FEASIBILITY STUDY OF GROUND PALM OIL FUEL ASH AS PARTIAL CEMENT REPLACEMENT MATERIAL IN OIL PALM SHELL LIGHTWEIGHT CONCRETE

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ABSTRACT

The fresh concrete properties and mechanical properties of oil palm shell concrete (OPSC) containing palm oil fuel ash (POFA) as partial cement replacement have been evaluated. The effects of POFA replacement levels of 0%, 5%, 10%, 15%, 20% & 25% under different curing regimes, namely air curing, full water curing and initial water curing were investigated. For the evaluation of fresh concrete properties various test like slump, vebe second, compaction factor and wet density test were performed. The highest 28-day compressive strength of 42 MPa was obtained for the OPSC containing 10% of POFA under continuous water curing condition. The results also denoted cost reduction about 14% is possible for concrete produced from POFA based OPSC. Conversely, the splitting tensile and flexural strengths of OPSC decreased when increased amount of POFA was used.

For durability properties, POFA was used as at 0%, 10%, 30% and 50% as replacement of ordinary Portland cement (OPC) when the water binder ratio (w/b) was 0.3 and again, OPC was replaced at 0% and 70% by POFA with w/b of 0.4.Different w/b was enacted to assess the outcome of pozzolanic reaction of POFA for different mixes. The durability tests include water absorption, sorptivity, drying shrinkage, sulphate attack and rapid chloride penetration test (RCPT) for 28- and 90-day water cured specimens. The water absorption and sorptivity values increase with the increase of POFA content. POFA based OPSC showed good resistance to sulphate attack. The drying shrinkage of POFA based concrete was higher with the increase of POFA content. The highest chloride ion penetration of about 5960 coulomb was recorded for the mix with 30% replacement of cement by POFA and with the further more replacement, the RCPT values were positively decreasing.

In view of the current criteria for a sustainable environmental benefits, green building rating systems, infrastructure, the use of industrial wastes such as POFA and OPS as binder and coarse aggregates, respectively could benefit the concrete industry.

ABSTRAK

Ciri-ciri konkrit dan sifat-sifat mekanikal konkrit shell kelapa sawit (OPSC) yang mengandungi abu bahan api kelapa sawit (POFA) sebagai sebahagian penggantian simen telah dinilai. Kesan tahap penggantian POFA 0%, 5%, 10%, 15%, 20% & 25% .Di bawah rejim pengawetan yang berbeza, iaitu pengawetan udara, pengawetan air penuh dan pengawetan air awal telah disiasat. Untuk penilaian civi konkrit segar pelbagai ujian seperti kemerosotan, kerugian kemerosotan, Vebe kedua, faktor pemadatan, ketumpatan basah dan peratusan ujian kandungan udara telah dijalankan. 28 kekuatan mampatan 42.40 MPa telah diperolehi bagi OPSC yang mengandungi 10% daripada POFA di bawah keadaan pengawetan air yang berterusan. Keputusan juga ditandakan pengurangan kos kira-kira 14% adalah mungkin untuk konkrit yang dihasilkan daripada OPSC POFA berasaskan.

Bagi hartanah ketahanan, POFA telah digantikan pada 0%, 10%, 30%, 50% dan 70% jisim simen Portland Biasa (OPC) di mana 0-50% penggantian dilakukan dengan w / c 0.3 dan satu lagi campuran dua untuk 0% dan 70% penggantian dianggap dengan w / c daripada 0.4. Berbeza w / c telah digubal untuk menilai hasil tindak balas pozzolanic untuk campuran yang berbeza. Ujian pelbagai telah dijalankan seperti penyerapan air, sorptivity, pengecutan kering, serangan sulfat dan ujian penembusan klorida pantas (RCPT) untuk sampel dingin pengawetan air 28- dan 90 hari. Nilai penyerapan air dan sorptivity telah semakin meningkat dengan peningkatan kandungan POFA. POFA kelapa sawit berdasarkan shell konkrit (OPSC) menunjukkan rintangan yang baik untuk serangan sulfat. Pengecutan pengeringan konkrit POFA berdasarkan lebih tinggi dengan peningkatan kandungan POFA. Penembusan ion klorida didapati maksimum kira-kira 5960 coulomb 30% penggantian simen oleh POFA dan dengan lebih penggantian lagi nilai-nilai yang positif RCPT berkurangan.

Memandangkan kriteria semasa bagi faedah alam sekitar yang berkaitan mampan, sistem penarafan bangunan hijau, infrastruktur dan membuat konkrit yang menggunakan bahan buangan industri seperti POFA dan OPS sebagai agregat boleh mendapat manfaat dalam mewujudkan industri konkrit mesra alam.

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LIST OF SYMBOLS AND ABBREVIATIONS

POFA	Palm oil fuel ash
OPS	Oil palm shell
SLWAC	Structural lightweight aggregate concrete
OPSC	Oil palm shell concrete
SP	Super-plasticizer
MPa	Mega Pascal
GPa	Giga Pascal
CO_2	Carbon di oxide
KNm/kg	Kilo newton meter/kilogram
UPV	Ultrasonic pulse velocity
RCPT	Rapid chloride penetration test
w/b	Water cement ratio
ASTM	American Society for Testing and Materials
AC	Air curing
FWC	Full water curing
PWC	Initial water curing
SEM	Scanning electron microscopic image
RM/kg	Ringgit per kg
CO_2-e	Carbon di oxide emission
$mm/\sqrt{min}$	Millimeter per minute$^{0.5}$
µm	Micro meter
OPC	Ordinary Portland cement
RHA	Rice husk ash

CHAPTER 1: INTRODUCTION

1.1 Background of the Study

Concrete is one the most versatile construction materials used in every part of the globe after water. The demand of concrete is increasing enormously with the passage of time. It is predicted that the demand of concrete will be 18 billion ton by the year 2050 (Povindar Kumar Mehta, Monteiro, & Education, 2006). Conversely the consumption of natural aggregate for concrete production is reported to be about 8-12 billion ton per year since 2010 (Loh, 2000). Moreover, the use of conventional binder, namely ordinary Portland cement (OPC) releases a huge amount of CO_2 during the manufacture process and results in the emission of large amount of greenhouse gases. It was reported that in near future the production of OPC will cause 10% of total anthropogenic CO_2 emissions throughout the world (H. F. Taylor, 1997) and the level of CO_2 may increase in the range of 380 ppm to 800 ppm by the end of the century (Bazant & Kaplan, 1996). Therefore, there has been a lot of research work carried out by researchers as explained below to investigate the possibility of utilizing alternate binders for cement and other industrial waste materials as coarse and fine aggregates to replace the conventional aggregates.

One of the research emphases is on the utilization of industrial and agricultural waste materials as alternative concrete materials. Many researchers in developed and under developed countries such as North America, Indonesia, Nigeria and Malaysia involved in research works to utilize locally available industrial and agricultural waste materials in an effective way. One of the significant research contributions from researchers in Malaysia, Indonesia and Nigeria has been the utilization of palm oil industrial wastes as construction material (Alengaram, Al Muhit, & bin Jumaat, 2013). Also some of these countries have been engrained with profitable plants, such as coconut, tea, sugar can, rubber, paddy, cocoa and oil palm and the wastes generated could be utilized in the development of construction materials (Kanadasan & Razak, 2015). Presently, Malaysia is one of the leading exporting countries of palm oil. In 2011, it was reported 5 million hectares area of land was used for oil palm plantation (Alengaram et al., 2013; Davidovits, 1999). This resulted enormous production of by-products such as empty fruit branches, fibers and oil palm shells (OPS), palm oil fuel ash (POFA) throughout the palm oil processing periods (Kanadasan & Razak, 2014). As such, a new window of prospect has opened up to utilize waste materials from the palm oil industry, namely POFA and OPS and as replacement materials for conventional OPC and crushed granite aggregate in the production of concrete.

The wastage from palm oil industries such as empty fruit bunches, fibres and nutshells are burnt at temperature 800-1000ºC as fuels to generate electricity in palm oil mills. One of the by-products from the burning process is ash which is 5% by weight of the residues, called POFA. In 2007, around 3 million tons of POFA was produced in Malaysia as reported by Malaysia Palm Oil Board (Johari, Zeyad, Bunnori, & Ariffin, 2012; MPO Board, 2012). This huge amount of POFA is disposed each year as waste with limited utilization in landfills and this could lead to health related issues at later stage, environmental problems and also financial loss. Similarly, the waste generated in the form of OPS also causes environmental issues. Malaysian government is providing large amount of financial aid in research to utilize these waste materials in an effective way. OPS as replacement of coarse aggregate has been used in manufacture of structural lightweight concrete and most researchers have shown that for oil palm shell concrete (OPSC), the 28-day cube compressive strength 35 MPa or more is possible (U. Alengaram, M. Jumaat, & H. Mahmud, 2008; Basri, Mannan, & Zain, 1999; Okafor, 1988). Yew et al., developed OPSC with a 28-day compressive strength of about 49 MPa by using heat treatment techniques on OPS aggregates (Yew, Mahmud, Ang, & Yew, 2014). OPSC can be considered as environment friendly concrete as it may reduce the demand for the conventional natural and non-renewable materials like stone and gravel and also simultaneously pave way to utilize waste materials such as OPS as coarse aggregate. Following the previous research works, fractional replacement of OPC with pozzolanic materials such as fly ash and slag was also done to develop the ultimate strength and durability of concrete (Ranjbar, Mehrali, Behnia, Alengaram, & Jumaat, 2014). The higher permeability resistance of denser concrete was accomplished because of the pore refinement provided by the pozzolanic reaction of these materials (Massazza, 1993; Povindar Kumar Mehta et al., 2006). The original size of the POFA is not appropriate to use as cement replacement because of large particle size which may weaken the microstructure (Mo, Alengaram, Visintin, Goh, & Jumaat, 2015; Tangchirapat, Saeting, Jaturapitakkul, Kiattikomol, & Siripanichgorn, 2007). Hence ground POFA has been used as the cement replacement as it increases the reactivity due to pozzolanic materials and also acts as the filling agent in cementitious composites (Islam, Alengaram, Jumaat, & Bashar, 2014). Various POFA contents were suggested to be used in concrete by previous researchers (Aldahdooh, Bunnori, & Johari, 2014; Lim, Tan, Lim, & Lee, 2013; Tangchirapat & Jaturapitakkul, 2010) but generally POFA was used up to 20percent replacement level for OPC.

As a pozzolanic material, the silicon di oxide content in POFA reacts with calcium hydroxide (CH) released from the hydration of OPC and produces more calcium silicate hydrate (C-S-H) which is a gel compound as well as reducing the amount of CH. The later age compressive strength could be improved by up to 90% associating to the conventional concrete when the POFA was used in normal weight concrete (NWC) as partial substitution of OPC (Tangchirapat & Jaturapitakkul, 2010). Alternatively, it has been established that the use of other pozzolanic materials like fly ash, ground granulated blast furnace slag and silica fume as partial substitution of OPC not only increases the ultimate strength but also considerably improves the durability (Mo, Alengaram, & Jumaat, 2014; Sivasundaram, Carette, & Malhotra, 1990). Recently the fineness of POFA has been studied by some researchers on the pore size distribution and microstructure of cement paste (Ranjbar, Mehrali, Alengaram, Metselaar, & Jumaat, 2014).

The use of industrial by-products as cement replacement materials such as slag and fly ash (Perraki, Kakali, & Kontoleon, 2003; Shafigh, Johnson Alengaram, Mahmud, & Jumaat, 2013; Tay, 1990) was trialed in OPSC previously. As detailed above, there had been research works on the POFA as pozzolanic material in NWC; however, the use of POFA as cement replacement material in the development of lightweight concrete with another palm oil industrial waste, OPS as lightweight aggregate for whole replacement of conventional crushed granite or normal weight aggregate hasn’t been explored. This is crucial in view of vastly available local waste materials from the palm oil industry which could be re-used in the production of lightweight concrete for environmental and financial advantages Therefore, this study underlines the investigation of the effects of POFA as partial cement replacement of up to 25% for mechanical properties and for durability properties the replacement was made up to 70%.

1.2 Objectives

The main objectives of this research works are:

a) To investigate the fresh concrete properties of POFA based OPSC at lower replacement levels of POFA in the range of 5 to 25% for OPC.

b) To evaluate the mechanical properties of concrete mixes for lower replacement of OPC by POFA in OPSC.

c) To analyse the advantage of POFA based OPSC with respect to efficiency factor, cost analysis and emission of CO_2 for the replacement levels of POFA in the range of 5 to 25% for OPC.

d) To assess the durability properties of different concrete mixes for higher POFA content levels varying between 10 to 70% in OPSC.

1.3 Outline of the study

This dissertation comprises five chapters. The contents of each chapter are described briefly here:

CHAPTER 1: This is the introduction chapter, gives the brief overview on the necessity of alternative construction materials, the opportunity to use the agricultural and industrial waste materials as alternate construction materials and environmental aspect. Backgrounds of the study, problems and the objectives of this study have been discussed in this chapter.

CHAPTER 2: This is the literature review chapter and in this chapter the present work, which have been done in this field have been highlighted. The literature review of this study has been focused on use the palm oil industrial waste like Oil Palm Shell (OPS) and POFA as construction materials. Then the recent achievements on various concrete mix have been discussed throughout this chapter. Finally, some works related to mechanical and durability properties are discussed.

CHAPTER 3: Methodology chapter contains main three parts. In this chapter, the collection and process of materials, methodology and concrete mix were described separately for the objectives of the dissertations.

CHAPTER 4: This is the result and discussion chapter. Where, firstly, fresh concrete properties are evaluated. Then the mechanical and durability properties were done and the data were taken from the experiment. Finally, the mathematical and graphical presentation was made to compare the data/result with experimental works of the previous research work.

CHAPTER 5: Conclusions and suggestions chapter. In this chapter the main outcome of the dissertation has been given very precisely.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter brands acquaintance with the palm oil industrial wastes like oil palm shell (OPS) and palm oil fuel ash (POFA) as construction materials. The previous research works on these two materials as construction materials are illustrated, especially on the evaluation of concrete mechanical properties and as well as durability properties of concrete. The opportunity with these alternate construction materials and the research gap are being described in specifics.

2.2 General

The higher demands of concrete for infrastructures and housing has contributed to augmentation of cement production as one of the main ingredients of concrete manufacture. It has been reported that the production of cement will increase about 2.1% by every year within the year of 2005 to 2030 which will be about 1.7 times higher than in 2005 because of continuous civilization and development in countries (Malhotra, 2002). It has been acknowledged that the manufacture of ordinary Portland cement (OPC) has a enormous environmental affect because of the huge quantity of greenhouse gas freed to the atmosphere (Kupaei, Alengaram, Jumaat, & Nikraz, 2013). The manufacture of one ton of OPC results the release of one ton of CO_2 into the air. Thus, the release of carbon di oxide from the manufacture of OPC is about 13,500 million tons annually which is responsible for 7% of the carbon di oxide release throughout the world (Malhotra, 2002). It was found that the production of one ton of OPC usually necessitates about 1.5 tons of natural materials like sand and limestone and it also consumes a lot of energy which is about 1700–1800 MJ (H. F. Taylor, 1997). Therefore, there has been a great number of research works performed by researchers to investigate the possibility of utilizing alternate cement substituting materials. Following the previous research work, the most effective resolution is to replace big portion of OPC with agricultural and industrial by-product like fly ash (P Kumar Mehta, 2004), silica fume (P Kumar Mehta, 2004), ground granulated blast-furnace slag (Oner & Akyuz, 2007; Wang, Yang, Liu, Wan, & Pu, 2012), disposed fly ash, salvaged glass powder (Kou & Xing, 2012), and rice husk ash (Van Tuan, Ye, Van Breugel, Fraaij, & Dai Bui, 2011) as supplementary cementitious materials.

2.3 Cementitious materials

The cementitious materials of today were among the chief cementitious components of concretes produced many centuries ago. Commonly termed “pozzolans,” these materials are capable of forming a durable binder. According to ASTM C125-11b, the pozzolan is an aluminous and siliceous material which does not possess a slight or nil cementitious properties but when it comes to the contact with moisture, it starts to react with $Ca(OH)_2$ chemically at normal temperature and tends to have the properties of cemetitious materials. These characteristics make pozzolans ideal additions to portland-cement concrete mixtures. They are composed of similar materials and react with the products of hydrating cement to create additional cementitious binder. **Figure 2.1** shows the physical appearance of the cementitious materials like fly ash, silica fume, ground granulated blast-furnace slag and natural pozzolans.

Figure 2.1: Cementitious materials. From left to right, fly ash (Class C), metakaolin (calcined clay), silica fume, fly ash (Class F), slag, and calcined shale

Slags and pozzolans are normally categorized as supplementary cementitious materials. **Table 2.1** lists the valid disclaim of these materials requirement.

Table 2.1: Specifications and Classes of Supplementary Cementitious Materials (Papadakis & Tsimas, 2002)

- Ground granulated iron blast-furnace slags—ASTM C 989 (AASHTO M 302)
  - Grade 80
    Slags with a low activity index
  - Grade 100
    Slags with a moderate activity index
  - Grade 120
    Slags with a high activity index
- Fly ash and natural pozzolans—ASTM C 618 (AASHTO M 295)
  - Class N
    - Raw or calcined natural pozzolans including:
    - Diatomaceous earths
    - Opaline cherts and shales
    - Tuffs and volcanic ashes or pumicites
    - Calcined clays, including metakaolin, and shales
  - Class F
    - Fly ash with pozzolanic properties
  - Class C
    - Fly ash with pozzolanic and cementitious properties
- Silica fume—ASTM C 1240

Last few centuries, natural pozzolans were used as cementing materials. The term “pozzolan” derives from a volcanic ash mined at Pozzuoli, a village near Naples, Italy, following the 79 AD eruption of Mount Vesuvius. The volcanic ash and calcined clay dates were used back in 2000 BC and in other cultures. A lot of pozzolan concrete structures can still be found which were built by Greek, Egyptian, Roman and Indian, proving the durability performance of these pozzolan concrete structures.

Ricehusk, metakaolin, calcined clay and calcined shale are heat treated in a kiln and then ground to fine powder from which the most common natural pozzolans are produced through processing. These natural pozzolans can be used up to 15% to 35% as replacement of cement to improve the resistance for permeability, sulphate attack and control alkali-silica reactivity. **Table 2.1** shows the natural pozzolans classification identified as Class N pozzolans which are classified by ASTM C 618 (AASHTO M 295). On the other hand a review has been given by ACI 232 (2000) for natural pozzolans. Recently, one of the pozzolanic materials POFA has been used as very effective cementitious materials. In this research work, the production of POFA and its pozzolanic activities are discussed below.

2.3.1 Palm oil fuel ash (POFA)

2.3.1.1 Production of POFA

The wastage produced from palm oil industries such as empty nutshells, fibers and fruit branches are burnt at a higher temperature of about 800-1000 ° C to produce electricity in oil palm mills. One of the by-products from the burning process is ash which is 5% of the mass of the residues, named as POFA.

Approximately, 3 million tons of POFA was generated in Malaysia in 2007 which was informed by Malaysian palm oil board (MPO Board, 2012). With the increase of POFA production, the usage of this waste material is limited and on the other hand, the disposal of this waste material in landfills is non profitable. It causes the environmental problem, financial loss and health hazard.

2.3.1.2 POFA as Pozzolanic Material

Pozzolans are enriched in aluminous and siliceous material which possesses itself small or nill cementitious properties but in finely divided form and with water and calcium hydroxide intends to chemical reaction which form the properties of cementitious materials. As POFA is high in silica content which ultimately refers to one of the effective pozzolanic materials.

Pozzolans (trass) are natural rocks (e.g. tuff) of volcanic origin and composed of silica and alumina oxides but almost no lime. Therefore, they cannot develop hydraulic properties in the absence of hydrated lime. Hydrated lime or material that can release it during its hydration (e.g. Portland cement) is then required to activate the natural pozzolans as a binding material. The natural pozzolans activity can be determined by the reactive silica content, is also closely controlled by its specific surface area, chemical and mineralogical composition. Reactive silica is readily dissolved in the matrix as calcium hydroxide becomes available while the hydration process going on. The additional C-S-H is formed by this pozzolanic reaction. Simply, the pozzolanic reaction can be represented as follows:

$$Ca(OH)_2 + H_4SiO_4 \rightarrow Ca^{2+} + H_2SiO_4^{2-} + 2\ H_2O \rightarrow CaH_2SiO_4 \cdot 2\ H_2O$$

or can be summarized as follows:

$$CH + SH \rightarrow C\text{-}S\text{-}H$$

There are many pozzolans which have alumina, react with $Ca(OH)_2$ and water to produce C_3AH_6, C_4AH_{13} or in arrangement with silica C_2ASH_8 or hydro garnet. Natural pozzolans with a high content of $SiO_2 + Al_2O_3$ (≥80%) but a low content of MgO and SO_3 generally exhibit a high pozzolanic activity.

It has been reported that the original size of the POFA cannot be used directly as cement replacement material due to having large particle size with structural pores which causes the weakness of the microstructure (Tangchirapat et al., 2007; Tay & Show, 1995) and because of that most of the previous researcher processed POFA to ground condition for obtaining better performance (A. A. Awal & Hussin, 1997; Kroehong, Sinsiri, Jaturapitakkul, & Chindaprasirt, 2011). This was done as the higher fineness of the minerals could contribute to increase the filling and reactivity action of POFA in cementitious composites (Isaia, GASTALDInI, & Moraes, 2003).

2.4 Lightweight aggregates

Most of the lightweight aggregates can be defined as raw materials from minerals; the rest of are synthetic products (Mason 1994). Lightweight aggregates can be normally categorized as four groups:

1. Manufactured structural lightweight aggregates—prepared by pyroprocessing shale, clay, or slate in rotary kilns or on traveling grate sintering machines.
2. Natural lightweight aggregate materials—prepared by crushing and sizing natural rock materials such as pumice, scoria, tuff, breccia, and volcanic cinders.
3. Manufactured insulating ultra-lightweight aggregates— prepared by pyro processing ground vermiculite and perlite (Kogel, 2006).
4. By-product lightweight aggregates—prepared by crushing and sizing foamed and granulated slag, organic cinders, and coke breeze. Other by-product lightweight aggregates in use include coal combustion by-products (fly ash and bottom ash), flue gas desulfurization by-products resulting from manufacturing processes, or other waste products.

There are lots of aggregates which has been used as lightweight aggregates and those are Scoria, expanded clay, volcanic cinders, pumice, shale, perlite, air cooled granulated and slate (Domone & Illston, 2010). There are also various agricultural and industrial waste materials, which has been introduced as lightweight aggregates in production of concrete. In Malaysia, palm oil industrial waste like oil palm shell has been used as the replacement of conventional coarse aggregates. In this research work the production and scope of oil palm shell has been discussed.

2.4.1 Oil Palm Shells (OPS)

In some countries like southeast Asia and Africa, the OPS from industrial waste is recognized as oil palm kernel shells (OPKS) where they have been utilizing this waste material for various research works as lightweight aggregate concrete (LWAC). Basically, OPS is the waste material from oil palm tree after extracting oil from it. OPS is like having hard endocarp which surrounds the palm kernel. **Figure 2.2** shows the crack path pattern. OPS is suitable as lightweight coarse aggregate as it has the varying size of in between 2.36 and 14 mm and also the weight is light comparatively. OPS has been used in floor roofing, road based material and water treatment as granular filter material.

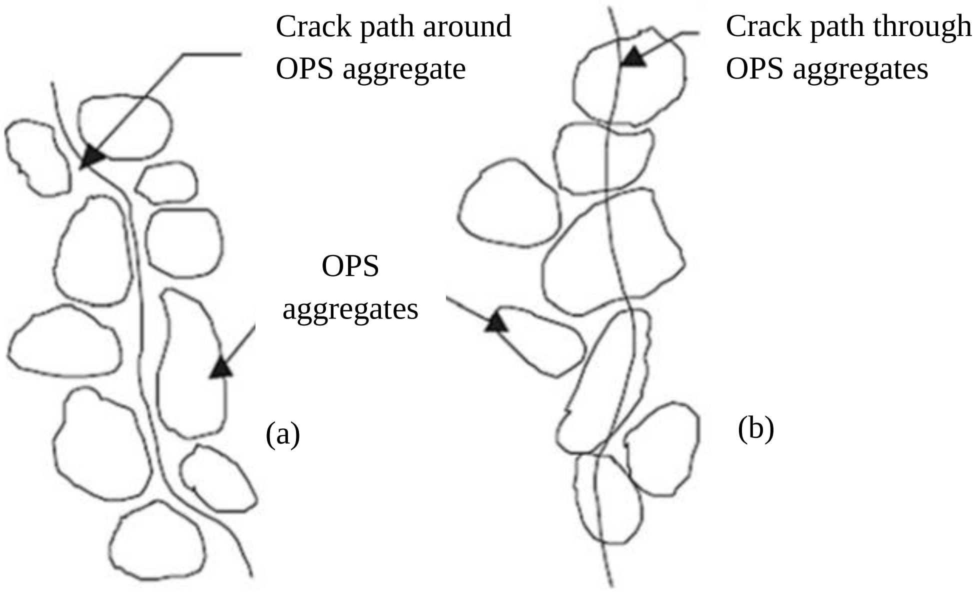

Figure 2.2: Crack paths (a) at earlier ages (b) at later ages (M. Mannan, Alexander, Ganapathy, & Teo, 2006)

It was reported that the highest compressive strength of about 25-30 MPa was achieved from the OPS based concrete (Okafor, 1988). Oil palm shell concrete (OPSC) can be used for different purpose where low to high strength required like infill panels for walls and flooring and pavements which might reduce the cost of concrete (M. Mannan & Ganapathy, 2004). It was found that the OPSC provided higher shear strength in comparison with normal weight concrete where the interlock properties of OPS aggregate helped in improving the shear strength (Jumaat, Alengaram, & Mahmud, 2009). One of the durability properties like water absorption for OPS is about 20%. The methods for producing high strength OPS concrete has been introduced by many researchers for past few decades (Shafigh, Jumaat, & Mahmud, 2011; Shafigh, Jumaat, Mahmud, & Alengaram, 2011; Shafigh, Mahmud, & Jumaat, 2011). They mentioned that processing the OPS to crushed OPS and old OPS, the quality of the OPSC could be improved. The old OPS provides good bond between the cement matrix and OPS as it has no fibre on the surface which results good compressive strength consequently. Again, crushing the old OPS is another technique to improve the OPSC. The crushed OPS has strong bond with cement paste. This strong bond was found due to the reduction in the smooth surface area of OPS and increasing the total surface area because of breaking the large size of OPS. For all the OPS (crushed OPS) lightweight concrete mixtures with normal strength, the highest size of OPS (as coarse aggregate) is 9.5 mm or more while for making high strength OPS concrete this highest size reduces to 8 mm (Shariq, Prasad, & Masood, 2010).

2.5 Fresh concrete property

Workability is one of the fresh concrete properties. Through slump test the workability of the concrete can be measured. ASTM C 143 (143, 2010) recommends that property determining the effort required to manipulate a freshly mixed quantity of concrete with minimum loss of homogeneity. There are some factors like mix proportion, environmental condition and materials on which the workability of the concrete depends on. Normally, aggregates possess 70% volume of total concrete. By selecting proper shape, size and proportion of the aggregates the total specific surface area can be minimized. This important as the void amount and the water requirement of concrete are greatly influenced by the surface texture and shape of the aggregates. Conversely, the roughness, texture and shape of the aggregates influence workability and bond between the mortar and aggregates significantly.

Previous researcher suggested that the slump value should be 50-75 mm structural lightweight concrete which is comparable with the slump value 100-125 mm of normal weight concrete (Povindar Kumar Mehta et al., 2006). The OPSC containing fly ash showed the slump values form 145-240 mm for 0 to 50percent replacement of cement (Shafigh, Alengaram, Mahmud, & Jumaat, 2013). But for only OPSC without any partial replacement of OPC the slump values ranged 55-230 mm (Shafigh, Jumaat, Mahmud, et al., 2011). It was found that fresh OPSC showed slightly better workability than NWC. This might be due to the smooth surface of the OPS (M. Mannan & Ganapathy, 2004). However, another research showed that in case of partial replacement of cement with POFA, the slump value might vary 30-90 mm (Tangchirapat & Jaturapitakkul, 2010).

2.6 Hardened concrete Properties

2.6.1 Compressive strength

In the study of strength of materials, the compressive strength is the capacity of a material or structure to withstand loads tending to reduce size. It can be measured by plotting applied force against deformation in a testing machine. Some materials fracture at their compressive strength limit; others deform irreversibly, so a given amount of deformation may be considered as the limit for compressive load. Compressive strength is a key value for design of structure.

When a specimen of material is loaded in such a way that it extends it is said to be in tension. On the other hand if the material compresses and shortens it is said to be in compression. On an atomic level, the molecules or atoms are forced apart when in tension whereas in compression they are forced together. Since atoms in solids always try to find an equilibrium position, and distance between other atoms, forces arise throughout the entire material which oppose both tension and compression. The phenomena prevailing on an atomic level are therefore similar.

The "strain" is the relative change in length under applied stress; positive strain characterizes an object under tension load which tends to lengthen it, and a compressive stress that shortens an object gives negative strain. Tension tends to pull small sideways deflections back into alignment, while compression tends to amplify such deflection into buckling. However, Compressive strength is measured on materials, components (Urbanik, Lee, & Johnson, 2006) and structures (Ritter, 1990).

By definition, the ultimate compressive strength of a material is that value of uniaxial compressive stress reached when the material fails completely. The compressive strength is usually obtained experimentally by means of a compressive test. The apparatus used for this experiment is the same as that used in a tensile test. However, rather than applying a uniaxial tensile load, a uniaxial compressive load is applied. As can be imagined, the specimen (usually cylindrical) is shortened as well as spread laterally. A stress–strain curve is plotted by the instrument and would look similar to the following **Figure 2.3.**

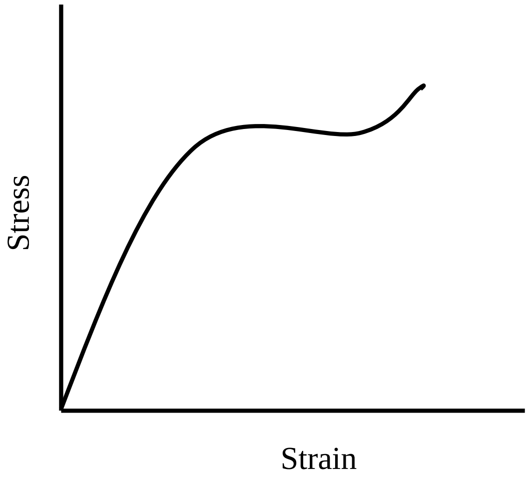

Figure 2.3: True Stress-Strain curve for a typical specimen

Previously, different materials were used in concrete and their compressive strength was investigated in aspect of developing structural concrete design. In this research work, the compressive strength of palm oil industrial solid waste has been focused on. When the POFA was used as filler materials in lightweight foamed concrete, the compressive strength was about 5.2-5.6 MPa for 28-day curing(Lim et al., 2013). They recommended the compressive strength could be improved when POFA was used as 10-20% of filler material. In another research work (Islam et al., 2014) POFA was used at optimum amount in producing geo-polymer mortar. They found compressive strength 18 MPa at 28-day when 100% POFA was used with Ground-granulated blast-furnace slag (GGBS) and for 30% and 40% POFA content in GGBS, the compressive strength was 66 and 60 MPa, respectively. Conversely, another study showed that for structural lightweight concrete (SLWC), one of the cementitious materials POFA helped in accelerating the strength and the strength was found 70 MPa and 72 MPa at 3-day and 28-day, respectively for the base material to improve the strength of high alkaline activated concrete, (Yusuf, Johari, Ahmad, & Maslehuddin, 2014). Again in another research work it was showed that the compressive strength was about 45-75 MPa for the ultrafine POFA when it was replaced with OPC about 10-30% along with nano-silica at 28-day (Noorvand, Ali, Demirboga, Noorvand, & Farzadnia, 2013). Compressive strength varied 31 to 33 MPa for 10-30percent replacement of OPC in conventional concrete by POFA (Tangchirapat & Jaturapitakkul, 2010). Olanipekun & Olusola (Olanipekun, Olusola, & Ata, 2006) replaced conventional aggregate 0-100% by OPS in NWC and found the strength 15-35 MPa at 28-day, respectively. They showed that compressive strength of OPSC reduced with the increased amount of OPS. But when the old large OPS crushed in to small portion it accelerated in developing the compressive strength. Payam et. al. reported that by crushing the old large OPS, the compressive strength could be developed up to 53 MPa for 28-day (Shafigh, Jumaat, Mahmud, et al., 2011). They reported that without including any cementitious materials the production of the 30 grade OPSC is possible. The effect of curing condition on OPS concrete was also investigated. It was reported that the compressive strength of the concrete is much more influenced by the movement of the moisture rather than the water content inside the concrete (Fauzi, 1995).

