concrete specimens of 100×100 mm^2 in cross-section and 500 mm in length were used to determine the drying shrinkage strain of concrete as shown in Figure 3.10. These specimens were removed from the moulds 24 hours after casting and cured in tap water for 7 days. Then the specimens were removed from the water and wiped with a damp cloth. Each specimen was fitted with demec points at the sides. The distance between the points was 200 mm. The concrete specimens were then placed in a room with a temperature of 28±3 oC and a relative humidity of 74±4%.

Figure 3.10: Drying shrinkage test specimens

3.5.2.3 Initial surface absorption test (ISAT)

To conduct Initial surface absorption test (ISAT), the 100 mm cube sizes were prepared and tested according to BS 1881-208. The ISAT test was carried out on the specimens after 7, 28, and 56 days water curing as shown in Figure 3.11. The concrete specimens were oven dried at 105±5^{o}C for 24 h and stored in airtight container prior to testing.

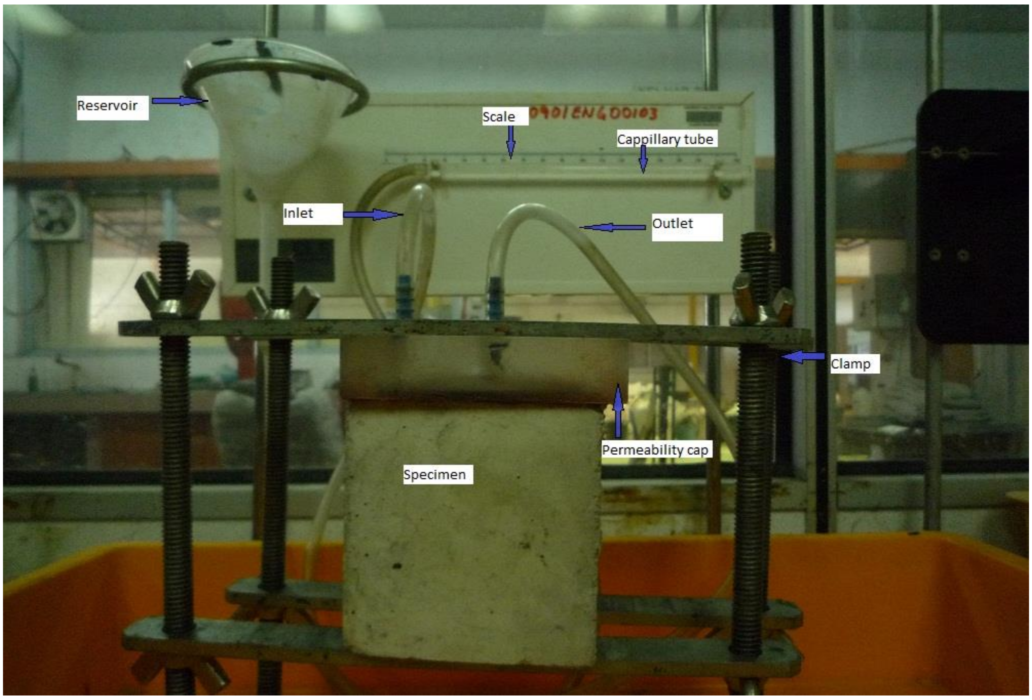

Figure 3.11: Initial surface absorption test

3.5.2.4 Acid attack test

The chemical resistance of the concrete specimens was investigated through chemical attack by immersing 100 mm cubes in an acid solution for 1800 hours (75 days). After 7 days moist curing, the specimens were immersed in 3% HCL solution with the pH of about 2. This solution was substituted at regular intervals of 2 weeks to keep a constant concentration during the test period. The compressive strength and mass of the concrete specimens were measured after 1800 hours.

3.5.2.5 Sulphate attack test

One of durability test conducted in this study was sulphate attack. 100 x 100 x 100 mm cubes were used in this test. The specimens were cured for 7 days and then immersed in 5% $MgSO_4$ by the weight of water as shown in Figure 3.12. After 12 months, loss in compressive strength was measured.

Figure 3.12: Concrete immersed in 5% MgSO4 solution

3.5.2.6 Rapid chloride permeability test

The rapid chloride permeability test (RCPT) was carried out to evaluate the resistance of concrete against ion penetration as per ASTM C1202 as shown in Figure 3.13. A cylindrical specimen of 52 mm in length and 100 mm in diameter was used. One side of the concrete specimen was in contact with a sodium chloride solution 3% (NaCl) and the other side with a sodium hydroxide solution 0.3 M (NaOH). Then, a current of 60 V (DC) was applied and maintained for 6 hours. The total charge passing through the specimen after 6 hours was measured.

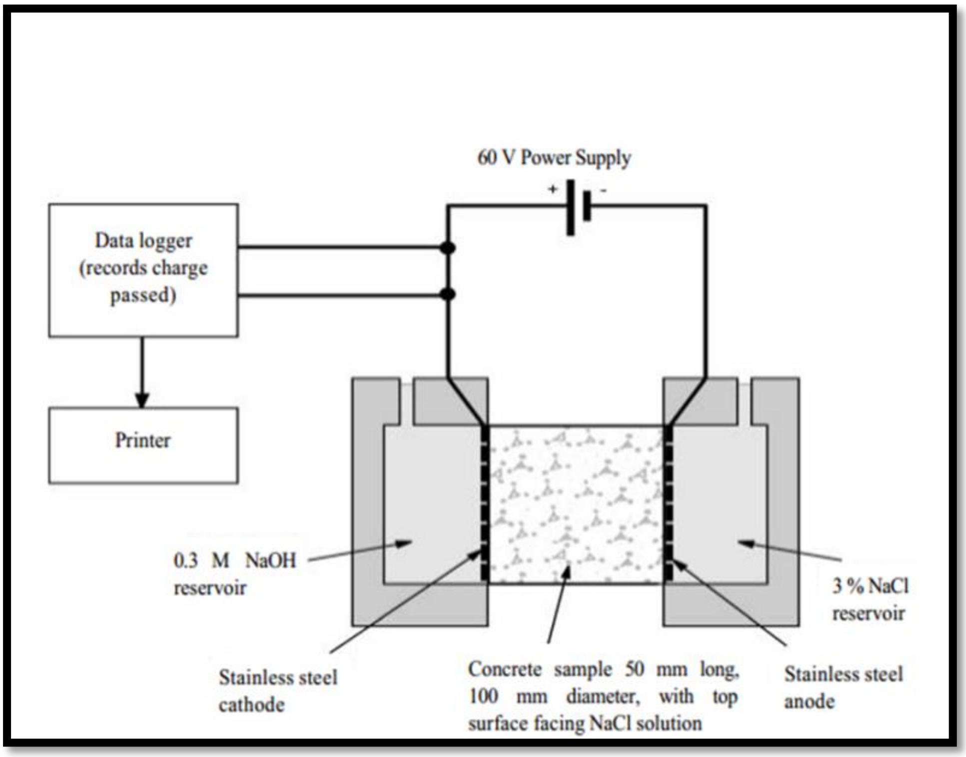

Figure 3.13: Rapid chloride permeability test setup (ASTM C1202, 2005)

3.5.2.7 Water absorption test

100-mm cubes were used and tested for water absorption test according to BS 1881-122. The specimens were cured in water for 7, 28 and 56 days. The concrete specimens were oven dried to a constant weight at 105 ± 5^{o} C for 48±2 hours before commencing the test. The weights of specimens were measured before immersion and after 30 minutes immersion in water.

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Introduction

This chapter deals with the test results of this research. The characteristics of palm oil fuel ash (POFA), fresh properties, and compressive strength of SCHSCs are discussed in this chapter. Durability characteristics in term of drying shrinkage strain, initial surface absorption, rapid chloride permeability, acid attack, sulphate attack, and water absorption tests have been explained and discussed in this chapter.

4.2 Materials characterisation

4.2.1 Characteristics of palm oil fuel ash

4.2.1.1 Chemical composition of POFA and OPC

The chemical composition of POFA and OPC were checked using X-ray fluorescence (XRF). As it can be seen in Table 4.1, silica content is the main component of POFA and the calcium oxide is the major element in OPC. Silica content in POFA will assist to increase the pozzolanic reaction to produce the secondary calcium-silicate-hydrate (C-S-H) gel. The total amount of SiO_2, Al_2O_3 and Fe_2O_3 in POFA was 69.23%. The values of LOI in POFA and OPC found to be 16.1 %, and 2.44% respectively.

Table 4.1: Chemical composition of OPC and POFA (%)

Oxide composition	OPC	POFA
Silicon dioxide (SiO_2)	17.60	59.17
Aluminum trioxide (Al_2O_3)	4.02	3.73
Iron oxide (Fe_2O_3)	4.47	6.33
Calcium oxide (CaO)	67.43	5.80
Magnesium oxide (MgO)	1.33	4.87
Sodium oxide (Na_2O)	0.03	0.18
Potassium oxide (K_2O)	0.39	8.25
Sulfur trioxide (SO_3)	4.18	0.72
$SiO_2 + Al_2O_3 + Fe_2O_3$	-	69.23
LOI	2.4	16.1

4.2.1.2 Particle size distribution

The particle size distribution of ground POFA was analysed at geology department, university of Malaya using particle size analyser as shown in Figure 4.1.

