OPTIMUM REPLACEMENT RATIO OF REINCINERATED PALM OIL FUEL ASH (REPOFA) MORTAR WITHOUT SACRIFICE ITS PROPERTIES

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Science (Hons.) Construction Management

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"OPTIMUM REPLACEMENT RATIO OF REINCINERATED PALM OIL FUEL ASH (REPOFA) MORTAR WITHOUT SACRIFICE ITS PROPERTIES"** was prepared by **YEO SHEN YEE** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Science (Hons.) Construction Management at Universiti Tunku Abdul Rahman.

Approved by,

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Supervisor : Dr. Wai Soon Han

Date : 1st May 2017

Specially dedicated to my

beloved parents, supervisor and friends.

Accomplishment would not be meet without their assistance.

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ABSTARCT

The abundance of Palm Oil Fuel Ash (POFA) which shows pozzolanic property as an agricultural waste makes it promising candidate to be utilized as a supplementary cementitious material (SCM). In enabling the POFA to result a highly efficient pozzolan, thermal treatment was conducted to eliminate unburnt carbon. It was heated at temperature of 700°C for 3 hours to produce Reincinerated Palm Oil Fuel Ash (RePOFA). This paper concentrates on the optimum replacement ratio of RePOFA mortar without sacrifice its properties. This research consisted of two phases whereby the first phase was to determine the optimum replacement range and the second phase was to examine the optimum replacement ratio. The engineering and durability performance of mortar containing RePOFA were tested at ages 7, 14, 28 and 56 days. Compressive strength test, flow table test, ultrasonic pulse velocity (UPV) test and density tests were executed to determine engineering performance. For durability aspects, porosity and permeability test were conducted in accordance with appropriate ASTM standards. Scanning Electron Microscopy (SEM) examination was conducted to study its microstructure. At age of 56 days, all the RePOFA mortar showed better performance than plain mortar. RePOFA-15 displayed best performance compared with others with achieved 48.48 N/mm^2 of compressive strength at 56-days. The performance of RePOFA mortar declined as the RePOFA replacement ratio elevated. Depending on the results of this investigation, it could be concluded that RePOFA could be successfully used as SCM to replace 15 % of cement in mortar.

Keywords: *palm oil fuel ash (POFA), reincinerated palm oil fuel ash (RePOFA), supplementary cementitious materials (SCM), pozzolanic reaction, engineering, durability, scanning electron microscopy (SEM)*

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LIST OF ABBREVIATIONS

EFB	Empty fruit bunches
GHG	Greenhouse gas emissions
MPOB	Malaysian Palm Oil Board
OPC	Ordinary Portland cement
OPT	Oil palm trunks
PPF	Palm pressed fibres
BA	Bagasse ash
BLA	Bamboo leaf ash
CCA	Corn cob ash
GPOFA	Ground palm oil fuel ash
POFA	Palm oil fuel ash
RePOFA	Reincinerated palm oil fuel ash
RHA	Rice husk ash
SCM	Supplementary cementitious material
SP	Superplasticizer
TPOFA	Treated palm oil fuel ash
ANOVA	Analysis of Variance
ASTM	American Society of the International Association for Testing and Materials
BS	British Standard
RILEM	International Union of Laboratories and Experts in Construction Materials, Systems and Structures

EDX	Energy-dispersive X-ray spectroscopy
SEM	Scanning electron microscopy
UPV	Ultrasonic pulse velocity
XRF	X-ray fluorescent
Al_2O_3	Aluminium oxide
CaO	Calcium oxide
$Ca(OH)_2$	Calcium hydroxide
CO_2	Carbon dioxide
C_2S	Belite
C_3S	Alite
C-S-H	Calcium silicate hydrate
Fe_2O_3	Iron oxide
K_2O	Potassium oxide
MgO	Manganese oxide
Na_2O	Sodium oxide
SiO_2	Silicon oxide
SO_3	Sulphur trioxide
LOI	Loss of ignition
w/c	water/cement ratio
w/b	water/binder ratio

LIST OF SYMBOLS

MPa	Megapascal
N	Newton
R^2	Coefficient of determination
Std. dev.	Standard deviation
ºC	Degree Celsius
%	Percentage
cm	Centimeter
mm	Millimeter
nm	Nanometer
µm	Micrometer
µs	Microsecond
cm^3	Cubic centimetre
g/cm^3	Gram per cubic centimeter
kg/m^3	Kilogram per cubic meter
km/s	Kilometer per second
m/s	Meter per second
m^2	Meter square
mm^2	Millimeter square
N/mm^2	Newton per millimetre square
N/s	Newton per second
atm	Atmosphere
g	Gram
kg	Kilogram

hrs	Hours
mins	Minutes
sec	Seconds
A	Area of the loaded surface, mm^2
fm	Compressive strength, MPa
P	Total maximum load, N
m_a	Mass of specimen in air, g
m_w	Mass of specimen submersed in water, g
ρ_m	Density of mortar, kg/m^3
ρ_w	Density of water, g/cm^3
L	Path length, mm
T	Measured travel time, µs
v	Pulse velocity, km/s
W_a	Saturated dry weight of specimen, g
W_d	Oven-dried weight of specimen, g
W_w	Saturated submerged weight of specimen, g
A	Cross sectional areas of specimens, m^2
D	Flowmeter diameter, cm
H	Length read on flowmeter, cm
K	Coefficient of intrinsic air permeability, m^2
L	Length of specimen, m
P_1	Absolute applied pressure (atm. pressure), 2 bars
P_2	Pressure at which the flow rate is measured (atm. pressure), 1 bars
T	Average time

CHAPTER 1

INTRODUCTION

1.1 RESEARCH BACKGROUND

Concrete is widely used as construction materials in the construction sector. The high usage of concrete as construction materials is mainly due to several reasons. First, concrete has high resistance to water, unlike other construction materials such as timber and steel. Besides, a variety of sizes and shapes can be formed by using concrete as the construction materials and this provides a certain mean of convenience. However, the high usage of ordinary concrete also leads to the increment of the cement used. As we know, the high usage of cement will cause the issuance of high carbon emission. According to Olivier et al. (2015), industrial processes such as the cement clinker and the combustion of fossil fuel cause a total emission of 35.7 billion tonnes of carbon dioxide (CO_2). Moreover, one ton of CO_2 is released into the atmosphere with the production of one ton of Portland cement. The cement industry is responsible for about 7 percent of the total CO_2 released into the atmosphere (Aprianti, 2015). It is acknowledged that an effective solution should be applied in order to reduce or eliminate the environmental issue without scarifying the advancement of the country from the perspective of the construction sector.