2.6.2 Splitting tensile and Flexural strengths

Tensile strength is one of the basic and important properties of the concrete. The concrete is not usually expected to resist the direct tension because of its low tensile strength and brittle nature. However, the determination of tensile strength of concrete is necessary to determine the load at which the concrete members may crack. The cracking is a form of tension failure.

Tensile strength is important for plain concrete structures such as dam under earthquake excitations. Other structures for example pavement slabs and airfield runways, which are designed based on bending strength, are subjected to tensile stresses. Therefore, in the design of these structures, tensile strength is more important than compressive strength (Xu & Shi, 2009; Zain, Mahmud, Ilham, & Faizal, 2002).

Generally, the splitting tensile strength can be established from compressive strength. National building codes propose various formulas for the splitting tensile strength and compressive strength. Various relationships for concrete were given in **Table 2.2.**

Table 2.2: National building code to evaluate splitting tensile strength from compressive strength (Yan, Xu, Shen, & Liu, 2013)

Code	**Equations**
CEB-FIP (1991)	$f_{spt} = 0.3\ f_c{}^{2/3}$
ACI363-92 (1992)	$f_{spt} = 0.59\ f_c{}^{1/2}$
ACI318-98 (1999)	$f_{spt} = 0.56\ f_c{}^{1/2}$

Where f_{spt} and f_c are expressed in MPa. Where f_{spt} = concrete splitting tensile strength and f_c = concrete compressive strength

Flexural strength is one measure of the tensile strength of concrete. It is a measure of an unreinforced concrete beam or slab to resist failure in bending. It is measured by loading 6 x 6 inch (150 x 150-mm) concrete beams with a span length at least three times the depth. The flexural strength is expressed as Modulus of Rupture (MR) in psi (MPa) and is determined by standard test methods ASTM C 78 (third-point loading) or ASTM C 293 (center-point loading).

Flexural Strength of Concrete Flexural MR is about 10 to 20 percent of compressive strength depending on the type, size and volume of coarse aggregate used (Lamond & Pielert, 2006). However, the best correlation for specific materials is obtained by laboratory tests for given materials and mix design. The MR determined by third-point loading is lower than the MR determined by center-point loading, sometimes by as much as 15%.

Designers of pavements use a theory based on flexural strength. Therefore, laboratory mix design based on flexural strength tests may be required, or a cementitious material content may be selected from past experience to obtain the needed design MR. Some also use MR for field control and acceptance of pavements. Very few use flexural testing for structural concrete. Agencies not using flexural strength for field control generally find the use of compressive strength convenient and reliable to judge the quality of the concrete as delivered.

Previously, the concrete from OPS and POFA was investigated for flexural strength and splitting tensile strength. It was found that OPS concrete with pozzolanic material like fly ash exhibited 20% lesser splitting tensile strength than OPSC without fly ash (Shafigh, Alengaram, et al., 2013) and minimum splitting tensile strength 2 MPa was found for the OPSC where fly ash was used for 50percent replacement of OPC which is applicable for the structural concrete members.

It was observed that flexural strength to splitting tensile strength as well as compressive strength ratio for OPSC is within the range of NWC whether pozzolanic material fly ash is used or not. Nevertheless for flexural strength, it was found 1.80 MPa and 1.83 MPa for 10-20% POFA content, respectively, at 28-day. In comparison between OPSC and NWC, for OPSC, the splitting tensile strength is about 6% of the compressive strength and for NWC, the splitting strength is about 8% of the compressive strength (Mahmud, 2010). In another study (Shafigh, Jumaat, Mahmud, & Hamid, 2012), for crushed OPS, the splitting tensile strength was found 7-8% of its compressive strength whereas for the NWC, this was 8-14% (S. H. Kosmatka, Panarese, & Association, 2002). They also reported that the flexural strength for OPSC varied from 4.5-7 MPa at 28-day (Mahmud, 2008; M. A. Mannan & Ganapathy, 2002; Okpala, 1990; D. C. Teo, Mannan, & Kurian, 2006) and the other researchers showed that the flexural strength of OPSC were in range of 2.14-4.95 MPa.

2.6.3 Modulus of elasticity (MOE)

The modulus of elasticity of concrete is a function of the modulus of elasticity of the aggregates and the cement matrix and their relative proportions. The modulus of elasticity of concrete is relatively constant at low stress levels but starts decreasing at higher stress levels as matrix cracking develops. The elastic modulus of the hardened paste may be in the order of 10-30 GPa and aggregates about 45 to 85 GPa. The concrete composite is then in the range of 30 to 50 GPa.

Following the previous research work, the MOE values of ground POFA based concretes varied within the range of 25.0–28.0 GPa at 28 days for the replacement of 10-30% ofOPC where the NWC showed 27.5 GPa (Tangchirapat & Jaturapitakkul, 2010). ACI 318 (Committee, 1995) reported that for the ground POFA based concrete, the MOE values increased with the increment of compressive strength which was approximately 7% higher than that of expected. Similar trend of results were found for the concrete with silica fume and fly ash (Luther & Hansen, 1989; Nassif, Najm, & Suksawang, 2005).

They observed that the MOE of concrete is more likely dependent on the aggregates strength rather than the strength of the paste.

The MOE values of OPSC is within the range of 5 - 11 GPa when the compressive strength was within the range of 24 - 37 MPa (Mahmud, 2008; M. Mannan, Basri, Zain, & Islam, 2002; D. C. Teo et al., 2006). Usually, the volume of components and stiffness were the primary factors to affect the MOE values of concrete (Gao, Sun, & Morino, 1997). It was found that the MOE of NWC was 25-50% higher than the LWAC when the strength for the both type of concrete was same (Neville, 1981). This might be due to the having higher modulus of the normal aggregates in comparison with lightweight aggregates (Holm & Bremner, 2000).

For example, the MOE of shale aggregates and expanded clay mainly from 5 to 15 GPa, however, the but this value for dense natural aggregates such as quartz, limestone and basalt is about 60, 80 and 100 GPa, respectively (Chandra & Berntsson, 2002). Wilson and Malhotra (Wilson & Malhotra, 1988) reported that the MOE of LWC made with expanded shale lightweight aggregate ranges from 23.8 to 27 GPa, for compressive strength range of 33.6 - 60.8 MPa. Another study mentioned that the MOE values of SLWAC varied within the range of 10-24 GPa which is normally lower than normal aggregate concrete (Chandra & Berntsson, 2002).

2.7 Durability properties

2.7.1 Water absorption and Sorptivity

Water absorption can be defined as the amount of water absorbed by a composite material when immersed in water for a stipulated period of time. Water absorption can be determined by the ratio of the weight of water absorbed by a material, to the weight of the dry materials. All organic polymeric materials will absorb moisture to some extent resulting in swelling, dissolving, leaching, plasticizing and/or hydrolysing, events which can result in discoloration, embrittlement, loss of mechanical and electrical properties, lower resistance to heat and weathering and stress cracking.

The sorptivity is commonly used in determining porous and soils construction materials such as stone, brick and concrete. It is an directory of water transport into specimens and recently, Sorptivity has been also considered as an vital index for durability of concrete

(Dias, 2000). During sorptivity process, the driving force for water ingress into concrete is capillary suction within the pore spaces of concrete, and not a pressure head (Hall, 1989). A detailed categorisation of concrete pore structure can be investigated by many types of techniques, but the progressive methods are cumbersome and are neither available nor useful for daily concrete practice (De Schutter & Audenaert, 2004). Sorptivity testing is also more representative of typical field conditions. Some experts have suggested that the method can also be used to measure the total pore volume of capillary and gel pores in the concrete (Mohr, 2004). It was reported that Sorptivity is vital to forecast the durability of concrete as an element of structure and to improve concrete's quality (Martys & Ferraris, 1997). The water absorption by immersion is also considered to be a relevant parameter about the performance of concrete. Some experimental results have found that the curing condition affected the capillary permeability considerably (Tasdemir, 2003). Adequate curing is needed to produce the high quality type concrete (Khatri & Sirivivatnanon, 1997).

The word sorptivity was first familiarized in 1957 by John Philip. He introduced Sorptivity as a standard to calculate the capacity the absorb or desorb amount of liquid by capillarity (Philip, 1957). Conversely, C Hall and W D Hoff defined that sorptivity characterizes the tendency of a material for absorption and transferring the water through capillarity (Hall, 1989).

It has been reported that the quality of concrete cannot be measured by water absorption, but generally, most of the good type of concrete has water absorption less than 10% by weight of concrete (Neville, 1981). In case of fully OPS coarse aggregate based concrete, at 28 days, water absorption were 10.65% to 11.23% (D. Teo, Mannan, Kurian, & Ganapathy, 2007). Normally, lightweight concretes possess greater water absorption results in comparison with normal weight concrete (JB Newman, 1993). The value of water absorption varies 3-6% for the SLWC which is produced from expanded polystyrene aggregates (Babu & Babu, 2003). Gu¨ du¨ z and Ug˘ ur (Gündüz & Uğur, 2005) have reported that the higher water absorption rates of 14-22% was found for structure lightweight concrete containing pumice aggregate. Another study (Tangchirapat & Jaturapitakkul, 2010) showed that 10–30% replacement of OPC by POFA in concrete gave a better result in permeability of water, relating to the concrete age and level of cement replacement. The compressive strength increased as the water permeability of ground POFA decreased. Conversely, between the water permeability and the compressive strength, there was good correlation for ground POFA.

2.7.2 Drying shrinkage

Drying shrinkage is defined as the contracting of a hardened concrete mixture due to the loss of capillary water. This shrinkage causes an increase in tensile stress, which may lead to cracking, internal warping, and external deflection, before the concrete is subjected to any kind of loading. All portland cement concrete undergoes drying shrinkage or hydral volume change as the concrete ages (Brooks, 2005). The hydral volume change in concrete is very important to the engineer in the design of a structure (Bazant & L'Hermite, 1988). Basically, Changes of pore water content due to drying or wetting processes cause significant volume changes of concrete in load-free specimens. They are called the shrinkage (typically causing strains between 0.0002 and 0.0005, and in low strength concretes even 0.0012) or swelling (< 0.00005 in normal concretes, < 0.00020 in high strength concretes) mentioned by ACI (209, 1982).

Drying shrinkage depends on some factors. These factors include (Neville, 1981):

a. The characteristics of the components,
b. Amounts of the constituents, mixing manner,

c. Volume of moisture while curing,
d. Dry environment, and member size.
e. Position of the structure and the adjacent temperature.

Concrete cured under normal conditions will undergo some volumetric change (Jirásek & Bazant, 2002). Drying shrinkage happens mostly because of the reduction of capillary water by evaporation and the water in the cement paste. The higher amount of water in the fresh concrete, the greater the drying shrinkage affects (Bazant & L'Hermite, 1988). The shrinkage potential of a particular concrete is influenced by the amount of mixing, the elapsed time after the addition of water, temperature fluctuation, slumping, placement, and curing. The makeup of concrete is also very important. Each aggregate and cement type has distinctive characteristics, each contributing to concrete shrinkage. The amounts of water and admixtures used during mixing also have direct and indirect effects on drying shrinkage of concrete (Troxell, Raphael, & Davis, 1958).

Drying shrinkage test was done for various lightweight materials based concrete. OPSC exhibited higher magnitude of drying shrinkage of an early age with lower w/b but decreases about 35% at 90-day and later on (Shafigh, Ghafari, Mahmud, & Jumaat, 2014). Previous research work (Shafigh, Alengaram, et al., 2013) showed that the use of 10% fly ash in OPS concrete did not affect the drying shrinkage of OPS high strength concrete. However, generally, for higher percent replacement levels (30% and 50%), the drying shrinkage increased but was not significant. The effect of POFA application in concrete on the drying shrinkage performance was examined by a number of researchers. Using the British standards in assessing the drying shrinkage, concretes incorporating unground OPA sieved through a 150 μm sieve exhibited slightly higher drying shrinkage readings in comparison with the control mix (Tay, 1990). An increase in drying shrinkage was observed with increasing POFA replacement levels. Awal and Nguong (A. Awal &

Nguong, 2010) investigated the drying shrinkage of concrete specimens having a 50percent replacement of cement by POFA sieved through a 45 μm sieve. After an initial curing of 7 days in water then exposed to drying shrinkage, cylindrical specimens were used. A detachable mechanical strain gauge with a strain length of 150 mm was used to measure the shrinkage strains on 4 vertical straight gauge lines spaced uniformly around the side-line of the specimen. The average temperature recorded in the laboratory was 27 ± 2 °C and relative humidity RH was 80 ± 5%. Higher drying shrinkage of POFA concretes were observed where at the same age a 21% increase in drying shrinkage was observed by the 50% POFA concrete in comparison with the control mix. The increase in drying shrinkage was attributed to the difference in the rate of moisture loss due to the different porosity and pore size distribution. Concrete mixes with 10%, 20% and 30% of coarse (19.9 μm) and fine (10.1 μm) POFA replacement levels have been studied for their drying shrinkage (Tangchirapat & Jaturapitakkul, 2010). Concrete mixes with a 10–30% replacement of cement by fine POFA (median particle size of 10.1 μm) showed lower drying shrinkage values than those of the OPC control mix. The 30% replacement was shown to be the most effective. The authors attributed this enhancement to the pozzolanic reaction and the packing effect of the fine POFA. These effects contributed in the transformation of large pores into finer pores. This pore refinement decreased the loss of moisture at the stated RH value; hence, reducing the drying shrinkage of fine POFA concretes. Using ASTM C596 in determining the drying shrinkage, the same results were observed with high strength concretes containing fine OPA replacements of 30% (Tangchirapat, Jaturapitakkul, & Chindaprasirt, 2009).

2.7.3 Sulphate attack

Sulphate attack in concrete and mortar can be 'external' or 'internal' (Cohen & Mather, 1991). External: due to penetration of sulphates in solution, in groundwater for example, into the concrete from outside. Internal: due to a soluble source being incorporated into the concrete at the time of mixing, gypsum in the aggregate, for example. This is the more common type and typically occurs where water containing dissolved sulfate penetrates the concrete.

A fairly well-defined reaction front can often be seen in polished sections; ahead of the front the concrete is normal, or near normal (Zuquan, Wei, Yunsheng, Jinyang, & Jianzhong, 2007). Behind the reaction front, the composition and microstructure of the concrete will have changed. These changes may vary in type or severity but commonly include (Ferraris, Stutzman, & Snyder, 2006):

Sulfate attack processes decrease the durability of concrete by changing the chemical nature of the cement paste, and of the mechanical properties of the concrete (Monteiro, Roesler, Kurtis, & Harvey, 2000). The sulphate ion + hydrated calcium aluminate and/or the calcium hydroxide components of hardened cement paste + water = ettringite (calcium sulphoaluminate hydrate)

$$C_3A.Cs.H_{18} + 2CH + 2s + 12H = C_3A.3Cs.H_{32}$$

$$C_3A.CH.H_{18} + 2CH + 3s + 11H = C_3A.3Cs.H_{32}$$

The sulphate ion + hydrated calcium aluminate and/or the calcium hydroxide components of hardened cement paste + water = gypsum (calcium sulphate hydrate).

$$Na_2SO_4 + Ca(OH)_2 + 2H_2O = CaSO_4.2HO + 2NaOH$$

$$MgSO_4 + Ca(OH)_2 + 2H_2O = CaSO_4.2H_2O + Mg(OH)_2$$

The expansion and compressive strength loss of concrete bars containing POFA with varying particle size and different levels of replacements was evaluated by Jaturapitakkul et al. (Jaturapitakkul, Kiattikomol, Tangchirapat, & Saeting, 2007). Concrete bars containing POFA were exposed to 5% magnesium sulphate solution for 24 months. It was found that higher the fineness of POFA used reduced the expansion level of the concrete bars. The use of fine POFA in replacing cement not only decreased the calcium hydroxide content of hydrated cement, but also assists as a filler leading to the reduction of voids between the aggregates and hydration products, leading to a denser concrete. The same findings were obtained when testing for the loss in compressive strength. A 20percent replacement level of cement by fine POFA would have no adverse effect on the expansion and loss in compressive strength of concrete bars in a 5% magnesium sulphate solution (Tangchirapat et al., 2007). Hussin et al. (Hussin, Ismail, Budiea, & Muthusamy, 2009) stated that mortar bars containing 10 μm POFA exhibited lower expansion and loss in compressive strength than both the control mix and mortar bars with 45 μm POFA when immersed in a 10% Na_2SO4 solution for 3 months. This was attributed to the high reactivity of fine OPA causing a lesser amount of calcium hydroxides and more C–H–S gel causing the densification of the matrix making it more resistant to the sulphate attack. Recycled aggregate concretes incorporating fine OPA as cement replacement exhibited lower expansion in comparison to the control and recycled aggregate concrete mixes when immersed in a 5% Na_2SO4 solution (Tangchirapat, Khamklai, & Jaturapitakkul, 2012). This is reasoned to the fact that when cement is replaced, the amount of both $Ca(OH)_2$ and C_3A are reduced in the hardened concrete; thus, reducing gypsum formation and ettringite re-crystallisation. Furthermore, POFA with high fineness is also responsible for the pozzolanic reaction and enhanced the pore structure, resulting in a highly impermeable matrix.

2.7.4 Rapid chloride penetration (RCPT)

The rapid chloride permeability test was originally developed for the Federal Highway Administration (FHWA) by the Portland Cement Association (Whiting, 1981) to provide a rapid test method that correlated well with ponding tests, such as AASHTO T 25902 (T. Zhang & Gjørv, 1994). Ponding tests are considered to be the best method of determining the chloride permeability of concrete, but they take 90 days or more to complete, making them impractical for project quality assurance testing.

Practically, the chloride permeability test is not capable of giving the direct measurement of chloride penetration in depth. Consequently, this becomes difficult to relate the results with the expected service life (Feldman, Chan, Brousseau, & Tumidajski, 1994; C. Shi, J. A. Stegemann, & R. J. Caldwell, 1998). However, ASTM C1202 recommends to maintain some standards which are shown in **Table 2.3** to control the quality and have acceptance for application of testing.

Table 2.3: The penetrability of Chloride ion depending on the amount of passing charge ASTM C 1202-05 (C-05, 2005)

Passage of charge (coulombs)	Penetration of chloride ion
> 4000	High
2000 to 4000	Moderate
1000 to 2000	Low
100 to 1000	Very low
< 100	Negligible

Through many specifications, the passage of charge are provided and a number of values are being used. In case of pozzolanic materials like flu ash and slag, it should be kept in mind that this limits may not valid before 56-day or later age. In that case, running test for chloride penetration at 28-day can be problematic (Hooton, Thomas, & Stanish, 2001). **Figure 2.4** shows the set up for rapid chloride penetration test.

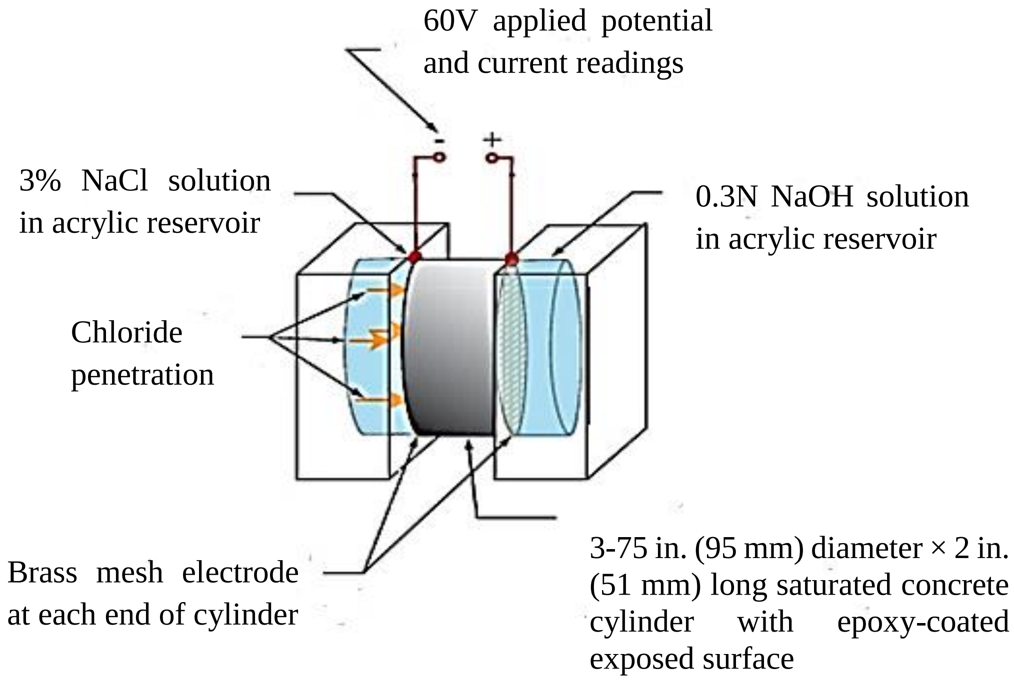

Figure 2.4: Schematic of rapid chloride penetration set up (ASTM C 1202)

The outcomes for the OPC of RCPT test and POFA based concrete were done before (S. O. BAMAGA, Ismail, & Hussin, 2011). With the application of 60V and 6 hours at both ends of the OPC concrete and POFA based concrete specimens, the RCPT values were 731.7 coulombs and 276 coulombs, respectively. It was found that passing charge can be reduced significantly with the 20% replacement of OPC by POFA in comparison with NWC. And with 10% replacement of OPC by silica fume can reduce about 60% of passing charge compare to OPC based concrete (Ahmed, Kayali, & Anderson, 2008). The significant chloride resistance also observed in case of mortar where the OPC was replaced by POFA at 20% for RCPT test (P Chindaprasirt, Homwuttiwong, & Jaturapitakkul, 2007). Previously, it was explained by the researchers that the pozzolanic reaction develops the bonding between aggregates and cement matrix which helped in forming the dense and impermeable concrete (Isaia et al., 2003; Tangchirapat, Jaturapitakkul, & Kiattikomol, 2009; M.-H. Zhang & Malhotra, 1996).

Another research work performed the RCPT test using POFA from three different palm oil mill (S. Bamaga, Hussin, & Ismail, 2013) and they designated them as CAPOFA, ALPOFA and KTPOFA. They reported that with the application of 60V and 6 hours' time period at the both ends of the specimen, the RCPT values were 731.7 coulombs. For ALPOFA, KTPOFA and CAPOFA concretes, the average passing of charge was 380.25, 463.25 and 276.3 coulombs, respectively (Tangchirapat, Jaturapitakkul, & Kiattikomol, 2009).

2.8 Research findings and gap

As reviewed in the literature, several research works were found to deal with the oil palm industrial waste.

1. Previously, one of the oil palm industrial wastes like POFA was used along with ground granulated blast furnace slag to develop the compressive strength of geo-polymer mortar for structural lightweight concrete (Islam et al., 2014).
2. Ultrafine palm oil fuel ash was used as replacement of cement to determine the transport and engineering properties of high strength sustainable concrete (Johari et al., 2012). The ultrafine palm oil fuel ash was obtained by treating with heat to eliminate extra carbon and the particle size of 2 μm was achieved after grounding.
3. Lightweight foamed concrete was produced where POFA was used as cementitious materials to evaluate the properties of fresh and hardened concrete properties(Lim et al., 2013).
4. POFA was used as pozzolanic material where two different fineness (coarser and fine) of POFA was used as replacement of cement to determine the mechanical properties and water absorption properties of concrete(Tangchirapat & Jaturapitakkul, 2010).

5. In another study, 75% ultrafine POFA was used as cement replacement to determine the ultimate tensile and flexural strength for high ultra-performance green concrete (Aldahdooh et al., 2014).

From the evaluation of the previous research works, it was found that POFA was used as cement replacement for various type of concrete. But no research work has been done before to use POFA as cement replacement in oil palm shell concrete (OPSC). Previous research work showed that OPSC could be one of the good concrete properties to use as SLWC and combining one of the palm oil industrial waste materials POFA with OPSC as cement replacement can be environment friendly and cost effective. In this research work, POFA was used as 5% to 70% replacement of cement to determine the fresh concrete properties and harden concrete properties like mechanical and durability properties.

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CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

The methodology section consists of the properties of materials, test method and curing condition details. The collection process, preparation and the properties of the samples are mentioned in this study. Various test for mechanical and durability properties were conducted and their test procedure and standard code of practice are discussed. In this chapter the curing condition and age are focused.

3.2 Materials

3.2.1 Cement

The ordinary Portland cement (OPC) was collected from a local cement company which compressive strength of 7 and 28 days are about 30 and 39 MPa, respectively. The Blaine surface area and specific gravity of the cement were respectively 332 m^2/kg and 3.14 g/cm^3. **Table 3.1** shows the chemical properties of OPC.

3.2.2 Palm Oil Fuel Ash (POFA)

In this research work, the OPC was replaced by POFA at different percentage. The un-processed POFA was collected from a local palm oil mill. The collected POFA was oven dried at 100˚C for 24 hours and then sieved using a 300 µm size sieve to remove coarse particles.

Figure 3.1: OPC and Cementitious material POFA

After that, the POFA was grinded in a rotating drum for 30,000 cycles lasting 16 hours to achieve the targeted fineness (>66%). After grinding, the POFA passing through 45 µm size sieve was collected. The total amount of POFA passing through the 45 µm was 88%. The POFA used had specific gravity and Blaine surface area of 2.1 and 506 m^2/kg, respectively**. Table 3.1** and **Table 3.2** show the chemical and physical properties of POFA, respectively. **Figure 3.1** shows the physical appearance of OPC and POFA.

Table 3.1: Chemical properties of POFA and OPC by using X-ray Fluorescence (XRF) analysis

Chemical composition	Materials	
	POFA (%)	OPC (%)
CaO	4.32	64.1
Al_2O_3	5.49	4.4
MgO	3.71	3.5
SiO_2	63.2	22.8
Na_2O	0.14	0.1
SO_3	0.92	2.6
P_2O_5	3.74	0.2
K_2O	6.37	0.8
TiO_2	0.36	0.2
MnO	0.17	0.8
Fe_2O_3	4.19	1.3
LOI	6.15	1.0

Table 3.2: Physical properties of POFA

Physical Properties	POFA
Blain surface area	506 m^2/kg
Passing 45- μm sieve (%)	88
Specific gravity	2.10
Color	dark

3.2.3 Oil Palm Shells (OPS)

The Crushed OPS from oil palm industry of sizes between 2.36 and 9 mm were used as coarse aggregate. The OPS were soaked 24 hours prior to casting and then air-dried to achieve saturated surface dry condition before used for casting. **Table 3.3** shows the physical properties of OPS. **Figure 3.2** shows the collection of OPS from factory and crushed OPS.

Figure 3.2: OPS collected from palm oil factory (left) and crushed OPS (right)

Table 3.3: Physical properties of OPS

Physical Properties	Crushed OPS
Bulk density (compacted) (kg/m^3)	685
Fineness modulus	5.92
Specific gravity	1.23
Water absorption (30 min) (%)	9.67
Water absorption (24 h) (%)	18.69

3.2.4 Super-plasticizer

A polycarboxylic-ether based super-plasticizer (SP) with a specific gravity of 1.20 was used in this study. The SP was supplied by BASF Sdn Bhd. with a commercial name Glenium Ace 388.

3.2.5 Normal Sand

Normal mining sand was used as fine aggregate in this study with highest grain size, water absorption, specific gravity and fineness modulus of 4.75 mm, 0.81 %, 2.79 and 2.88, respectively.

3.2.6 Water

The laboratory pipeline water was used for all the mixes.

3.3 Mix Proportion

The variable in the mix design of the study is the amount of cement replacement with POFA. The ground POFA was used as partial cement replacement at 0%, 5%, 10%, 15%, 20% and 25 % by mass of binder and their mix design are named as M0, M5, M10, M15, M20 and M25, respectively for mechanical properties. But for durability test, POFA was used as partial cement replacement at 0%, 10%, 30% and 50% for w/b of 0.3 and for w/b of 0.4, 0% and 70% by mass of binder. The mixes are designated as M0, M10, M30, M50 and M02 and M70 for w/b of 0.3 and 0.4, respectively.

In this investigation, a fixed binder, sand, OPS and water contents of 565, 960, 368 and 170 kg/m^3, respectively were used. Super-plasticizer was used at a dosage of 0.6% by mass of binder to facilitate workability. The mix proportions (kg/m^3) are given in **Table 3.4** and **Table 3.5** for mechanical and durability properties, respectively.

Table 3.4: Mixture Proportions of concrete for mechanical properties. (kg/m^3)

Mix No.	Cement	POFA*	Water	Super-plasticizer	Sand	Coarse aggregate (OPS)
M0	565	0	170	3.4	960	368
M5	537	28 (5)	170	3.4	960	368
M10	508	56 (10)	170	3.4	960	368
M15	480	84 (15)	170	3.4	960	368
M20	452	113 (20)	170	3.4	960	368
M25	423	141 (25)	170	3.4	960	368

*values indicate percentages of replacement

Table 3.5: Mixture proportions of concrete for durability properties. (kg/m^3)

w/b	Mix No.	Cement	POFA*	Water	Super-plasticizer	Sand	Coarse aggregate (OPS)
0.3	M0	565	0	170	3.4	960	368
	M10	508	57 (10)	170	3.4	960	368
	M30	395	170 (30)	170	4.9	960	368
	M50	283	282 (50)	170	6.2	960	368
0.4	M02	565	0	170	0	960	368
	M70	170	395 (70)	170	6.2	960	368

*value indicates percentages of replacement

3.4 Mixing Procedure

Both OPS and sand were mixed in a drum mixer for 2 min followed by binder materials (cement and POFA) which was further mixed for 3 minutes. Then, half of the mixing water was added for mixing of 2 minutes followed by the addition of the remaining mixing water and super-plasticizer. The mixing procedure continued for a further 2 minutes before slump test was performed to check the workability of the fresh concrete mix. The concrete specimens were cast in 100-mm cubes, small cylinders of 100-mm diameter × 200-mm height, cylinders of 150-mm diameter ×300-mm height and prisms of 100 × 100 × 500 mm^3 for the determination of the compressive strength splitting tensile strength, modulus of elasticity and flexural strength, respectively. In case of water absorption, rapid chloride penetration and sorptivity test, small cylinders were used from which later 50 mm height and 100 mm diameter size was cut off. For sulphate attack, compressive strength and residual strength 100 mm cube were used. The specimen were de-moulded after 24 hours and cured according to the specified curing regimes.

3.5 Curing regime

In order to determine the influence of different environmental condition on the hardened concrete properties, the concrete specimens were subjected to three different curing regimes, namely air curing (AC), full water curing (FWC) and partial water curing (PWC) for 7-day and then kept in air for the remaining period till tested. In the AC regime, the specimens were stored in the laboratory with a temperature of 31 ± 2˚C and relative humidity of 85% while in the WC regime, the specimens were fully immersed in water curing tank with temperature of 22 ± 1˚C until the day of testing. In the PWC regime, upon de-moulding, the concrete specimens were water cured for 7-day and then removed from the water curing tank and exposed to the laboratory condition similar to the AC regime for a further 21-day for the determination of concrete properties at age of 28-day.

For durability test the samples were kept in the water tank for water curing of the samples up to 28-day and 90-day. After 28- and 90-day of water curing, the samples were extracted from the water tank and then the samples were prepared for the respective test according to the standard test methods. The water tank temperature was 23 ± 1 °C and relative humidity was about 86 ± 1. The normal laboratory air temperature varied 31 ± 2 °C.

3.6 Test method

3.6.1 Fresh concrete properties:

3.6.1.1 Slump

The initial slump was measured in accordance with ASTM C 143 (143, 2010) . **Figure 3.3(a)** shows the measurement of slump value.

3.6.1.2 Vebe second

Vebe second was calculated according to ACI 211.3 (Committee, 1977). **Figure 3.3 (b)** shows the procedure of vebe test.