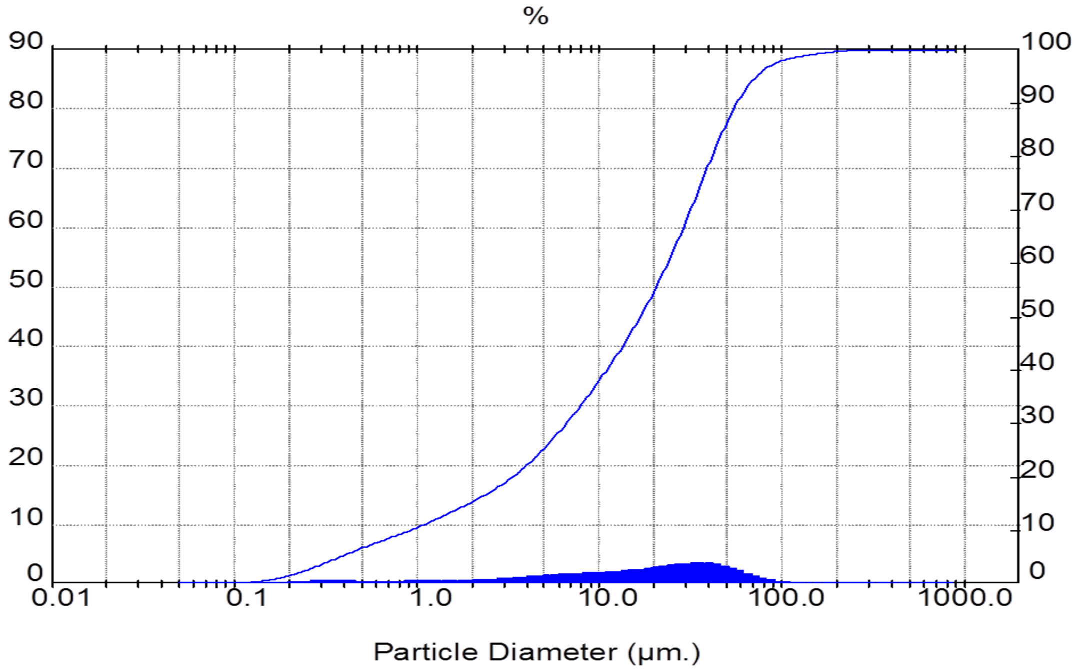

Figure 4.1: Particle size distribution of ground POFA

4.2.1.3 Surface area of POFA

Surface area of POFA was analysed using the single point BET. It was found that ground POFA possess surface area of 4.94 m^2/g. The surface area of POFA was increased due to the grinding process using Los Angeles abrasion machine. The higher specific surface area of POFA indicates that it would lead to increase the pozzolanic reactions which will enhance the concrete properties. However, the increased specific surface increases the water demand and thus reduces the workability of concrete. This problem can be overcome by using an adequate dosage of superplasticizer.

4.2.1.4 Microstructure analysis of POFA

Field emission scanning electron microscopy (FESEM) technique was used to study the microstructure of POFA. As can be seen in figure 4.2, that the POFA particles have irregular, angular shapes and amorphous content as shown in Figure 4.3. Also, energy dispersive X-ray was used to check the percentage of elements and silica variations at 3 different positions of the samples. Silica, carbon and oxogyn elements were found to have the higher precentage in ground POFA.