As mentioned above, the concrete is highly used as a construction material due to its important properties. Unfortunately, the component of cement within the concrete leads to many side-effects affecting our environment. Therefore, it is essential to find an alternative which can be utilised as cement replacement materials.

Furthermore, it is believed that many researchers try to transform the waste into the useful materials in different industries and it is highly applicable in the construction industry especially in the intention to substitute the composition of construction materials. Turk et al. (2015) stated that the waste can be recognized as an essential source of raw materials for different industries instead of considering it as an environmental problem. The utilization of waste not only provides an efficient use of resources, it also contributes to less pollution and improves the economic competitiveness too (Blengini & Garbarino, 2010). The examples of waste materials which act as the supplementary cementitious material (SCM) and have been used for decades are silica fume, rice husk ash, fly ash, granulated blast slag and palm oil fuel ash (POFA). As acknowledged by Aprianti and Turk et al. in 2015, the utilization of the waste materials mentioned as complete or partially replacement of cement in concrete contributes to the cost reduction of the building materials and provides a pleasant alternative in dealing with the environmental issues plus the landfill problem. Nevertheless, by using the SCM, the environment is protected from the pollution and the energy consumption is saved which can lead to the reduction of the carbon emission and also the greenhouse gas emissions (GHG).

In this study, the usefulness of treated POFA which used as the SCM is studied. The oil palm is recognized as the most important product in Malaysia as it helps to increase the economy of Malaysia. As a reference, half of the world palm oil production is produced by Malaysia and statistics show that the world palm oil production is double from the year 1990 to the year 2000 which is from 11.0 million tonnes to 21.8 million tonnes (Uemura et al., 2013). Furthermore, according to the palm oil production report from Malaysian Palm Oil Board (MPOB) in 2016, the annual palm oil production in Malaysia reached 19.9 million in 2015 (MPOB, 2016). However, oil palm mill also causes environmental degradation despite the understandable benefit as aforementioned. With the high production of palm oil, it sarcastically becomes the main contributor to the pollution problem. This is due to the fact that it is reported that a huge amount of solid waste (2.6 million tonnes) are produced annually by the palm industry (Usman et al., 2014). Therefore, the utilization of POFA as the SCM due to the high amount of disposed POFA is highly recommended. Moreover, many researchers also discovered that the properties of POFA are suitable to act as the SCM due to its contribution in high strength concrete and the elimination of environmental issues (Bamaga et al., 2013; Karim et al., 2011; Rani & Tejaanvesh, 2015; Safiuddin et al., 2011). However, this paper concentrates on the effect of mortar after mixing with the reincinerated palm oil fuel ash (RePOFA). This is mainly because there are rare researches focus on the thermal treated POFA as the SCM. It is believed that this research can help to level the awareness in using the treated POFA as a replacement of cement.

1.2 PROBLEM STATEMENT

From the researches which used POFA as the SCM done by the previous researchers, the concrete or mortar which used the cement replacement material mentioned have shown inconsistency and lack of promising performance. In fact, the performance of concrete or the mortar which uses agricultural waste as the cement replacement material need to consider the chemical composition of the waste. This is supported by Parande et al. (2011) as the researchers mentioned that the factors of ash content plus the chemical constituents need to be considered if agro-residue is intended to be utilized as the SCM. In the case of using the POFA as the replacement materials of cement, different compositions within the POFA especially the carbon content leads to different performances in the finishing product. According to Altwair et al (2011), the carbon content within the POFA is the most significant factor need to be considered. The different carbon content contributes to a different percentage of other chemical compositions within the ash. It is acknowledged that the burning temperature of POFA and the burning duration are the factors which lead to a different percentage of chemical compositions within the ash. The different percentages of chemical constituents shown in Table 1.1 have led to the inconsistent performances of the concrete or mortar which used POFA as the supplementary materials. Besides, the aforementioned factors need to be concerned as Sata et al (2004) also suggested that POFA can only be utilized as a SCM when it is processed properly.

Table 1.1 Chemical composition analysis in POFA

Chemical Composition (%)	Altwair et al. (2011)	Chindaprasirt & Rukzon (2009)	Jaturapitakkul et al. (2011)	Usman et al. (2014)	Usman et al. (2015)	Sata et al. (2007)
SiO_2	66.91	63.60	65.30	55.50	63.70	65.30
Al_2O_3	6.44	1.60	2.56	8.96	3.70	2.60
Fe_2O_3	5.72	1.40	1.98	3.25	6.30	2.00
CaO	5.56	7.60	6.42	8.81	6.00	6.40
MgO	3.13	3.90	3.08	2.45	4.10	3.10
Na_2O	0.19	0.10	0.36	1.10	-	0.30
K_2O	5.20	6.90	5.72	7.81	9.15	5.70
SO_3	0.33	0.20	0.47	2.11	1.60	0.50
LOI	2.30	9.60	10.05	4.20	8.00	10.1

In addition, the arising issue in order to have a promising outcome by using POFA as SCM is the inconsistent replacement ratio suggested by the previous researchers. For instance, as compared with the result obtained by researchers, Altwair et al. (2011) and Zeyad et al. (2016), the performance of the concrete using same substitution ratio of POFA as the SCM displayed different performance. The former researcher suggested that POFA replacement percentage should be limited as 20 % while the latter repulsed the statement as he achieved better performance of POFA substituted concrete with high amount of POFA percentage. The issue of unpromising performance is concreted as results evaluated by the mentioned researchers had huge different though other influence factors were kept similar in both condition beside the burning temperature of the POFA. Therefore, as an intention to enable an astonishing result to be achieved while studying the optimum replacement ratio, the reincinerated temperature of the POFA is kept constant in this research. The effort is essential to deal with the problem of different incineration temperature practised by the previous researchers which then caused the aftermath of obtaining inconsistent result.