3.6.1.3 Compaction factor

Compaction factor was done through the compaction factor apparatus. Fresh concrete was put in to the upper hopper and later allowed to fall in to the cylinder freely. Partial compacted concrete weight was measured after levelling the excess portion above cylinder. Then the cylinder was filled with the fresh concrete in to equal four layers for full compaction and weight of fully compacted concrete was measured. **Figure 3.3 (c)** represents the compaction factor test apparatus.

3.6.1.4 Wet density

A measuring bowl was used to determine the wet density. Fresh concrete was filled in to the bowl for equal height of three layers. Each layer was compacted evenly 25 times with tamping rode. Then the mass of bowl and concrete was measured. **Figure 3.3(d)** shows the wet density measuring apparatus.

Figure 3.3: Test apparatus: (a) slump test, (b) vebe test, (c) compaction factor test and (d) wet density

3.6.2 Concrete mechanical properties

The compressive strength test was done in accordance with BS EN 12390-3: 2002 (EN, 2002). The flexural (BS EN 12390-5: 2009) (EN, 2009b), splitting tensile (BS EN 12390-6: 2009) (EN, 2009a) and the modulus of elasticity (ASTM C 469) (Astm, 2001) were done according to the standard code of practice. The UPV test was done on 100 mm cube specimens. A portable ultrasonic non-destructive digital indicating tester with adjoining transducers was used to measure the travelling time for pulse between the ends of specimens. The UPV is calculated by dividing the length of pulse travel with the time measured.

3.6.3 Concrete durability properties

3.6.3.1 Water absorption

The water absorption test was done on a concrete disc specimen of 100 mm ϕ × 50 mm thick, in accordance to ASTM C 642 (C642, 2001), at the ages of 28- and 90-days. The disc specimens were obtained by cutting the 100 mm ϕ × 200 mm height cylindrical specimens that were moist cured. The disc specimen was then oven-dried at 105 ± 5°C for 48 hours until constant mass was achieved. The specimens were then allowed to cool to room temperature before being immersed in water. The specimens were wiped off using cloth to remove any excess water on the surface of the specimen and the weight of the specimens was observed. The weights of the specimens were taken after 30 minutes and 72 hours after immersion for the determination of initial and final water absorptions, respectively. The water absorption was taken as:

Water absorption = $(w_s - w_d) / w_s \times 100\%$

where w_s = saturated surface dry mass (g) of specimen in air (30 minutes and 72 hours), w_d = oven dry mass (g) of specimen in air.

3.6.3.2 Sorptivity

Sorptivity determines the capability of concrete to transmit and absorb water by means capillary suction. Based on the previous research procedure (Liu et al., 2014), the sorptivity test set up is showed in **Figure 3.4**. The sorptivity test was carried out at 28- and 90-days on 100 mm ϕ × 50 mm thick disc specimens. Similar to the water absorption test, the samples were oven dried at a temperature of 105 ± 5˚C for 48 h before the test. After cooling to room temperature, the sides of the specimens were sealed with silicone and placed in a tray such that the bottom surface of the specimens was in contact with water up to a height of 5 mm. The specimens were weighed at intervals of 1, 4, 9, 16, 25, 36, 49 and 64 minutes and the sorptivity was then calculated using the following equation:

$i = A + st^{0.5}$

where i = cumulative volume of water absorbed at time t (mm^3), s = sorptivity coefficient ($mm/min^{0.5}$), A = constant which takes into account effect of initial water filling at concrete surface.

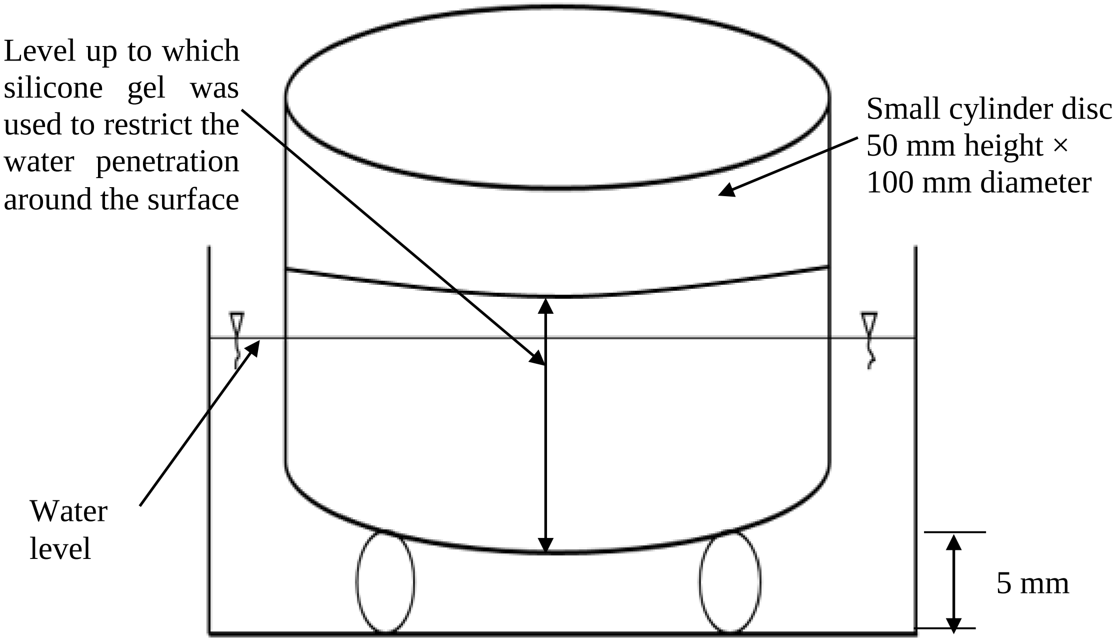


Figure 3.4: Sorptivity test set-up

3.6.3.3 Drying shrinkage

The prisms of dimensions 100 × 100 × 500 mm^3 were moist cured for 28 days prior to the free shrinkage test. The Demountable Mechanical (DEMEC) strain gauge studs were attached on the specimen. The free shrinkage specimens were then kept in a room in which the temperature and humidity were maintained at 31 ± 2˚C and 85 ± 3%, respectively. The observations on the initial position of DEMEC studs were taken using a length comparator. The change in length of the specimens was measured continuously up to 90-day for the determination of the free shrinkage of concrete. **Figure 3.5** shows the drying samples and DEMEC on the samples.

Figure 3.5: Drying samples with DEMEC studs.

3.6.3.4 Sulphate attack

Tests for sulphate resistance are made to study the sulphate resistance of different cements and various combinations of materials. These tests include field exposures under natural conditions and laboratory tests of concrete or mortar specimens exposed to artificial and generally accelerated exposure conditions. The effects are typical of attack by solutions of sodium sulphate or potassium sulphate. Solutions containing magnesium sulphate are generally more aggressive, for the same concentration. This is because magnesium also takes part in the reactions, replacing calcium in the solid phases with the formation of brucite (magnesium hydroxide) and magnesium silicate hydrates. That's why in this research work magnesium sulphate was used to evaluate the sulphate resistance of the specimen.

In this research work, the test for sulphate-induced expansion was done following the procedures described in ASTM C1012 (Patzias, 1987). 100 mm cube specimens were immersed in the solution containing about 5% magnesium sulphate (**Figure 3.6**). Every after 2 weeks the cubes were pulled out of the container and waited another 2 weeks to dry them in normal laboratory room temperature. After drying for 2 weeks, the samples were weighted and compressive strength test was performed for three samples. Again the rest of the samples were immersed in to the replaced new magnesium sulphate solution and the cycle was continued. The compressive strength and weight loss was measured periodically over 3 months. At predetermined intervals, the specimens were tested for compressive strength.

Figure 3.6: Samples in magnesium sulphate solution

3.6.3.5 Rapid chloride penetration test (RCPT)

The RCPT method was carried out in accordance to ASTM C1202 (C. Shi, J. Stegemann, & R. Caldwell, 1998). This test measures the current passing through cement-based materials in 6 h, giving an indication of the concrete resistance to chloride ion penetration. The concrete specimen used for this test was 100 mm diameter × 50 mm thick specimen sliced from middle portion of a 100 mm diameter × 200 mm height cylindrical specimen.

A direct current voltage of 60.0 ± 0.1 V was applied across the two faces and the current passing through the concrete specimen was monitored at 30 min intervals over a period of 6 h. The total charge passed in Coulombs was determined and the rating of the concrete was determined. **Figure 3.7** shows the RCPT set up in accordance with ASTM C1202.

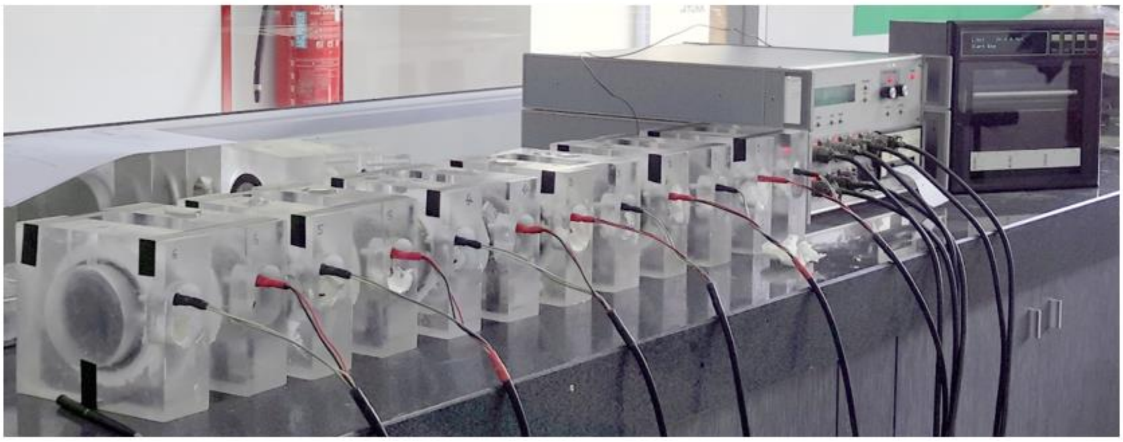


Figure 3.7: RCPT test at the laboratory

CHAPTER 4: RESULT AND DISCUSSION

4.1 Introduction

The chapter performs various calculation and analysis of different parameters of the data found from test. The results of the mechanical properties and durability properties are mentioned and various technical analyses are shown through table and graphical representation. The outcomes of the results are discussed elaborately and technically. Following the previous research work, various test results of this research work are compared and established.

4.2 Fresh concrete properties

As observed in **Figure 4.1**, the M0 mix had slump of 35 mm while the use of POFA at 5% to 25% cement replacement levels increased the slump to between 45-55 mm. Mehta and Monteiro recommended the slump value for structural lightweight concrete of about 50-75 mm which is comparable to the slump value of about 100-125 mm for conventional concrete (Povindar Kumar Mehta et al., 2006). However, the lower slump value of this study could be attributed to high loss of ignition (LOI) of POFA. It increases water demand for POFA based OPSC to get same slump associating with the normal weight concrete (NWC). To maintain the slump, super-plasticizer of 0.6% of cement weight was added. Super-plasticizer was used to reduce the water demand as in this study the water-binder ratio was kept constant at 0.3 and POFA content was increased to 25% as cement replacement. It was observed that when the amount of POFA was increased 5-15% of OPC as replacement, the slump value was found to be increased. This is because of high POFA volume in concrete which could act as a filler material to fill up the voids in the fresh concrete and hence improves the fluidity of the mix. This is commonly associated with other kinds of pozzolanic materials such as rice husk ash and meta-kaolin (Hassan, Lachemi, & Hossain, 2012; Modarres & Hosseini, 2014; Yin, Mahmud, & Shaaban, 2006). However, when POFA content was increased 20% to 25%, the slump value reduced which could be due to increased water demand of the higher POFA content. As the water binder ratio and the supply of super-plasticizer were kept constant, the concrete mixes were physically sticky enough to reduce the slump value.

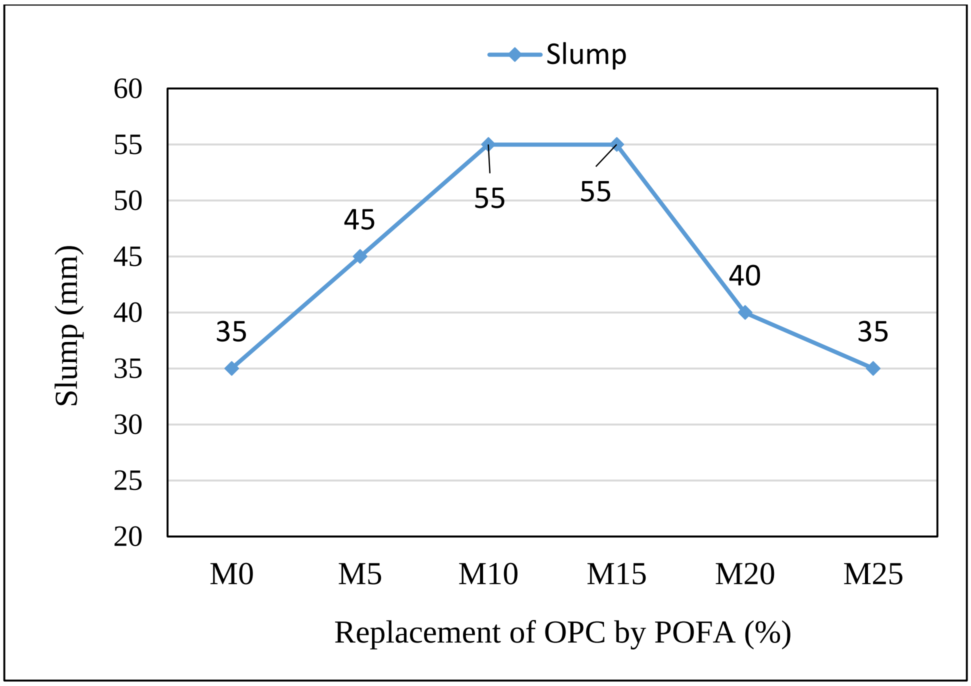


Figure 4.1: The slump values of various POFA based OPSC

The relationship between slump and vebe second was shown in **Figure 4.2**. Highest vebe second 10.92 second was found for the mix M25 with slump 35 mm. All the mixes in this study were in dry to plastic consistency based on the slump and vebe second ratio according to the classification established by Delibes apud Canovas (Katcho et al., 2007). In this study, the vebe second was found to be increased with respect to the increase of POFA content.

The relationship between wet density and compaction factor is shown in **Figure 4.3**. In this study, compaction factor was highest for 5% replacement and got reduced gradually with the increase of POFA content. This may be due to the increase volume of concrete as same mass replacement of OPC was considered with POFA. In case of ground POFA, the particle size and porosity are lower (Sata, Jaturapitakkul, & Kiattikomol, 2004) than the OPC particle which spontaneously contribute to increase the surface area of total concrete. As a result more water was absorbed by the particle to produce POFA based OPSC. At the impact of compaction time, this absorbed water was responsible to reduce the compaction factor. However, the wet density for OPSC without POFA was minimum in comparison with the POFA based other OPSC and the density was also got reduced for continuous adding of POFA in OPSC. This could be attributed to higher water absorption of POFA as the POFA used in this research has higher surface area than cement.

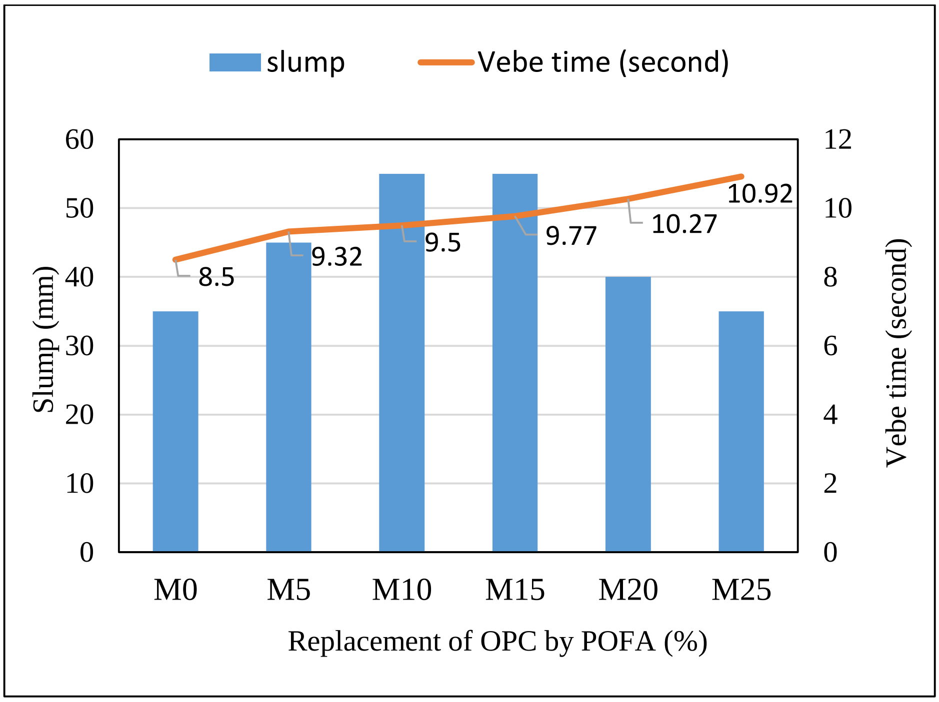


Figure 4.2: Slump vs vebe second for different mix

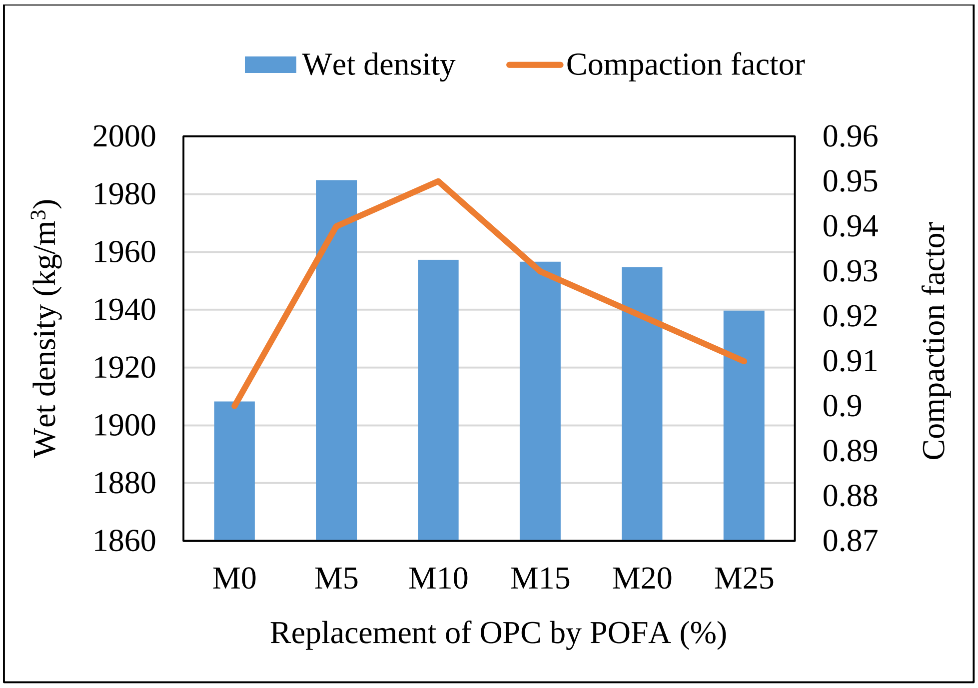


Figure 4.3: Wet density vs compaction factor for various mix

4.3 Hardened concrete properties

4.3.1 Ultrasonic pulse velocity (UPV):

The ultrasonic pulse velocity (UPV) denotes the soundness of concrete and the variation in the structure of concrete due to aging and curing. **Table 4.1** shows the variation of the UPV values with curing age under AC, FWC and PWC curing conditions for all the mixes. Generally, for all mixes and curing regimes, the UPV values increased as the curing age was increased. The range of UPV values obtained was found in the range of 3.40-4.15 km/s at the ages of 1-, 3-, 7- and 28-day for all mixes under AC, FWC and PWC condition. Regardless of the curing condition, at curing age of more than 3-day, all OPSC exhibited good quality based on the UPV value classification (Mindess, Young, & Darwin, 2003).

Table 4.1: UPV values for different mix design under AC, FWC and PWC conditions

Mix	UPV (km/s)							
	1-day	3-day		7-day		28-day		
	AC	AC	FWC	AC	FWC	AC	FWC	PWC
M0	3.65	3.76	3.87	3.83	3.90	3.86	4.06	3.91
M5	3.65	3.79	3.88	3.85	4.03	3.91	4.16	4.02
M10	3.66	3.78	3.83	3.87	3.98	3.91	4.09	3.98
M15	3.55	3.83	3.83	3.90	4.01	3.86	4.13	3.94
M20	3.44	3.72	3.72	3.66	3.85	3.69	3.92	3.82
M25	3.41	3.60	3.64	3.68	3.76	3.73	3.80	3.75

It was found that AC condition produced the lowest UPV among the curing regimes adopted followed by the PWC condition; however, the specimens cured under FWC condition produced the highest UPV values for the OPSC mixes containing POFA. The lower UPV value for the air-cured OPSC could be due to the lack of water for hydration process; this could reduce the production of CH to react with the pozzolanic POFA (Al-Amoudi, 2002). Conversely, when water was available for curing of specimens in PWC and FWC, cement hydration could be developed and facilitated the reaction between CH and POFA to produce additional C-S-H (Çolak, 2003). Consequently, the UPV values were increased as the C-S-H fill up the voids in the concrete due to its densification effect. The UPV values were increased by up to 2% and 7% for the PWC and FWC conditions, respectively.

Figure 4.4 shows the variation of ultrasonic pulse velocity with varying POFA replacement levels under 28-day AC, FWC and PWC conditions. It was shown that in all curing conditions, the 5% POFA replacement level shows improved UPV values while further increase in the POFA content reduced the UPV values. This might be attributed to the increment of pores inside the concrete with the increase of POFA content in OPSC. The interconnected pores inside the concrete provided free space which caused the UPV values to be reduced ultimately.

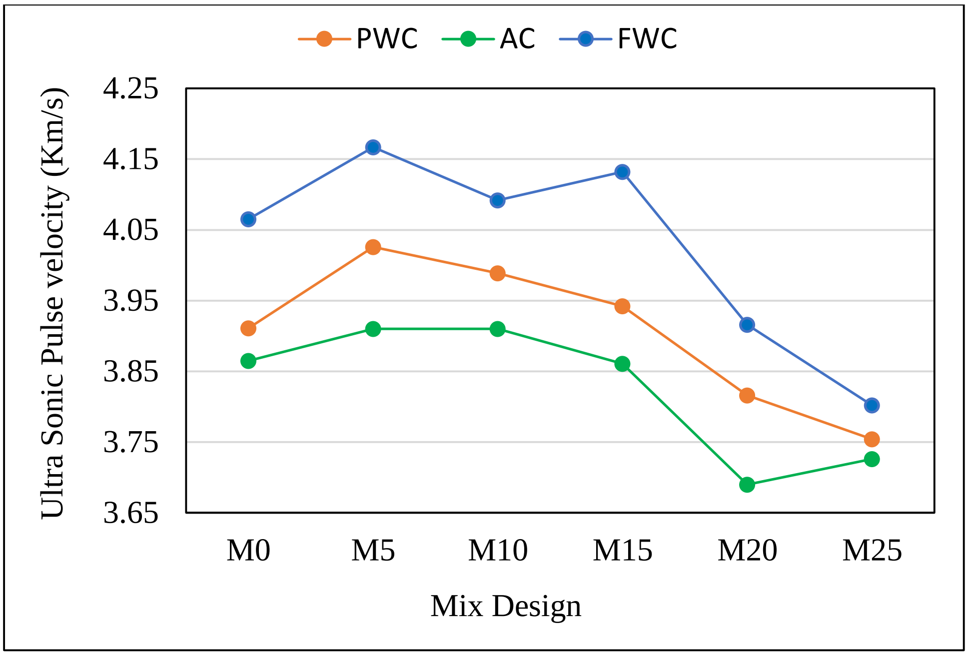


Figure 4.4: Variation of ultrasonic pulse velocity (km/s) with various mixes under 28-day AC, FWC and PWC condition

4.3.2 Compressive Strength:

4.3.2.1 Effect of curing

The 1-, 3-, 7- & 28- day compressive strengths under AC condition for various mixes are shown in **Figure 4.7**. Specimens in AC condition had comparatively lower compressive strength for all curing ages. This is due to lack of curing water for enough hydration process. As known, hydration process accelerates the strength of concrete.

Figure 4.5 shows at 1-day, the mix M0 (OPSC without POFA) gained 88% of 28-day compressive strength and other OPSC mixes containing POFA achieved 59-87% of the 28-day compressive strength. Conversely, M10 mix also had highest compressive strength than other mixes at 3-day curing age and the compressive strength ranged 75-96% of28- day compressive strength. It was found that at 3-day, the strengths of mixes M0 and M10 were found to be similar.

But at 7-day, the compressive strength ranged 93-99% of 28-day compressive strength and highest strength was achieved for mix M10 with 10% replacement of cement by POFA. It was found that the overall strength for all mixes was increasing proportionally with the increase of curing age. It was likely to occur as the rate of developing strength of earlier curing age is lower than the later curing age (Shafigh, Jumaat, & Mahmud, 2011).

The drop of compressive strength for mixes M20 and M25 could be due to reduced pozzolanic reaction. As in pozzolanic reaction, portlandite from OPC reacts with the major chemical composition SiO_2 of POFA and the C-S-H help to increase the strength but with the increase of POFA means lack of portlandite which hampers the pozzolanic reaction to produce much by-product and reduces the strength level. The compressive strength was found to decrease when pozzolanic materials content increased like fly ash in the OPSC (Basri et al., 1999). In the present investigation, 15 to 25% of cement replacement by POFA reduced the bond between the OPS surfaces and cement matrix and this could be attributed to low hydration. This hampered the development of bonding strength between them and causing the compressive strength to be lowered. Shafiq et al. reported the cube compressive strength for OPSC is about 25 MPa for OPSC (Shafigh, Jumaat, Mahmud, et al., 2011) . Okafor (Okafor, 1988) showed that by using the palm kernel shell the highest compressive strength was about 25-35 MPa for light--weight concrete which was within the range of typical structural lightweight concrete (SLWC) 20-35 MPa.

Under AC condition the compressive strengths of the specimens were in the range of 20 to 38.5 MPa for all curing ages. The highest compressive strength of 38.5 MPa was obtained for the mix M15.

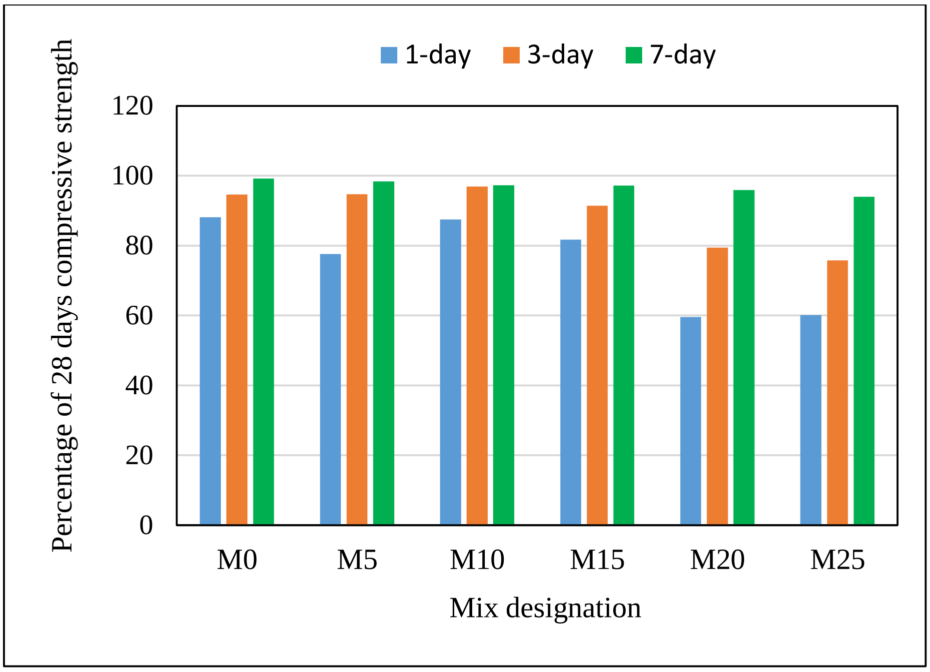


Figure 4.5: Percentage of 28-day compressive strength for 1-, 3- & 7-day under AC condition for different mixes

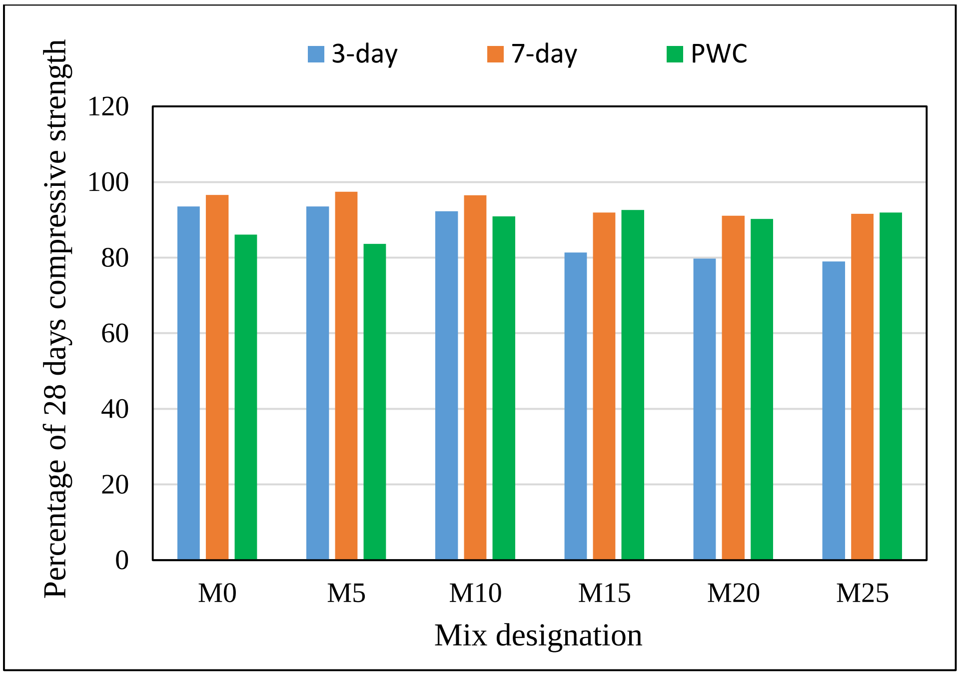


Figure 4.6: Percentage of 28-day compressive strength for FWC (3- & 7-day) and PWC condition for different mixes

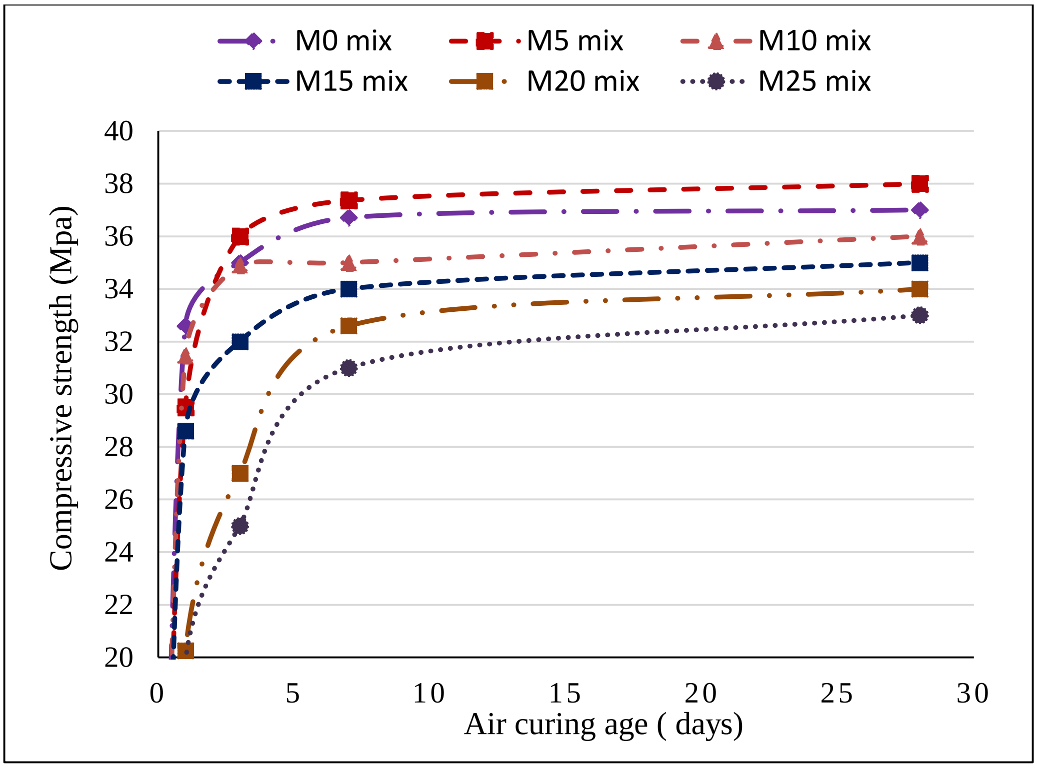


Figure 4.7: Variation of compressive strength with different AC age for various mixes

Figure 4.6 denotes the percentage of 28 day compressive strengths for all mixes at the ages of 3-, 7-day under FWC and PWC condition. **Figure 4.8** and **Figure 4.9** show the development of compressive strength for FWC and PWC condition at 3-, 7- and 28-day. At the age of 3-day, the compressive strengths of OPSC containing POFA (mixes M5 to M25) were found between 79-93% of the corresponding 28-day compressive strength and for OPSC without POFA (mix M0), it was 93%. The highest compressive strength of 38.6 MPa was obtained for mix M10%.