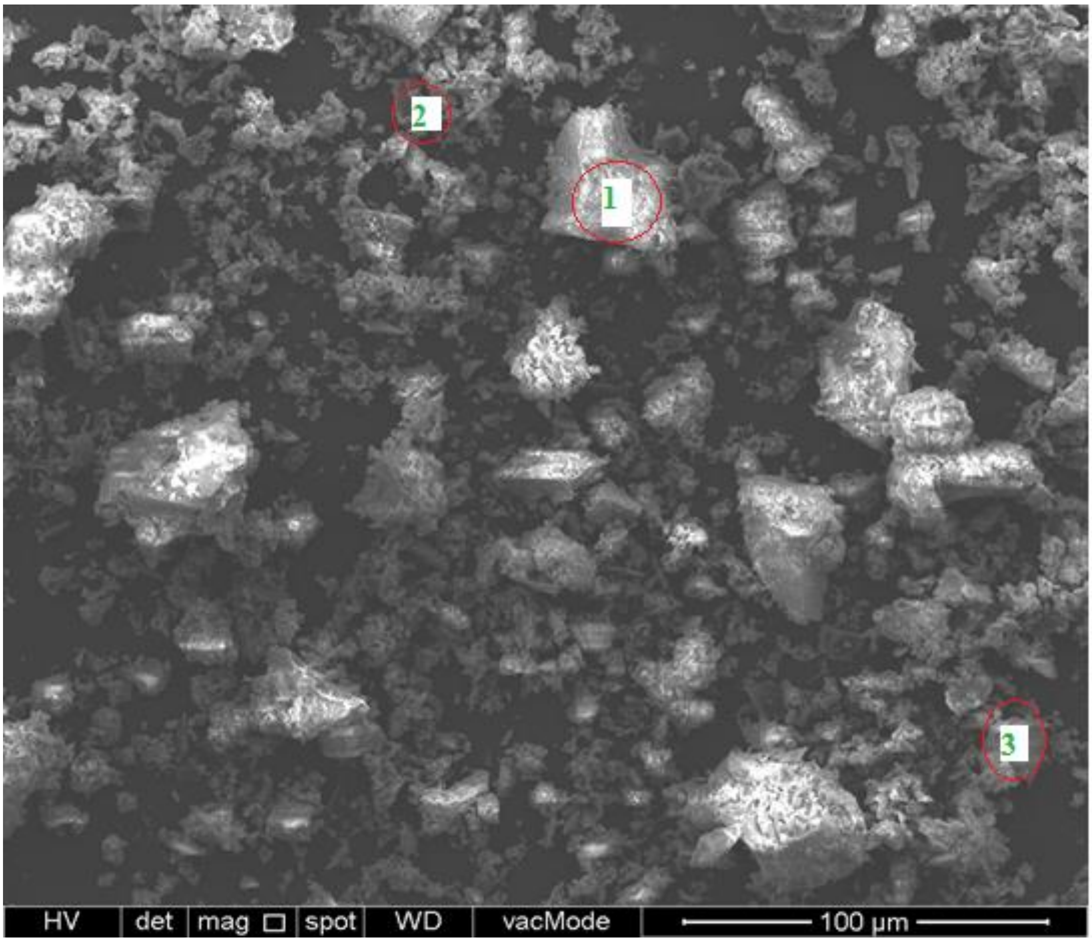

Figure 4.2: Particle size and shape of POFA through FESEM magnification

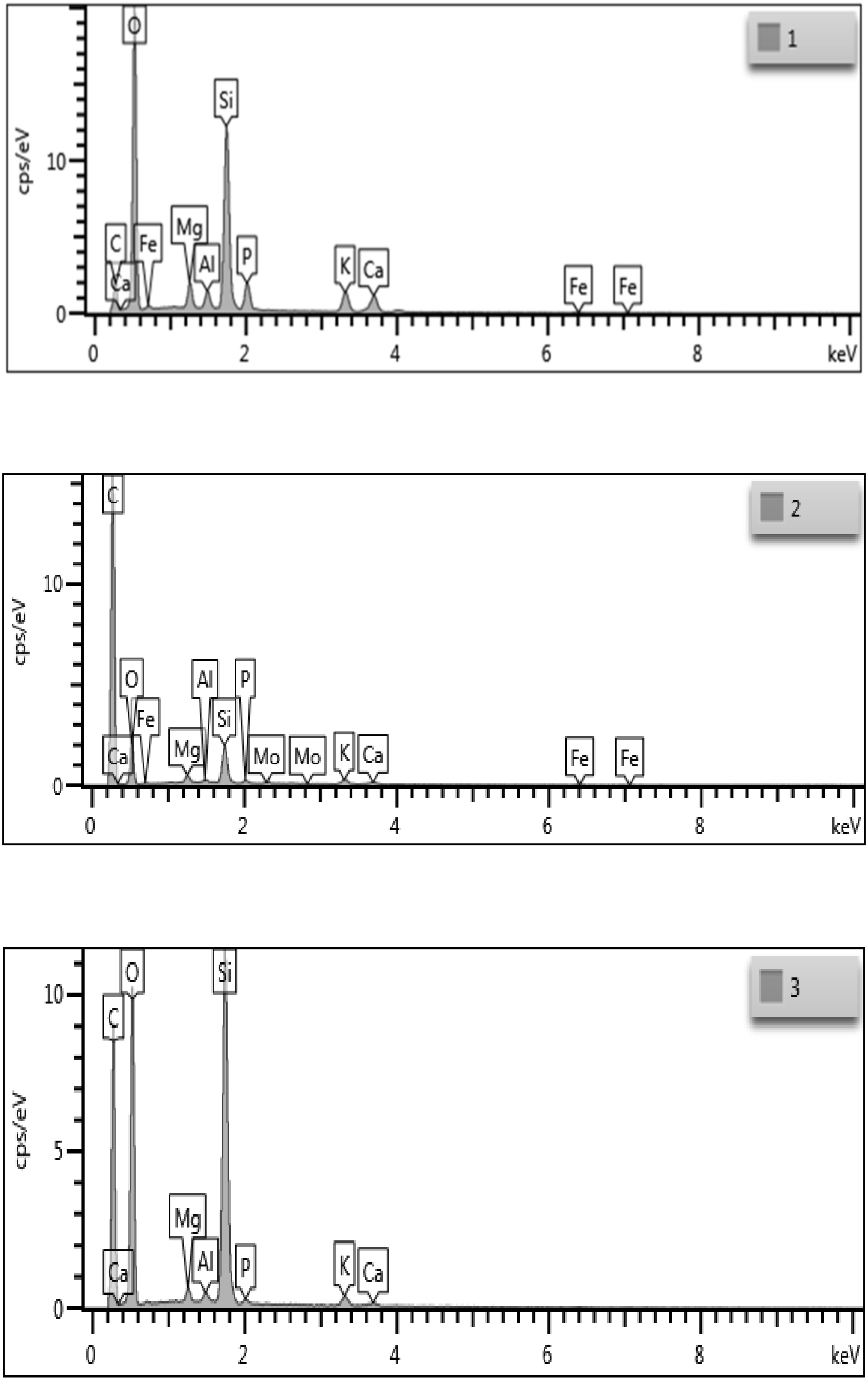

Figure 4.3: EDX micrographs analysis of POFA

4.3 Fresh properties of SCHSC

The fresh properties of SCHSC were determined by conducting the filling ability tests (slump flow, T_{50}cm spread time, and V-funnel flow time), passing ability tests (J-ring flow and L-box), and segregation resistance test (segregation index), the test results for the different SCHSC mixtures are given in Table 4.1 For filling ability requirements, all the concrete mixes were designed to have a slump flow of average diameter of 680 ± 20 mm, which was achieved by using varying amounts of ViscoCrete superplasticiser. As shown in Figure 4.4, the slump flow of all concrete mixes was in the range of 660-700 mm, which is in agreement with EFNARC standard 2002 criteria (EFNARC, 2002). In addition, the V-funnel and T_{50cm} flow times for the POFA mixtures were close to the control mixture and ranged between 6.6-8.75 s and 3.5-4.57 s, respectively, as shown in Table 4.1. The other fresh properties, such as L-box, J-ring, and GTM screen stability test were also checked as shown in Figure 4.5. All mixtures exhibited good passing ability and segregation resistance as shown in Table 4.1, and the values obtained were in the range determined by EFNARC (2002).

Figure 4.4: Slump flow test

Figure 4.5: J-ring test

It can be seen that the mixtures including POFA in concrete do not cause any severe adverse effect on filling ability, passing ability and segregation resistance. The higher content of POFA showed a lower slump flow, J-ring, and L-box; however, it increased T_{50} and v-funnel flow time and segregation index. This can be attributed to the porosity of POFA particles and the higher surface area, which absorbs more water than OPC, and thus reduce the free water content needed for workability. From Table 4.2, it can be seen that up to 20% of cement can be replaced by ground palm oil fuel ash without affecting the fresh properties of SCHSC. This result is in agreement with the results of other researchers for normal, high strength and self-consolidating concretes (Safiuddin, Rahman, et al., 2012; Sata et al., 2007)

Table 4.2: Fresh properties of concretes

Mix No.	Filling ability			Passing ability		Segregation resistance
	Slump Flow (mm)	T_{50} spread time (s)	V-funnel time (S)	J-ring (mm)	L-box	Segregation Index
SCHSC0	700	3.5	6.6	690	94	6.7
SCHSC10	690	3.6	6.8	670	93	8.7
SCHSC15	680	4.2	8.4	650	89	10.8
SCHSC20	660	4.6	8.8	630	84	13.9

4.4 Hardened properties and durability characteristics

4.4.1 Compressive strength of SCHSC

The development of compressive strength for all mixes is shown in Figure 4.6 The compressive strength at 28 days curing for different cement replacements for SCHSC0, SCHSC10, SCHSC15, and SCHSC20 mixes were 67, 69.5, 62.5, and 60 MPa, respectively. Thus, all the concrete mixtures could be categorized as self-consolidating high-strength concrete.

The compressive strength of the mixtures containing ground POFA showed lower strength at the early ages of 3 and 7 days of curing. Compared to mix SCHSC0, the mixes of SCHSC10, SCHSC15 and SCHSC20 showed a reduction in compressive strength of about 4%, 18% and 20% at 3 days, and 3%, 21% and 24% at 7 days, respectively. For both early ages, the reduction of the compressive strength at the 10% cement replacement level was negligible. However, at the 15% and 20% cement replacement levels the reduction was significant. In addition, the reduction in the compressive strength at 15% and 20% cement replacements were almost the same. This showed that in respect of the compressive strength, 20% replacement level can be chosen instead of 15%. The reduction in the early age compressive strength can be attributed to the reduction in the cement content in the mix design (Hussin & Abdul Awal, 1996). However, the effect of ground POFA on the 28-day compressive strength was found to be higher for mix SCHSC10 or comparable for mixes of SCHSC15 and SCHSC20 to the corresponding plain concrete.

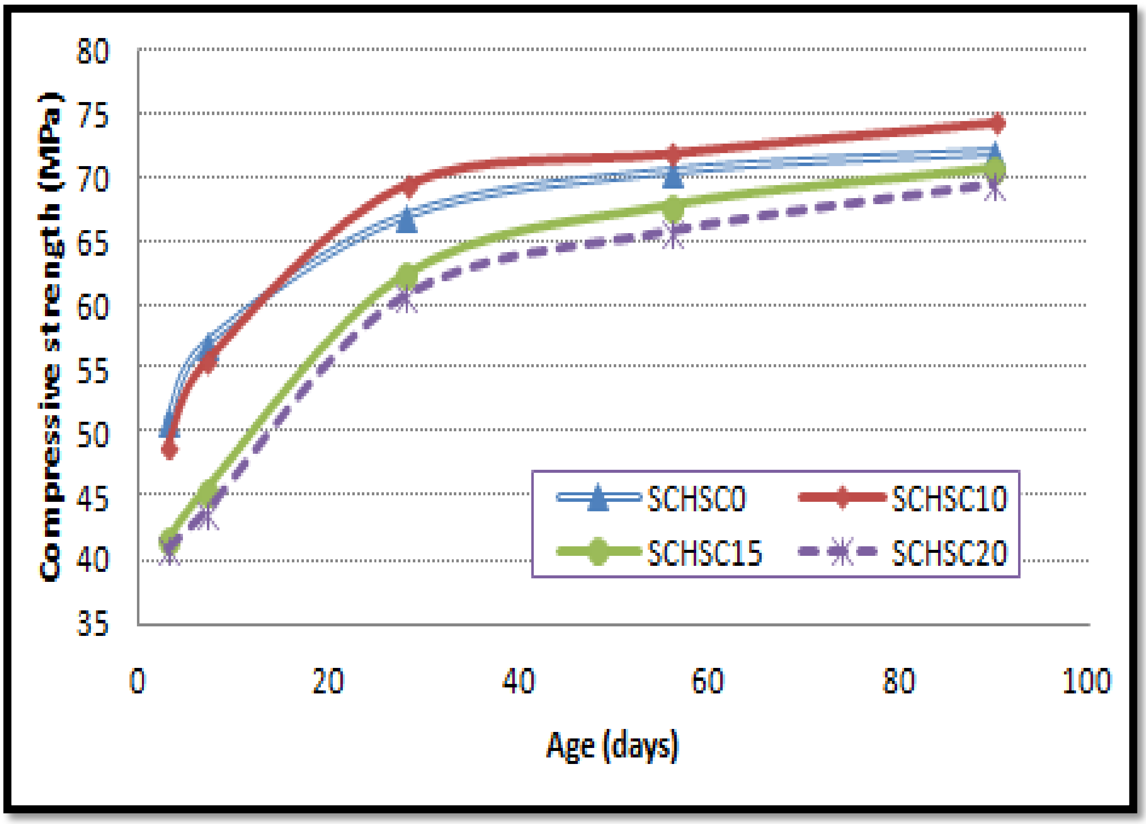

Figure 4.6: Development of compressive strength of concretes

The improvement of SCHSC containing ground POFA is due to the pozzolanic activity of this pozzolan, which reacts with the Ca $(OH)_2$ liberated from the cement hydration in the presence of water, and forms secondary calcium silicate hydrate (C–S–H). The pozzolanic reaction mainly contributes to an increase in the compressive strength of concrete at the later ages by improving the interfacial bond between the paste and the aggregate (Ismail et al., 2010). In addition, the high fineness of ground POFA improves the strength of the concrete by filling the voids between the cement particles (Ismail et al., 2010; Tay & Show, 1995). The highest compressive strength at 28 days curing was for the mixture containing 10% POFA (mix SCHSC10). However, it should be noted that reports have shown that the highest 28-day compressive strength in normal vibrated concrete was found at 20% replacement level (Sata et al., 2004, 2007). It may be due to the higher LOI content of the POFA in this study (16.1%) compared to most of the previous studies, in which LOI was around 10%. In addition, compressive strength of concrete containing POFA with higher silica content was better compared to concrete containing POFA with lower silica content (Galau & Ismail, 2010).

4.4.2 Drying shrinkage strain

The results of the drying shrinkage strain of all mixes are shown in Figure 4.7 Drying shrinkage strain takes place when concrete hardens and dries out. About 70% of drying shrinkage occurs in the first 3 months (Tangchirapat et al., 2009). It induces potential flow channels in the form of microcracks. These cracks initiate the access to harmful agents, and thus affect the durability of concrete. The test results of this study showed that the incorporation of palm oil fuel ash reduced the drying shrinkage strain at any percentage of replacement (up to 20%) in comparison with the concrete made with

Type I Portland cement. At age 120 days of drying, the drying shrinkage strain of the control sample was 375 microstrains while those of concretes with 10%, 15% and 20% POFA were 280, 315 and 315 microstrains, respectively. These results agree with the observations reported that high strength concrete with ground POFA produced lower drying shrinkage strain than OPC concrete for any amount of POFA up to 30% replacement (Tangchirapat et al., 2009). In addition, these results agree with the findings for another type of cementitious material; namely, rice husk ash (RHA), which was reported by Mahmud et al. (2009).