As aforementioned, Malaysia is currently one of the largest producers of palm oil in the world. With around 40 % of total world supply in the years of 2008 to 2010, Malaysia is known as the second largest palm oil producer in the world (Altwair et al., 2012). According to Altwair et al. (2011) and Chandara et al. (2010), a large amount of solid waste with approximately 70 % of the raw material are produced in the form of nutshells, fibers, plus the empty fruit bunches. Table 1.2 pictures the wastes-breakdown from the palm oil production. Due to the increased price of the oil, the diesel generators are relied on to provide power supply and the solid waste discussed above are used as the fuel to heat the steam for the generation of electricity (Altwair et al., 2012). It is observed that 5 % palm oil fuel ash (POFA) is left behind after the operation. Due to the deficiency in nutrients as the fertilizers plus the underutilization of POFA, it is then disposed as the waste in landfill (Islam et al., 2014; Jamo et al., 2015; Jaturapitakkul et al., 2011). This issue leads to the environmental degradation as the landfill not only causes the pollution to the environment by contaminating groundwater and aquifers, the issues of rise in methane levels and soil contamination also emerged due to the landfill activity. As stated by Aljaradin (2012), the waste disposed in landfill causes the production of leachate and gaseous emissions as the waste undergoes biochemical and physical processes. The water and ground water will get polluted when the leachate reaches the water resources. Therefore, in order to solve the landfill problems, the POFA which is used as landfill materials need to be utilized as useful materials and the pozzolanic reaction shown by treated POFA provides a stepping stone for the POFA to become the SCM in concrete or mortar.

Table 1.2 Waste from palm oil production (Uemura et al., 2013)

Waste	Quantity (k tonnes)
Fronds	46,837
Empty fruit bunches (EFB)	18,022
Palm pressed fibres (PPF)	11,059
Oil palm trunks (OPT)	10,827
Shell	4,506

1.3 AIM AND OBJECTIVES

Aim

- To establish an optimum replacement ratio Reincinerated Palm Oil Fuel Ash (RePOFA) in mortar without sacrificing its properties.

Objective

- To determine the engineering properties of mortar with RePOFA as supplementary cementitious material in mortar.
- To determine the durability properties of mortar with RePOFA as supplementary cementitious material in mortar.

1.4 SCOPE OF STUDY

In this research, the optimum replacement ratio of RePOFA in mortar was established without scarifying its properties. This research consisted of two phases which the former was to determine the optimum range of replacement ratio. The replacement percentage of RePOFA in the mortar was set to be 10 %, 20 % and 30 % by weight initially at phase one and the optimum replacement ratio of the SCM was further studied at phase two. The dependent variables in this research were the engineering properties and the durability properties of the mortar. The engineering tests that were involved in this research included the flow table test, compressive test, ultrasonic pulse velocity (UPV) test and density test. The microstructure analysis used for this study was scanning electron microscopy (SEM) examination while the durability tests involved were porosity and permeability test. The results of the tests were collected at 7, 14, 28 and 56 days.

As this research was concerned on the thermal treated POFA, the POFA collected was thermally treated at the controlled temperature of 700°C. The controlled temperature was the independent variable in this research. The POFA was incinerated for 180 minutes under the temperature mentioned. The water to binder ratio used was set at 0.40 while 2.75 of sand to binder ratio was used in this research. Furthermore, the samples were cured at the ambient temperature. The mining sand was also used as the fine aggregate in this research. The limitation of this research was that the effect of different incineration temperature on the POFA was not investigated. The chemical composition within the ash due to different incineration temperature was not observed. In addition, the accelerated curing method on the performance of RePOFA mortar was not studied.

1.5 SIGNIFICANCE OF STUDY

After conducting this research, it is possible to unfold the promising performance of the concrete or mortar using the thermal treated palm oil fuel ash as the alternative to the cement. With the optimum replacement ratio of the SCM to be studied in this research, this research is likely to be acted as an addition indicator for other researchers to perform the research about treated POFA as the SCM in either concrete or mortar. In addition, this research is possible to encourage future researchers to utilize the waste in the construction sector. It can likely help to trigger other researchers to use either agricultural waste, industrial waste or other types of waste materials in their future study and this can also contribute to the environmental friendly purpose.

By utilizing the waste found in the environment, instead of bookmarking it as pollutants, it can be considered as a useful material. For example, as the agricultural waste such as the rice husk ash, palm oil fuel ash, wood waste ash and the industrial waste like silica fume, fly ash and slag are utilized as the cement replacement materials, this helps to reduce the use of cement and also aid in diminishing the carbon dioxide emission directly. As the carbon dioxide present in the environment is reduced, most of the environmental issues can be solved such as the greenhouse effect. The exploitation of waste from the construction sector is likely contributing to the development of a sustainable environment due to the emerging of green products.