At 7-day, the highest compressive strength of 41 MPa was found for OPSC without POFA and the compressive strength ranged 91-97% of 28-day strength for OPSC containing POFA. The rate of development of compressive strength from 3 to 7-day was 3-16%. Generally, for mixes with 15-25% of POFA, the rate of strength development was found higher compared to mixes with low amount of POFA. On the other hand, the addition of POFA beyond 10% showed strength reduction for FWC specimens. As explained earlier the increase in POFA content could have led to slower hydration due to possible water absorption by POFA owing to its higher fineness. Under PWC condition, the compressive strength ranged 83-92% of 28 days compressive strength.

The highest compressive strengths 42.40 MPa & 38.55 MPa were obtained for 10% substitution of cement by POFA at 28-day for FWC and PWC, respectively.

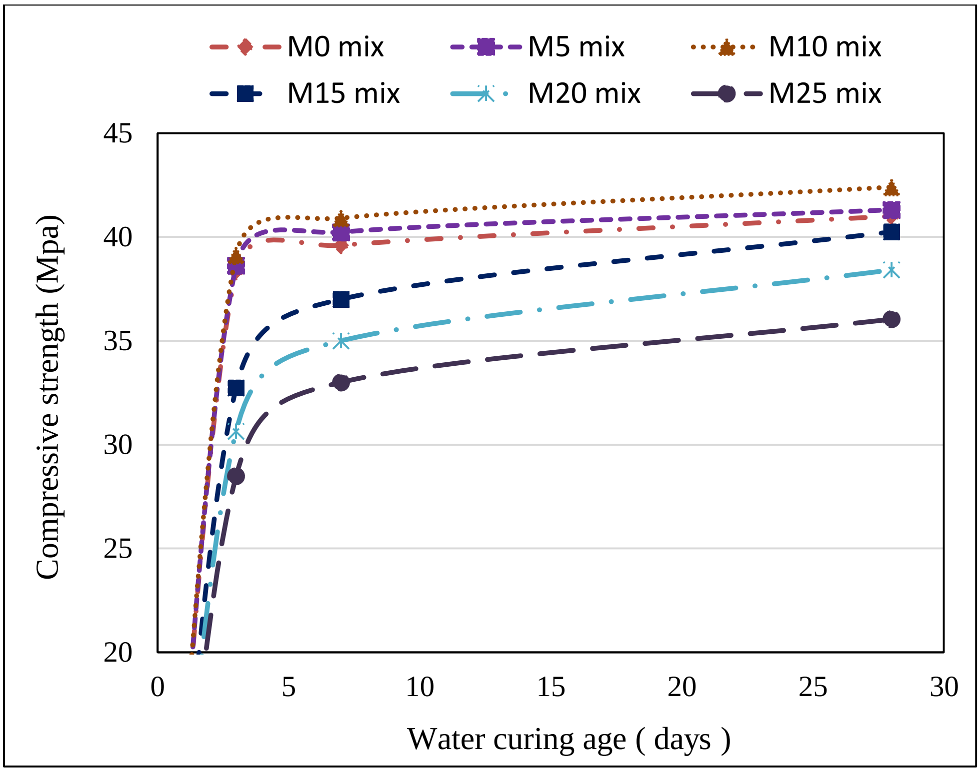


Figure 4.8: Development of compressive strength under FWC age for various mixes

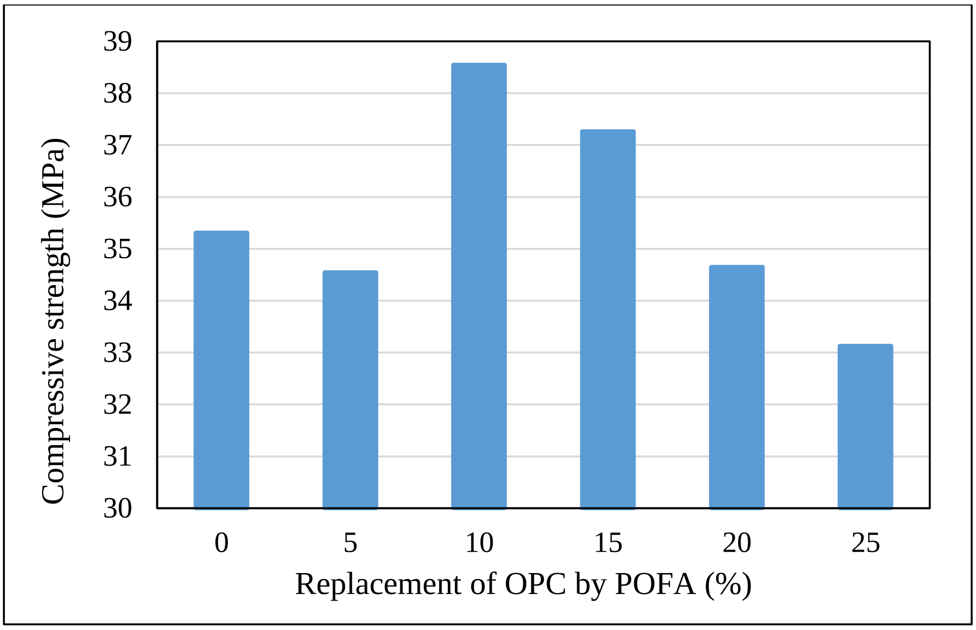


Figure 4.9: Variation of 28-day compressive strength with percent replacement of cement by POFA under PWC condition

The comparison of 28-day compressive strengths for OPSC with and without POFA for three curing conditions is shown in **Table 4.2**. The compressive strengths of specimens cured in FWC condition had higher strength compared to specimens cured in AC and PWC conditions. In case of FWC condition, the samples were kept in water till the day of testing and this enabled hydration and enhanced the compressive strength. For AC condition, the compressive strength was about 8-17% lesser than the 28-day compressive strength of FWC and this could be attributed to low hydration of AC specimens. On the other hand, the pre-soaking of OPS could have contributed to the hydration of AC specimens, but this has to be verified with further tests. The compressive strength for PWC was 8-16% lower than the 28-day compressive strength of FWC. During PWC condition, water provision was not available all the way through the curing period. Absorbed water from the pore structure reservoir was consumed when the water was required to track ahead the hydration process. But the pozzolanic material POFA delayed the hydration process which affected the strength consequently. Similar reason was explained by Newman and Choo (John Newman & Choo, 2003). They found that pozzolanic materials like fly ash caused the lack of enough curing which affected the final product because of delaying the hydration process (John Newman & Choo, 2003; Shafigh, Johnson Alengaram, et al., 2013).Ultimately, there was no significant change of compressive strength between AC and PWC condition.

Table 4.2 : Comparison of 28-day compressive strengths of AC, PPWC and FWC specimens

Mix	28-day compressive strength (MPa)		
	AC	PWC	FWC
M0	37 (89%)	35.31 (83%)	41
M5	38 (92%)	34.54 (80%)	41.30
M10	36 (82%)	38.55 (90%)	42.39
M15	35 (85%)	37.26 (91%)	40.24
M20	34 (87%)	34.65 (89%)	38.41
M25	33 (90%)	33.13 (91%)	36.04

4.3.2.2 Effect of POFA

In this study, compressive strength was decreasing with the increase of POFA content. The concrete of 10% (for FWC and PWC)) and 15% (for AC) POFA gave higher compressive strength than those of 20% and 25% for all curing type and age. For curing age 1-, 3- and 7-day, the compressive strength of OPSC containing POFA was lower than the OPSC without POFA and later age the compressive strength was increased under three different curing condition. As the POFA is available in alumina oxides and silica where lime is absent almost and the hydraulic properties cannot progress without the hydrated lime. The main function of hydrated lime is to accelerate the hydration process for making the natural pozzolans acting as binding materials like OPC. But in case of POFA, the reactive silica is readily dissolved in the matrix as $Ca(OH)_2$ becomes available during the hydration process. These pozzolanic reactions lead to the formation of additional C-S-H with binding properties. Simply, this reaction can be schematically represented as follows:

$$Ca(OH)_2 + H_4SiO_4 \rightarrow Ca^{2+} + H_2SiO_4^{2-} + 2\ H_2O \rightarrow CaH_2SiO_4 \cdot 2\ H_2O$$

or summarized in abbreviated notation of cement chemists:

$$CH + SH \rightarrow C\text{-}S\text{-}H$$

The product of general formula ($CaH_2SiO_4 \cdot 2\ H_2O$) formed is a calcium silicate hydrate, also abbreviated as C-S-H in cement chemist notation which contributes in increasing the compressive strength at later age. **Figure 4.10** shows the SEM image of POFA.

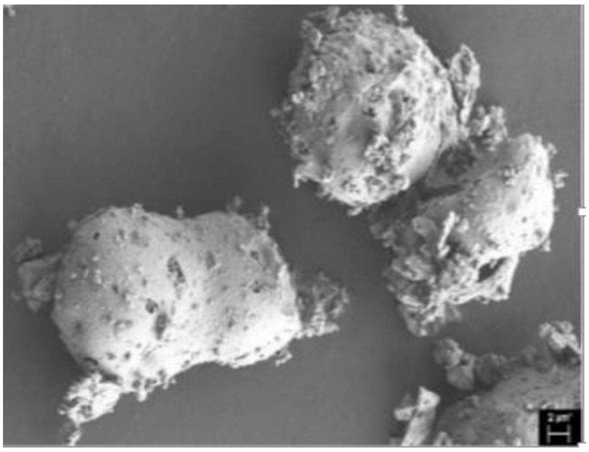


Figure 4.10: Scanning electron microscopic (SEM) image of POFA (Ranjbar, Mehrali, Behnia, et al., 2014)

4.3.3 Splitting tensile strength:

Splitting tensile strength test has vital role in developing shear strength estimation, alleviating cracking complications and also in prediction of required tensile strength to avoid the unexpected failure of concrete in tension (Sukumar, Nagamani, & Srinivasa Raghavan, 2008; Zain et al., 2002). The splitting tensile strengths of all mixes under AC, FWC and PWC conditions are shown in **Figure 4.11**. The measured splitting tensile strengths of all mixes for 28 days under AC, FWC and PWC conditions were found to be within the range of 2.55 to 3.97 MPa. According to ASTM C330, a minimum splitting tensile strength of 2.0 MPa is a requirement for structural grade lightweight aggregate concrete. In general, the splitting tensile strength of the air-cured OPSC was lower compared to those subjected to FWC and PWC conditions.

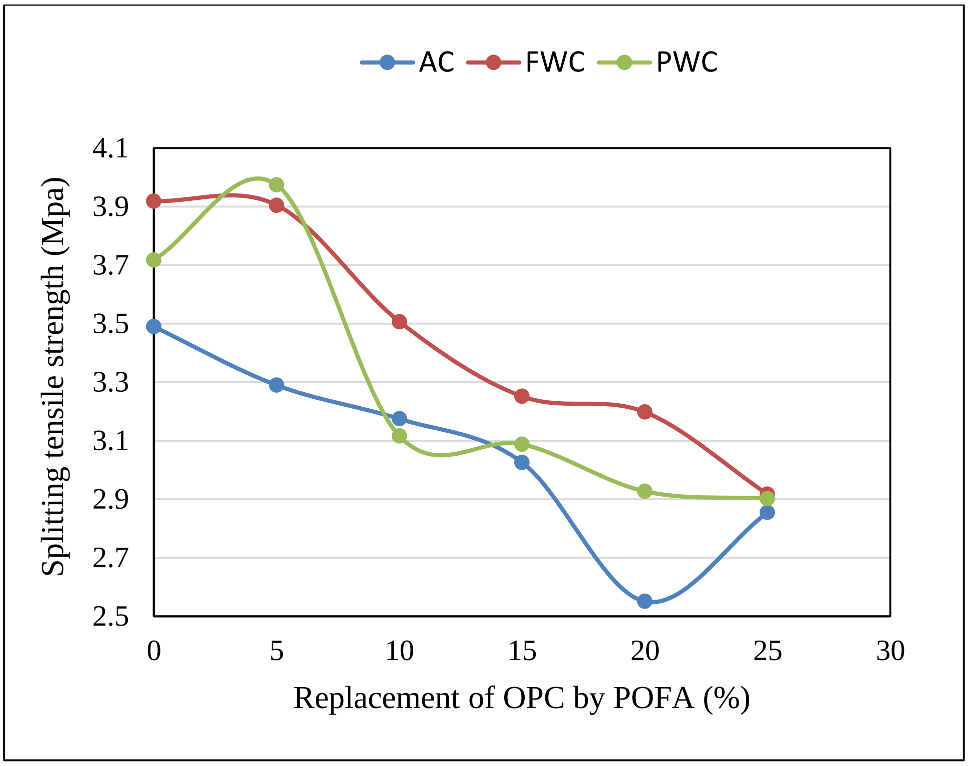


Figure 4.11: Variation of splitting tensile strength with compressive strength for different % of cement replacement under 28-day AC, FWC and PWC condition

It was observed that the splitting tensile strength of the OPSC containing POFA was lower than the control mix M0 regardless of the type of curing regime adopted. One of the reasons can be accounted for the poor quality of the interfacial transition zone (ITZ) which has an important role in splitting tensile strength (Shafigh, Johnson Alengaram, et al., 2013). This was despite higher compressive strength was obtained for mix M10 and this could suggest that the use of POFA to partially replace cement had little effect on the splitting tensile strength enhancement. Similar trend of reduced splitting tensile strength of OPSC with the increased use of cement replacement material in OPSC was also reported by Mo et al. (Mo, Yap, Alengaram, & Jumaat, 2014) and Shafigh et al. (Shafigh, Johnson Alengaram, et al., 2013; Shafigh, Jumaat, Mahmud, & Alengaram, 2013; Shafigh et al., 2012) for slag and fly ash.

The 28-day splitting tensile strength of OPSC containing POFA was 9-14% of compressive strength for all type of curing conditions. Generally, the splitting tensile strength of conventional concrete is 8-14% of compressive strength (S. Kosmatka, Kerkhoff, Panarese, MacLeod, & McGrath, 2002). The compressive to splitting tensile strength ratio found in this study is within the range of conventional concrete.

Figure 4.12 shows the failure pattern after splitting tensile strength. It was found that the failure between the OPS surface and the cement paste was very much uneven. This could be due to the uneven and angular shape of the crushed OPS. On the other hand, for the POFA based OPSC, the bond between the OPS surface and binding paste was not strong enough to take the tensile force at greater number and because of that with the increase of POFA content, the splitting tensile strength was found to be decreased continuously.

Figure 4.12: Failure pattern after splitting tensile strength test

Table 4.3 shows different established empirical equations for determining splitting tensile strength from compressive strength of various type of concrete which were proposed by the previous researchers and those equations were used to compare with the experimental 28-day splitting tensile strength of OPSC containing POFA under AC, FWC and PWC conditions.

The predicted splitting tensile strength was found using the existing equation (1-5) and the percentage of deviations from the experimental results were calculated. Eq. (1) forecast the splitting tensile strength 3.70-4.50 MPa which was close to the experimental results 2.55-4 MPa under AC, FWC and PWC conditions. The other percent deviation was intended to 3-16%, 3-18 %, 15-30 % and 2-16% for equations (2), (3), (4) and (5), respectively under FWC condition. In this research work, the three empirical equations were developed for AC, FWC and PWC conditions and these are given below.

1. $f_t = 0.501 f_{cu}^{0.505}$ (for AC)
2. $f_t = 0.0.027 f_{cu}^{0.1.311}$ (for FWC)
3. $f_t = 4.98 f_{cu}^{0.119}$ (for PWC)

Table 4.3: Empirical equations to determine splitting tensile strength for various type of concrete

Equation	Equation number	Type of concrete	Percentage of deviation (%)
$f_t = 0.358 f_{cu}^{0.675}$	(1)	LEPAC (Lightweight expanded polystyrene aggregate concretes)(Saradhi Babu, Ganesh Babu, & Wee, 2005)	6-14
$f_t = 0.4887 f_{cu}^{0.5}$	(2)	OPSC (Crushed OPS concretes with cube compressive strength ranging from 35 to 53 MPa)(Shafigh et al., 2012)	3-16
$f_t = 0.23 f_{cu}^{2/3}$	(3)	BFS LWAC (Blast furnace slag lightweight aggregate concrete)(Neville, Neville, & Neville, 1963)	3-18
$f_t = 0.20 f_{cu}^{2/3}$	(4)	OPSC (OPS concretes containing original OPS aggregates with cube compressive strength ranging from17 to 37 MPa)(Shafigh, Jumaat, & Mahmud, 2010)	15-30
$f_t = 0.27 f_{cu}^{2/3}$	(5)	CFA LWAC (Cold-bonded fly ash LWAC with a cube compressive strength ranging from 20 to 47 MPa)(Gesoğlu, Özturan, & Güneyisi, 2004)	2-16

4.3.4 Flexural Strength:

Figure 4.14 shows the values of flexural strength test for all mixes under different AC, FWC and PWC conditions. In this study, the 28-day flexural strength of the OPS concrete containing POFA ranged from 3 to 6.5 MPa under three different curing conditions. This is in agreement with the results obtained from previous studies (U. J. Alengaram, M. Z. Jumaat, & H. Mahmud, 2008; Johnson Alengaram, Jumaat, Mahmud, & Fayyadh, 2011; Park & Kang, 2008; Shafigh et al., 2012) which reported the flexural strength to be in the range of 2.13-4.93 MPa. The 28-day flexural strength for OPSC mixes was found to be 6-10.80% of the corresponding cube compressive strength.

In this study, the flexural to splitting tensile strength ratio for all mixes was found to be in the range of 1.4 – 1.7 under 28-day water curing condition and for AC and PWC conditions, the flexural to splitting tensile strength ratios were measured to be between 1.03 - 1.45 and 1.22 - 1.43, respectively. Shafigh et al. (Shafigh et al., 2014) reported that the ratio of flexural to splitting tensile strength was lower for OPSC containing fly ash. This study also showed the OPSC concrete containing pozzolanic material POFA had lower flexural / splitting tensile ratio.

Figure 4.13 shows the flexural strength test and the failure pattern after the test. The flexural strength test result was found to be decreased continuously with the increase of POFA content in OPSC. Through the failure pattern, it was found that the interfacial transition zone between the OPS and the binding paste was not strong much to resist the shear force that was applied during the flexural strength test at greater number. POFA could not contribute much to develop the resistance to shear force.

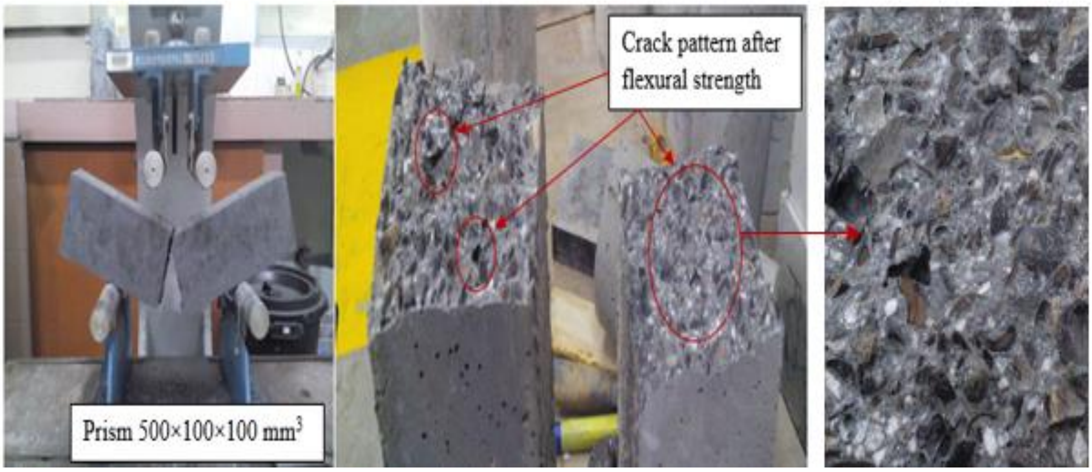


Figure 4.13: Flexural strength test and failure pattern after the test

Table 4.4 shows the existing equations which were found form previous research works and these equations were used to predict the flexural strength from compressive strength made from different type of concrete. The percent (%) deviation from experimental values were determined through the evaluation of equations (6) to (10) and Eq. (9) gave the nearest predicted results 4.65-5.60 MPa with respect to the experimental results 3-6.5 MPa under FWC curing condition. But the flexural strength of this study was similar or higher than the other empirical equations (6), (7), (8) and (10). In this research work, the three empirical equations were developed for AC, FWC and PWC conditions and these are given below.

1. $f_r = 0.0148 f_{cu}^{1.54}$ (for AC)
2. $f_r = 0.0002 f_{cu}^{2.83}$ (for FWC)
3. $f_r = 0.158 f_{cu}^{0.921}$ (for PWC)

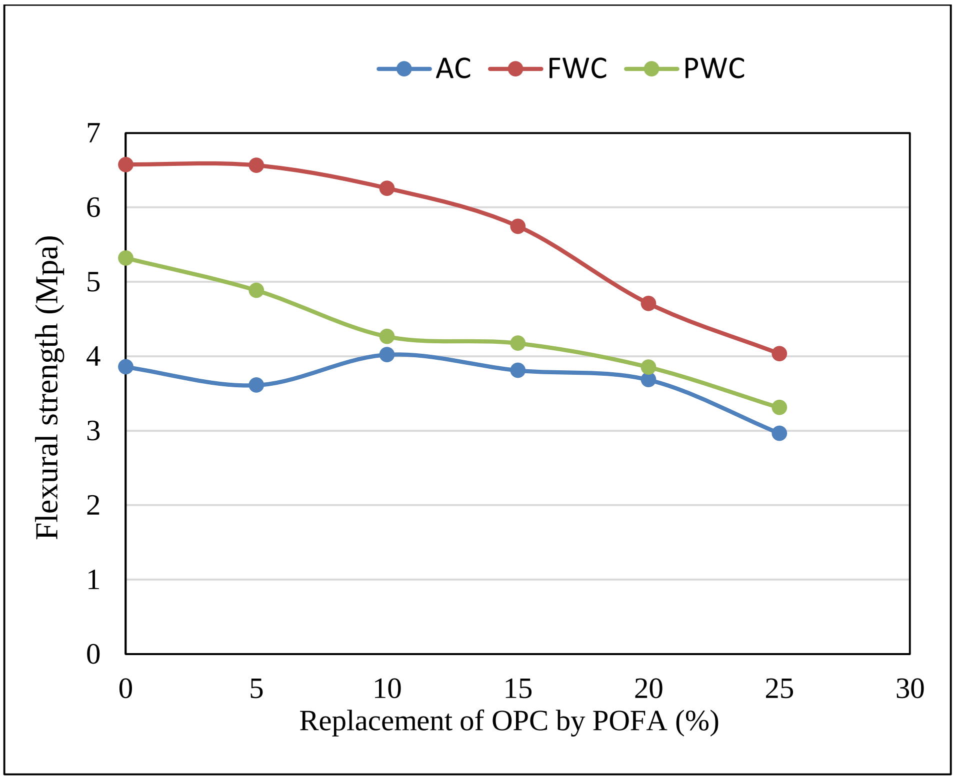


Figure 4.14: Flexural strength with compressive strength for different % of cement replacement under 28-day AC, FWC and PWC condition

Table 4.4: Empirical equations to determine the flexural strength for various type of concrete

Equation	Equation number	Type of concrete	Percentage of deviation (%)
$f_r = 0.12 f_{cu}^{1.03}$	(6)	OPSC (Crushed OPS concretes with cube compressive strength ranging from 35 to 53 MPa)(Shafigh et al., 2012)	2-15
$f_r = 0.30 f_{cu}^{2/3}$	(7)	OPSC (OPS concretes with compressive strength ranging from 15 to 37 MPa)(U. J. Alengaram, M. Jumaat, & H. Mahmud, 2008)	6-18
$f_r = 0.69 f_{cu}^{0.5}$	(8)	EC LWAC (Expanded clay lightweight aggregate concrete with cube compressive strength ranging from 29 to 43 MPa)(Lo, Cui, & Li, 2004)	4-11
$f_r = 0.46 f_{cu}^{2/3}$	(9)	ESCA LWC (Lightweight concrete made with expanded shale and clay aggregates with cube compressive strength ranging from 20 to 60 MPa)(Manual, 1977)	5-11
$f_r = 0.58 f_{cu}^{0.5}$	(10)	OPSC (Lightweight concrete made with tuff lightweight aggregate) (Shafigh et al., 2010)	6-15

4.3.5 Modula's of Elasticity:

The results of modulus of elasticity (MOE) test are shown in **Table 4.5** for all mixes under AC, FWC and PWC conditions. The MOE values for the mixes under AC condition were about 11 – 12.50 GPa whereas the range of 12.75 – 15.45 GPa and 12 – 13.80 GPa were found for FWC and PWC, respectively. Previously the modulus of elasticity of OPSC was found 25-50% lower than the NWC and the modulus of elasticity 25-28 GPa was found for the POFA based normal weight concrete only (Tangchirapat & Jaturapitakkul, 2010). Again, for structural lightweight concrete the modulus of elasticity varies from 10 to 24 GPa which is significantly lower than NWC (Manual, 1977). This is due to lower modulus of elasticity of the lightweight aggregates compared to normal weight aggregate. For example, the modulus of elasticity in the range of 5 to 15 GPa was found for expanded clay and shale aggregates. Conversely, the modulus of elasticity for high specific gravity based natural aggregates like basalt, quartz, and limestone is about 60, 80 and 100 GPa, respectively (béton, 1993). Similar characteristics were found for fly ash and silica fume(Nassif et al., 2005).

However, in this research work, the modulus of elasticity for the sample of AC condition is 7-29% and 11-36% lower than the FWC and PWC, respectively. This is due to the weaker interfacial transition zone between paste and aggregate in AC than FWC and PWC. However, the stiffness of coarse aggregate OPS also influenced the values of modulus of elasticity. The modulus of elasticity value was found to be increased with the increase of POFA up to 10% replacement of cement and the highest value was also found at 10% POFA content in OPSC for AC, FWC and PWC conditions at 28-day. This could be due to the formation of stronger bond between the binding paste and the OPS. Again, with the further increase of POFA content 15% to 25% in OPSC, the modulus of elasticity value was found to be decreased for allcases. This might be due to the higher POFA content which caused the increase of pores inside the concrete. In this study the modulus of elasticity test values were in a range of acceptable limit of 10-25 GPa for SLWC (Manual, 1977) .

Table 4.5: Modulus of Elasticity test for all mixes under 28 days different curing condition

Mix Design	Modulus of Elasticity (GPa)		
	AC	FWC	PWC
M0	11.91	15.42	13.25
M5	11.57	14.23	12.89
M10	12.55	14.02	13.77
M15	12.02	13.13	12.90
M20	11.08	13.05	12.45
M25	11.44	12.73	11.90

4.4 Environmental Aspect

4.4.1 Efficiency factor

Figure 4.15 expresses the variation of efficiency factor with the reduction of cement for the range of certain percentage of 0 to 25 by POFA under 28-day AC, FWC and PWC conditions. Efficiency factor is the strength (MPa)/weight (kg/m^3) ratio of concrete which has very vital role in determining the behavior of concrete structure. Likewise, the efficiency factor of lightweight structural concrete has outstandingly greater impact than NWC at the similar compressive strength and it was found that the efficiency factor for OPSC was 17,025-22,128 KNm/kg for the 28-day compressive strength of 30-44.5 MPa (Shafigh et al., 2014).

The calculated efficiency factor of this study varies 17,070-21,482 KNm/kg for 28-day compressive strength of 32.03-42.393 MPa under AC, FWC and PWC. In this study, mix M10 showed highest compressive strength under FWC and FWC condition and under AC condition mix M15 showed highest compressive strength value. The efficiency factor was decreasing after the certain replacement of cement by POFA content in OPSC. This could be due to the lower density and strength of the higher POFA based OPSC. As the specific gravity of POFA is lower than OPC and also POFA has higher LOI content than OPC, with the increase of POFA content the density reduced and as well as the strength which affected the efficiency factor too. In every cases, the efficiency factor of FWC was higher than AC and PWC conditions. This is due to the higher strength development of FWC condition in comparison with AC and PWC conditions. Based on the criteria of highest compressive strength, POFA can be used in producing high strength lightweight concrete at certain amount of 10 % of replacement of cement.

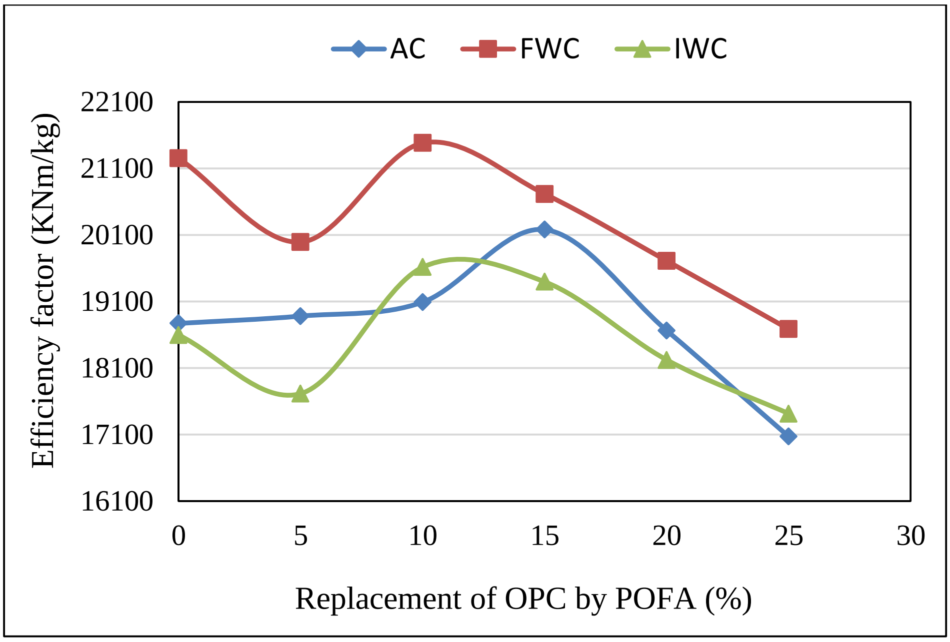


Figure 4.15 : replacement of cement by POFA vs efficiency factor (KNm/kg) under 28-day AC, FWC and PWC curing age

4.4.2 Cost analysis

The reduction of cost associated with the lightweight properties might be advantageous to the environmental as well as economical point of view **Table 4.6** shows the estimated cost (Malaysian ringgit per kilogram, (Kanadasan & Razak, 2015)) of concrete materials that were used in this study . The unit price of POFA was considered according to the Malaysian local industries. The cost could be reduced up to about 14% for M25 mix comparing with the mix M0 without POFA. Conversely, the mix M10 with highest compressive strength could save approximately 6% of OPSC cost. It can be one of the cost redeemable measures in construction engineering, especially in large scale of concreting projects. Presently, the construction industries are focusing on the environment friendly and sustainable resources like the replacement of natural materials with agricultural and industrial wastes. There are some specific industries who need to implement cost saving and green products , can be the beneficiary one by utilizing POFA as partial replacement of binding materials and also can contribute to keep the environment safe. Considering the compressive strength 32-42 MPa, **Table 4.7** shows that the cost of producing POFA based LWAC could be saved up to 7.5% with respect to the ground granulated blast furnace slag (GGBS) based OPSC (Mo, Alengaram, et al., 2014). On the other hand, the cost of POFA based OPSC in this study was close enough or slight higher than the other SLWC like fly ash based OPSC (Shafigh, Alengaram, et al., 2013) and OPSC (Shafigh, Jumaat, Mahmud, et al., 2011).