The lower value of drying shrinkage strain can be attributed to two main factors: First, the concrete containing ground POFA, which will cause densification of the pore structure due to the pozzolanic reactions of POFA. The incorporation of ground POFA reduces the pore sizes in concrete due to pore refinement. The transformation of large pores into fine pores decreases the evaporation of water from the concrete surface, and, hence, reduces the drying shrinkage strain of concrete (Haque & Kayali, 1998; Tangchirapat et al., 2009). The second factor for lowering the drying shrinkage can be attributed to the porosity of the concrete. SCC includes lower aggregate content and more binder, which would be expected to cause higher drying shrinkage strain. However, SCC has lower porosity compared to normal concrete (Attiogbe et al., 2002). This is due to the better compacting, lower water/binder ratio, the use of a high range water reducer and the utilization of mineral admixture, which contributes to reduce the pore structure of SCC. In addition, SCC has less empty voids on the concrete surface that are mainly responsible for the drying shrinkage strain (Safiuddin et al., 2008). Generally, the drying shrinkage strain of a SCC is more than for normal vibrated concrete. This is due to the lower coarse aggregate and higher binder content in the SCC mixture. Therefore, by incorporating POFA in the SCC mixture it compensates for the negative effect of low coarse aggregate and high binder content in SCC.

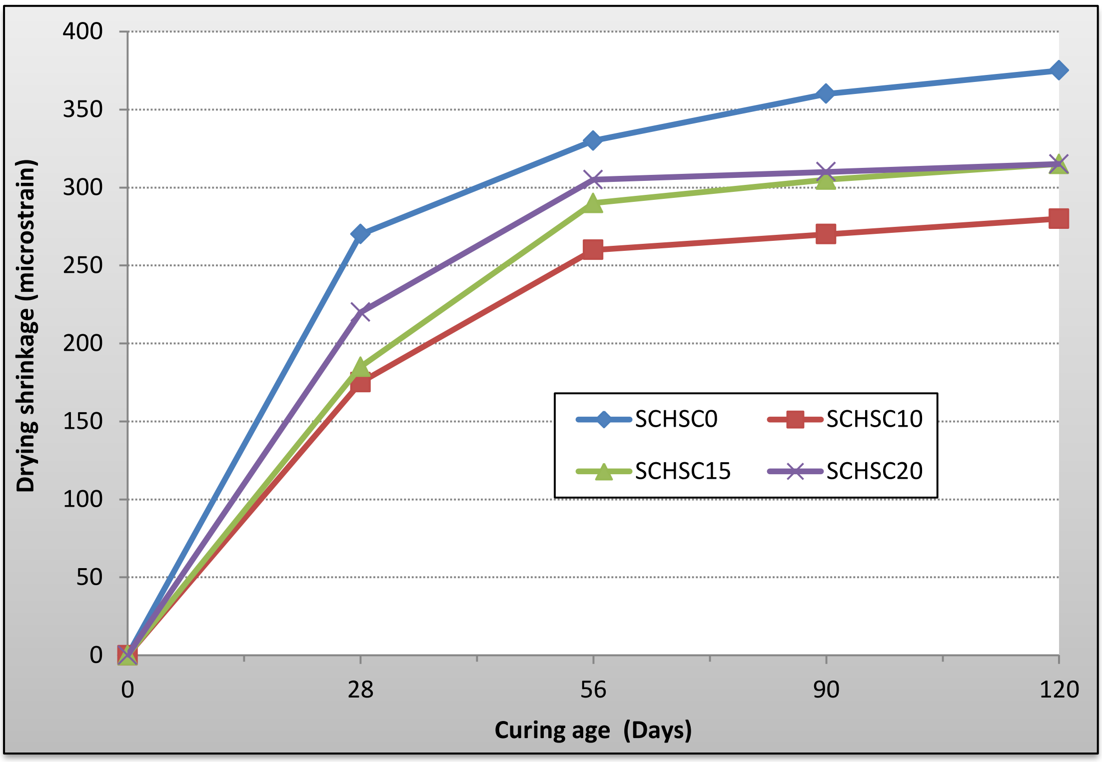

Figure 4.7: Development of drying shrinkage strain with time

4.4.3 Initial surface absorption test (ISAT)

The initial surface absorption test was performed to obtain the flow within the concrete surface at intervals of 10, 30 and 60 minutes. The test results show that by incorporating POFA in SCHSC the ISAT value decreases. The lowest flow rate was at the 20% cement replacement level at all ages. The initial surface absorption of SCHSC10, SCHSC15 and SCHSC20 for the 10 min interval was 16%, 25%, and 32% lower than the control mix (SCHSC0) at 28 days. Although SCHSC20 has a slightly lower compressive strength than that of SCHSC0, SCHSC10 and SCHSC15, it has lower concrete surface absorption. Consequently, SCHSC20 has better durability than that of SCHSC0, SCHSC10, and SCHSC15. Figure 4.8 shows the relationship between ISAT values and POFA content for all mixes. It can be seen that as the POFA content increased, the flow of water into the surface of concrete reduced.

The observed reduction in initial surface absorption could be attributed to the more refined microstructure of the concrete containing POFA due to the formation of C-S-H gel by the pozzolanic reaction that gradually fills the original water filled space. Therefore, the pozzolanic effect of POFA reduces the pore diameters and improves the strength and permeation characteristics of the concrete. Another possible reason is the high fineness of POFA that would act as a filler between the cement particles (Kartini et al., 2010). The results obtained from this research agreed with a study on cementitious material replacement of cement by zeolite, PFA and silica fume at cement replacement levels in the range of 5% to 30% (Chan & JI, 1998).

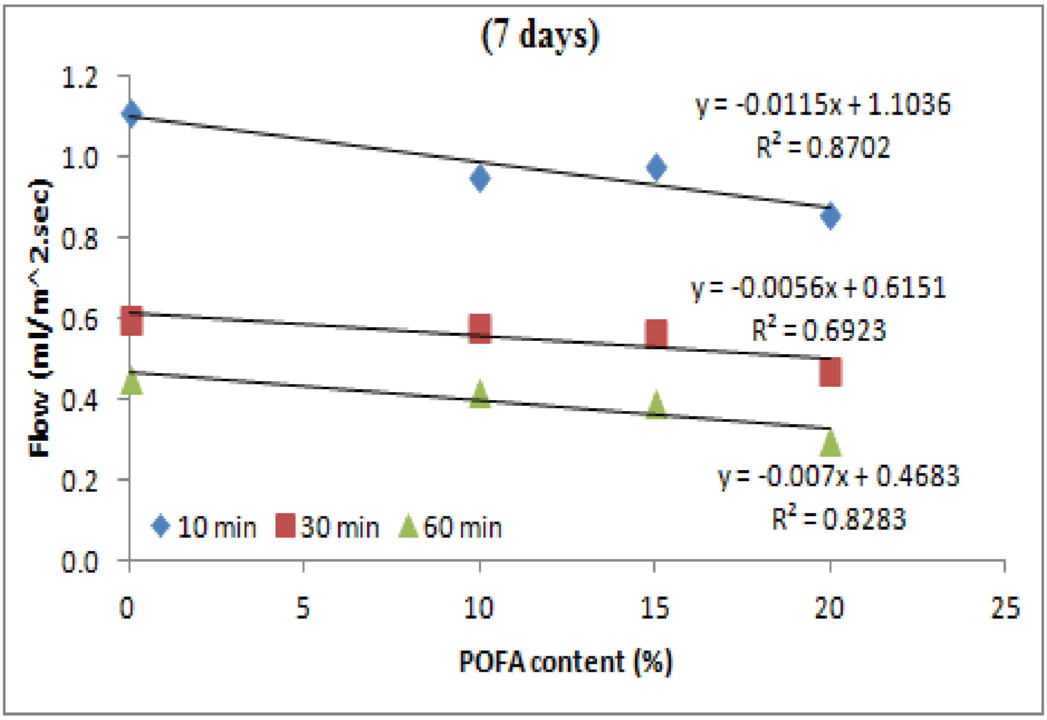

Figure. 4.8 (a)