1.6 RESEARCH FRAMEWORK

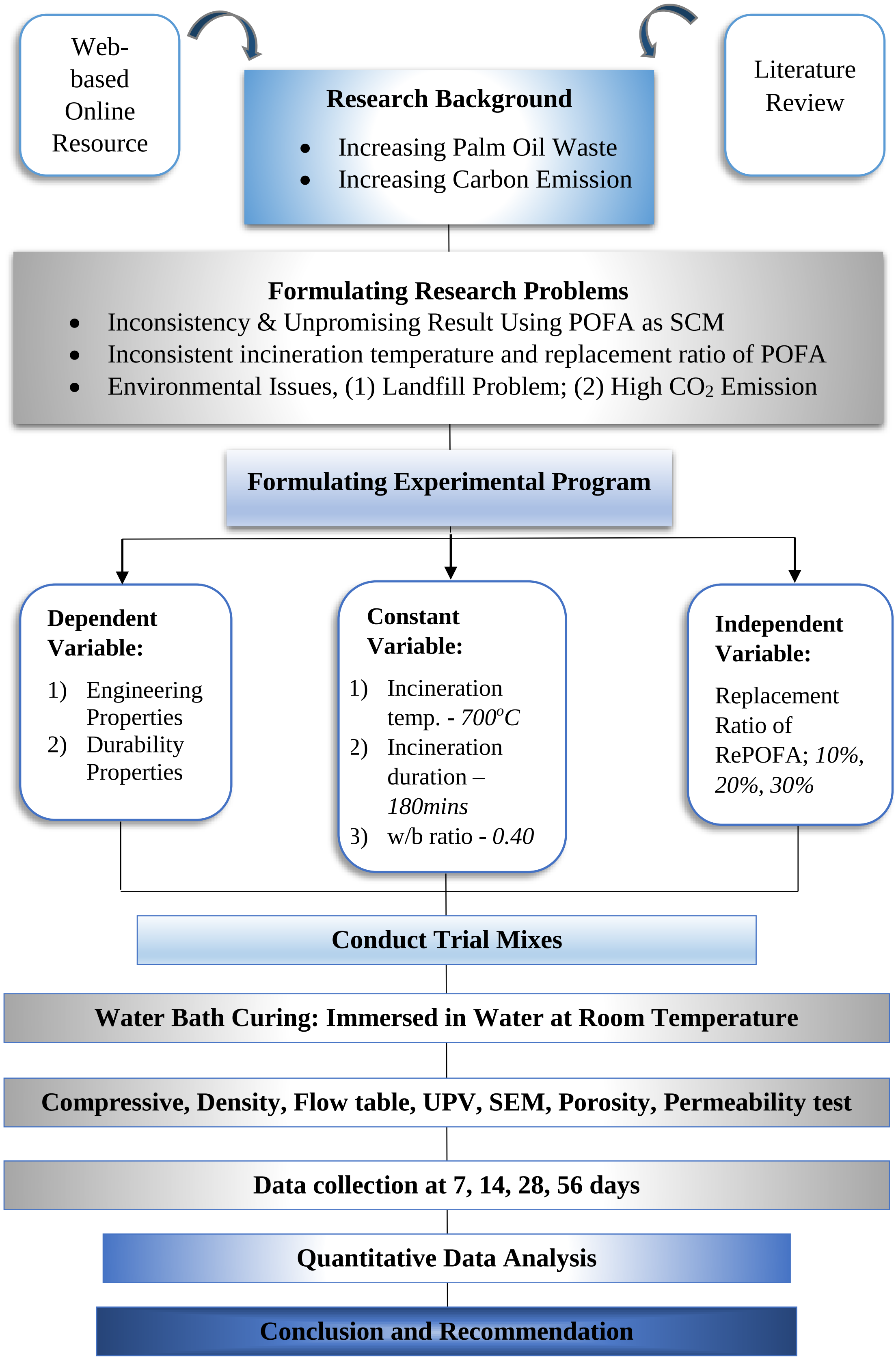

Figure 1.1 Research framework

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

In this chapter, the factors that affecting the performance of mortar or concrete are discussed. Besides, some of the waste which can be used as the pozzolanic materials are introduced including the pozzolanic reaction involved. The effect of POFA after being thermal treated are also be discussed in this chapter. Furthermore, the effect of RePOFA to the engineering and durability properties of the mortar are deliberated in the following to review the performance of the mortar mixed with the RePOFA.

2.2 FACTORS INFLUENCE PERFORMANCE OF MORTAR

There are many factors affecting the performance of the concrete or mortar. For example, the water/cement (w/c) ratio, aggregate/cement ratio, properties of coarse aggregate, the age of the concrete or mortar, the curing condition of the concrete or mortar and others. For the setting of the constant variable purpose, the information regarding the water/cement ratio and the curing condition of the mortar are further discussed below.

2.2.1 Water/Cement Ratio

The w/c ratio plays an important role in determining the performance of the concrete or mortar especially in terms of the strength and durability of them. This is due to the fact that the increase in the w/c ratio leads to the decreasing effect of the strength and durability of hardened concrete. It is supported by Singh et al. (2015) and Schulze (1999) that the mechanical properties of mortar were reduced as the w/c ratio increased though the workability increased. Instead of the effect of the compressive strength of the mortar, the high w/c ratio also causes the increase of the porosity of the mortar. Kim et al. (2014) experimented that as the w/c ratio was increased from 0.45 to 0.60, the porosity of the mortar reached 150 % and the strength of the mortar drops to 75.6 %. Beside the contribution of the compressive strength of mortar or concrete, the low w/c ratio also contributes to the low porosity of the specimen (Živica, 2009). According to Sear et al. (1996), the compression of the concrete showed the inverse relationship with the w/c ratio through Abram's generalization law within the w/c ratio of 0.3 to 1.20. Figure 2.1 shows the relationship of the compressive strength and the w/c ratio. However, the usage of an overly low w/c ratio needs to be avoided as a ratio which is too low will lead to the reducing effect of workability and this may bring the unwanted consequences too. As the workability reduces, the concrete or mortar will show difficulties in compacting and it will then cause the dropping of the strength. Therefore, the optimum w/c cement ratio need to be considered.

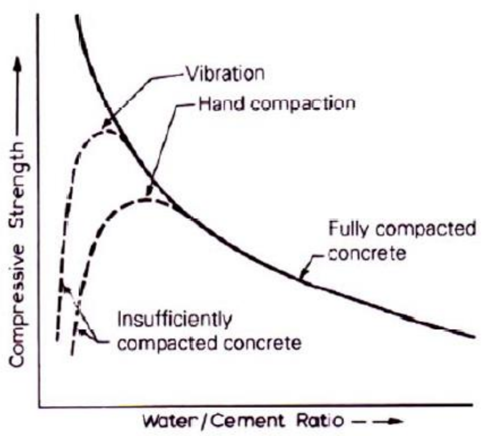

Figure 2.1 Strength versus w/c ratio curve (Sear et al., 1996)

2.2.2 Curing Condition

Curing plays an essential role in the development of strength and durability of the concrete. The properly cured concrete enables the concrete to have an adequate amount of moisture for hydration and contribute to the strength development. Moreover, the curing condition will influence the properties of the concrete or mortar by the curing temperature and the curing time. According to Turuallo & Soutsos (2015), the strength development of concrete at high curing temperature was faster than the concrete cured at the low temperature at early stages. However, concrete that is cured under the latter conditions shows higher strength at later ages. The example of the effect of curing temperature on the compressive strength is shown in Figure 2.2. For the curing time, the increasing curing duration will contribute to the rise of compressive strength of the concrete generally as presented in Figure 2.3.