Table 4.6 : Cost of materials by weight (RM/kg)

Materials	Cost (RM/kg)
Cement	0.430
POFA	0.020
OPS	0.020
Sand	0.078
Super-plasticizer	15.40
Gravel	0.057

Table 4.7: Mix design comparison with the conventional SLWC for cost analysis

Material (kg/m^3)	GGBS based OPSC (Mo, Alengaram, et al., 2014)	Fly ash based OPSC (Shafigh, Alengaram, et al., 2013)	Normal OPSC (Shafigh, Jumaat, Mahmud, et al., 2011)	Mix M10 (this study)
Cement	440	495	500	508.5
Granite	-	178	-	-
OPS	357.5	326	435	368
Sand	935	900	726	960
Ground granular blast-furnace slag	110	-	-	-
Fly ash	-	165	-	-
Limestone powder	-	-	-	-
POFA	-	-	-	56.5
Super-plasticizer (SP)	10	55.5	6.65	6
Total cost (RM/kg)	428.87	391.7	389.19	398.91

4.4.3 Emission of Carbon dioxide (CO2-e)

Considering the utilization of waste materials in producing SLWC, one of the main reasons is to reduce the greenhouse effect. In this research, the CO_2 emission of POFA based OPSC of all mixes was investigated to compare with conventional NWC. The amount of CO_2 emission was evaluated for each consisting material component as unit of 1 m^3 amount of concrete. In view of the process of disintegration of lime, heating and grinding in kiln and transportation, the CO_2-e for OPC was taken as 0.82 t CO_2-e/ton. The CO_2-e factor for normal sand aggregate was taken as 0.0139 per ton. These factors were used to evaluate the emission by multiplying with the mix proportion (kg/m^3) of respective concrete materials (Mo, Alengaram, et al., 2014). The CO_2-e for POFA and OPS was not accounted for being the industrial by-product. It was found that OPSC had 0.50 CO_2-e/m^3 which was higher than the carbon dioxide emission 0.44 CO_2-e/m^3 of NWC and the other POFA based OPSC mixes had continuous reduction of emission up to 0.39 CO_2-e/m^3 which was found for 25percent replacement of cement by POFA. It can be said that the higher of POFA replacement as cementitious material lowers the carbon dioxide emission. The higher CO_2 emission for the OPSC is attributed to the higher cement content required to produce grade 40 concrete compared to NWC. For the other POFA based OPSC, the low liberation of CO_2 resulted in a significant reduction of the total CO_2 emitted; a reduction as high as 11.60% was noticed for the mix M25 that contains 25% POFA compared to NWC. **Figure 4.16** shows the relationship between the carbon emission and cost of concrete per unit strength for different POFA based OPSC. A similar study of such a performance indicator was previously done by J. Kanadasan and H. Abdul Razak (Kanadasan & Razak, 2015). The OPSC with POFA can recommended for the application in concrete members in case of sustainability and low carbon dioxide emission. Considering the amount of the CO_2-e and cost analysis, 10% POFA based OPSC can be recommended for structural application or low-load bearing structural members.

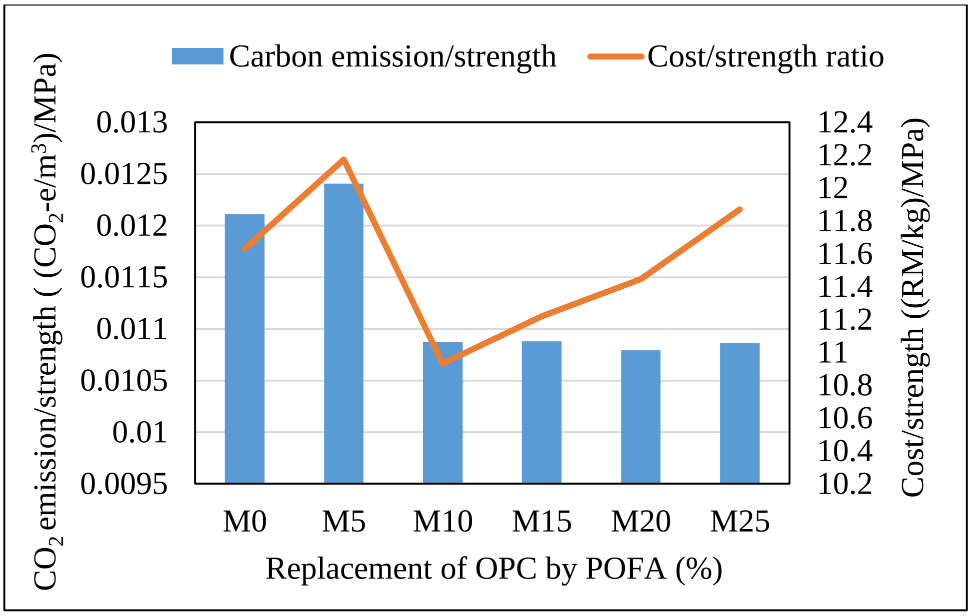


Figure 4.16: Relationship between the carbon emission/strength ratio, POFA replacement ratio and cost/strength ratio

4.5 Effect of high volume POFA on durability properties

In the previous section, the effect of low volume POFA (0-25%) on fresh and hardened concrete properties of OPSC was evaluated; however, the pinnacle of the study lies with durability studies of high volume POFA. As POFA slower the hydration process which reduces the strength initially but at later age the strength development rate is much higher that control mix (OPSC without POFA). In this research work, durability properties were evaluated for long duration and it was an opportunity to use POFA at high percentage to establish more effective green and sustainable concrete. On the other hand, no research work has been done to evaluate durability properties with the high percentage (70%) of POFA replacement along with OPS in structural lightweight concrete. Hence to evaluate the effect of high volume POFA on some durability properties such as water absorption, sorptivity, drying shrinkage, sulphate attack and rapid chloride penetration were investigated; further, basis characteristics – workability and compressive strength of the mixes were also investigated and compared. As outlined in the methodology and **Table 4.8** in this section, w/b ratio was varied to accommodate the high volume of 70% POFA.

4.5.1 Workability and compressive strength

4.5.1.1 Workability

As seen from **Table 4.8**, the M0 mix had slump of 25 mm while the use of POFA from 10 – 50% of cement replacement levels had slump values between 25 and40 mm.

Table 4.8: Slump values for various mix designation

w/b	Mix No.	Super-plasticizer (kg/m^3)	Slump (mm)
0.3	M0	3.4	25
	M10	3.4	25
	M30	4.9	30
	M50	6.2	40
0.4	M02	0	25
	M70	6.2	180

To maintain the slump within the range of 25-40 mm, super-plasticizer was added in the order of 0.6-1.1% of cement weight. Super-plasticizer was used to reduce the water demand as in this study the water- binder ratio was kept constant at 0.3. Mixes M0 and M10 had the same slump value 25 mm where the same quantity of super-plasticizer was used for both of the mix. It was found that slight increase of POFA in OPSC hasn't had much effect the workability of the concrete.

But in case of mixes M30 and M50, with insufficient amount of super-plasticizer and constant w/b the concrete was sticky which can be denoted as agglomeration. **Figure 4.17** shows the physical appearance of the mix M30 and M50 at low amount of super-plasticizer. This is because of high amount of POFA in OPSC. As POFA is more porous than OPC and also higher in LOI, POFA requires more water to mix up. Considering that, later the amount of super-plasticizer was increased to keep the mix away from agglomeration. This is also commonly associated with other kinds of pozzolanic materials such as rice husk ash and metakaolin (Hassan et al., 2012; Modarres & Hosseini, 2014; Yin et al., 2006). Mehta and Monteiro recommended the slump value for structural lightweight concrete of about 50-75 mm which is comparable to the slump value of about 100-125 mm for conventional concrete (Povindar Kumar Mehta et al., 2006).

Figure 4.17: Mix M30 and M50 in concrete mixer machine at lower super-plasticizer content

Again when the w/b ratio was increased to 0.4 for the mix of M02 and M70, the slump was 25 mm and 180 mm, respectively. In this research work the w/b ratio was increased directly for mix M70, as previously agglomeration was found for mix M50 with the lower w/b ratio. This was done to keep the use of super-plasticizer in safe limit. As the high amount of super-plasticizer might cause the bleeding of concrete and as well as would affect the strength properties of concrete. For mix M70, the slump value was much higher than any other mix in this study. This might be for the increased w/b where the excess water reacted with the super-plasticizer and the great quantity of POFA acted like a filler material which caused much higher slump value.

The same slump value 25 mm was found for both mix M0 (w/b 0.3) and M02 (w/b 0.4). This could be due to using super-plasticizer for mix M0 with low w/b of 0.3 where for mix M02, no super-plasticizer was used as the w/b was increased to 0.4.

4.5.1.2 Compressive Strength

The 7-, 28-, 56- and 90-day compressive strengths for various mixes with different w/b ratio of 0.3 and 0.4 are shown in **Figure 4.18**. There is clear trend of increasing compressive strength with increase of age. Considering the w/b ratio of 0.3, the compressive strengths of 7-day ranged 21-39 MPa where the highest compressive strength was found for mix M0 (without POFA) and other POFA based OPSC gave lower compressive strength. Basically, with the increase of POFA content the compressive strength was decreasing continuously for 7-day. This could be attributed to hydration of cement and pozzolanic reactivity during the initial stage of curing. Conversely, the pozzolanic material POFA delayed the hydration process because POFA has greater loss of ignition (LOI) than OPC which was previously discussed and for the same reason it increased the water demand to mix up with the concrete constituent materials. This increased demand of water hindered the hydration process inside concrete and affected the strength development consequently. Conversely, this was also explained by researchers and (John Newman & Choo, 2003) they found that pozzolanic materials like fly ash caused the lack of curing which affected the final product because of delaying the hydration process. **Table 4.9** shows at the age of 7-day, the control mix M0 gained 97% of28-day compressive strength and other OPSC mixes containing POFA achieved 71-88% of28-day compressive strength.

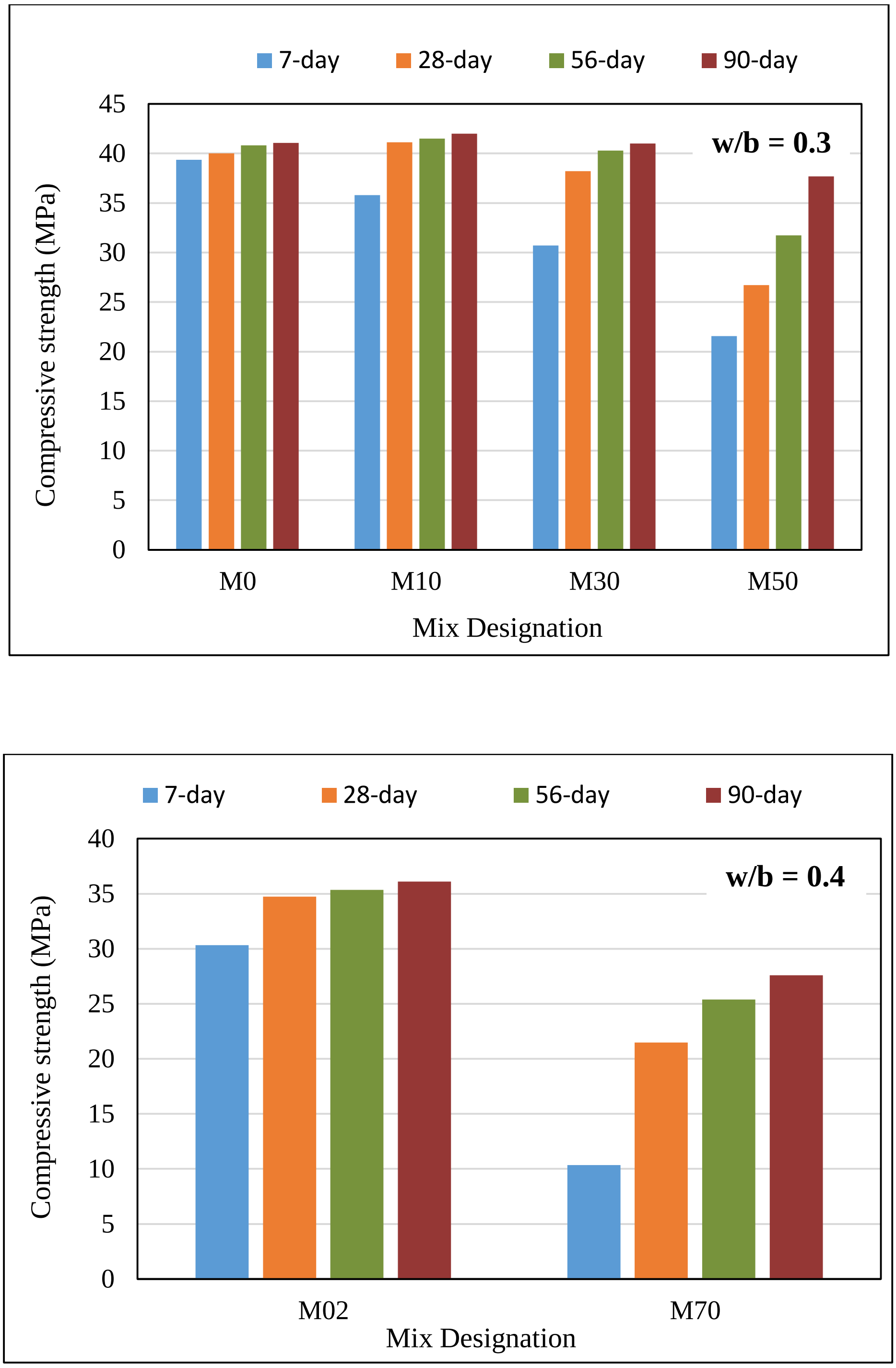


Figure 4.18: Variation of Compressive strength with different various mixes

Table 4.9: Comparison of 28-day compressive strength with 7-, 56- and 90-day compressive strength

w/b	Mix	Compressive strength (MPa)			
		7-day	28-day	56-day	90-day
0.3	M0	39.35 (97%)	40	40.82 (101%)	41.06 (103%)
	M10	35.79 (88%)	41.14	41.5 (101%)	42 (102%)
	M30	30.72 (80%)	38.22	40.28 (102%)	41 (105%)
	M50	21.56 (71%)	26.7	31.75 (108%)	37.7 (113%)
0.4	M02	30.30 (87%)	34.75	35.35 (101%)	36 (103%)
	M70	10.35 (48%)	21.50	25.4 (118%)	27.6 (128%)

Values in bracket denote the %s of 28-day compressive strength achieved at 7-, 56- and 90-day

At 28-day, the highest compressive strength was found for mix M10 and the strength developed within the range of 26-40 MPa. This could be due to the pozzolanic reaction. The strength development rate was also found higher with the increase of POFA in OPSC. As the POFA is available in alumina oxides and silica where lime is absent almost and the hydraulic properties cannot progress without the hydrated lime (Mertens et al., 2009). The main function of hydrated lime is to accelerate the hydration process for making the natural pozzolans acting as binding materials like OPC. But in case of POFA, the reactive silica is readily dissolved in the matrix as $Ca(OH)_2$ becomes available during the hydration process. These pozzolanic reactions lead to the formation of additional C-S-H with binding properties. Simply, this reaction can be schematically represented as follows:

$$Ca(OH)_2 + H_4SiO_4 \rightarrow Ca^{2+} + H_2SiO_4^{2-} + 2\ H_2O \rightarrow CaH_2SiO_4 \cdot 2\ H_2O$$

The product of general formula ($CaH_2SiO_4 \cdot 2\ H_2O$) formed is a calcium silicate hydrate, also abbreviated as C-S-H in cement chemistry notation which contributes in the enhancement of the compressive strength. The rate of strength development for POFA based OPSC was lower at the initial stage of curing rather than the later age curing. This similar case was also explained by (Shafigh, Jumaat, & Mahmud, 2011). They reported that the rate of development of strength for pozzolanic material based structural lightweight concrete at the early age is lower than the later curing age. The rate of development of compressive strength from 7-day to 28-day was 2-40%.

At 56-day the compressive strength ranged 32-40 MPa, where highest strength was found for mix M10. Compressive strength of mix M10 was higher than M0 and the other mixes M30 and M50, showed lesser strength in comparison with 10percent replacement of cement by POFA. But the rate of strength development was higher with the higher % of POFA content in OPSC which was explained previously. At 90-day, the compressive strength ranged 38-41 MPa where the highest strength was found for mix M10. But at 90-day, a slight increase in compressive strength of about 2% was found in the Mix M10 compared to 28-day compressive strength; however, POFA based mixes achieved higher strength increment in the range of 101-108% of28-day compressive strength. However, for 90-day, the same strength behavior of the specimens were found for different concrete mixes. The overall strength for all mixes was increasing proportionally with the curing age; it was also observed that the compressive strength for mixes M30 and M50 was found lower at every curing age compared to other mixes. But the rate of strength development was found highest for mix M30 and M50.

When the water binder ratio was increased to 0.4, the compressive strength was 30, 34, 35 and 36 MPa at 7-, 28- , 56- and 90-day, respectively for mix M02 and 10, 21, 25 and 27 MPa at 7-, 28- , 56- and 90-day, respectively for mix M70. It was observed that the increased w/b of the concrete mix effected the strength properties adversely for OPSC without POFA. When the cement was replaced at the optimal limit of 70% with POFA, the strength was found to be very lower than any mixes discussed in this research work for any curing age which were in the range of minimum required cylindrical compressive strength 17 MPa for the SLWC as specified in ASTM C 330 (213, 2003).

Figure 4.19 shows the failure pattern after cube compressive strength test and it shows in the cube specimens of mixes M30 and M50, there is more breakdown of bond between mortar and OPS compared to the mixes M0 and M10. For the increased w/b of 0.4, the mix M70 showed very weak bonding and more cracks inside the specimen. It was reported that the low compressive strength of the OPSC could be attributed to weaker bond between the OPS and cement matrix (Alengaram et al., 2013; Shafiq, Nuruddin, & Kamaruddin, 2007). In this research work, the increased amount of POFA absorbed more water to mix up and which could not help much in creating good enough bond between OPS and cement matrix because of slower hydration process. The slow hydration process might have hampered the development of strength and C-S-H that in turn resulted in poor bonding between OPS and mortar.

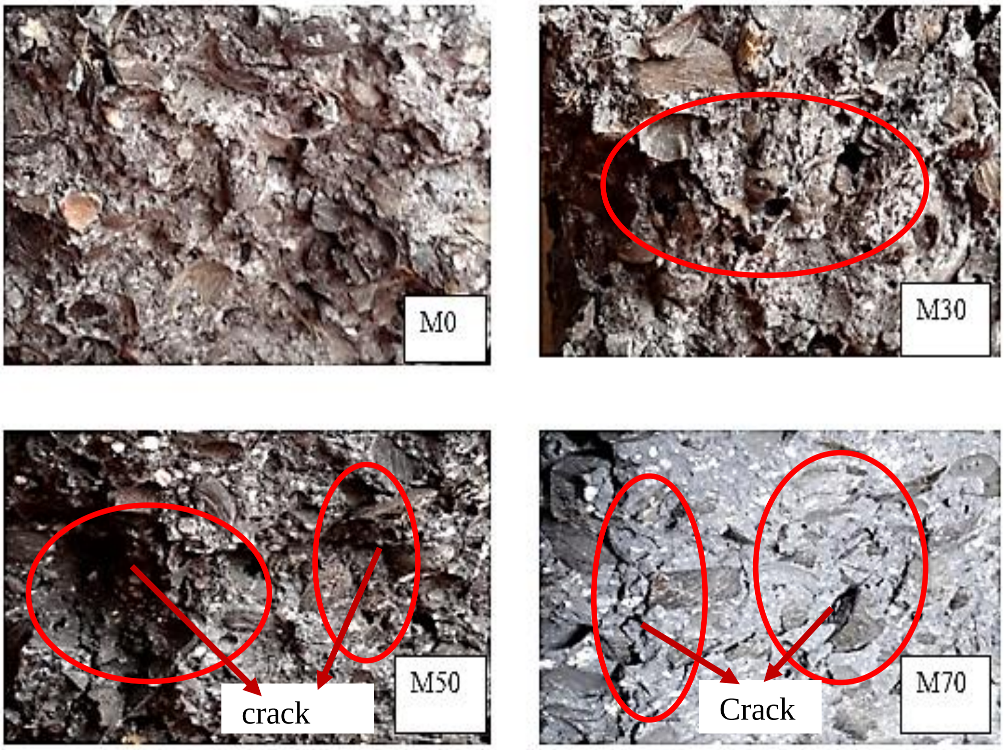


Figure 4.19: Failure pattern (normal images after breaking the sample) for M0, M10, M30, M50, M02 and M70 mix after compressive strength test at 28-day

4.5.2 Durability properties

4.5.2.1 Water absorption

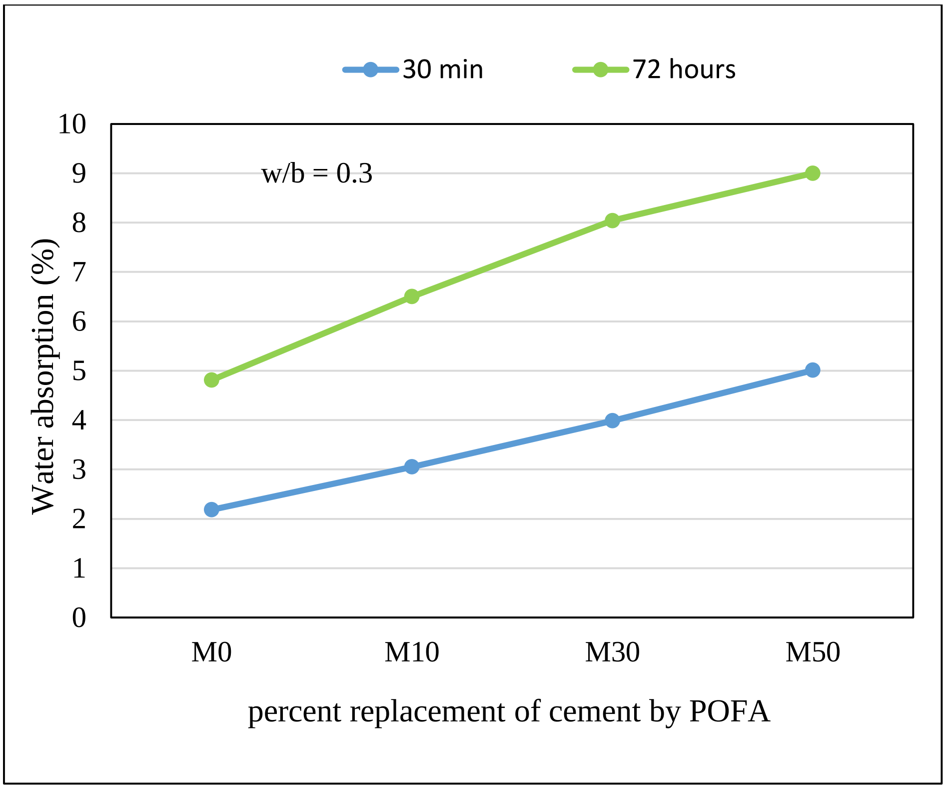
Water absorption is one of the methods to estimate pore volume in concrete. It is the quickest test method to evaluate the total amount of water absorbed in certain period of time.

Figure 4.20 and **Figure 4.21** show the water absorption for different percent replacement of cement with POFA at 30 min and 72 hours. These periods were maintained to have concept about the amount of water could be absorbed by the concrete mix at the initial and final stages. It will be time saving and cost effective in determining the concrete water absorption properties obtained after initial (30 min).

For w/b 0.3, the POFA based OPSC absorbed water about 39-129% higher than OPSC without POFA at 28-day whereas for 90-day specimens, it was about 24-124%. Conversely, 90-day samples absorbed about 17-29% less water than 28-day water cured samples over 30 min period. This is because of keeping the sample in continuous water curing condition for long period of time which later age helped the concrete mix to have the hydration process better than that of 28-day samples. The possibility of C-S-H formation could have helped to reduce the pores inside the concrete.

Again for w/b 0.4, mix M02 absorbed water about 80% higher than mix M0 (w/b 0.3) under both 28- and 90-day FWC condition. However, mix M70 (w/b 0.4) showed the highest water absorption capability of about 185 % higher than M0 (w/b 0.3) and 58% higher than M02 (w/b 0.40) for 28-day; as for 90-day, it was 193% and 60% higher than M0 and M02, respectively. The higher water-POFA ratio caused relatively weaker and pervious matrix in concrete which accelerated the ability to absorb more water. It was reported that the interaction of the lightweight aggregates and paste matrix differs from that of normal concrete (Lo & Cui, 2004).

Similar trend was found for the change of percentage of water absorption for 72 hours immersion after 28- and 90-day water curing conditions. Here for w/b 0.3, about 54-84% water was absorbed by the POFA based OPSC than normal OPSC (without POFA) at 28-day and at 90-day, it was 19-58% higher. For 72 hours of immersion, the 28-day samples absorbed about 21-30% more water than 90-day samples. However, for w/b 0.4, similar trend was found for mixes M02 and M70.



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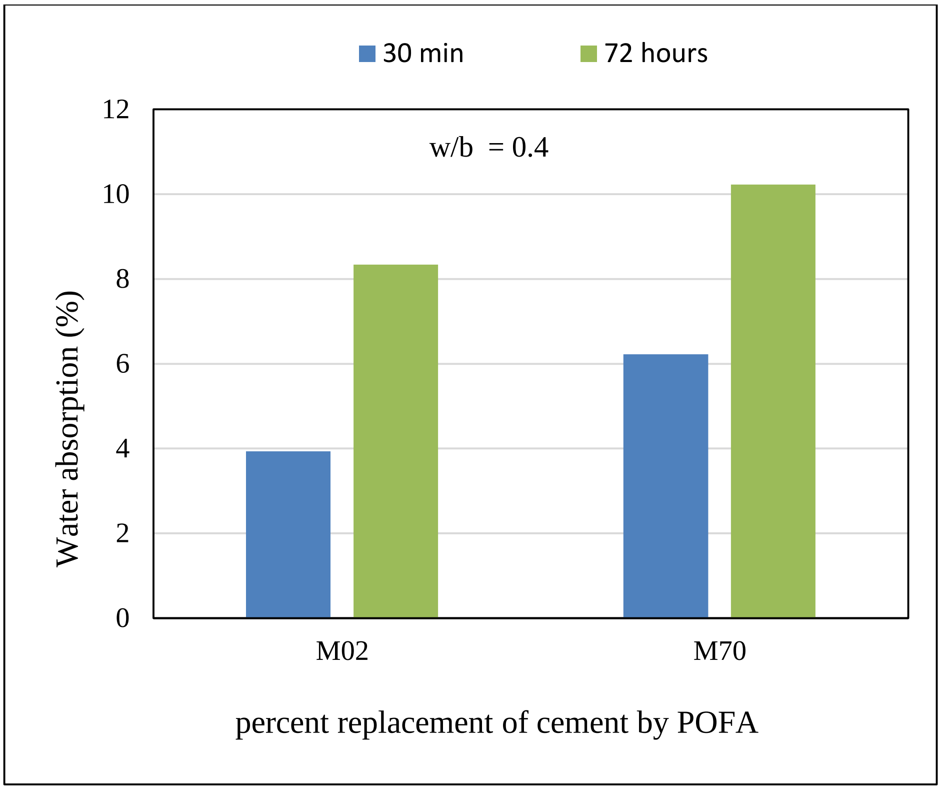

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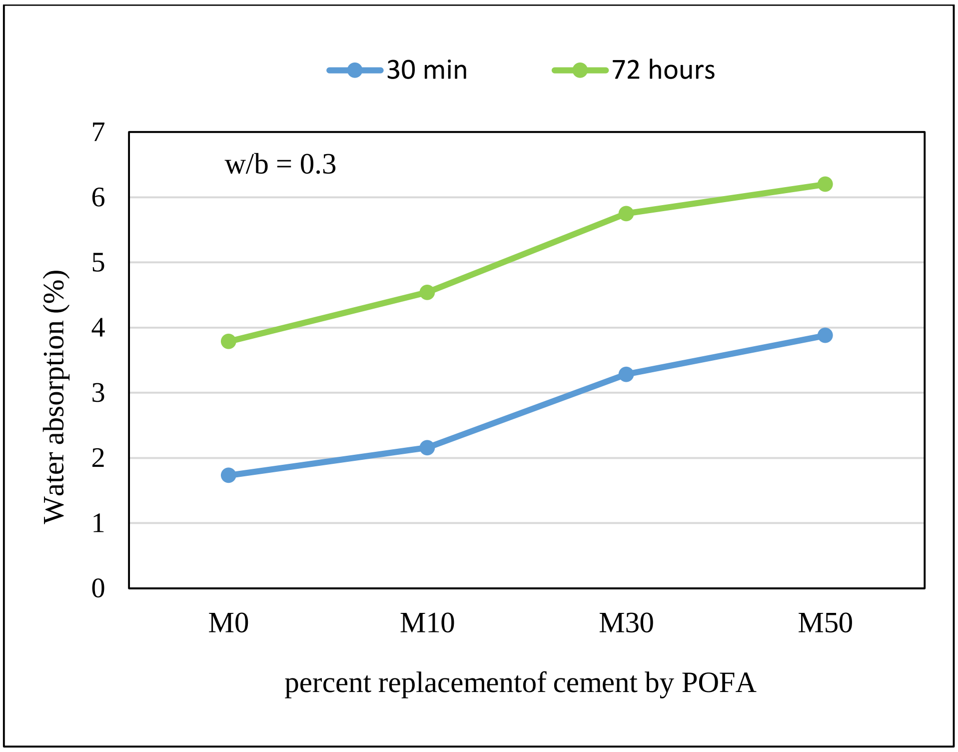
Figure 4.20: Water absorption (%) vs. different concrete mix at 28-day for (a) w/b 0.3 and (b) w/b 0.4



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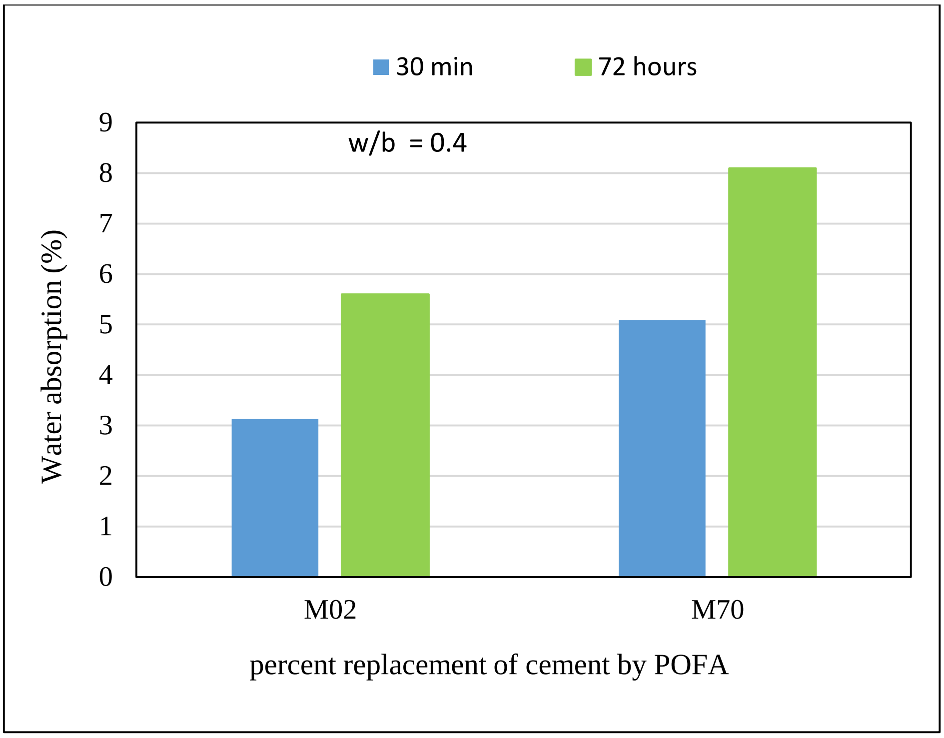


(b)

Figure 4.21: Water absorption (%) vs. different concrete mix at 90-day for (a) w/b 0.3 and (b) w/b of 0.4

At 28- and 90-day for w/b 0.3, the water absorption for OPSC (without POFA) was minimum for both 30 min and 72 hours period. Conversely, with the increased amount of POFA content more water was absorbed progressively and the highest amount of water was absorbed by mix M50. This is because of the high water absorption ability of POFA than OPC which is because of having higher LOI content and specific surface area of POFA than OPC and these contribute in increasing the water absorption with the increased percentage of POFA content in different concrete mixes. As with the increase of POFA, the amount of SiO_2 increases and the CH decreases in the concrete mixes. When there was in excess of SiO_2 and lower CH in POFA based OPSC, the formation of C-S-H reduced which later age affected the densification process and accelerate the formation of more pores inside the concrete. Similar mechanism for formation of C-S-H was explained by another researcher (Phoo-ngernkham, Chindaprasirt, Sata, Pangdaeng, & Sinsiri, 2013) where due to pozzolanic reaction and at higher replacement of OPC caused the increase of pore inside the concrete. These excess pore contributed to absorb more water for these particular concrete mixes. This similar occurrence was found for another pozzolanic material fly ash (Nambiar & Ramamurthy, 2007).