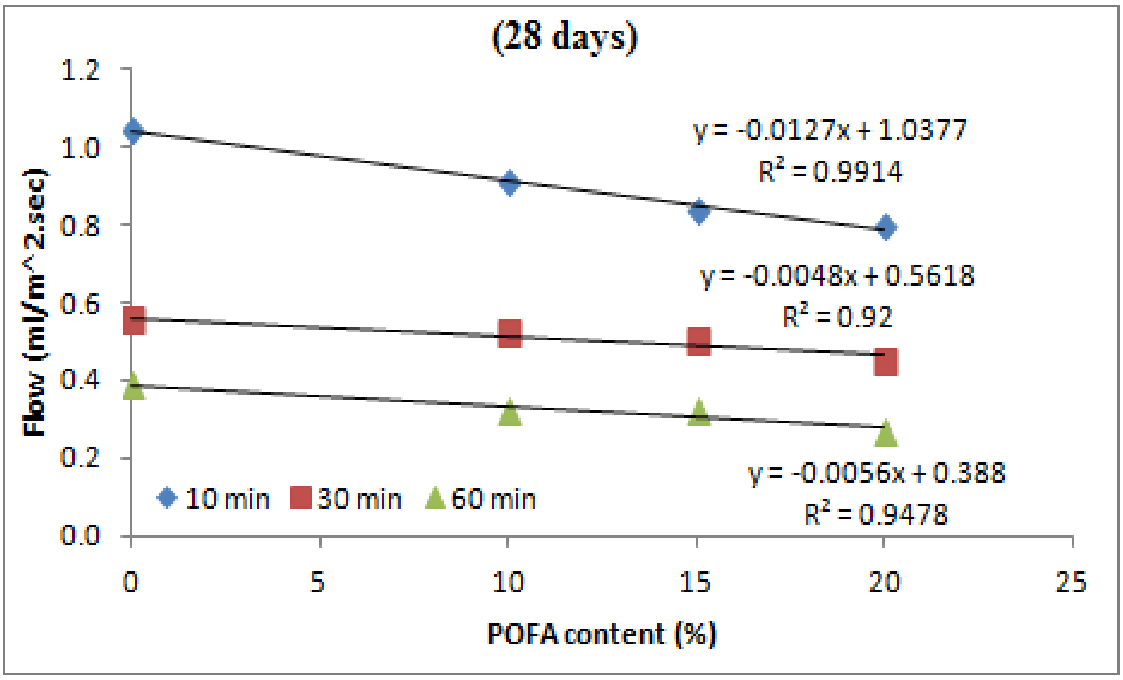

Figure. 4.8 (b)

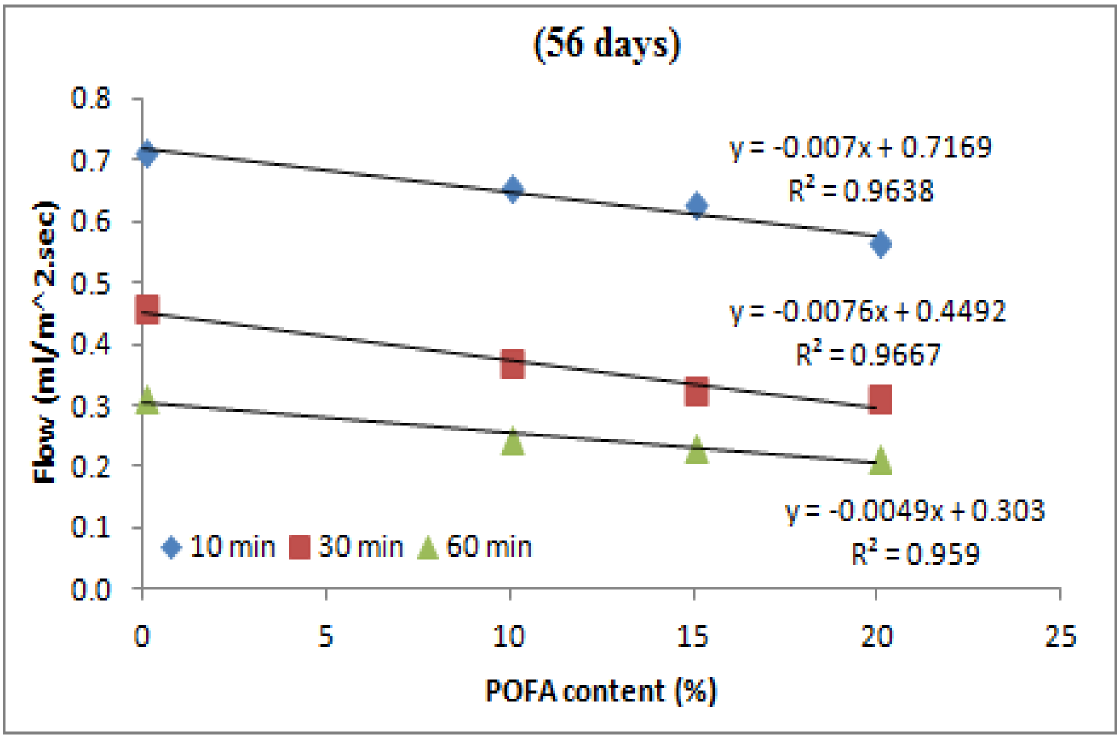

Figure. 4.8 (c)

Figure 4.8: Effect of POFA content on the initial surface water absorption of concrete at the ages of 7 days (a), 28 days (b), and 56 days (c)

4.4.4 Acid attack test

The resistance to acid attack of concrete cube specimens was carried out by measuring the loss of mass and compressive strength of the samples immersed in a 3% hydrochloric acid solution for 1800 hours. Figure 4.9 shows a relationship with a strong correlation between the POFA content and the mass loss of concrete. It can be seen that the loss in mass of the SCHSC mix without POFA is higher compared to the losses in the POFA concrete specimens. By incorporating POFA in the SCHSC mixture the mass loss of concrete significantly reduced. This result is in line with the findings reported by Siad, et.al (2010) in the case of SCC with natural pozzolan, and in the case of high strength concrete containing POFA (Budiea et al., 2010).

The loss in compressive strength was also measured at the end of the testing period of acid attack. Figure 4.10 shows a relationship with strong correlation between the POFA content and the compressive strength loss of concrete. The test results have shown that SCHSC concretes with POFA exhibited better resistance against the acid after 1800 hours of immersion. In addition, for measuring the mass and strength loss of concrete, visual observations were carried out to determine the difference in colour and corner losses of specimens immersed in acid and cured in water. From Figure 4.11, it can be seen that SCHSC0 samples exhibited changes in colour and corner losses due to the effect of the acid. However, there was not much change in colour and corner loss for the SCHSC containing POFA. This result matches the findings for normally vibrated high performance and high strength concretes containing POFA reported by Abdul Awal & Hussin (1999), Budiea et al., 2010) and Hussin et al., (2009).

The high acid resistance of SCHSC incorporating POFA was attributed to the pozzolanic reaction of POFA conversion of free lime $Ca(OH)_2$ to the additional C-S-H gel (secondary C-S-H gel). Therefore, the $Ca(OH)_2$, which considered as the weakest product from cement hydration and is highly susceptible to chemical attacks, will be reduced (Safiuddin et al., 2011). In addition, the calcium oxide (CaO) content of POFA was very low (about 6%) in comparison to the high content (about 64.17%) of CaO in OPC. As POFA contains a low amount of CaO, the amount of $Ca(OH)_2$ would be less in the products of hydration. Moreover, the good finish and the minimum empty voids on the concrete surface of SCHSCs with POFA led to a reduced penetration of acid solution into the interior of concrete, and enhanced its resistance to the acid attack (Safiuddin et al., 2011; Safiuddin et al., 2008).