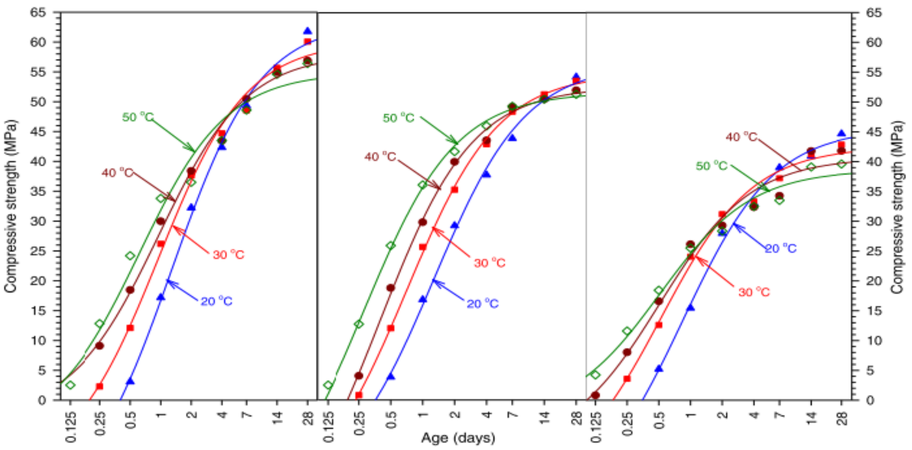

Figure 2.2 Strength development of concrete cured at different temperature (Turuallo & Soutsos, 2015)

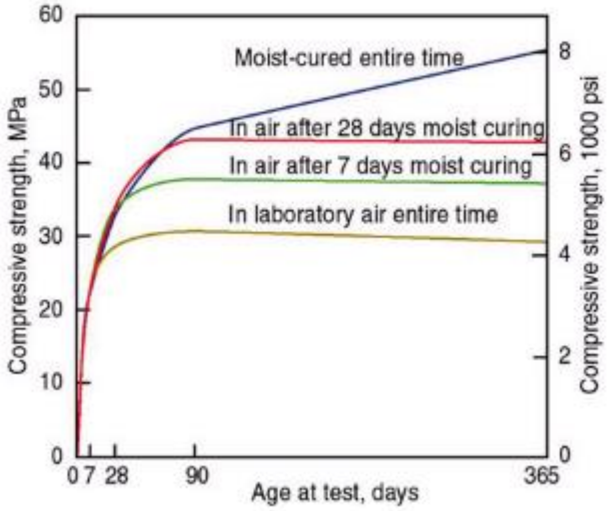

Figure 2.3 Moist curing time and compressive strength gain (Zemajtis, 2015)

2.3 SUPPLEMENTARY CEMENTITIOUS MATERIALS

In its basic form, the Portland cement is the cementitious material in the concrete and mortar. However, due to the high energy consumption and high carbon emission associated with the production of cement, SCM is introduced and most of the concrete or mortar consist of SCM as a portion of the cementitious constituent in concrete and mortar. According to Vishwakarma et al. (2016), 7% of the total carbon dioxide emitted globally is emitted by the cement industry during the manufacturing process of cement. Moreover, the agricultural and industrial waste which are found everywhere nowadays have also brought to light arising environmental issues. The agricultural and industrial wastes mentioned are rice husk ash (RHA), POFA, bagasse ash (BA), wood waste ash, bamboo leaf ash (BLA), corn cob ash (CCA), fly ash, silica fume, and slag. The wastes mentioned are mostly the by-products from the processes and these materials have generally disposed as the landfill materials. As aforementioned, the landfill creates many negative effects to the environment. Moreover, Shafigh et al. (2014) commented that current state of the cement manufacturing shows no environmental sustainability. In order to eliminate this issue, the wastes which lead to the degradation of environment can be used as the SCM.

These SCM are widely been used as the pozzolanic materials due to the pozzolanic reaction involved which may contribute to the creation of extra strength compared to the ordinary concrete (Aprianti et al., 2015). The researcher, Yap & Foong (2013) also stated that the utilization of these waste as the pozzolan materials paves the way for the emergence of sustainable concrete which ameliorates the environmental issue.

Furthermore, the SCM which can be utilized as the pozzolan materials is highly recommended by many researchers due to the contribution of SCM on either the engineering properties or the durability properties of the concrete or mortar. According to the experiment done by Turuallo & Soutsos (2015), the use of the SCM can increase the workability, durability plus the strength of the concrete. In addition, with the high usage of the Portland cement in the concrete or either mortar, the products are vulnerable to cracking and also the increment of heat generation. As the solution, the implement of SCM is suggested as the materials help to enhance the durability properties of the concrete and mortar. By using the SCM, the heat generated during the hydration of the cement can be reduced plus the potential for thermal cracking can also be curtailed. In the following subsection, the SCM such as RHA, silica fume, and fly ash are briefly introduced. The detail of the POFA is then discussed in the next section.

2.3.1 Rice Husk Ash (RHA)

Rice husk is a sheath covering around rice grains during their growth. According to FAO (2016), it is reported that around 746.8 million metric tons of rice paddies have been harvested annually by the worldwide. It is bitter to be said that the rice husk disposed as the landfill materials has caused the environmental problem. It is supported by Aprianti et al. (2015) that these rice husks which is dumped as waste covers a huge area and the waste will undergo self-incinerate, thereby resulting in an environmental problem as its ash is spread over a wide area. The RHA is gained from the raw rice husk through the combustion process.

In the effort of utilizing the RHA as the beneficial materials, it is also used as the SCM in the formation of concrete and mortar. The RHA contributes to the engineering properties of the concrete as it helps to increase the strength of the concrete due to its fine particles yield a large surface area. Vishwakarma et al. (2016) also proves that the increasing strength of the RHA is because of the fine particle size which aids in reducing the porosity of the concrete. Moreover, with the high amount of the silica content which is around 80.7 % to 95.9 % in the RHA, the material which constitutes high reactive pozzolanic material is then bookmarked as a super-pozzolan material in the concrete production. RHA also reduces the quantity of large pores which provides a path of transforming the pores which are continuous into discontinuous. Eventually, the microstructure of the paste becomes denser and more homogeneous and these act as essential characteristics for durability (Vishwakarma et al., 2016).

2.3.2 Silica Fume

During the manufacturing process of the silicon metal or silicon alloys, the silica fume is produced as a by-product from the electric furnaces (Sezer, 2012). Silica fume is known as an extremely fine powder as its particle is 100 times smaller compared to an average cement grain. However, special precautions need to be assured while handling and curing the silica fume concrete due to its extreme fine particles. As mentioned by Antoni et al. (2015), the presence of supplementary cementing materials like silica fume can solves the side effects of high heat hydration, cracks and shrinkage due to the usage of the high amount of cement on concrete. Furthermore, the silica fume which is used as the admixture or the cement replacement materials can notably improve the mechanical properties of concrete. This is probably due to the high content (more than 80 %) of silicon dioxide present in the silica fume and its very fine particle size of 100nm average diameter. These reasons contribute to its high pozzolanic reaction and make it becomes the most common admixture been used in forming the high-strength concrete (Wongkeo & Chaipanich, 2010).