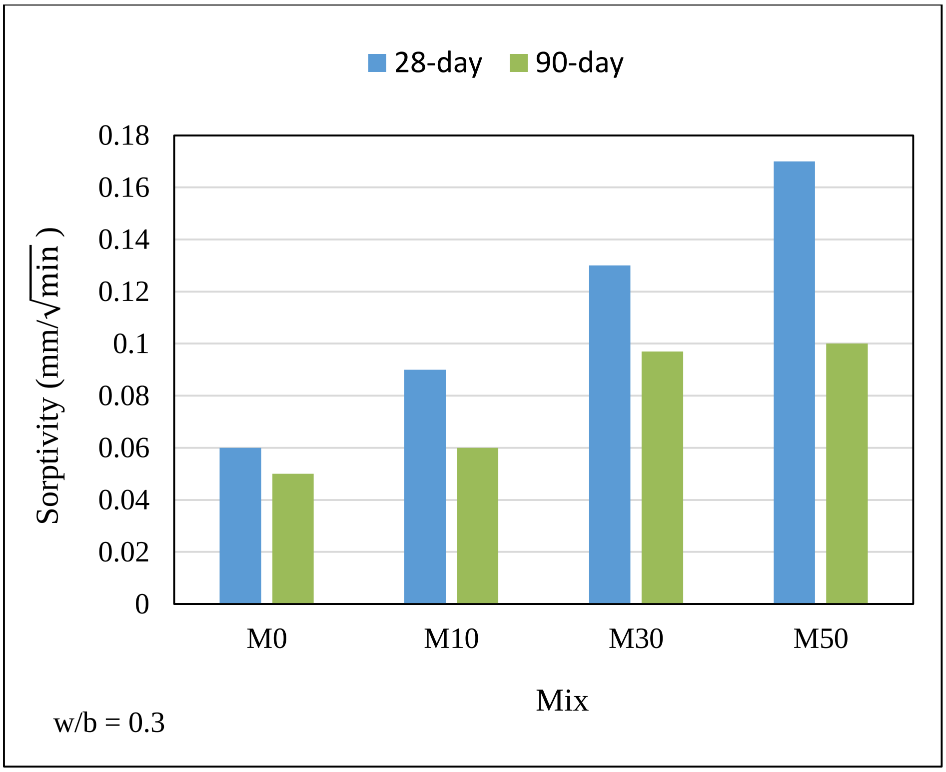
Mix M70 with w/b 0.4 also absorbed more water compared to any other mixes in this research work. This happened as higher w/b affects the pore structure densification. Previous researcher showed in case of structural lightweight concrete there is increase in water absorption with the increase of w/b ratio (Topçu & Uygunoğlu, 2010). In this research work, similar occurrence was found for mix M02 with w/b 0.4, where the amount of absorbed water was higher for mix M02 than the other mix M0 with lower w/b 0.3.

4.5.2.2 Sorptivity

Sorptivity of concrete provides the concept about pore structure inside the concrete (Khatib & Mangat, 1995). Low sorptivity values denote the higher resistance against water absorption in concrete. It was reported that the Sorptivity values of high quality type concrete should have less than 0.1 mm/min$^{0.5}$ (D. Teo, Mannan, & Kurian, 2010) **Figure 4.22** shows the development of sorptivity with increased replacement of cement by POFA for w/b of 0.3 and 0.4 at 28- and 90-day. In this research work, at 28-day for w/b of 0.3, the sorptivity was 0.06 to 0.17 mm/min$^{0.5}$ for 0 to 50% replacement of OPC by POFA with the highest sorptivity of 0.17 mm/min$^{0.5}$ found for 50% replacement. These values can be compared with OPS based concrete where the sorptivity values were reported in the range of 0.06-0.14 mm/min$^{0.5}$ (D. Teo et al., 2010). For mix M10, the sorptivity was 50% higher than mix M0 and the mixes M30 and M50 showed 116% and 183% higher than the mix M0, respectively. It was found that with increment of POFA in concrete mix showed increase of sorptivity. When POFA was used as replacement of OPC there was lack of hydration to associate the pozzolanic reaction. It was reported that with the increased percentage of pozzolanic material in replacement of OPC delays the hydration process (John Newman & Choo, 2003) which leads to slower strength development, especially in the initial few weeks (Targan, Olgun, Erdogan, & Sevinc, 2003). Accordingly, concrete could not get enough curing period for hydration process which affected the densification because of less production of by-product and it increases the pores inside the concrete. Basically, the water absorption is caused by capillary effect of pores. If the pores are at large number and greater size, this may diminish the capillary effect (Liu, Chia, & Zhang, 2011). This capillary effect also depends on the strength property of the concrete. It was reported that the capillary sorptivity coefficient of concrete decreased with the increase in the compressive strength (Tasdemir, 2003). As in this study, the strength was decreasing with the increase of POFA content, the capillary effect was also increasing with the higher POFA content which ultimately caused higher sorptivity values.

Similar trend was found for w/b of 0.4 where mix M02 and M70 produced sorptivity values of 0.12 and 0.19 mm/min$^{0.5}$, respectively. Mix M70 was 58% higher than mix M02. It was found that the increased w/b of 0.4 helped to reduce the sorptivity of the POFA based OPSC. But in case of mix M02 (w/b 0.4), the sorptivity was about 100% higher than mix M0 (w/b of 0.3) where the increased w/b ratio affected the sorptivity value for concrete mix without POFA. Conversely, the increased w/b affected the densification process which later age reduce the strength of mix M02. With this strength reduction the capillary sorptivity coefficient increased consequently which was discussed previously.

For 90-day specimens with w/b of 0.3, the sorptivity ranged 0.05 to 0.10 mm/min$^{0.5}$ for 0 to 50%replacement of cement by POFA where the highest sorptivity 0.10 mm/min$^{0.5}$ was found for mix M50. As usual the increase of sorptivity value was found with the increase of POFA content in concrete mix. But the sorptivity values at 90-day were lower than 28-day for every mix due to hydration process for 90-day. The C-S-H formation from adequate hydration process at later ages enables decrease the pore inside the concrete and reduces the sorptivity. Similarly, for w/b of 0.4, the sorptivity values for mixes M02 and M70 were found as 0.07 and 0.16 mm/min$^{0.5}$, respectively where mix M70 had 128% higher sorptivity value than M02. It was found that with the adequate hydration process at 90-day, the sorptivity value for mixes M02 and M70 got reduced about 41% and 15%, respectively compared to 28-day curing. This might be due to having higher amount of POFA in M70 which required more water for pozzolanic reaction rather than the mix M02 without POFA.



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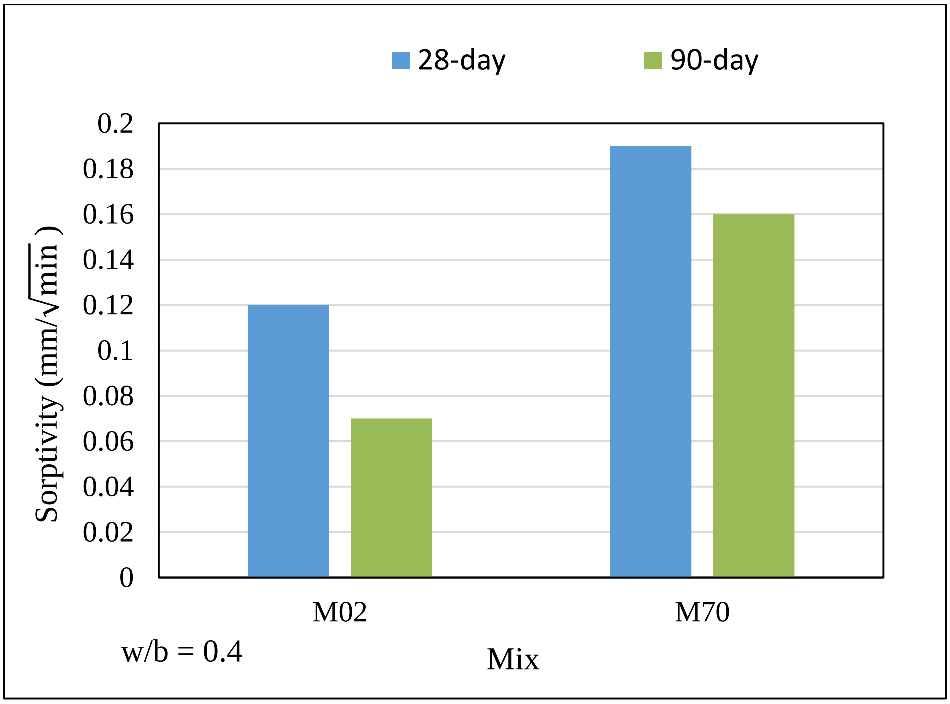


(b)

Figure 4.22: Development of sorptivity with increased percent replacement of cement by POFA for (a) w/b of 0.3 and (b) w/b of 0.4

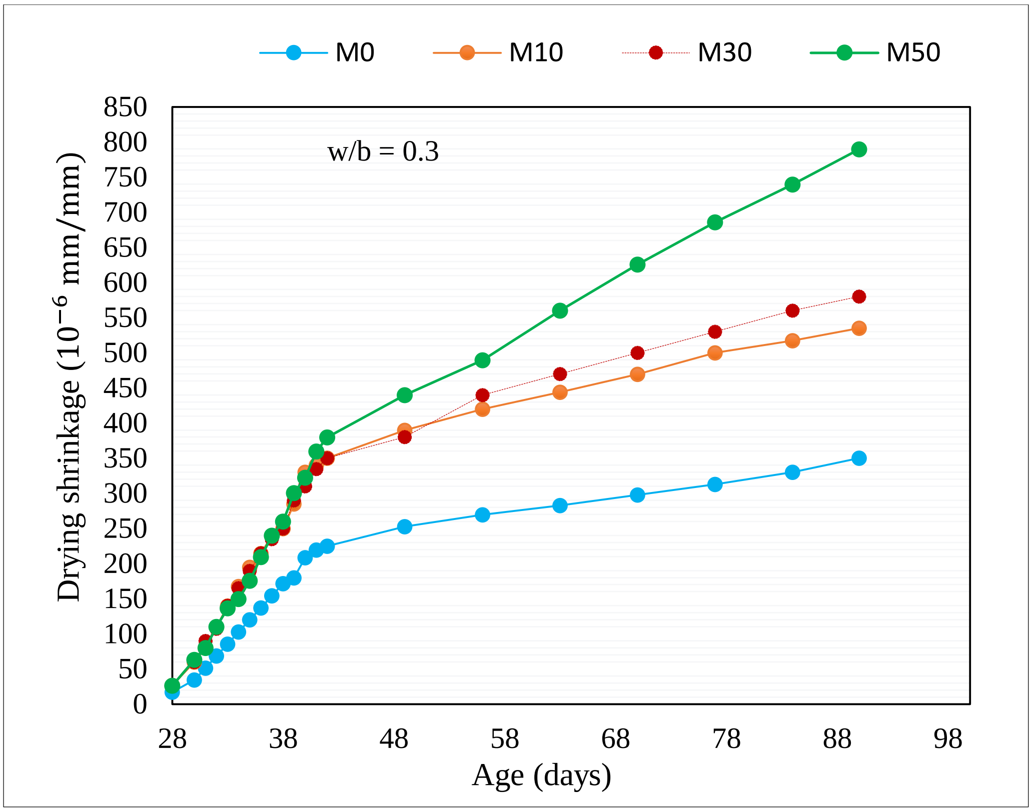
4.5.2.3 Drying shrinkage

Figure 4.23 shows the development of drying shrinkage ($10^{-}6$ mm/mm) of POFA based oil palm shell lightweight concrete for two different w/b ratios of 0.3 and 0.4.

The dying shrinkage with higher POFA content 30-50% was higher compared to mixes with lower POFA content 0-10%. The rate of increment of drying shrinkage value was higher at the initial three weeks but the development rate of drying shrinkage got slower after three weeks and with passing days up to 90-day, the rate of drying shrinkage was decreasing continuously..

For w/b of 0.3, drying shrinkage of 0-50% POFA content ranged 269.5 µm and 490 µm, at 56-day where highest shrinkage was found for 50% POFA content in OPSC. Drying shrinkage mix M0 was 56 % lower than mix M10 which indicated that with 10%

replacement of OPC by POFA accelerated the development of shrinkage in OPSC. But when POFA content was increased gradually 30 to 50% as cement replacement, the shrinkage development rate was lower comparatively. The shrinkage development rate was up to 16.6 % for 10-50% POFA content in concrete mixes (M10, M30 and M50). It can be explained by the extra amount of smaller pores in the hardened POFA based OPS concrete which is dependent on the water content in the concrete. It was reported that lower water content will consequence lesser water lost during the drying process (Altwair, Johari, & Hashim, 2013). On the other hand, the drying shrinkage of concrete is dependent on the magnitude of porosity, size and the continuous capillary system of hydrated cement concrete (Aitcin, Neville, & Acker, 1997). However, the finer water-filled capillary pores seems to be increased with the loss of water content during the drying process which caused the formation of curved menisci. As a result the walls of the pores in concrete are pulled by the water surface tension which develop the internal negative pressure (Altwair et al., 2013). This pressure causes the compressive force that tends to the shrinkage in concrete. This similar condition was also applicable to the increased POFA based OPSC. The continuous drying caused the loss of adsorbed water in the volume of unrestrained POFA based OPSC and the attraction forces between the C-S-H surfaces also increase which tend to shrinkage.



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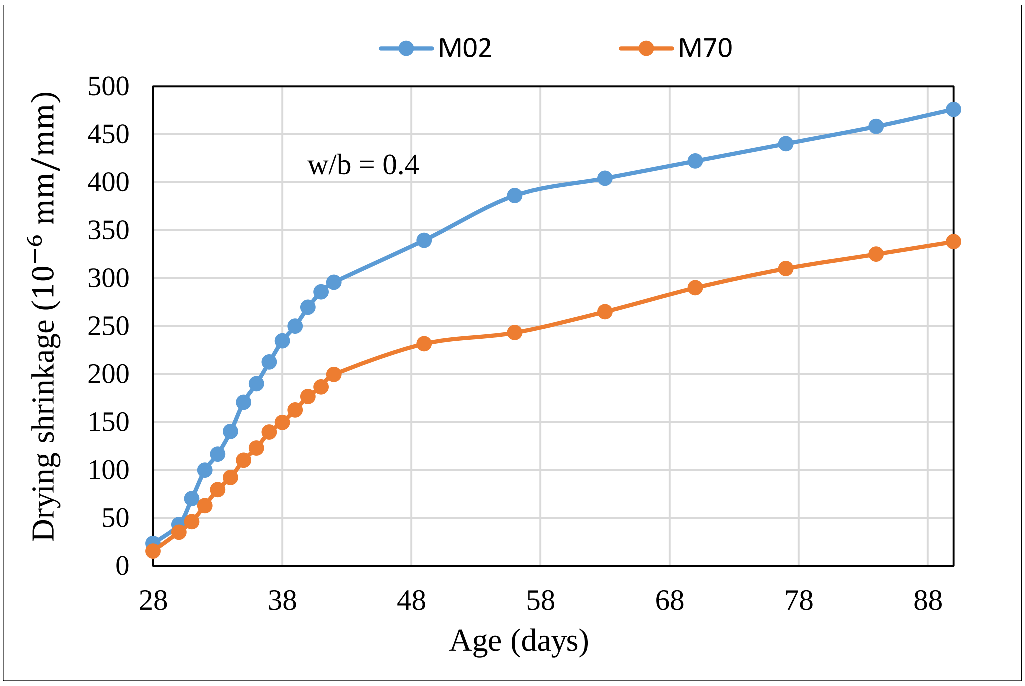


(b)

Figure 4.23: Drying shrinkage of different concrete mix with days for (a) w/b = 0.3 and (b) w/b = 0.4 at 90-day

It was reported that the absorbed water in POFA based OPSC tends to make the adsorbed water layer thicker as there were available pores which ultimately contribute to increase the drying shrinkage. Similar characteristics were also reported for slag and fly ash (Atiş, Kilic, & Sevim, 2004; Dellinghausen, Gastaldini, Vanzin, & Veiga, 2012; Mindess et al., 2003).

Again for w/b of 0.4, the mix M02 (OPSC without POFA) had 59% higher shrinkage value than mix M70 and 43 % higher than mix M0 (w/b of 0.3) with same mix proportion. This could be because of using super-plasticizer in mix M70 where in mix M02, no super-plasticizer was used. It was reported that super-plasticizer effects in improving the dispersion of concrete mix (Shafigh et al., 2014) which quickens the hydration products within very short time. Though super-plasticizer was not used in M02 but because of higher w/b ratio, it acquired drying shrinkage values compared to control mix, M0. Again, in mix M70, the higher POFA content showed greater water demand and consequently absorbed more water than other lower POFA content 0-50% in concrete mix. Considering the excess water demand of mix M70 and to keep the w/b ratio 0.4 fixed, super-plasticizer was increased to highest amount 1.10% of cement content. As POFA has high LOI, the absorbed water forced POFA to act as a filler material which reduces the amount of pore inside. The reduced amount of pores inside caused the lower shrinkage value.

At 90-day, similar pattern of results were found where for w/b of 0.3, the shrinkage of 0-50 percent replacement ranged 350×10^{-6} -789×10^{-6} mm/mm where mix M10 had 53% higher shrinkage value than mix M0 and the shrinkage development rate was up to 48% for POFA based other OPSC (mixes M10, M30 and M50). In this research work it was found that POFA contributed to increase the shrinkage with the increase of curing age and drying process in OPSC.

For w/b of 0.4 at 90-day, the mix M02 had 40% higher shrinkage value than mix M70 which outlined that the shrinkage development rate of OPSC (without POFA) was lower than OPSC with POFA content. Previous researchers (Abdullah, 1996; M. A. Mannan & Ganapathy, 2002) showed that OPSC (without POFA) rendered higher shrinkage value of OPSC than NWC. They explained that the loss of water in early age of plastic concrete and the irregular surface of OPS caused the higher shrinkage.

4.5.2.4 Sulphate attack

It was observed that POFA contributed to slight increase in the weight of OPSC for all cases of curing. This slight mass gaining could be due to the numbers of factors like hydration of cement, increase in absorbed water in specimens and formation of gypsum.

From the past research work, it was found that Magnesium sulphate initially reacts with calcium aluminates and calcium sulphoaluminate which was formed from magnesium hydroxide. The continuous action of magnesium sulphate tends the unstable calcium sulphoaluminate to form gypsum, hydrated alumina and magnesium hydroxide (H. Taylor & Gollop, 1997). It was found that the surface of the POFA based OPSC exposed to the magnesium sulphate solution was free from calcium sulphoaluminate crystals as gypsum formed on surface in large quantity. The white layer on the surface of cube samples is gypsum ($CaSO_4$) which can be shown in **Figure 4.24 .** But in the interior of the sample, the ingestion of solution was slower where both calcium sulphoaluminate and gypsum were present as white crystals and this crystals also increased with the passage of time. This is shown in **Figure 4.25** as white crystals on the broken specimens. This entire process of conversion of calcium hydroxide to gypsum and combination of hydrated calcium aluminate and gypsum in the solution to form calcium sulphoaluminate which increased the volume and weight of the OPSC.

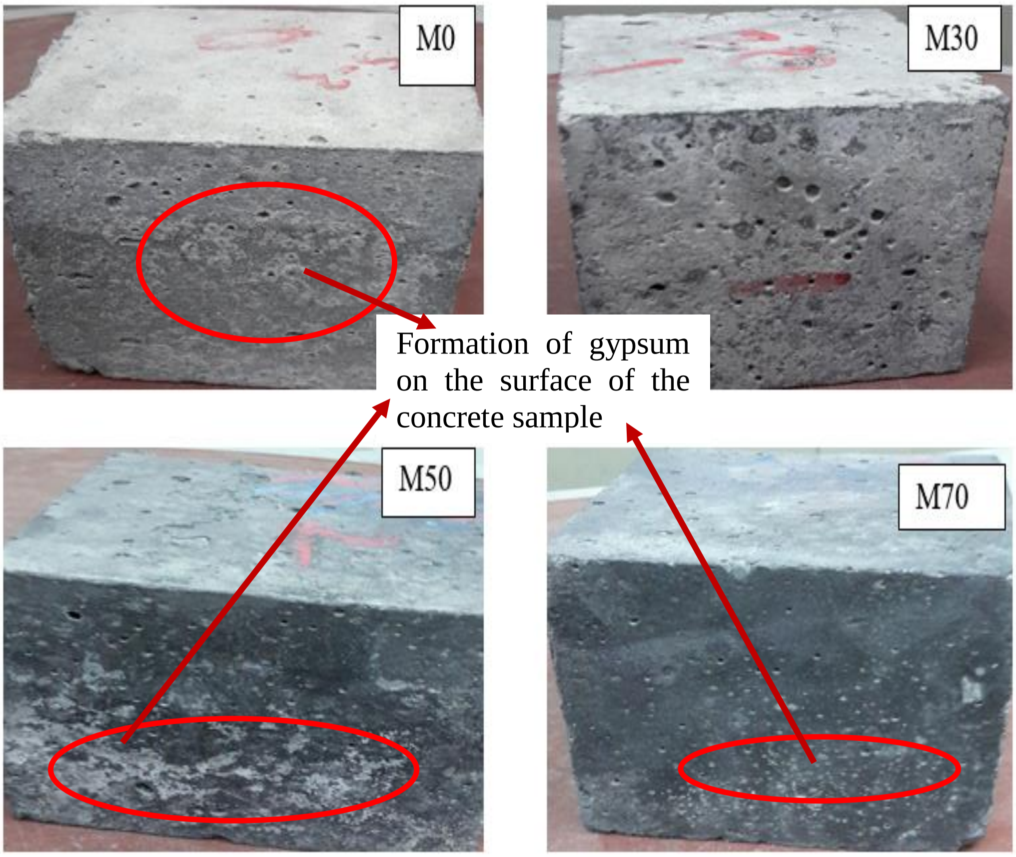


Figure 4.24: Formation of gypsum on the sample surface after withdrawing from sulphate solution and during drying process

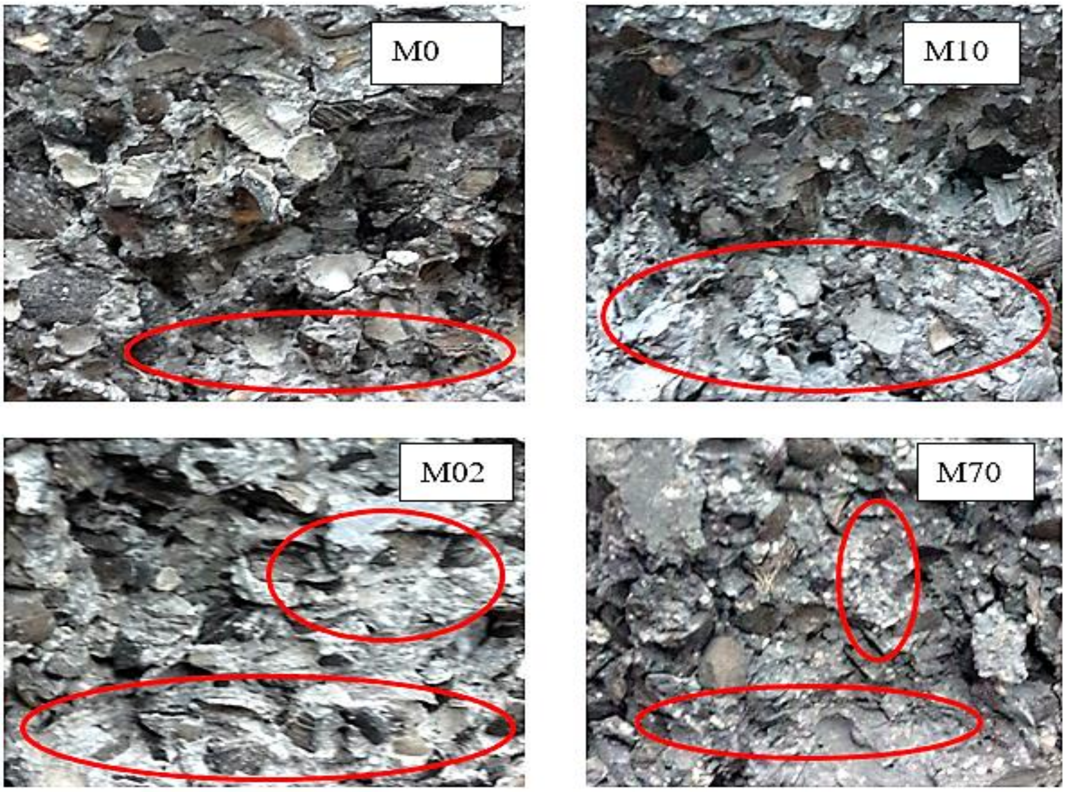


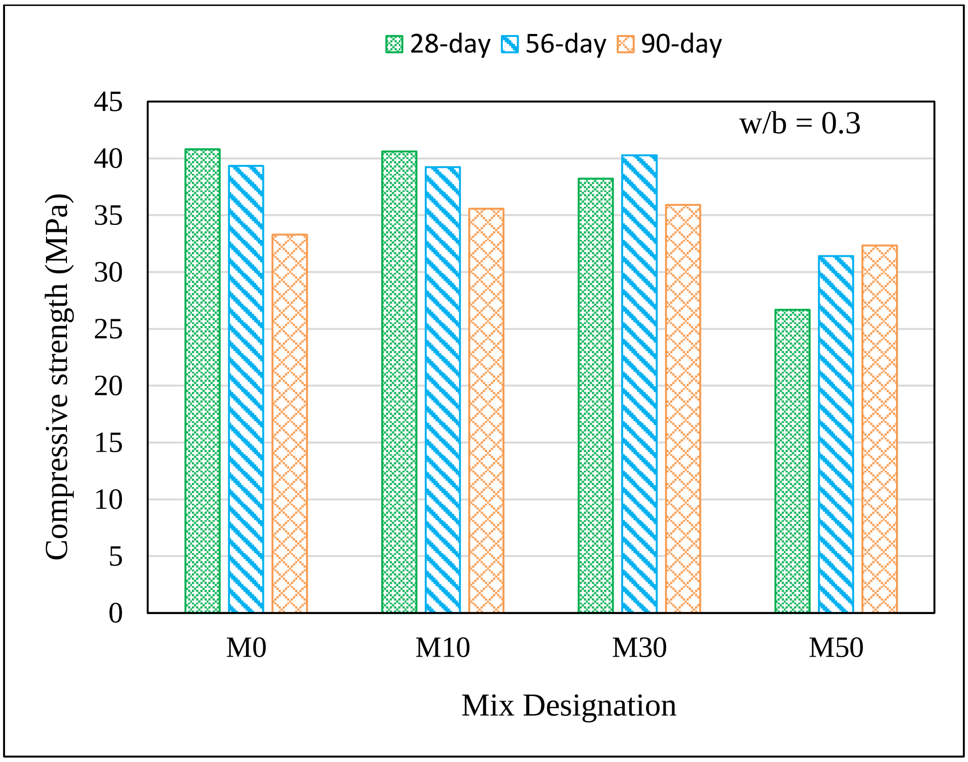
Figure 4.25: Ingestion of magnesium sulphate solution in various POFA based OPSC and formation of calcium sulphoaluminate and gypsum as white crystals (marked places).

Figure 4.26 shows the compressive strength of all mixes for the immersion period of 56- and 90-day in magnesium sulphate solution. The 28-day compressive strength of control specimens was taken from those specimens which were not soaked in magnesium sulphate solution as reference strength.

At 56-day for w/b of 0.3, the strengths for both mix M0 and M10 were found to be decreased after the immersion in magnesium sulphate solution with respect to 28-day water curing samples compressive strength. It was reported that the sulphate attack in OPC concrete is determined by the chemical reaction between sulphate ions and the hardened cement concrete (Rasheeduzzafar, Al-Gahrani, Al-Saadoun, & Bader, 1990; Thorvaldson, 1952). This reaction produces ettringite and gypsum. At the same time during the sulphate attack, the magnesium ions attacks C-S-H when CH is depleted (Bonen, 1992; Bonen & Cohen, 1992) and this attacks causes the decalcification and precipitation of C-S-H by gypsum. The binding capacity of C-S-H is affected by decalcification of C-S-H which leads to the loss of adhesion and strength in concrete(Gollop & Taylor, 1992, 1994). As in mix M0 and M10, the amount of POFA was nil or very low and the amount of OPC was higher which caused the decalcification of C-S-H consequently as the availability of CH was higher. But the solution could not affect much for 30-50% replacement of OPC by POFA in OPSC. This might be due to the pozzolanic reaction in the concrete with higher POFA content and produced more calcium silicate hydrate gel which prevent calcium hydroxide to react with magnesium sulphate (S. Bamaga et al., 2013).

For w/b of 0.4 at 56-day, the compressive strength of mix M02 and M70 were higher comparatively than that of 28-day strength of water curing samples. In this case, the strength of mix M02 (without POFA) was not affected much by the sulphate solution whereas the mix M0 (w/b of 0.3) was affected by the solution. This might be due to increased w/b of 0.4 for mix M02 where the extra water accelerated the formation of C-S-H than mix M0. As a result the decalcification of C-S-H could not affect much on the strength for mix M02 comparing with M0.

Again at 90-day for w/b of 0.3, the compressive strength of 0-30% POFA based OPSC gradually decreased with respect to 28-day and 56-day compressive strength. This is due to the formation of gypsum on the surface of the samples in higher quantity than 28- and 56-day samples as seen in the **Figure 4.24**. This higher formation of gypsum caused more decalcification of C-S-H which affected the strength up to 30% replacement of cement. But for 50% POFA based OPSC, the 90-day compressive strength was higher than both 28- and 56-day compressive strength. This could be due to pozzolanic reaction where the formation of C-S-H accelerated with long curing duration and also with the higher POFA content, the higher silica content in higher POFA based OPSC protected the concrete from sulphate attack. However, for w/b of 0.4 at 90-day, the compressive strength of mix M02 was lower than both 28- and 56-day strength. This could be due to the formation of higher amount of gypsum on the surface of the sample for long immersion in the solution and the continuous decalcification of C-S-H. But the 90-day strength of mix M70 was lower than 56-day strength and higher than 28-day strength. Though the amount of POFA was higher in mix M70 but with the increased amount of POFA, there was not much availability of CH as the amount of OPC was very low. As a result, there was not much decalcification of C-S-H. On the other hand, because of the pozzolanic reaction the formation of C-S-H was also increased and that's why the 90-day strength was higher than 28-day strength after decalcification of C-S-H.