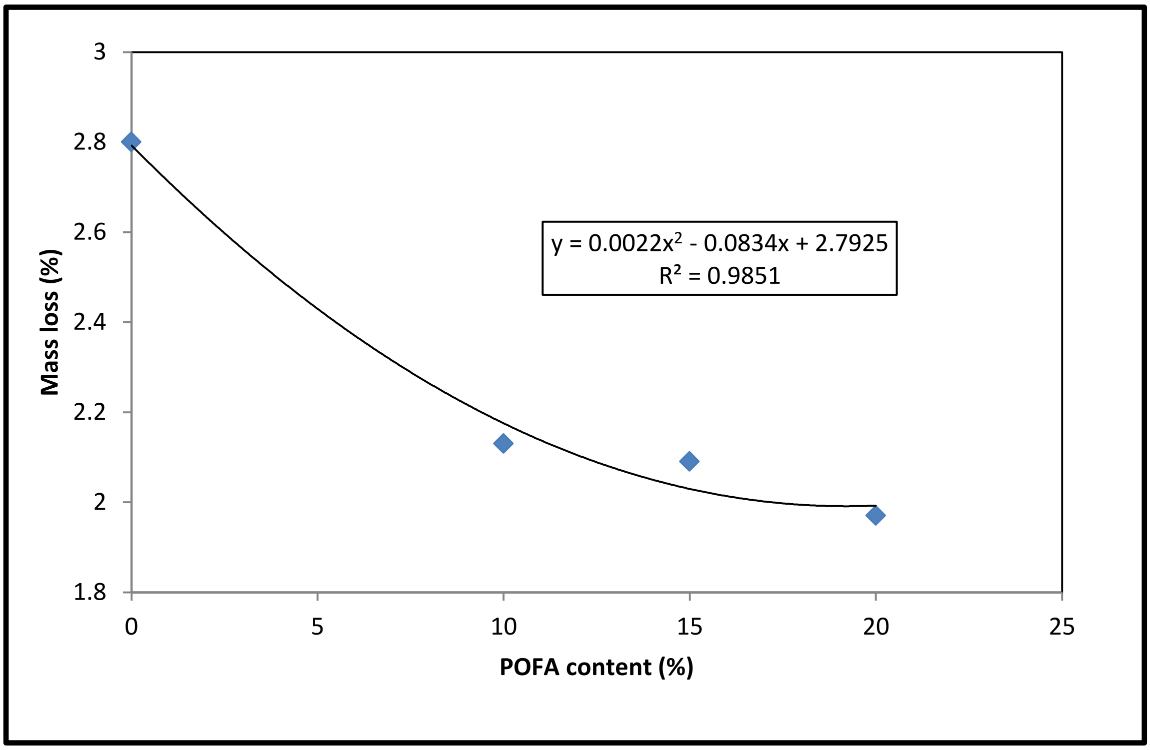

Figure 4.9: Relationship between POFA content (%) and mass loss of concrete

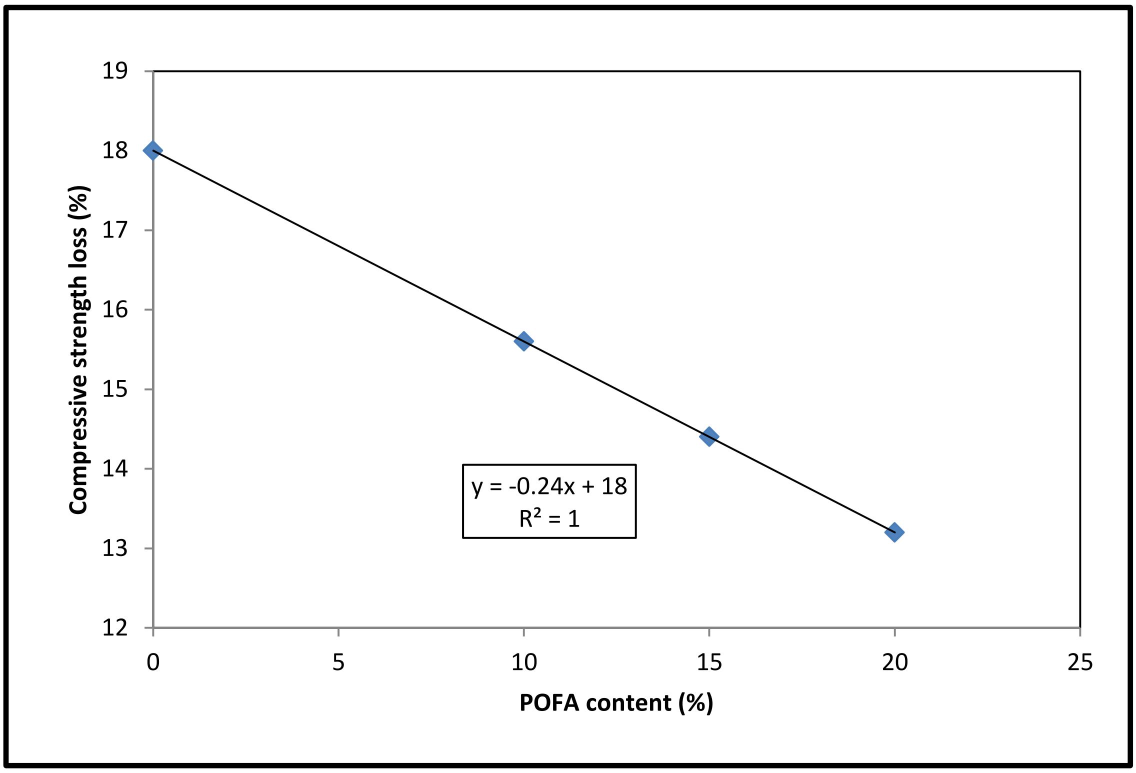

Figure 4.10: Relationship between POFA content (%) and compressive strength loss of concrete

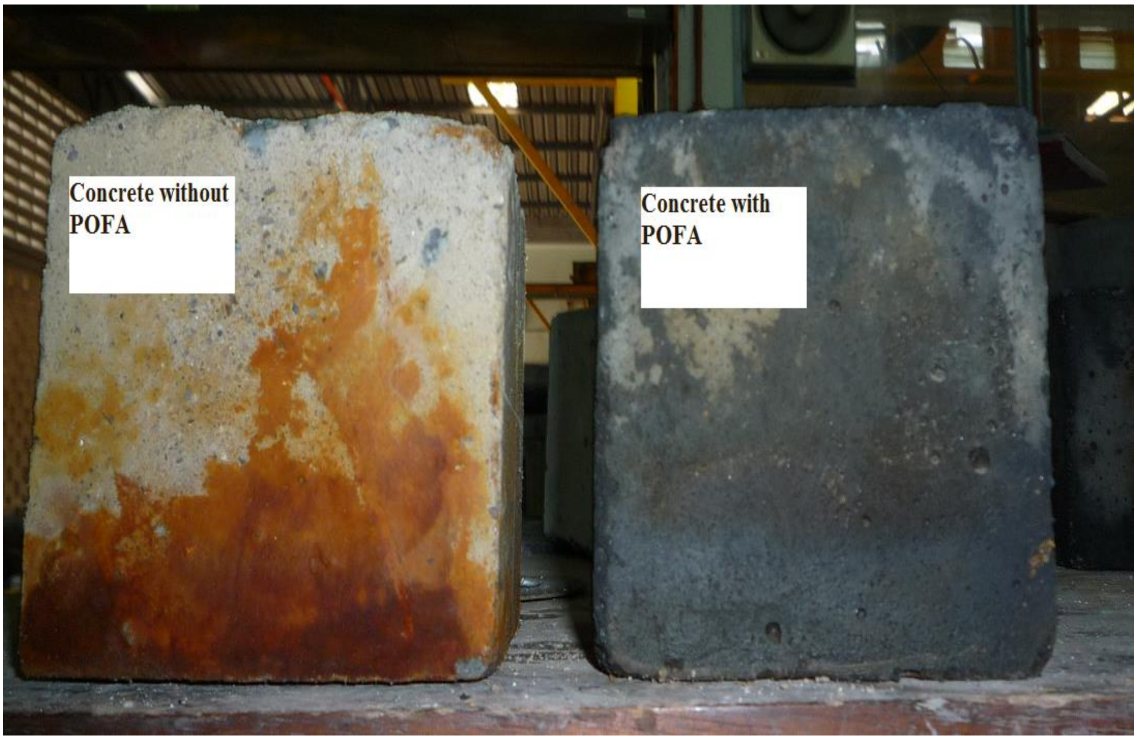

Figure 4.11: Effect of acid on colour and corners of a concrete with and without POFA

4.4.5 Sulphate attack test

The reaction between sulphate ions and calcium hydroxide $Ca(OH)_2$ produced from cement hydration to produce calcium salt (gypsum). The formation of gypsum can cause softening and loss of concrete strength (ACI Committee 201 , 1990). The reduction in compressive strength for concrete immersed in 5% magnesium sulphate (5% MgSO4 by the weight of water) for 12 months is shown in Figure 4.12. The loss in compressive of SCHSC0, SCHSC10, SCHSC15, and SCHSC20 immersed in 5% $MgSO_4$ solution were approximately 9.6% and 8.3%, 7.8%, and 7.2% respectively compared to the same mixtures cured in water for the same period.

It can be seen that the highest reduction in compressive strength is in the plain concrete SCHSC0, while the lowest loss in compressive strength found in 20% cement replacement. The higher resistance to sulphate attack for concrete included POFA can be attributed to the pozzolanic reaction for POFA. The pozzolanic reaction will reduce the amount of free calcium $Ca(OH)_2$ produced from the cement hydration and form secondary C-S-H which lead for pore refinement and denser concrete. In addition, the high fineness of POFA reduced the permeability of concrete, hence improved the resistance to sulphate attack and also the durability of concrete. The results for sulphate attack agreed with the previous results from this research on the initial water absorption and acid attack. Also the results are in line with previous studies conducted on normally vibrated and high strength concrete. Tangchirapat et al. (2009; 2012) reported that the use of POFA in concrete can increase the resistance to sulphate attack and the recommended percentage was 20%.

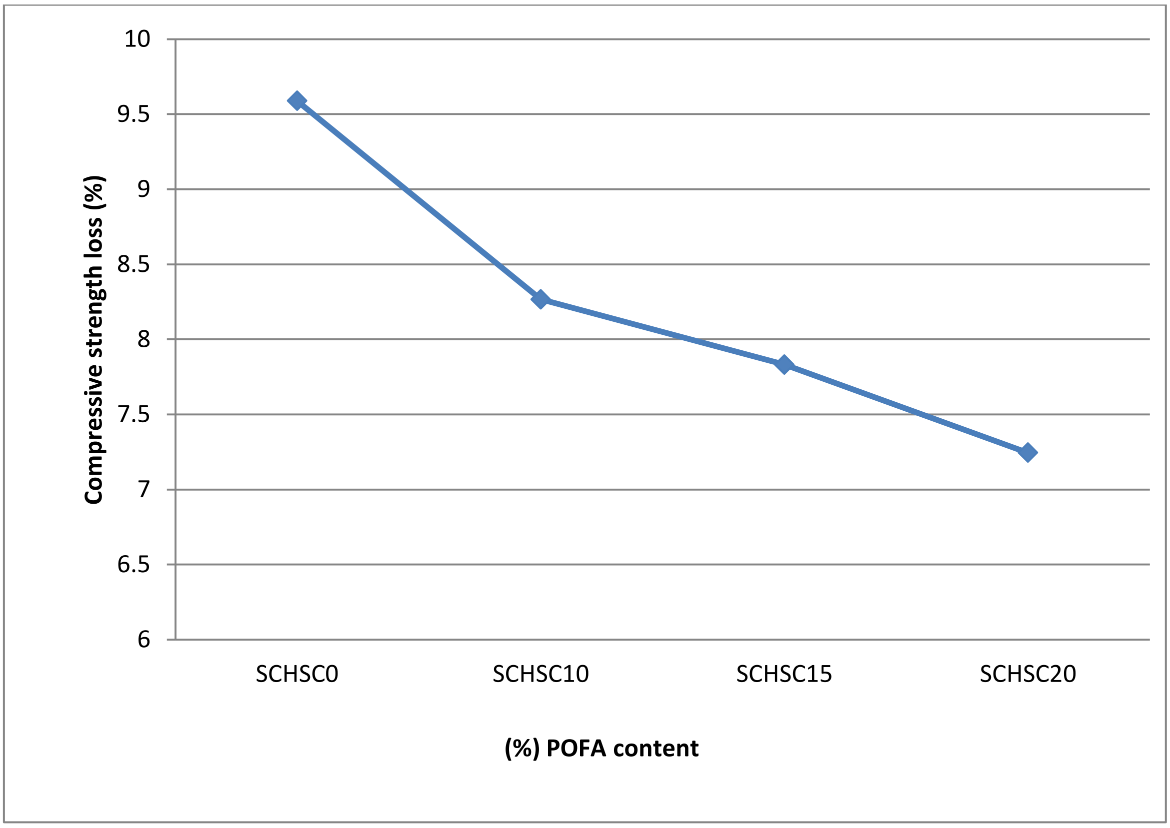

Figure 4.12: Reduction in compressive strength for concrete immersed in 5% $MgSO_4$