2.3.3 Fly Ash

The production of fly ash is by burning of coal in thermal power plants and an approximated of 11 million tonnes of coal are consumed annually. It is reported that an amount around 3 million tonnes of the fly ash is formed per annum (Yap & Foong, 2013). Due to the problems caused by storage of the disposed fly ash plus environmental issues, studies on the potential other usages of fly ash have been performed by researchers. For example, Poon et al. (2000) experimented that a high strength concrete had achieved a compressive strength of 80 MPa in 28 days with the 45 % of fly ash content. Furthermore, another research done by Jaturapitakkul et al. (2004) showed that fly ash contributed to the compressive strength (28 days) of concrete by allowing it to achieve a strength of 82.5 MPa. The fly ash cement also enhances the durability of the concrete by improving its resistance against chloride ingress. Moreover, it is concluded by Pastor et al. (2016) that the usage of fly ash cement contributed to higher microstructure refinement than ordinary Portland cement.

2.4 PALM OIL FUEL ASH (POFA) AS THE SCM

As discussed above, the POFA is known as the by-product form from the incineration of the palm oil fibers, shells, and empty fruit bunches in the biomass thermal power plant to generate the energy. However, it was found that 5 % of the residue was then produced as the result of combustion and the wastes are then managed by disposing as landfill materials which lead to environmental hazards eventually. As stated by Aprianti et al. (2015), POFA is tagged as the environmental disruption pollutant which ends up in the atmosphere without being utilized in 20^{th} and 21^{st} century, if compared to other types of palm oil by-products.

In order to promote the utilization of POFA, many researchers established the researches regarding the POFA as the SCM in either concrete or mortar. The properties and performances of the finished products are examined and the researchers commented that the utilization of the POFA as the supplementary materials of cement is suitable. This is because the ash can increase the engineering and durability properties of either concrete or mortar. The reviews regarding the influence of POFA and RePOFA to the properties of the mortar are discussed in the following section. In this section, the properties of POFA and the pozzolanic reaction of POFA are deliberated including the comparison between the POFA and the RePOFA.

2.4.1 Properties of POFA

For the physical characteristics of POFA, it is easily affected by the operating system in the factory. Based on the previous researches, it is observed that the temperature of the incinerator that the industries controlled in the combustion of the palm oil wastes are between 800-1000°C and the duration of the operation is different. The difference of the controlled temperature and incinerating duration result in the different properties of the POFA whether in physical or chemical properties. This is because the differences mentioned cause the amount of the carbon in the ash to differ from the others as the unburnt carbon is altered.

In physical properties, the POFA is greyish in colour and it changes into darker colour as the result of the increase of the proportion of unburnt carbon (Altwair et al., 2013; Noorvand et al., 2013; Aprianti et al., 2015). Moreover, in chemical properties, the amount of the unburnt carbon causes the chemical constituents existing in the POFA to vary. The range of the amount of the chemical composition present in the POFA is displayed in Table 2.1. In addition, Table 2.1 also pictures the comparison of the chemical composition of the ordinary Portland cement (OPC) with the POFA. From the statement by Aprianti et al. (2015), the authors urged that the source of materials, combustion process and the efficiency of the palm oil industry are the factors that prompt the difference in the amount of the chemical components in the ash.

Table 2.1 Chemical composition range of OPC and POFA (Altwair et al., 2011; Aprianti et al., 2015; Chindaprasirt & Rukzon, 2009; Jaturapitakkul et al., 2011; Sata et al., 2007; Usman et al., 2014; Usman et al., 2015)

Chemical Composition (%)	OPC	POFA
SiO_2	20.4-22.0	55.5-66.9
Al_2O_3	3.7-5.3	1.6-8.9
Fe_2O_3	2.3-4.2	1.4-6.3
CaO	61.5-65.4	5.5-8.8
MgO	1.2-4.8	2.4-4.1
Na_2O	0.1-0.2	0.1-0.3
K_2O	0.3-1.1	5.2-9.1
SO_3	2.20-3.0	0.2-2.1
LOI	0.4-2.3	2.3-10.1

The properties of the POFA enable the ash to act as the SCM can also be proved by the efficiency factor, k-value of POFA and treated POFA (T-POFA) calculated by Alsubari et al. (2016). The concept of the k-value of the supplementary cementitious materials is adopted by Papadakis et al. (2002) and also deliberated by Sethy et al. (2015). According to the information retrieved from the mentioned researchers, the k-value indicates the ability of the supplementary materials to act as the cementitious material. In other words, it refers to the ability of SCM to react with calcium dioxide, $Ca(OH)_2$ emerged during the hydration process of cement. When the k-value is less than 1.0, it delivers the idea that the cement hydration rate with the absence of SCM is faster than the pozzolanic reaction rate in the concrete with the presence of SCM. However, the k-value which is more than 1.0 reflects the idea contrary to the situation mentioned before. From the data collected by Alsubari et al. (2016), the k-value of T-POFA is more than 1.0 at 28 days and after though its k-value did not reach 1.0 at early ages. It was explained by the authors that the pozzolanic reaction rate of POFA is slow at the early age if compared with the reaction of hydration of the cement. Table 2.2 illustrates the k-value of T-POFA up to 180 days. Furthermore, the T-POFA is categorized as a pozzolan due to the requirement it met as the accumulation of the three main components; silicon dioxide, aluminium trioxide and iron oxide have compromised 70 % of the total amount of chemical constituents (ASTM C 618).