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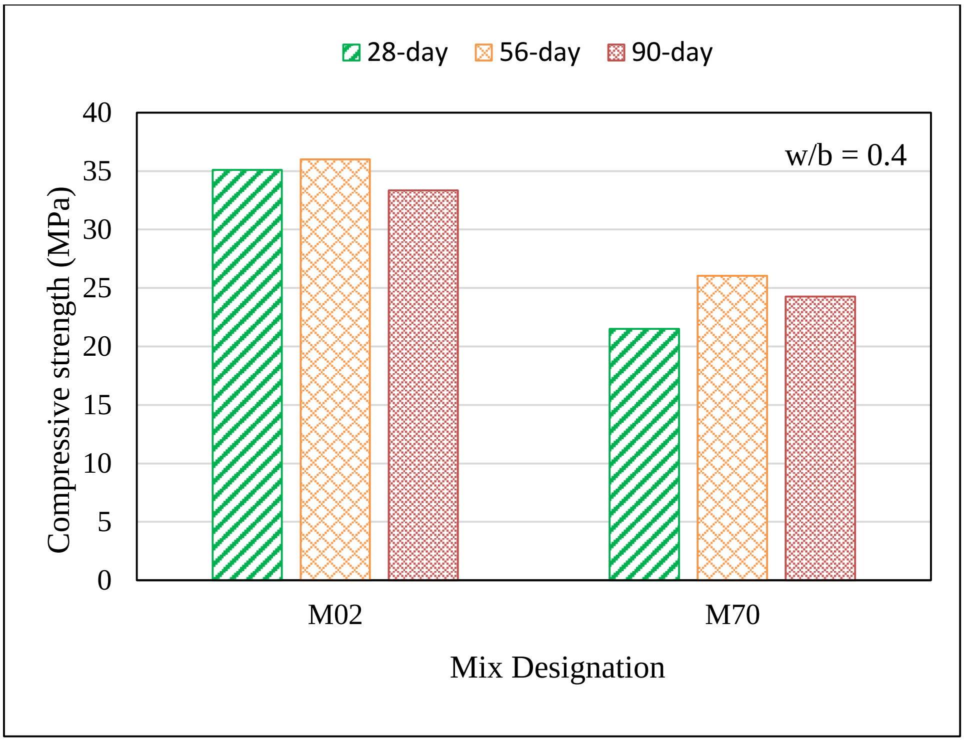


(b)

Figure 4.26: Compressive strength of different mix for the immersion period of 28-, 56- and 90-day in sulphate solution where (a) w/b =0.3 and (b) w/b = 0.4

Table 4.10 shows the variation of compressive strength between the sulphate solution and water curing samples for 56- and 90-day. In case of w/b of 0.3 at 56-day, it was found that the compressive strength of sulphate affected samples were 1-6% lower than the samples of water cured where the highest reduction about 6% occurred for 10% POFA based OPSC. For mix M30, the strength reduction was very low which could be negligible. With further increased POFA based mix M50, the strength reduction was only 1 %. It was obvious that Magnesium sulphate solution could not affect much on the strength of the higher POFA based OPSC. The compressive strength was also not affected much by the Magnesium sulphate solution when the w/b was increased to 0.4. For w/b of 0.4, the strength reduction for mix M02 and M70 were also much smaller, which were negligible.

Table 4.10: Reduction of compressive strength between sulphate solution and water curing of various mixes for 56- and 90-day

w/b	Mix	56-day compressive strength (MPa)			90-day compressive strength (MPa)		
		Immersion in sulphate Solution	Fully Water cured	Reduction in compressive strength (%)	Immersion in sulphate Solution	Fully Water Cured	Reduction in compressive strength (%)
0.3	M0	39.35	41.15	4.38	33.30	41.70	20.18
	M10	39.20	41.85	6.30	35.60	42.00	15.27
	M30	40.25	40.30	0.041	35.90	37.00	2.93
	M50	31.40	31.75	1.10	32.30	37.30	13.26
0.4	M02	35.35	36.00	1.80	33.35	35.85	7.00
	M70	26.00	26.20	0.60	24.25	27.60	12.10

Again for 90-day, the rate of reduction of compressive strength was higher than of 56-day. For w/b of 0.3, the compressive strength reduced 2-20% and the highest reduction was found for OPSC without POFA (mix M0). The strength reduction for mix M10 was lower than mix M0 which denoted that with the passing time, the POFA based OPSC had good resistance against sulphate attack.

For w/b of 0.4 at 90-day, the reduction rate of strength for mix M02 and M70 were also increasing at 90-day and this time the compressive strength of M70 was higher than M02. The rate of strength reduction for mix M02 (w/b of 0.4) was lower than mix M0 (w/b of 0.3) and mix M70 (w/b of 0.4) had also lower strength reduction rate than mix M50 (w/b of 0.3).

4.5.2.5 Rapid chloride penetration test (RCPT)

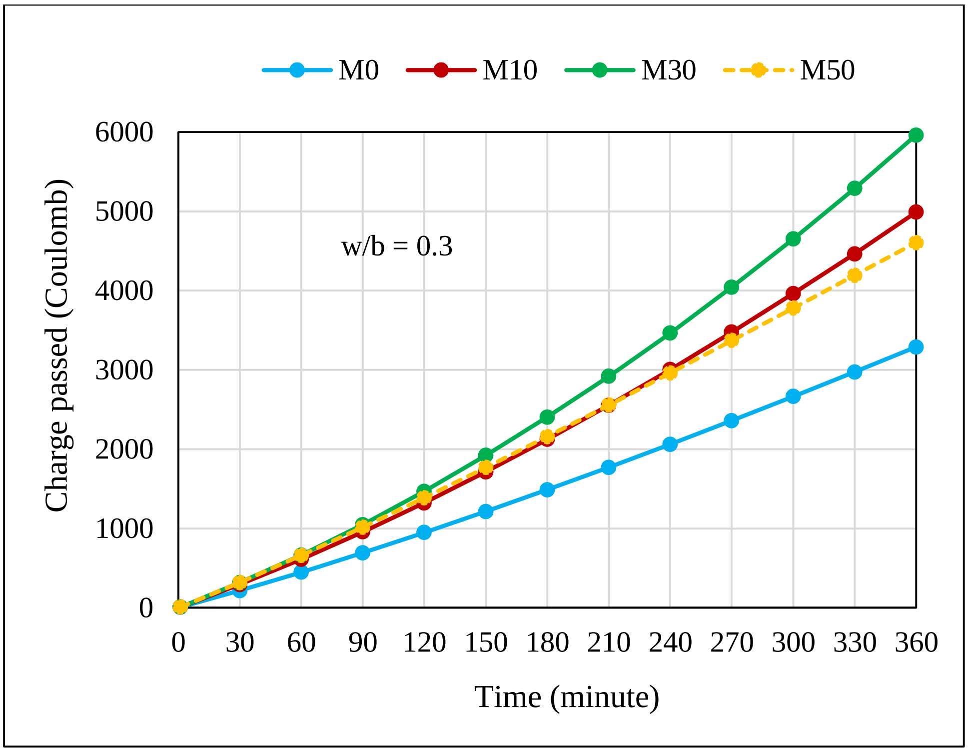
Figure 4.27 shows the RCPT values obtained from different POFA based OPSC mix at 90-day. In this research work, RCPT was performed on 90-day specimens as it was reported that POFA showed good resistance to chloride penetration at 90-day than 28-day (Prinya Chindaprasirt & Rukzon).

The RCPT values of 0% to 50% POFA based OPSC ranged from about 3288 to 5960 coulombs, where the highest charge passed for 50% replacement of OPC by POFA. It was reported that the RCPT values ranged 3,581 to 4,549 coulombs and 3500 to 4250 coulombs of 28- and 90-day samples, respectively, for the OPSC concrete where OPS was used as a replacement of conventional coarse aggregate (D. Teo et al., 2010). The lowest RCPT value was found for mix M0 and with the increase in POFA content from 10 to 50% in OPSC, the RCPT values were found to be increased. The highest RCPT value was found for mix M30 which was about 81% higher than mix M0 and the other POFA based OPSC mix M10 and M50 were about 51% and 40% higher than mix M0 (OPSC without POFA content), respectively.

In this research work for w/b of 0.3, according to ASTM C 1202(C-05, 2005), the mix M0 was moderate concrete in chloride ion penetrability and other 10% to 50% POFA based OPSC had high chloride ion penetrability. From the previous studies, it was found that POFA, as pozzolanic materials helped to lower the chlorine ion penetration throughout the concrete (Prinya Chindaprasirt, Chotetanorm, & Rukzon, 2010; Goyal et al., 2007; Isaia et al., 2003; Li & Roy, 1986; P. Mehta, 1987). They mentioned that POFA is a filler material at high content in concrete as the fineness of POFA is higher than OPC and the LOI in POFA is also higher than OPC. Consequently, at higher POFA content the pore inside the concrete structure decreases because of the densification. On the other hand POFA is higher in alumina and silica content which also helps in resisting the chloride ion penetration. It was reported that the alumina content reacts with the calcium hydroxide and formed additional calcium aluminate hydrate. The chloride ion reacted with CAH (calcium aluminate hydrates) and formed Fridel’s salt which reduces chloride ion penetration (Rukzon & Chindaprasirt, 2014). But in this research work, with the increase of POFA content 10-30%, the supply of CH also decreased as the amount of OPC was also not much available and this hampered the formation of CAH (Alexander, Beushausen, Dehn, & Moyo, 2008). It was found that with the higher POFA content the amount of charge passed increased. This might be also due to the increased pore inside the concrete with the higher POFA content in OPSC. This increased pore inside the concrete accelerates the penetration of chloride ion and caused the higher charge passing through the sample. It was reported that for the lightweight concrete using OPS as replacement of conventional coarse aggregate caused the higher RCPT values (D. Teo et al., 2010). This could be explained by the interfacial transition zone of OPS and the matrix between the POFA and OPS inside the concrete. With the higher amount of POFA, the bonding between the OPS and POFA weakened. In case of OPSC, there are interconnection of along the interfacial zone through which chloride ion may pass through. In addition, there are also small capillary path in these interconnected area which allow the chloride ion to travel through the matrix. Another researcher also showed that the difference in electrical conductivity between the fibre and matrix might also cause the chloride ion penetration (El-Dieb, 2009). However, in this research work, mix M50 had 8% and 29% lower amount of passing charge than mix M10 and M30, respectively.

This phenomenon indicated that although the bond between POFA and OPS was getting weaker but the filler effect of POFA was also increasing after 30% replacement of OPC by POFA in OPSC.

Again for w/b of 0.4, the RCPT values were 5453 coulombs and 3510 coulombs for mixes M02 and M70, respectively. The amount of passing charge for the mix M02 was 65% higher than mix M0 (w/b of 0.3) - both mixes are control mixes without POFA. Similar trend was found by another study where they showed that for POFA/OPC of 0 and w/b of 0.3 , the RCPT value was about 5000 coulombs and when w/b was increased to 0.38, the RCPT value was found about 7000 coulombs at 90-day(Altwair, Johari, & Hashim, 2014). This could be due to the increased w/b which helped in increasing the amount of passing the charge through concrete. But in case of mix M70, the amount passing charge was 55% lower than mix M02. It was found that with the increased amount of w/b and higher POFA content in concrete mix the RCPT values decreased (Altwair et al., 2014). This could be due to the filler effect of POFA with increased w/b ratio and densification. As a result the penetration of chloride ion reduced as well as the amount of passing charge. This reason was more justified when mix M70 (w/b of 0.4) had 31% lower amount of passing charge than mix M50 (w/b of 0.3) though w/b was increased for mix M70.



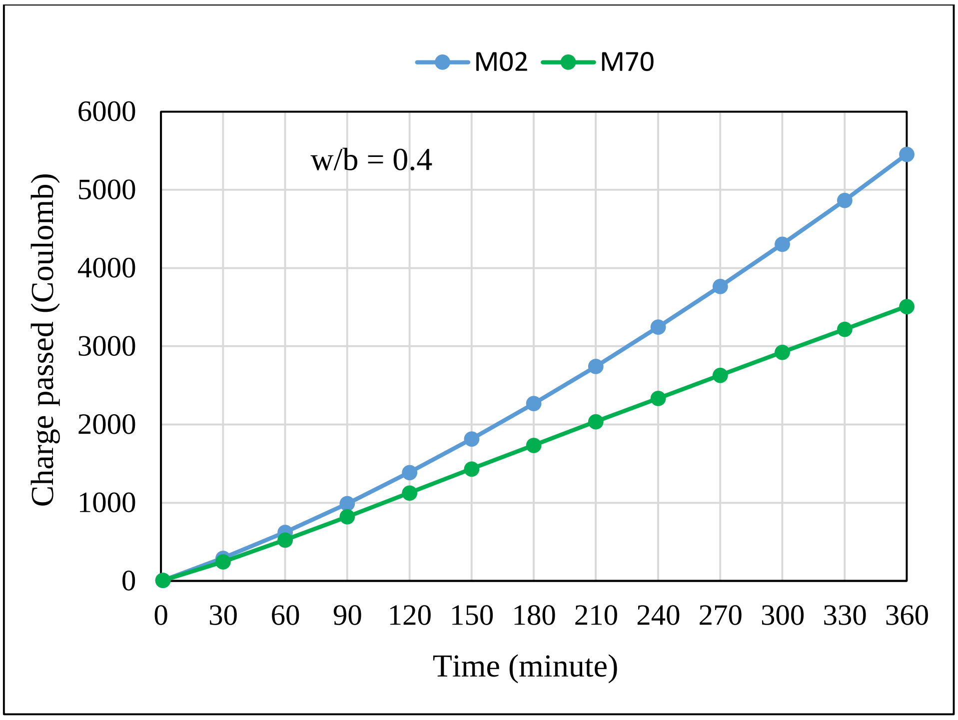


Figure 4.27: Variation of RCPT values for POFA based OPSC with time for different concrete mix designation at 90-day

Table 4.11 shows the development of temperature with respect to time elapsed for different POFA based concrete mix. It was found that the temperature continued to increase as the time progressed. High temperatures were measured on the respective samples. In this research work for w/b of 0.3, the highest temperature was found for the mix M30 and the other POFA mixes M10 and M50 showed higher temperature compared to mix M0. But the mix M0 without POFA showed the lowest heat. It was reported that for the lower quality of concrete in consideration of high strength tends to acquire more heat as the temperature development is connected to the product of the voltage and the current (Stanish, Hooton, & Thomas, 1997). They mentioned that the greater current at a provided voltage passed through the lower quality of concrete (concrete with lower strength) which caused the higher heat energy to be formed. This high heat energy leads to the increment in the amount of charge passed through the concrete.

Again for w/b of 0.4, the final temperature for mixes M02 and M70 was also high where M70 gained lower heat than mix M02. This might be due to the high content of POFA in OPSC where POFA acted as filler material for mix M70 where the higher POFA content reduced the voids inside because of its fineness compared to OPC (Pushpakumara, De Silva, & De Silva, 2013) and also for long term water curing, the adequate hydration process helped to form enough C-S-H which reduced the pore inside the concrete. It was found that the temperature for mix M02 (w/b of 0.4) was higher than that of mix M0 (w/b of 0.3). As these two mixes were without POFA based OPSC, increasing w/b ratio could be the reason for gaining higher temperature.

Table 4.11: Development of temperature at initial and final time for different POFA based OPSC

w/b	Mix	Temperature, (°C)			
		Initial (1 min)		Final(360 min)	
		NaCl cell	NaOH cell	NaCl cell	NaOH cell
0.3	M0	29.4	29.2	48.0	47.5
	M10	29.4	29.0	57.5	57.1
	M30	29.4	29.3	63.8	63.8
	M50	29.2	29.5	54.6	52.0
0.4	M02	29.3	29.6	58.2	56.1
	M70	29.1	29.9	49.8	46.1

Figure 4.28 shows the RCPT test and the physical appearance of the samples after 6 hours of testing and the formation of chloride on the surface of the specimens were also marked. It was found that there was not much sign of chloride formation on the surface of M0 but with the POFA increment the formation of chloride was found to be more obvious on the surface of the concrete mixes. The formation of more yellowish white colour was found for the specimens of mix M30. Considering the above discussion, mix M30 could be lower quality type of concrete than other POFA based OPSC mix.

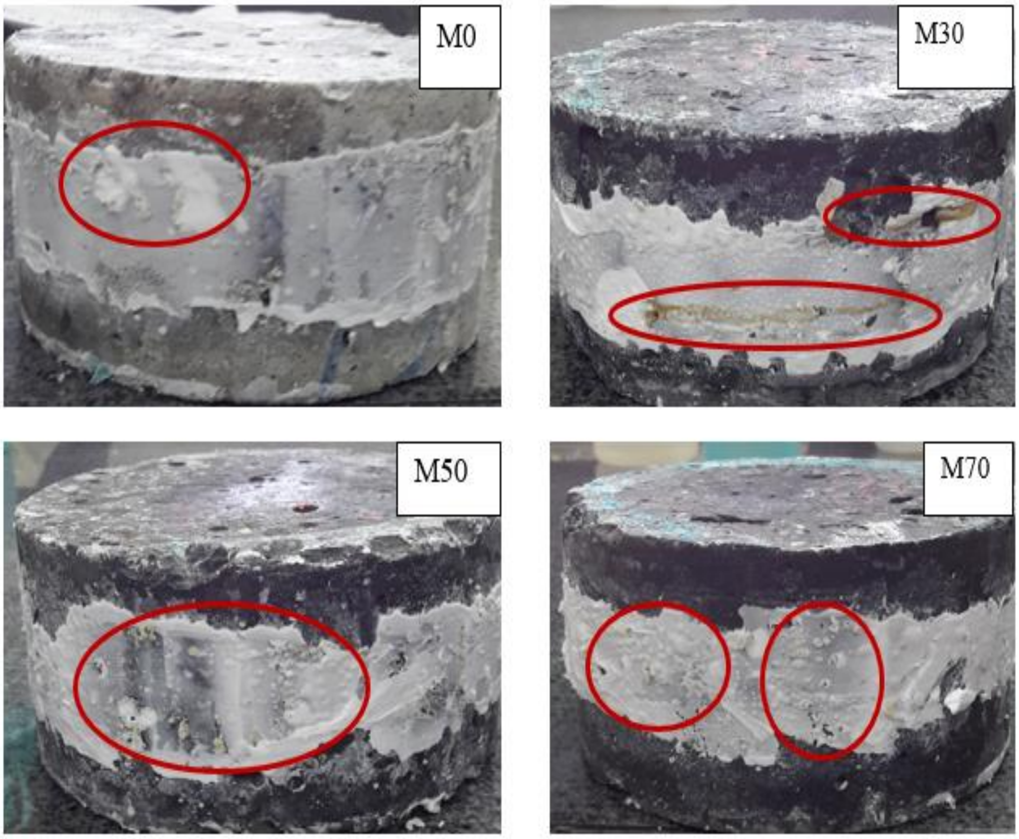


Figure 4.28: RCPT test with ASTM C1202 (2005) – physical appearance of samples after 6 hours of chlorine ion penetration

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusions

The main objective of this research is to investigate the mechanical and durability properties of POFA based oil palm shell lightweight concrete. To achieve thesis aims, the fresh and hardened concrete properties for 0% to 25% and some of the durability properties for 0% to 70%replacement of OPC by POFA in OPSC had been investigated. The fresh concrete properties like slump, vebe second, compaction factor and wet density were introduced. To evaluate the hardened concrete and some durability properties, tests such as ultrasonic pulse velocity, compressive strength, tensile strength, flexural strength, modulus of elasticity and water absorption, sorptivity, drying shrinkage, sulphate attack and rapid chloride penetration test were performed. Based on the research work, the following conclusions were drawn:

5.2 The fresh concrete Properties

5.2.1 The slump test for 0-25% (w/b of 0.3) and 0-70% (w/b of 0.4) POFA content in OPSC, as replacement of OPC were performed. It was found that the slump values were ranged 35-55 mm and 25-45 mm for 0-25% and 0-50% replacement, respectively, which were comparatively lower than the slump value 50-75 mm of structural lightweight concrete. For the maximum 70% replacement of OPC by POFA, OPSC with w/b ratio of 0.4 produced a slump value of about 180 mm.

5.2.2 The maximum vebe second, wet density and compaction factor were found 10.92 second, 1984 kg/m^3 and 0.95,respectively for the mix M25, M10 and M10, respectively.

5.3 The Mechanical properties

5.3.1 A non-destructive test ultrasonic pulse velocity (UPV) was performed for three different curing conditions (AC, FWC and PWC) while investigation on the mechanical properties of 0-25% replacement of OPC in OPSC by POFA. It was found that UPV values ranged 3.40-4.15 km/s which could be designated as good quality type structural lightweight concrete. The highest UPV value were found maximum for 5% replacement of OPC by POFA for all curing conditions.

5.3.2 Compressive strength for POFA based OPSC was lower at the initial curing condition but found to increase with later curing age. For concrete mix of 0-25% POFA content, in most of the cases higher compressive strength was achieved at the curing age of 28 days. 10% replacement of OPC by mass with POFA produced the highest compressive strength for both water and initial water curing conditions and for air curing condition 15% POFA content was found to be the highest compressive strength. POFA accelerated the strength up to 15% replacement but later with 20-25% higher POFA content, the strength was lower in comparison with OPSC without POFA. Again for the samples of 0-70% POFA content in OPSC the highest 90-day compressive strength was obtained for the mix with 10% replacement of OPC by POFA. At 28-day, the highest strength was found for 10% replacement and the development of strength was lower than 90-day because of slow pozzolanic reaction. It was observed that for the highest replacement of 70% of OPC by POFA, the strengths obtained were 21 MPa and 27 MPa for 28-day and 90-day, respectively, which were in the range of minimum required cylindrical compressive strength 17 MPa for the SLWC as specified in ASTM C 330 (213, 2003).

5.3.3 The highest splitting tensile strength value was found for 5% POFA content in OPSC and it was observed that the higher the POFA content lower the splitting tensile strength for all curing conditions. In this study, the splitting tensile strength values varied between 2.55 and3.97 MPa for all curing conditions and this range was more than the minimum required splitting strength of 2.00 MPa for SLWC as stated in ASTM C 330 (213, 2003).

5.3.4 The 28-day flexural strength of POFA based OPSC ranged 3-6.5 MPa for all type of curing conditions which was within the flexural strength range of 2.13-4.93 MPa for SLWC. It was observed that the flexural strength was decreasing with the increase of POFA content in OPSC.

5.3.5 The 28-day modulus of elasticity value under AC condition was about 11-12.5 GPa whereas the range of 12.75-15.45 GPa and 12-13.80 GPa were found for FWC and PWC condition, respectively. The modulus of elasticity of this research work was found to be within the range 10-24 GPa of structural lightweight aggregate concrete.

5.4 The Durability properties

5.4.1 The water absorption of POFA based OPSC increased with increase of POFA content in OPSC. When the w/b ratio was increased from 0.3 to 0.4, the water absorption for w/b of 0.4 was higher than 0.3 in comparison between same concrete proportions of 0% POFA content in OPSC.

5.4.2 The 28-day sorptivity varied 0.06 to 0.17 mm/√min for w/b of 0.3 and in case of w/b of 0.4, the sorptivity values ranged in between 0.12 and 0.19 for 0% and 70% replacement of OPC, respectively. It was observed that POFA contributed to increase the sorptivity values and the increased w/b also accelerated the sorptivity values. The sorptivity value for 90-day was comparatively lower than 28-day.

5.4.3 The dying shrinkage was increasing with the increase of POFA content in OPSC for w/b of 0.3 and for w/b of 0.4, the drying shrinkage for 70% POFA content was lower than the control mix (OPSC without POFA). The rate of increment of drying shrinkage value was rapid during first three weeks but it started to slowing down after 3 weeks and at 90-day, the rate was very low.

5.4.4 The effect of sulphate attack was found up to 10% replacement of OPC by POFA for w/b of 0.3. But the solution could not effect much on 30-50% (w/b of 0.3) replacement of OPC by POFA in OPSC and also for 0% and 70% replacement with w/b ratio of 0.4.

5.4.5 The rapid chloride penetration in POFA based OPSC was increasing with the increase of POFA content compared to the control mix M0 (0% POFA content) for w/b ratio of 0.3. But for w/b of 0.4, 70% POFA based OPSC showed lower RCPT values than the control mix M02.

As aggregate covers about 60–80% of the volume of the concrete, the replacement of industrial waste as full or partial replacement for conventional aggregate may reduce energy used in the quarrying industries, cost effectiveness and modification of the environmental effect through construction diligence. In view of the current criteria for a sustainable related environmental benefits, green building rating systems, infrastructure and making concrete using industrial wastes like POFA and OPS as aggregate can benefit the concrete industry.

5.5 Recommendation for further application

Though various and thorough evaluations had been made in this study, the effectiveness and opportunity of POFA as cementitious materials has to be further researched.

1. The findings from this research about the mechanical and durability properties of POFA based OPSC, however, have flagged up a number of new questions for further research.

2. As POFA is agro-based industrial waste material, its chemical and physical properties may vary depending on the source and process. It was found that standardizing the composition of the POFA is complex. POFA has high loss of ignition (LOI) and its fineness is higher than OPC. Therefore, detailed further study is required to find out the chemical composition and develop procedural guideline for local POFA from different regions in Malaysia in order to prepare the eco-friendly and cost-effective POFA based structural lightweight concrete.
3. More durability tests have to be done for mixes with high POFA contents. It has been observed that the bond between the interfacial transition zone of the lightweight aggregate OPS and the binding matrix (cement + POFA) was weak because of the surface texture of OPS at higher percentage replacement of OPC by POFA. To overcome this problem, further research work is needed to find an appropriate way to process OPS as coarse aggregate.
4. The cost effectiveness of POFA based concrete with other structural lightweight concrete has to be investigated.
5. Further investigation on the use of POFA based concrete using both lightweight and normal weight aggregates is required for structural application.

REFERENCES

ASTM C 143, (2010). Standard Test Method for Slump of Hydraulic-Cement Concrete: ASTM International.

ACI 209, (1982). Prediction of creep, shrinkage, and temperature effects in concrete structures. ACI Special Publication, 76.

ASTM C 330, (2003). Standard Specification for Lightweight Aggregates for Structural Concrete.

Abdullah, A. (1996). Palm oil shell aggregate for lightweight concrete. *Waste material used in concrete manufacturing*, 624-636.

Ahmed, M. S., Kayali, O., & Anderson, W. (2008). Chloride penetration in binary and ternary blended cement concretes as measured by two different rapid methods. *Cement and Concrete Composites, 30*(7), 576-582.

Aitcin, P.-C., Neville, A., & Acker, P. (1997). Integrated view of shrinkage deformation. *Concrete International, 19*(9), 35-41.

Al-Amoudi, O. S. B. (2002). Attack on plain and blended cements exposed to aggressive sulfate environments. *Cement and Concrete Composites, 24*(3), 305-316.

Aldahdooh, M., Bunnori, N. M., & Johari, M. M. (2014). Influence of palm oil fuel ash on ultimate flexural and uniaxial tensile strength of green ultra-high performance fiber reinforced cementitious composites. *Materials & Design, 54*, 694-701.

Alengaram, U., Jumaat, M., & Mahmud, H. (2008). Influence of cementitious materials and aggregates content on compressive strength of palm kernel shell concrete. *J Appl Sci, 8*(18), 3207-3213.

Alengaram, U. J., Al Muhit, B. A., & bin Jumaat, M. Z. (2013). Utilization of oil palm kernel shell as lightweight aggregate in concrete–a review. *Construction and Building Materials, 38*, 161-172.

Alengaram, U. J., Jumaat, M., & Mahmud, H. (2008). *Influence of sand content and silica fume on mechanical properties of palm kernel shell concrete.* Paper presented at the International conference on construction and building technology ICCBT.

Alengaram, U. J., Jumaat, M. Z., & Mahmud, H. (2008). Ductility behaviour of reinforced palm kernel shell concrete beams. *European Journal of Scientific Research, 23*(3), 406-420.

Alexander, M. G., Beushausen, H.-D., Dehn, F., & Moyo, P. (2008). *Concrete Repair, Rehabilitation and Retrofitting II: 2nd International Conference on Concrete Repair, Rehabilitation and Retrofitting, ICCRRR-2, 24-26 November 2008, Cape Town, South Africa*: CRC Press.

Altwair, N. M., Johari, M., & Hashim, S. F. S. (2013). *Shrinkage Characteristics of Green Engineered Cementitious Composites with Varying Palm Oil Fuel Ash Contents and Water-Binder Ratios.* Paper presented at the Advanced Materials Research.

Altwair, N. M., Johari, M. M., & Hashim, S. F. S. (2014). Influence of treated palm oil fuel ash on compressive properties and chloride resistance of engineered cementitious composites. *Materials and structures, 47*(4), 667-682.

ASTM C469, (2001). 469. *Standard test method for static modulus of elasticity and Poisson's ratio of concrete in compression. West Conshohochen: American Society for Testing and Materials*.

Atiş, C. D., Kilic, A., & Sevim, U. K. (2004). Strength and shrinkage properties of mortar containing a nonstandard high-calcium fly ash. *Cement and Concrete Research, 34*(1), 99-102.

Awal, A., & Nguong, S. K. (2010). A short-term investigation on high volume palm oil fuel ash (pofa) concrete. *Proceedings of the 35th Conferenece on our World in Concrete and Structure*, 185-192.

Awal, A. A., & Hussin, M. W. (1997). The effectiveness of palm oil fuel ash in preventing expansion due to alkali-silica reaction. *Cement and Concrete Composites, 19*(4), 367-372.

Babu, K. G., & Babu, D. S. (2003). Behaviour of lightweight expanded polystyrene concrete containing silica fume. *Cement and Concrete Research, 33*(5), 755-762.

Bamaga, S., Hussin, M., & Ismail, M. A. (2013). Palm Oil Fuel Ash: Promising supplementary cementing materials. *KSCE Journal of Civil Engineering, 17*(7), 1708-1713.

Bamaga, S. O., Ismail, M. A., & Hussin, M. W. (2011). Chloride resistance of concrete containing palm oil fuel ash. *Concrete Research Letters, 1*(4), 158-166.

Basri, H., Mannan, M., & Zain, M. (1999). Concrete using waste oil palm shells as aggregate. *Cement and Concrete Research, 29*(4), 619-622.

Bazant, Z. P., & Kaplan, M. F. (1996). *Concrete at high temperatures: material properties and mathematical models*: Longman Group Limited.

Bazant, Z. P., & L'Hermite, R. (1988). *Mathematical modeling of creep and shrinkage of concrete*: Wiley Chichester.

Béton, C. e.-i. d. (1993). *CEB-FIP Model Code 1990: Design Code*: FIB-Féd. Int. du Béton.

Bonen, D. (1992). Composition and Appearance of Magnesium Silicate Hydrate and Its Relation to Deterioration of Cement-Based Materials. *Journal of the American Ceramic Society, 75*(10), 2904-2906.

Bonen, D., & Cohen, M. D. (1992). Magnesium sulfate attack on Portland cement paste-I. Microstructural analysis. *Cement and Concrete Research, 22*(1), 169-180.

Brooks, J. (2005). 30-year creep and shrinkage of concrete. *Magazine of Concrete Research, 57*(9), 545-556.

ASTM C 642, (2001). *Standard Test Method for Density, Absorption, and Voids in Hardened Concrete*.

ASTM C1202, (2005). Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration.

Chandra, S., & Berntsson, L. (2002). *Lightweight aggregate concrete*: Elsevier.

Chindaprasirt, P., Chotetanorm, C., & Rukzon, S. (2010). Use of palm oil fuel ash to improve chloride and corrosion resistance of high-strength and high-workability concrete. *Journal of Materials in Civil Engineering, 23*(4), 499-503.

Chindaprasirt, P., Homwuttiwong, S., & Jaturapitakkul, C. (2007). Strength and water permeability of concrete containing palm oil fuel ash and rice husk–bark ash. *Construction and Building Materials, 21*(7), 1492-1499.

Chindaprasirt, P., & Rukzon, S. Strength and chloride resistance of the blended Portland cement mortar containing rice husk ash and ground river sand. *Materials and structures*, 1-7.

Cohen, M. D., & Mather, B. (1991). Sulfate attack on concrete: research needs. *ACI Materials Journal, 88*(1).

Çolak, A. (2003). Characteristics of pastes from a Portland cement containing different amounts of natural pozzolan. *Cement and Concrete Research, 33*(4), 585-593.

ACI Committee, (1977). Comittee 211–ACI 211.3 R-97. *Guide of Selecting Proportiones for No-Slump Concrete*.

ACI Committee, (1995). Building code requirements for structural concrete. *Standard ACI 318R–95. American Concrete Institute, Farmington Hills, Mich*.

Davidovits, J. (1999). *Chemistry of geopolymeric systems, terminology.* Paper presented at the Geopolymer.