4.4.6 Rapid chloride permeability test (RCPT)

The RCPT was carried out on cylindrical specimens for concrete mixture at the ages of 7, 28 and 90 days. The 7 days total charged passed for SCHSC0, SCHSC10, SCHSC15 and SCHSC20 mixes were 2040, 2180, 2320, and 2610 coulombs, respectively. The lowest value was for the control sample. It is because the concretes containing POFA were still weak and less dense compared to the ordinary Portland cement concrete at the early age. Conversely, the 28 days total charge passed for SCHSC0, SCHSC10, SCHSC15 and SCHSC20 were 1260, 1080, 1040, and 1020 coulombs, respectively. At the 90-day curing, the total charge passed for concrete containing 0%, 10%, 15% and 20% POFA was 530, 410, 370, and 320 coulombs, respectively. As can be seen in Table 4.3, according to ASTM1202 (2005), all concretes at 7, 28 and 90 days can be classified as moderate, low and very low permeable concrete, respectively. As the age of curing increases, the internal pore structure of the concrete becomes less permeable. Hence, the chloride ion of POFA concrete has a lower charge passed through the specimen compared with the ordinary Portland cement at 28 and 90 days of curing. This may be due to the reaction of POFA with calcium hydroxide $Ca(OH)_2$ to produce pozzolanic products (C-S-H). Therefore, the pozzolanic products fill in the pores in the bulk binder paste and transition zone, and, consequently, improve the internal pore structure, which decreases the permeability of concrete, and thus increases the resistance to chloride penetration. These results agreed with the findings reported by Chindaprasirt et al., (2010) who stated that high strength and high workability concrete can be produced with a partial replacement using POFA up to 20% with good resistance against chloride ion penetration. In addition, Hussin et al. (2009) reported that, concrete containing POFA with higher fineness showed better durability performance compared to concrete containing POFA with lower fineness. This is due to the larger surface area of finer POFA, which increases the pozzolanic reaction.

Table 4.3: Chloride permeability and classification of concrete

Sample	7 days		28 days		90 days	
	Charge Passed (Coulombs)	Remarks	Charge Passed (Coulombs)	Remarks	Charge Passed (Coulombs)	Remarks
SCHSC0	2044	Moderate	1264	Low	528	Very low
SCHSC10	2176	Moderate	1083	Low	412	Very low
SCHSC15	2324	Moderate	1046	Low	366	Very low
SCHSC20	2608	Moderate	1016	Low	320	Very low

4.4.7 Water absorption test

Caldarone (2008) stated that the cover porosity of concrete and largest capillary size are two major factors for concrete durability. He reported that the water absorption test could be used for assessing both of these factors. Figure 4.13 shows a relationship with strong correlation between POFA content and water absorption at 7, 28 and 56 days. As can be seen in this figure, for early and later ages, the water absorption of SCHSC decreased as the percentage of POFA content increased.

According to CEB-FIP (1993), the quality of a concrete with a water absorption value in the range of 0 to 3% is categorized as good concrete. It can be seen in Figure 4.13 that all the mixes can be evaluated as good concrete at all three ages. It is clear that by incorporating POFA in SCHSC the quality of concrete significantly improved. The reduction in the water absorption of concrete containing POFA was, on average, about 14%, 24% and 31% at 7, 28 and 56 days, respectively. These test results showed a significant improvement in the quality of concrete containing POFA over time. This is due to the pozzolanic effect of POFA at the later ages.

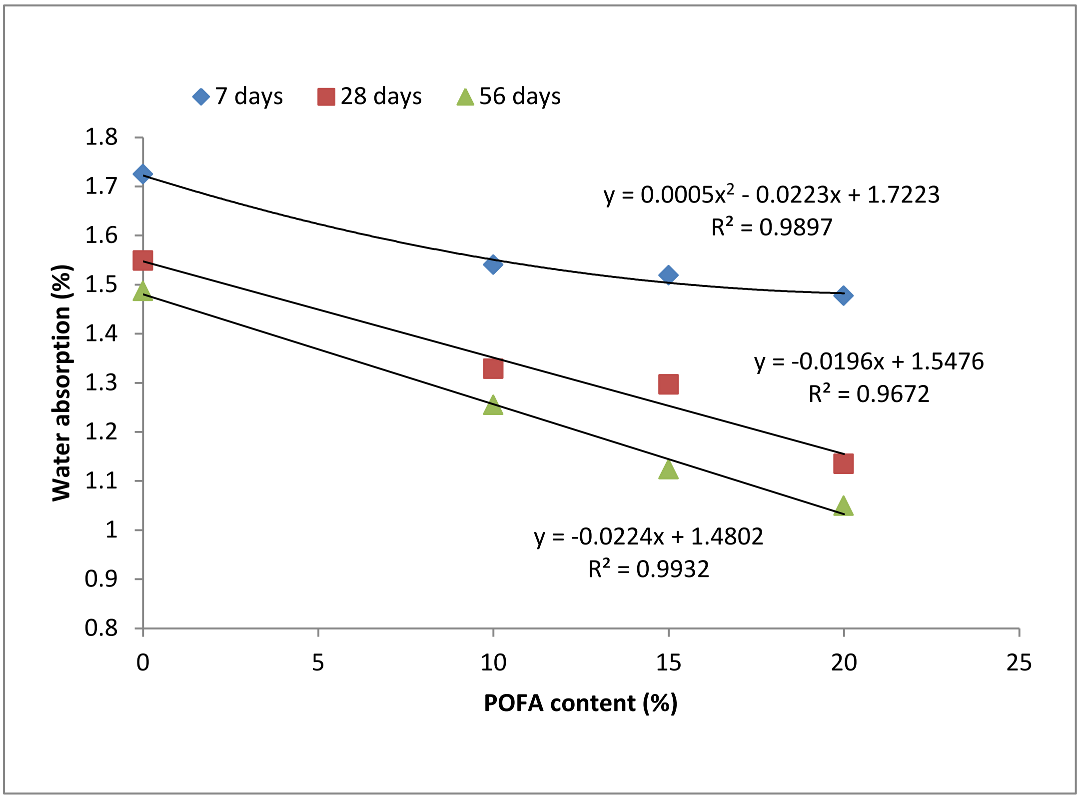

Figure 4.13: Relationship between POFA content (%) and water absorption (%)

4.5 Relationship between ISAT and water absorption

Compared to ISAT test, performing the water absorption test is simpler. Therefore, finding a relationship with good correlation between water absorption and ISAT will be very useful. Figure 4.14 shows the relationship between water absorption and ISAT test results at 10, 30 and 60 minutes for early and later ages. It can be observed that there is a strong correlation between the values of these two durability characteristics of concrete at all ages. This can be attributed to the improvement caused by POFA, which acts as a filler between particles of cement. This will reduce its porosity and enhance its resistance to fluid penetration.