Table 2.2 Efficiency factor of T-POFA (Alsubari et al., 2016)

Day	1	3	7	28	56	90	180
k-value	0.72	0.73	1.01	1.05	1.12	1.16	1.22

2.4.2 Pozzolanic Reaction of POFA

As stated in ASTM C595, pozzolan is defined as "a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide to form compounds possessing cementitious properties (pozzolanic activity)." The POFA which consists of high amount of silicon dioxide (SiO_2) is suitable to act as the pozzolan for the pozzolanic reaction because the SiO_2 and the aluminium trioxide (Al_2O_3) presence in POFA reacts with the $Ca(OH)_2$ to produce calcium silicate hydrate (C-S-H) (Kroehong et al., 2011). The C-S-H is the particle-binding glue of concrete which can assist in improving the properties of the finished product. As mentioned by Aprianti et al. (2015), the $Ca(OH)_2$ acts as the indicator in the pozzolanic reaction of POFA. However, the $Ca(OH)_2$ is also bookmarked as the by-products which have no contribution to the strength or the density. Meanwhile, the high amount of $Ca(OH)_2$ will cause the increase of porosity within the concrete or mortar. Therefore, the POFA which consists of a high percentage of SiO_2 is suggested as the good pozzolan due to the fact that the SiO_2 will help to eliminate the by-product through the chemical equation as below.

$$Ca(OH)_2 + SiO_2 \rightarrow \text{C-S-H} \qquad (2.1)$$

However, the early-age compressive strength of the POFA concrete or mortar is lower than the ordinary Portland cement concrete. It is mainly because of the reducing amount of the hydration product, C-S-H due to the dilution of the cement composition (Alsubari et al., 2016). Moreover, the slow pozzolanic reaction of POFA also indicates the low early age compressive strength and this is confirmed by Aprianti et al. (2015). On the other hand, as stated by Sata et al. (2010), only the POFA with high fineness is encouraged to be used as the SCM. The author explained that the original POFA is not suitable to be utilized as the SCM because of the presence of large particles size and the result of high porosity. The high fineness POFA will act as the filler to the concrete or mortar and this will contribute to the development of high strength and durable concrete (Munir et al., 2015).

2.4.3 Comparison between POFA and RePOFA

In this research, the RePOFA means the reincineration of the palm oil fuel ash at a constant temperature in order to remove the unburnt carbon existing within the ash. According to the study done by Chandara et al. (2010), the unburnt carbon will absorb the superplasticizer (SP) which is added into the concrete to improve the fluidity if compared to other constituents found in the cement paste. It is shown in Table 2.3 that the removal of the unburnt carbon influences the chemical composition within the POFA especially the chemical percentage of SiO_2 which plays an important role in pozzolanic reaction. From the table, it is noticed that the LOI value of the RePOFA was decreased to a certain amount and this situation can be explained by Altwair et al. (2012) as the author commented that the reduction of the value of LOI was due to the increasing mass percentage of the other chemical constituents resulting from the reducing amount of unburnt carbon content. Nevertheless, Chandara et al. (2012) quoted that besides removing the unburnt carbon, the thermal treatment of the POFA also helps to preserve the amorphous phase of SiO_2 and avoid the agglomeration of particles. The author explained the importance of the treatment because the issues mentioned influencing the pozzolanic properties of POFA.

Table 2.3 Difference of chemical constituent between POFA and RePOFA (Alsubari et al., 2016; Chandara et al., 2012)

Chemical Constituent (%)	POFA	RePOFA
SiO_2	59.17-61.85	67.09-69.02
Al_2O_3	3.73-5.65	3.90-6.12
Fe_2O_3	5.45-6.33	4.33-5.92
CaO	5.09-5.80	5.01-5.58
MgO	2.79-4.87	3.06-5.18
Na_2O	0.10-0.18	0.11-0.18
K_2O	5.09-8.25	5.45-6.90
SO_3	0.28-0.72	0.32-0.41
LOI	9.88-16.1	1.80-2.20

The RePOFA and POFA show similarity in their particle size though the RePOFA has undergone thermal treatment. From the result obtained by Altwair et al. (2011), the particles of the treated POFA showed no agglomeration and it was supported by the Figure 2.4 which shows the cumulative passing percentage of the treated and untreated POFA particles. Therefore, the RePOFA which shows no negative effect in term of the particles size if compared with POFA and contributes to the distribution of a higher amount of required SiO_2 provides a certain image that the RePOFA can act as a better SCM compared to POFA.

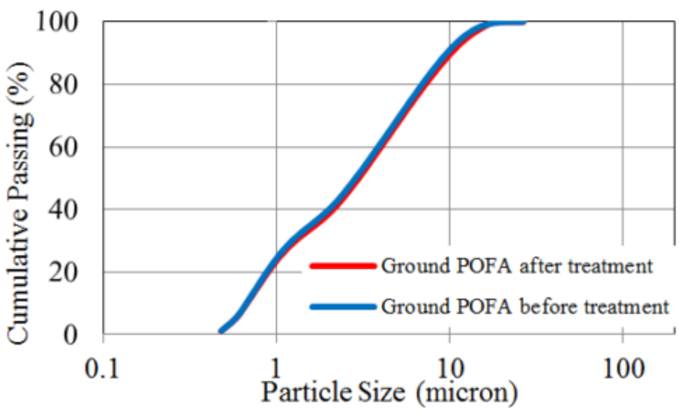

Figure 2.4 Result of cumulative passing percentage between treated and untreated POFA (Altwair et al., 2012)

2.5 INFLUENCE OF REPOFA ON ENGINEERING PROPERTIES OF MORTAR

In this section, the effect of different replacement ratio of POFA and RePOFA on the engineering properties of the mortar is studied. The engineering properties that are reviewed in this section are compressive strength, density, ultrasonic pulse velocity (UPV), scanning electron microscope (SEM) and workability.

2.5.1 Compressive Strength

The compressive strength of the mortar which uses the POFA or RePOFA as the SCM has a relationship with the ratio of the ash replacement. From research that has been done by other researchers, it is clearly observed that the compressive strength of either mortar or concrete is increasing as the replacing ratio increases until a limit. However, the strength of the concrete and mortar will start to reduce as the replacement ratio is beyond the limit.

As a review, from the research done by Jaturapitakkul et al. (2011), the authors used the replacement percentage of 10 % - 40 % as the SCM and the result explained that the 28-days strength of the palm oil fuel ash mortar showed an increase from the replacement percentage of 10 % to 30 %. The compressive strength of the mortar which used 40 % of POFA had shown the lowest strength if compared to the others including the ordinary mortar without the addition of POFA. The result is the same as the result obtained by Kroehong et al. (2011) as the research done by the researcher pictured that the 20 % replacement of the POFA has the highest compressive strength as the strength was compared to the ordinary Portland cement and paste with 20 % and 40 % of POFA replacement. In the research, the author also discovered that the paste with the replacement of 40 % POFA had the weakest strength. The compressive strength of the paste was found around 20 MPa lower than the paste with 20 % POFA replacement. From the result published by Sata et al. (2004), the concrete which used 30 % of POFA as SCM shown a drop in compressive strength compared to the concrete with 20 % of POFA even though all of the POFA concrete showed the higher compressive strength than the control concrete. From the research mentioned, it is observed that the water/binder ratio was fixed at 0.40 and this provides a meaning that 30 % to 40 % of the replacement percentage might be the limit for the POFA replacement ratio. According to the research above, the trend of the compressive strength of concrete or mortar regarding the factor of the POFA replacement ratio is obtained.