De Schutter, G., & Audenaert, K. (2004). Evaluation of water absorption of concrete as a measure for resistance against carbonation and chloride migration. *Materials and structures, 37*(9), 591-596.

Dellinghausen, L., Gastaldini, A., Vanzin, F., & Veiga, K. (2012). Total shrinkage, oxygen permeability, and chloride ion penetration in concrete made with white Portland cement and blast-furnace slag. *Construction and Building Materials, 37,* 652-659.

Dias, W. (2000). Reduction of concrete sorptivity with age through carbonation. *Cement and Concrete Research, 30*(8), 1255-1261.

Domone, P., & Illston, J. (2010). *Construction materials: their nature and behaviour*: CRC Press.

El-Dieb, A. S. (2009). Mechanical, durability and microstructural characteristics of ultra-high-strength self-compacting concrete incorporating steel fibers. *Materials & Design, 30*(10), 4286-4292.

BS EN, (2002). 12390-3: 2002. *Standard Test Method for Compressive Strength of Cement Mortar*.

BS EN, (2009a). 12390-6 (2000). Testing hardened concrete: Tensile splitting strength of test specimens. *British Standards Institution. London, UK.*

BS EN, (2009b). 12390–5 Testing hardened concrete–Part 5: Flexural strength of test specimens. *British Standards Institution-BSI and CEN European Committee for Standardization*.

Fauzi, M. (1995). *The study on the physical properties of surface layer concrete under the influence of medium temperature environments.* Ph. D. Thesis, Kyushu University, Japan.

Feldman, R. F., Chan, G. W., Brousseau, R. J., & Tumidajski, P. J. (1994). Investigation of the rapid chloride permeability test. *ACI Materials Journal*, *91*(2), 246-255.

Ferraris, C. F., Stutzman, P. E., & Snyder, K. A. (2006). Sulfate resistance of concrete: a new approach. *R&D Serial*(2486).

Gao, J., Sun, W., & Morino, K. (1997). Mechanical properties of steel fiber-reinforced, high-strength, lightweight concrete. *Cement and Concrete Composites, 19*(4), 307-313.

Gesoğlu, M., Özturan, T., & Güneyisi, E. (2004). Shrinkage cracking of lightweight concrete made with cold-bonded fly ash aggregates. *Cement and concrete research, 34*(7), 1121-1130.

Gollop, R., & Taylor, H. (1992). Microstructural and microanalytical studies of sulfate attack. I. Ordinary Portland cement paste. *Cement and Concrete Research, 22*(6), 1027-1038.

Gollop, R., & Taylor, H. (1994). Microstructural and microanalytical studies of sulfate attack. II. Sulfate-resisting Portland cement: ferrite composition and hydration chemistry. *Cement and Concrete Research, 24*(7), 1347-1358.

Goyal, A., Kunio, H., Ogata, H., Garg, M., Anwar, A., & Ashraf, M. (2007). Synergic effect of wheat straw ash and rice-husk ash on strength properties of mortar. *Journal of Applied Sciences, 7,* 3256-3261.

Gündüz, L., & Uğur, İ. (2005). The effects of different fine and coarse pumice aggregate/cement ratios on the structural concrete properties without using any admixtures. *Cement and Concrete Research, 35*(9), 1859-1864.

Hall, C. (1989). Water sorptivity of mortars and concretes: a review. *Magazine of Concrete Research, 41*(147), 51-61.

Hassan, A. A., Lachemi, M., & Hossain, K. (2012). Effect of metakaolin and silica fume on the durability of self-consolidating concrete. *Cement and concrete composites, 34*(6), 801-807.

Holm, T. A., & Bremner, T. W. (2000). *State-of-the-art report on high-strength, high-durability structural low-density concrete for applications in severe marine environments*: US Army Corps of Engineers, Engineer Research and Development Center.

Hooton, R. D., Thomas, M., & Stanish, K. (2001). Prediction of chloride penetration in concrete.

Hussin, M., Ismail, M. A., Budiea, A., & Muthusamy, K. (2009). Durability of high strength concrete containing palm oil fuel ash of different fineness. *Malaysian Journal of Civil Engineering, 21*(2), 180-194.

Isaia, G. C., GASTALDInI, A. L. G., & Moraes, R. (2003). Physical and pozzolanic action of mineral additions on the mechanical strength of high-performance concrete. *Cement and Concrete Composites, 25*(1), 69-76.

Islam, A., Alengaram, U. J., Jumaat, M. Z., & Bashar, I. I. (2014). The development of compressive strength of ground granulated blast furnace slag-palm oil fuel ash-fly ash based geopolymer mortar. *Materials & Design, 56,* 833-841.

Jaturapitakkul, C., Kiattikomol, K., Tangchirapat, W., & Saeting, T. (2007). Evaluation of the sulfate resistance of concrete containing palm oil fuel ash. *Construction and Building Materials, 21*(7), 1399-1405.

Jirásek, M., & Bazant, Z. P. (2002). *Inelastic analysis of structures*: John Wiley & Sons.

Johari, M. M., Zeyad, A., Bunnori, N. M., & Ariffin, K. (2012). Engineering and transport properties of high-strength green concrete containing high volume of ultrafine palm oil fuel ash. *Construction and Building Materials, 30*, 281-288.

Johnson Alengaram, U., Jumaat, M. Z., Mahmud, H., & Fayyadh, M. M. (2011). Shear behaviour of reinforced palm kernel shell concrete beams. *Construction and Building Materials, 25*(6), 2918-2927.

Jumaat, M. Z., Alengaram, U. J., & Mahmud, H. (2009). Shear strength of oil palm shell foamed concrete beams. *Materials & Design, 30*(6), 2227-2236.

Kanadasan, J., & Razak, H. A. (2014). Mix design for self-compacting palm oil clinker concrete based on particle packing. *Materials & Design, 56*, 9-19.

Kanadasan, J., & Razak, H. A. (2015). Engineering and sustainability performance of self-compacting palm oil mill incinerated waste concrete. *Journal of Cleaner Production, 89*, 78-86.

Katcho, N. A., Urones-Garrote, E., Ávila-Brande, D., Gómez-Herrero, A., Urbonaite, S., Csillag, S., . . . Otero-Díaz, L. C. (2007). Carbon hollow nanospheres from chlorination of ferrocene. *Chemistry of materials, 19*(9), 2304-2309.

Khatib, J., & Mangat, P. (1995). Absorption characteristics of concrete as a function of location relative to casting position. *Cement and Concrete Research, 25*(5), 999-1010.

Khatri, R., & Sirivivatnanon, V. (1997). Effect of curing on water permeability of concretes prepared with normal Portland cement and with slag and silica fume. *Magazine of Concrete Research, 49*(180), 167-172.

Kogel, J. E. (2006). *Industrial minerals & rocks: commodities, markets, and uses*: SME.

Kosmatka, S., Kerkhoff, B., Panarese, W., MacLeod, N., & McGrath, R. (2002). Design and control of concrete mixtures Cement Association of Canada. *Ottawa, Ontario, Canada*.

Kosmatka, S. H., Panarese, W. C., & Association, P. C. (2002). Design and control of concrete mixtures.

Kou, S. C., & Xing, F. (2012). The effect of recycled glass powder and reject fly ash on the mechanical properties of fibre-reinforced ultrahigh performance concrete. *Advances in Materials Science and Engineering, 2012*.

Kroehong, W., Sinsiri, T., Jaturapitakkul, C., & Chindaprasirt, P. (2011). Effect of palm oil fuel ash fineness on the microstructure of blended cement paste. *Construction and Building Materials, 25*(11), 4095-4104.

Kupaei, R. H., Alengaram, U. J., Jumaat, M. Z. B., & Nikraz, H. (2013). Mix design for fly ash based oil palm shell geopolymer lightweight concrete. *Construction and Building Materials, 43*, 490-496.

Lamond, J. F., & Pielert, J. H. (2006). *Significance of tests and properties of concrete and concrete-making materials* (Vol. 169): ASTM International.

Li, S., & Roy, D. M. (1986). Investigation of relations between porosity, pore structure, and C1− diffusion of fly ash and blended cement pastes. *Cement and Concrete Research, 16*(5), 749-759.

Lim, S. K., Tan, C. S., Lim, O. Y., & Lee, Y. L. (2013). Fresh and hardened properties of lightweight foamed concrete with palm oil fuel ash as filler. *Construction and Building Materials, 46*, 39-47.

Liu, X., Chia, K. S., & Zhang, M.-H. (2011). Water absorption, permeability, and resistance to chloride-ion penetration of lightweight aggregate concrete. *Construction and Building Materials, 25*(1), 335-343.

Lo, T., & Cui, H. (2004). Effect of porous lightweight aggregate on strength of concrete. *Materials Letters, 58*(6), 916-919.

Lo, T., Cui, H., & Li, Z. (2004). Influence of aggregate pre-wetting and fly ash on mechanical properties of lightweight concrete. *Waste management, 24*(4), 333-338.

Loh, J. (2000). *Living planet report 2000*: WWF--World Wide Fund for Nature.

Luther, M. D., & Hansen, W. (1989). Comparison of creep and shrinkage of high-strength silica fume concretes with fly ash concretes of similar strengths. *ACI Special Publication, 114*.

Mahmud, H. (2008). Ductility behaviour of reinforced palm kernel shell concrete beams. *European Journal of Scientific Research*, *23*(3), 406-420.

Mahmud, H. (2010). Comparison of mechanical and bond properties of oil palm kernel shell concrete with normal weight concrete. *International Journal of the Physical Sciences, 5*(8), 1231-1239.

Malhotra, V. (2002). Introduction: sustainable development and concrete technology. *Concrete International, 24*(7), 22.

Mannan, M., Alexander, J., Ganapathy, C., & Teo, D. (2006). Quality improvement of oil palm shell (OPS) as coarse aggregate in lightweight concrete. *Building and environment, 41*(9), 1239-1242.

Mannan, M., Basri, H., Zain, M., & Islam, M. (2002). Effect of curing conditions on the properties of OPS-concrete. *Building and environment, 37*(11), 1167-1171.

Mannan, M., & Ganapathy, C. (2004). Concrete from an agricultural waste-oil palm shell (OPS). *Building and environment, 39*(4), 441-448.

Mannan, M. A., & Ganapathy, C. (2002). Engineering properties of concrete with oil palm shell as coarse aggregate. *Construction and Building Materials, 16*(1), 29-34.

Manual, C. (1977). Lightweight Aggregate Concrete. CEB-FIP Manual of Design and Technology: The Construction Press, London.

Martys, N. S., & Ferraris, C. F. (1997). Capillary transport in mortars and concrete. *Cement and Concrete Research, 27*(5), 747-760.

Massazza, F. (1993). Pozzolanic cements. *Cement and Concrete composites, 15*(4), 185-214.

Mehta, P. (1987). *Studies on the mechanisms by which condensed silica fume improves the properties of concrete: durability aspects.* Paper presented at the Proceedings of international workshop on condensed silica fume in concrete, Ottawa.

Mehta, P. K. (2004). *High-performance, high-volume fly ash concrete for sustainable development.* Paper presented at the Proceedings of the international workshop on sustainable development and concrete technology.

Mehta, P. K., Monteiro, P. J., & Education, M.-H. (2006). *Concrete: microstructure, properties, and materials* (Vol. 3): McGraw-Hill New York.

Mertens, G., Snellings, R., Van Balen, K., Bicer-Simsir, B., Verlooy, P., & Elsen, J. (2009). Pozzolanic reactions of common natural zeolites with lime and parameters affecting their reactivity. *Cement and Concrete Research, 39*(3), 233-240.

Mindess, S., Young, J. F., & Darwin, D. (2003). *Concrete*.

Mo, K. H., Alengaram, U. J., & Jumaat, M. Z. (2014). Utilization of ground granulated blast furnace slag as partial cement replacement in lightweight oil palm shell concrete. *Materials and structures*, 1-12.

Mo, K. H., Alengaram, U. J., Visintin, P., Goh, S. H., & Jumaat, M. Z. (2015). Influence of lightweight aggregate on the bond properties of concrete with various strength grades. *Construction and Building Materials, 84*, 377-386.

Mo, K. H., Yap, K. K. Q., Alengaram, U. J., & Jumaat, M. Z. (2014). The effect of steel fibres on the enhancement of flexural and compressive toughness and fracture characteristics of oil palm shell concrete. *Construction and Building Materials, 55*, 20-28.

Modarres, A., & Hosseini, Z. (2014). Mechanical properties of roller compacted concrete containing rice husk ash with original and recycled asphalt pavement material. *Materials & Design, 64*, 227-236.

Mohr, P. (2004). *Mechanisms of improved transport phenomena in mature portland cement concrete pavements: a macro and microstructural evaluation*: University of Michigan.

Monteiro, P. J., Roesler, J., Kurtis, K. E., & Harvey, J. (2000). Accelerated test for measuring sulfate resistance of hydraulic cements for Caltrans LLPRS program. *University of California, Berkeley, 510*, 643-8251.

MPO Board, M. P. O. (2012). Overview of the Malaysian oil palm industry 2011: Selangor: Economics & Industry Development Division.

Nambiar, E. K., & Ramamurthy, K. (2007). Sorption characteristics of foam concrete. *Cement and Concrete Research, 37*(9), 1341-1347.

Nassif, H. H., Najm, H., & Suksawang, N. (2005). Effect of pozzolanic materials and curing methods on the elastic modulus of HPC. *Cement and Concrete Composites, 27*(6), 661-670.

Neville, A. M. (1981). *Properties of concrete*.

Neville, A. M., Neville, A. M., & Neville, A. M. (1963). *Properties of concrete*: Pitman London.

Newman, J. (1993). Properties of structural lightweight aggregate concrete. *Structural lightweight aggregate concrete*, 19-44.

Newman, J., & Choo, B. S. (2003). *Advanced concrete technology 3: processes*: Butterworth-Heinemann.

Noorvand, H., Ali, A. A. A., Demirboga, R., Noorvand, H., & Farzadnia, N. (2013). Physical and chemical characteristics of unground palm oil fuel ash cement mortars with nanosilica. *Construction and Building Materials, 48,* 1104-1113

Okafor, F. O. (1988). Palm kernel shell as a lightweight aggregate for concrete. *Cement and Concrete Research, 18*(6), 901-910.

Okpala, D. (1990). Palm kernel shell as a lightweight aggregate in concrete. *Building and environment*, *25*(4), 291-296.

Olanipekun, E., Olusola, K., & Ata, O. (2006). A comparative study of concrete properties using coconut shell and palm kernel shell as coarse aggregates. *Building and environment, 41*(3), 297-301.

Oner, A., & Akyuz, S. (2007). An experimental study on optimum usage of GGBS for the compressive strength of concrete. *Cement and Concrete Composites, 29*(6), 505-514.

Papadakis, V., & Tsimas, S. (2002). Supplementary cementing materials in concrete: Part I: efficiency and design. *Cement and Concrete Research, 32*(10), 1525-1532.

Park, S.-S., & Kang, H.-Y. (2008). Characterization of fly ash-pastes synthesized at different activator conditions. *Korean Journal of Chemical Engineering, 25*(1), 78-83.

ASTM C 1012 (1987). Evaluation of Sulfate Resistance of Hydraulic-Cement Mortars by the ASTM C 1012 Test Method. *Special Publication, 100*, 2103-2120.

Perraki, T., Kakali, G., & Kontoleon, F. (2003). The effect of natural zeolites on the early hydration of Portland cement. *Microporous and Mesoporous Materials, 61*(1), 205-212.

Philip, J. R. (1957). The theory of infiltration: 4. Sorptivity and algebraic infiltration equations. *Soil science, 84*(3), 257-264.

Phoo-ngernkham, T., Chindaprasirt, P., Sata, V., Pangdaeng, S., & Sinsiri, T. (2013). Properties of high calcium fly ash geopolymer pastes with Portland cement as an additive. *International Journal of Minerals, Metallurgy, and Materials, 20*(2), 214-220.

Pushpakumara, B., De Silva, S., & De Silva, G. S. (2013). Investigation on Efficiency of Repairing and Retrofitting Methods for Chloride induced Corrosion of Reinforced Concrete Structures. *ENGINEER, 46*(04), 19-30.

Ranjbar, N., Mehrali, M., Alengaram, U. J., Metselaar, H. S. C., & Jumaat, M. Z. (2014). Compressive strength and microstructural analysis of fly ash/palm oil fuel ash based geopolymer mortar under elevated temperatures. *Construction and Building Materials, 65*, 114-121.

Ranjbar, N., Mehrali, M., Behnia, A., Alengaram, U. J., & Jumaat, M. Z. (2014). Compressive strength and microstructural analysis of fly ash/palm oil fuel ash based geopolymer mortar. *Materials & Design, 59*, 532-539.

Rasheeduzzafar, F. H. D., Al-Gahrani, A. S., Al-Saadoun, S., & Bader, M. A. (1990). Influence of cement composition on the corrosion of reinforcement and sulfate resistance of concrete. *ACI Materials Journal, 87*(2).

Ritter, M. A. (1990). Timber bridges: Design, construction, inspection, and maintenance.

Rukzon, S., & Chindaprasirt, P. (2014). Use of ternary blend of Portland cement and two pozzolans to improve durability of high-strength concrete. *KSCE Journal of Civil Engineering, 18*(6), 1745-1752.

Saradhi Babu, D., Ganesh Babu, K., & Wee, T. (2005). Properties of lightweight expanded polystyrene aggregate concretes containing fly ash. *Cement and concrete research, 35*(6), 1218-1223.

Sata, V., Jaturapitakkul, C., & Kiattikomol, K. (2004). Utilization of palm oil fuel ash in high-strength concrete. *Journal of Materials in Civil Engineering, 16*(6), 623-628.

Shafigh, P., Alengaram, U. J., Mahmud, H. B., & Jumaat, M. Z. (2013). Engineering properties of oil palm shell lightweight concrete containing fly ash. *Materials & Design, 49*, 613-621.

Shafigh, P., Ghafari, H., Mahmud, H. B., & Jumaat, M. Z. (2014). A comparison study of the mechanical properties and drying shrinkage of oil palm shell and expanded clay lightweight aggregate concretes. *Materials & Design, 60*, 320-327.

Shafigh, P., Johnson Alengaram, U., Mahmud, H. B., & Jumaat, M. Z. (2013). Engineering properties of oil palm shell lightweight concrete containing fly ash. *Materials & Design, 49*, 613-621.

Shafigh, P., Jumaat, M. Z., & Mahmud, H. (2010). Mix design and mechanical properties of oil palm shell lightweight aggregate concrete: a review. *International Journal of the Physical Sciences, 5*(14), 2127-2134.

Shafigh, P., Jumaat, M. Z., & Mahmud, H. (2011). Oil palm shell as a lightweight aggregate for production high strength lightweight concrete. *Construction and Building Materials, 25*(4), 1848-1853.

Shafigh, P., Jumaat, M. Z., Mahmud, H. B., & Alengaram, U. J. (2011). A new method of producing high strength oil palm shell lightweight concrete. *Materials & Design, 32*(10), 4839-4843.

Shafigh, P., Jumaat, M. Z., Mahmud, H. B., & Alengaram, U. J. (2013). Oil palm shell lightweight concrete containing high volume ground granulated blast furnace slag. *Construction and Building Materials, 40*, 231-238.

Shafigh, P., Jumaat, M. Z., Mahmud, H. B., & Hamid, N. A. A. (2012). Lightweight concrete made from crushed oil palm shell: tensile strength and effect of initial curing on compressive strength. *Construction and Building Materials, 27*(1), 252-258.

Shafigh, P., Mahmud, H., & Jumaat, M. Z. (2011). Effect of steel fiber on the mechanical properties of oil palm shell lightweight concrete. *Materials & Design, 32*(7), 3926-3932.

Shafiq, N., Nuruddin, M., & Kamaruddin, I. (2007). Comparison of engineering and durability properties of fly ash blended cement concrete made in UK and Malaysia. *Advances in applied ceramics, 106*(6), 314-318.

Shariq, M., Prasad, J., & Masood, A. (2010). Effect of GGBFS on time dependent compressive strength of concrete. *Construction and Building Materials, 24*(8), 1469-1478.

Shi, C., Stegemann, J., & Caldwell, R. (1998). Effect of supplementary cementing materials on the rapid chloride permeability test (AASHTO T 277 and ASTM C1202) results. *ACI Mater, 95*(4), 389-394.

Shi, C., Stegemann, J. A., & Caldwell, R. J. (1998). Effect of supplementary cementing materials on the specific conductivity of pore solution and its implications on the rapid chloride permeability test (AASHTO T277 and ASTM C1202) results. *ACI Materials Journal, 95*(4).

Sivasundaram, V., Carette, G., & Malhotra, V. (1990). Long-term strength development of high-volume fly ash concrete. *Cement and Concrete Composites, 12*(4), 263-270.

Stanish, K., Hooton, R., & Thomas, M. (1997). Testing the chloride penetration resistance of concrete: a literature review. *FHWA contract DTFH61*, 19-22.

Sukumar, B., Nagamani, K., & Srinivasa Raghavan, R. (2008). Evaluation of strength at early ages of self-compacting concrete with high volume fly ash. *Construction and Building Materials, 22*(7), 1394-1401.

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

Tangchirapat, W., Jaturapitakkul, C., & Chindaprasirt, P. (2009). Use of palm oil fuel ash as a supplementary cementitious material for producing high-strength concrete. *Construction and Building Materials, 23*(7), 2641-2646.

Tangchirapat, W., Jaturapitakkul, C., & Kiattikomol, K. (2009). Compressive strength and expansion of blended cement mortar containing palm oil fuel ash. *Journal of Materials in Civil Engineering, 21*(8), 426-431.

Tangchirapat, W., Khamklai, S., & Jaturapitakkul, C. (2012). Use of ground palm oil fuel ash to improve strength, sulfate resistance, and water permeability of concrete containing high amount of recycled concrete aggregates. *Materials & Design, 41*, 150-157.

Tangchirapat, W., Saeting, T., Jaturapitakkul, C., Kiattikomol, K., & Siripanichgorn, A. (2007). Use of waste ash from palm oil industry in concrete. *Waste Management, 27*(1), 81-88.

Targan, Ş., Olgun, A., Erdogan, Y., & Sevinc, V. (2003). Influence of natural pozzolan, colemanite ore waste, bottom ash, and fly ash on the properties of Portland cement. *Cement and Concrete Research, 33*(8), 1175-1182.

Tasdemir, C. (2003). Combined effects of mineral admixtures and curing conditions on the sorptivity coefficient of concrete. *Cement and Concrete Research, 33*(10), 1637-1642.

Tay, J.-H. (1990). Ash from oil-palm waste as a concrete material. *Journal of Materials in Civil Engineering, 2*(2), 94-105.

Tay, J.-H., & Show, K.-Y. (1995). Use of ash derived from oil-palm waste incineration as a cement replacement material. *Resources, Conservation and Recycling, 13*(1), 27-36.

Taylor, H., & Gollop, R. (1997). Some chemical and microstructural aspects of concrete durability. *Mechanisms of chemical degradation of cement-based systems. E & FN Spon, London*, 177-184.

Taylor, H. F. (1997). *Cement chemistry*: Thomas Telford.

Teo, D., Mannan, M., & Kurian, V. (2010). Durability of lightweight OPS concrete under different curing conditions. *Materials and structures, 43*(1-2), 1-13.

Teo, D., Mannan, M. A., Kurian, V., & Ganapathy, C. (2007). Lightweight concrete made from oil palm shell (OPS): Structural bond and durability properties. *Building and environment, 42*(7), 2614-2621.

Teo, D. C., Mannan, M. A., & Kurian, J. V. (2006). Flexural behaviour of reinforced lightweight concrete beams made with oil palm shell (OPS). *Journal of advanced concrete technology, 4*(3), 459-468.

Thorvaldson, T. (1952). *Chemical aspects of the durability of cement products.* Paper presented at the Proceedings of the 3rd Intern. Symp. Chem. Cem.

Topçu, İ. B., & Uygunoğlu, T. (2010). Effect of aggregate type on properties of hardened self-consolidating lightweight concrete (SCLC). *Construction and Building Materials, 24*(7), 1286-1295.

Troxell, G., Raphael, J., & Davis, R. (1958). *Long-time creep and shrinkage tests of plain and reinforced concrete.* Paper presented at the ASTM Proceedings.

Urbanik, T. J., Lee, S. K., & Johnson, C. G. (2006). Column compression strength of tubular packaging forms made from paper. *Journal of testing and evaluation, 34*(6), 477.

Van Tuan, N., Ye, G., Van Breugel, K., Fraaij, A. L., & Dai Bui, D. (2011). The study of using rice husk ash to produce ultra high performance concrete. *Construction and Building Materials, 25*(4), 2030-2035.

Wang, C., Yang, C., Liu, F., Wan, C., & Pu, X. (2012). Preparation of ultra-high performance concrete with common technology and materials. *Cement and Concrete Composites, 34*(4), 538-544.

Whiting, D. (1981). Rapid determination of the chloride permeability of concrete. *Final Report Portland Cement Association, Skokie, IL. Construction Technology Labs., 1*.

Wilson, H., & Malhotra, V. (1988). Development of high strength lightweight concrete for structural applications. *International Journal of Cement Composites and Lightweight Concrete, 10*(2), 79-90.

Xu, B., & Shi, H. (2009). Correlations among mechanical properties of steel fiber reinforced concrete. *Construction and Building Materials, 23*(12), 3468-3474.

Yan, K., Xu, H., Shen, G., & Liu, P. (2013). Prediction of Splitting Tensile Strength from Cylinder Compressive Strength of Concrete by Support Vector Machine. *Advances in Materials Science and Engineering, 2013*.

Yew, M. K., Mahmud, H. B., Ang, B. C., & Yew, M. C. (2014). Effects of heat treatment on oil palm shell coarse aggregates for high strength lightweight concrete. *Materials & Design, 54,* 702-707.

Yin, C.-Y., Mahmud, H. B., & Shaaban, M. G. (2006). Stabilization/solidification of lead-contaminated soil using cement and rice husk ash. *Journal of hazardous materials, 137*(3), 1758-1764.

Yusuf, M. O., Johari, M. A. M., Ahmad, Z. A., & Maslehuddin, M. (2014). Evolution of alkaline activated ground blast furnace slag–ultrafine palm oil fuel ash based concrete. *Materials & Design*, *55*, 387-393.

Zain, M., Mahmud, H., Ilham, A., & Faizal, M. (2002). Prediction of splitting tensile strength of high-performance concrete. *Cement and Concrete Research*, *32*(8), 1251-1258.

Zhang, M.-H., & Malhotra, V. M. (1996). High-performance concrete incorporating rice husk ash as a supplementary cementing material. *ACI Materials Journal*, *93*(6).

Zhang, T., & Gjørv, O. E. (1994). An electrochemical method for accelerated testing of chloride diffusivity in concrete. *Cement and Concrete Research*, *24*(8), 1534-1548.

Zuquan, J., Wei, S., Yunsheng, Z., Jinyang, J., & Jianzhong, L. (2007). Interaction between sulfate and chloride solution attack of concretes with and without fly ash. *Cement and Concrete Research*, *37*(8), 1223-1232.

LIST OF PUBLICATIONS AND PAPERS PRESENTED

Mohammad Momeen Ul ISLAM, BEng, (MEng); Mo Kim Hung, BEng, (PhD); Mohd Z Jumaat, BEng, MEng, PhD, Mechanical and fresh properties of sustainable oil palm shell lightweight concrete incorporating palm oil fuel ash, Journal of Cleaner Production. (ISI, Q1, Accepted 16th December, 2015).

Mohammad Momeen Ul ISLAM, BEng, (MEng); Mo Kim Hung, BEng, (PhD); Mohd Z Jumaat, BEng, MEng, PhD, Investigation on some durability properties of palm oil fuel ash based lightweight concrete from palm oil industrial wastes, Journal of Cleaner Production. (ISI, Q1-Under review).

Mohammad Momeen Ul ISLAM, BEng, (MEng); Mohd Z Jumaat, BEng, MEng, PhD, Iftekhair Ibnul BASHAR, 'Experimental study of palm oil fuel ash based lightweight concrete from palm oil industrial wastes' Civil Engineering and Environmental Systems. (ISI, Q4-Under review).

Mohammad Momeen Ul Islam, U. Johnson Alengaram, Mohd Zamin Jumaat, Iftekhair Ibnul Bashar, Usage of palm oil industrial wastes as construction materials - A review, Proceeding of the International Conference on Civil, Environmental and Medical Engineering (ICEME) Kuala Lumpur, Malaysia 14th March 2015.

APPENDICES

Appendix A: Mix design for POFA based OPSC

Sand/cement ratio = 1.70
Water/cement ratio = 0.30
Aggregate/cement ratio = 0.65

Table A1: Mix Design for POFA based OPSC

Material	Mass (kg)	Specific gravity	Volume	
Cement	100	3.10	32.26	m^3
Sand	170	2.56	66.41	m^3
Water	30	1.00	30.00	m^3
OPS	65	1.35	48.15	m^3
		TOTAL	= 176.81	m^3

Material	Density	
Cement	565.57	kg/m^3
Sand	961.47	kg/m^3
Water	169.67	kg/m^3
OPS	367.62	kg/m^3
TOTAL	2064.334	kg/m^3

Appendix B: Mechanical properties of POFA based OPSC

Table B1: Splitting tensile strength of POFA based OPSC samples

Mix	Workability	Density (kg/m^3)							
	Slump (mm)	Curing Age							
		1 day	3 days		7 days		28 days		
		AC	AC	FWC	AC	FWC	AC	WC	PWC
M0	60	1920	1858	1916	1887	1927	1899	1970	1898
M5	90	1928	1904	1959	1942	1958	1872	1952	1949
M10	80	1936	1937	1956	2036	2056	1939	1973	1964
M15	30	1917	1936	1978	1914	1932	1906	1942	1921
M20	35	1948	1916	1930	1899	1934	1886	1948	1901
M25	65	1905	2010	2034	1899	1918	1876	1928	1902

Table B2: Compressive strength of POFA based OPSC samples

Mix	Compressive Strength test (MPa)			
	Air Curing Age			
	1 day	3 days	7 days	28 days
M0	32.595	36.31	34.23	35.65
M5	29.5	34.73	36.33	35.35
M10	31.48	36.435	37.34	37.03
M15	28.61	36.626	37.523	38.48
M20	20.253	30.126	32.6	35.21
M25	19.84	27.83	32.95	32.03

Table B2: Continue

Mix	Compressive Strength test (MPa)			
	Water Curing Age			
	3 days	7 days	28 days	PWC
M0	38.335	41.336	41.88	35.313
M5	38.616	38.39	39.04	34.543
M10	39.13	40.24	42.393	38.546
M15	32.74	38.87	40.245	37.263
M20	30.646	33.63	38.413	34.65
M25	28.48	35.55	36.04	33.13

Table B3: Splitting tensile strength of POFA based OPSC samples

Mix	Splitting tensile strength (MPa)		
	28 day air curing	28 day water curing	PWC
M0	3.49	3.919	3.718
M5	3.290	3.905	3.974
M10	3.175	3.507	3.116
M15	3.026	3.2516	3.088
M20	2.551	3.198	2.927
M25	2.855	2.917	2.902

Table B4: Flexural strength of POFA based OPSC samples

Mix	Flexural strength (MPa)		
	28 day air curing	28 day water curing	PWC
M0	3.857	6.575	5.320
M5	3.611	6.563	4.885
M10	4.022	6.256	4.265
M15	3.811	5.746	4.174
M20	3.684	4.709	3.854
M25	2.965	4.035	3.3105

Appendix C: Durability properties of POFA based OPSC samples

Table C1: Water absorption POFA based OPSC samples

w/b	Mix	Water absorption (%)			
		28-day		90-day	
		30 min	72 hours	30 min	72 hours
0.3	M0	2.182	4.8101	1.731	3.787
	M10	3.052	7.413	2.155	4.540
	M30	3.987	8.0402	3.282	5.75
	M50	5.010	8.880	3.879	6.2
0.4	M02	6.223	10.225	5.088	8.092
	M70	3.931	8.341	3.129	5.595

Table C2: Sorptivity of POFA based OPSC samples

w/b	Mix	Sorptivity (mm/$\sqrt{\text{min}}$)	
		28-day	90-day
0.3	M0	0.565	0.441
	M10	0.738	0.510
	M30	0.998	0.700
	M50	1.250	0.853
0.4	M02	1.003	0.629
	M70	1.439	1.298