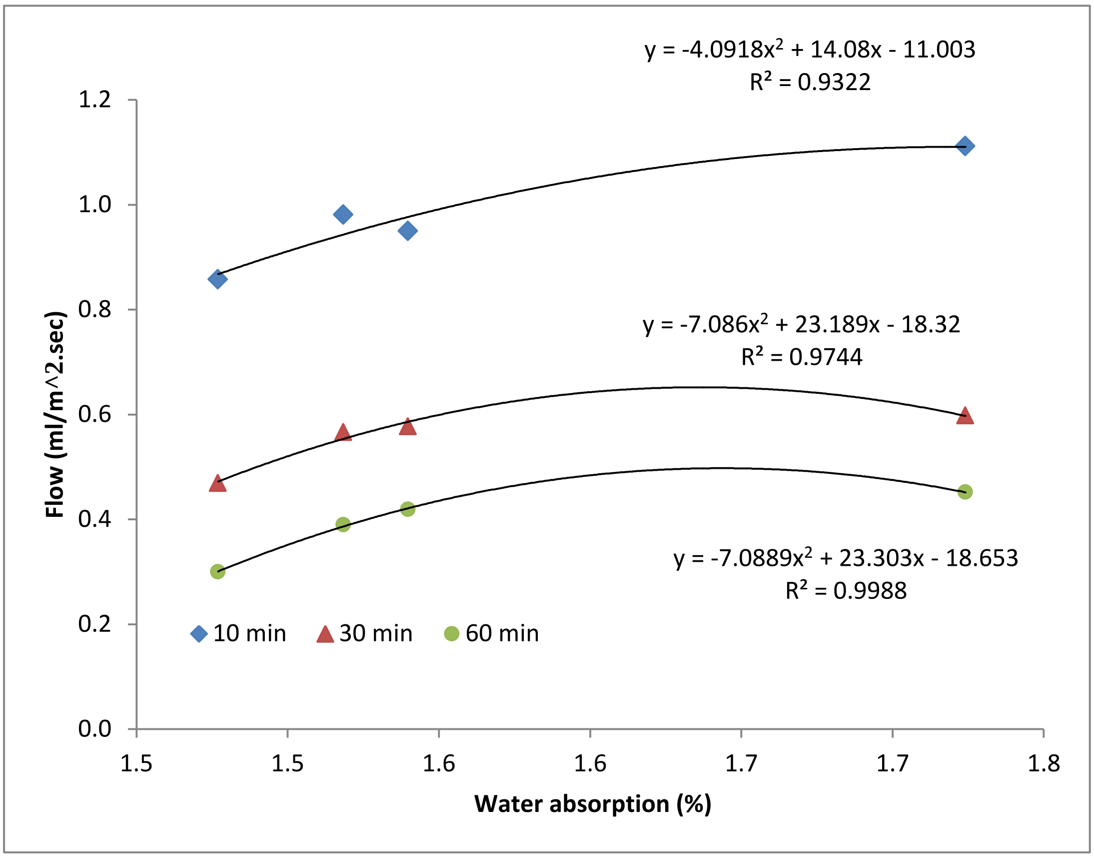

Fig. 4.14(a)

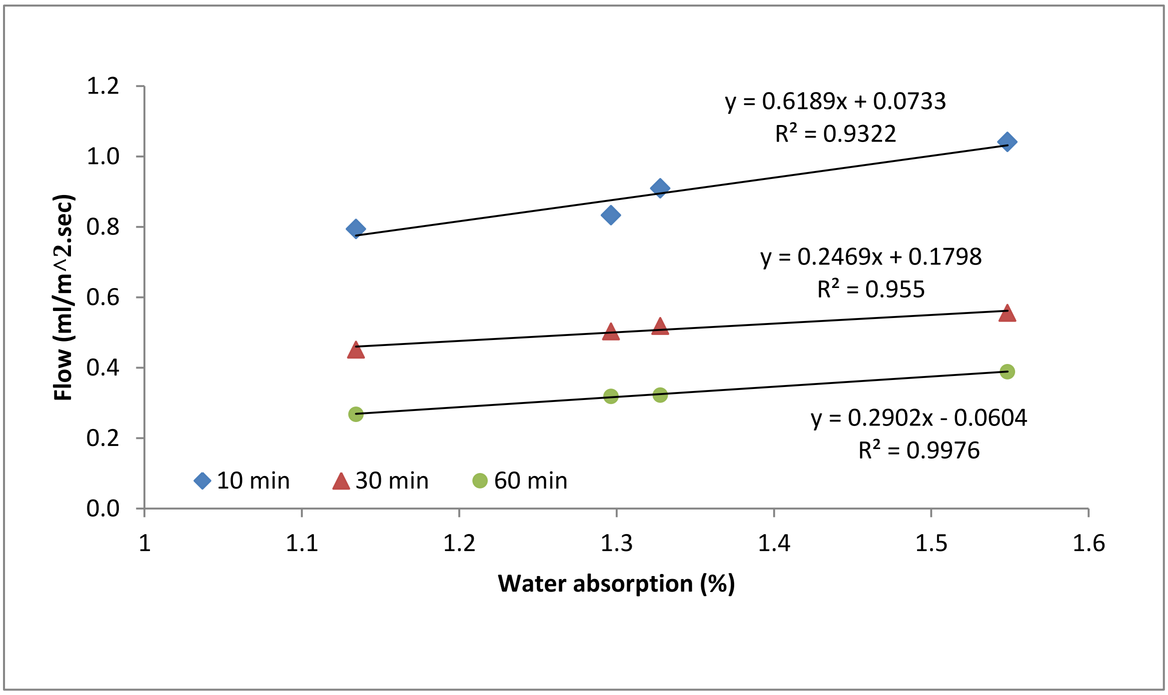

Fig. 4.14(b)

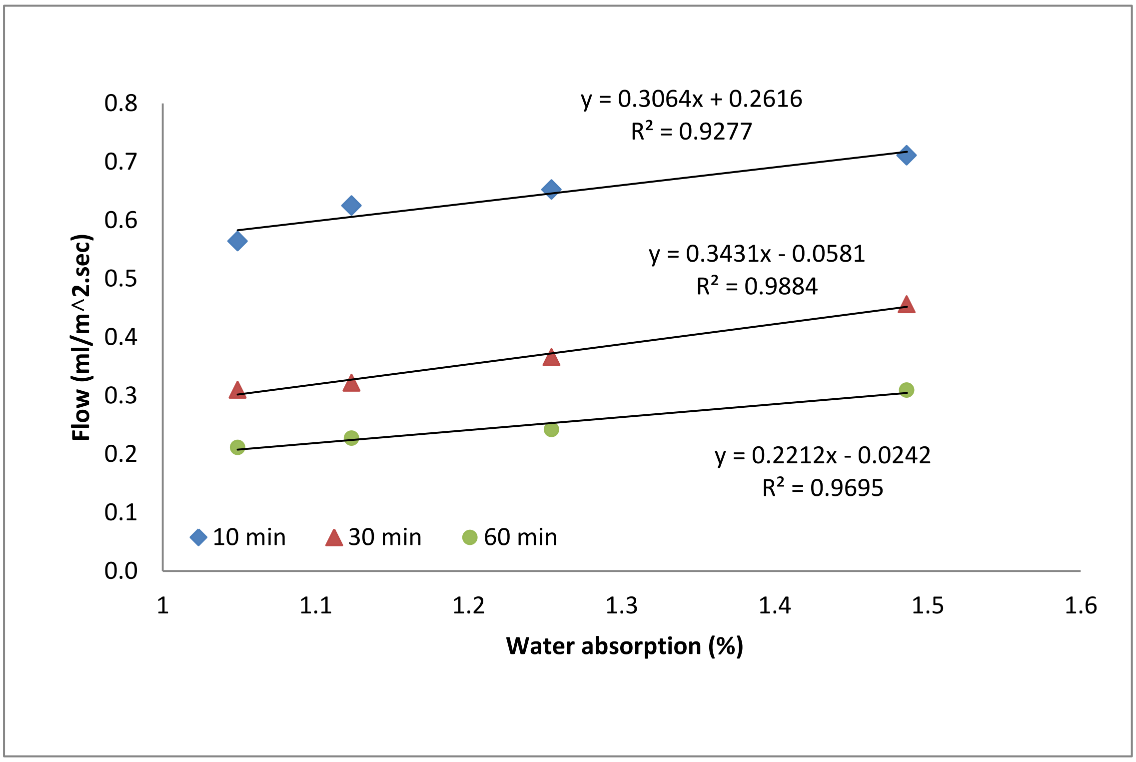

Fig. 4.14(c)

Fig.4.14. Relationship between water absorption (%) and ISAT at the ages of 7 days (a), 28 days (b), and 56 days(c)

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

Based on the findings of this research, the following conclusions can be drawn:

1) Self-consolidating high strength concrete can be produced incorporating ground POFA up to 20% without an adverse effect on the fresh properties.
2) Ground POFA with high fineness can be used as a pozzalonic cement replacement material to produce SCHSC with a compressive strength as high as 60 MPa at 28 days when used to replace Type I Portland cement at 20% by weight of binder. Concrete containing 10% ground POFA exhibited higher compressive strength (70 MPa) than concrete made from Type I Portland cement at the age of 28 days.
3) Incorporating ground POFA causes a reduction in the drying shrinkage strain of all the mixes containing POFA as compared to concrete made from Type I Portland cement.
4) Self-consolidating high strength concrete containing ground POFA showed a significant reduction in the initial surface absorption. 20% cement replacement level with the POFA exhibited the lowest initial surface absorption as compared to all mixes.
5) The specimens containing ground POFA were found to be more resistant against hydrochloric acid solution than the specimens without POFA.
6) Self-consolidating high strength concrete containing POFA shows more resistance against sulphate attack.
7) The results confirm that concrete containing up to 20% of ground POFA gives better resistance to rapid chloride penetration at 28 days. The 20% POFA

provides the best resistance to chloride penetration compared to concrete made with Type I Portland cement.

8) By incorporating POFA in self-compacting high strength concrete its water absorption reduces significantly. The reduction is more significant at later ages.

5.2 Recommendations for future investigation.

1- The effects of different curing conditions on the hardened properties and durability of SCHSC containing POFA should be studied.

2- Appropriate classification of POFA as a supplementary cementing material for concrete.

3- Study the high volume palm oil fuel ash in high strength concrete.

4- Fire resistance for concrete including POFA should be investigated.

5- To investigate the use of heat treatment for reducing the carbon content of POFA

6- The effects of POFA from different locations and different mills on the fresh and hardened properties and durability of SCHSC should be investigated.

7- The mixture design procedure for SCHSC developed in this study by incorporating POFA; it should be employed to determine the mixture proportions of SCHSC including other SCMs to validate its applicability.

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