In order to obtain the compressive strength of the RePOFA mortar, the research about the thermal treated POFA is concerned. It is assumed that the trend of the compressive strength for the RePOFA mortar or concrete will be same as the POFA mortar or concrete. It is supported by Altwair et al. (2013) as the researcher used the replacement ratio of 0.2, 0.3, 0.5 and 0.6 as the variables to determine the compressive strength of the engineered cementitious composites. The POFA is incinerated under the temperature of 450°C for 90 minutes. The result displays that the compressive strength started to decrease as the replacement ratio reached 0.3. Meanwhile, it is also observed that the compressive strength commenced reducing as the water/binder ratio increased from 0.33 to 0.38. Alsubari et al. (2013) have conducted the research regarding the treated POFA in 2016, the researcher used the RePOFA with the incineration temperature of 600°C in 2 hours and replacement percentage from 50 % to 70 % as the variables to determine the compressive strength of the product. The result pictured that the compressive strength was reduced with the increasing percentage of RePOFA replacement. Even though the compressive strength was reduced, the value of 83 MPa of strength led to the conclusion made by the author that the RePOFA can be utilized as SCM for self-compacting concrete with the replacement percentage of 70 %. However, Safiuddin et al. (2012) suggested that the replacement level of POFA should be limited to 30 % maximum as the replacement ratio more than that will cause the decrement of workability and then result in low compressive strength. In short, the trend of the compressive strength of either POFA or RePOFA regarding the replacement ratio is displayed as in Figure 2.5. The reduction of the compressive strength with a high percentage of POFA replacement is because it reflects the amount of cement used is lessened and leads to the reduction of the hydration products which result in the consequence that the silica is unable to react with $Ca(OH)_2$ to produce C-S-H (Muthusamy & Zamri, 2015).

On the other hand, based on the studies, it is noticed that the early-age compressive strength of the POFA and RePOFA mortar or concrete is less than the ordinary Portland cement. This is due to the reason of the dilution effect as the amount of carbon oxide is reduced plus the delayed onset of pozzolanic reaction between SiO_2 and $Ca(OH)_2$. However, the POFA and RePOFA contribute to its long-term strength due to the continuous pozzolanic reaction because of the fine particle size, the greater glassy phase of SiO_2 and the reduced composition of carbon (Zeyad et al., 2012). This is also proved by Altwair et al. (2011) using the strength activity index which is the ratio of the strength of SCM-cement mortar to cement mortar at specific curing time. Figure 2.6 illustrates the strength activity index of POFA-cement mortar.

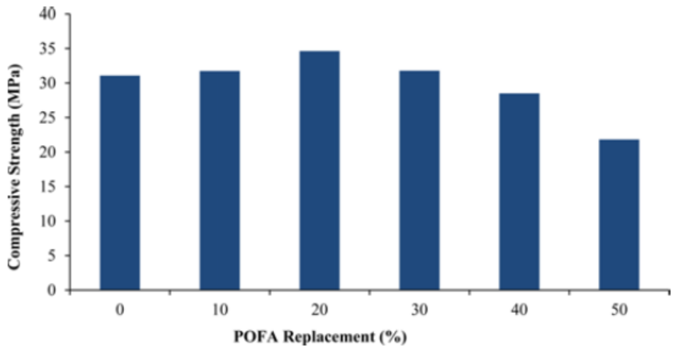

Figure 2.5 Compressive strength versus POFA replacement percentage (Muthusamy & Zamri, 2015)

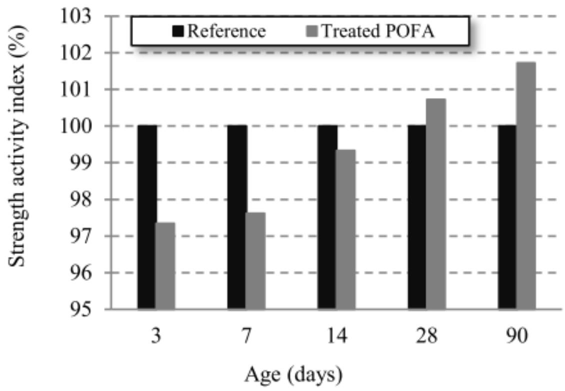

Figure 2.6 Strength activity index of POFA mortar (Altwair et al., 2011)

2.5.2 Density

The density of the RePOFA mortar has the relationship with the production of C-S-H. The C-S-H gel that formed resulted by the pozzolanic reaction of SiO_2 helps to strengthen the bonding between the aggregate and the paste which can contribute to the increment of strength plus density of concrete (Isaia et al., 2003). Therefore, the density of the RePOFA mortar is assumed to be levelled as the replacement percentage of the SCM increases. The concept is supported by Liu et al. (2014) as the growing density of the concrete was projected when the replacement ratio was increased. As supported by Muthusamy et al. (2015), the concrete containing POFA consist huge amount of C-S-H gel cause concrete densification and have higher density than control specimen eventually. From the research done by Boon et al. (2004), the average density for POFA concrete is around 2100 kg/m^3.

However, the density of the mortar might be dropped as the replacement ratio exceed the limit. This can be proven by the research conducted by Muthusamy & Zamri (2015) on the lightweight concrete. The replacement ratio of 20 % resulted in the highest compressive strength with the density around 1843 kg/m^3 among the three replacement ratio of 10 to 30 percent and the density reduced as the ratio raised. Furthermore, as retrieved from the result of Oyejobi et al. (2016), as the replacement percentage of POFA was elevated, the weights of the concrete cubes were reduced and lead to a reduction in their densities. In short, it is known that the density reflects a linear relationship with compressive strength.

2.5.3 Ultrasonic Pulse Velocity (UPV)

The result of the UPV is better in the concrete or mortar with SCM than the ordinary concrete or mortar. The reason is that the SCM increases the packing level of the product by the filling of the void within the microstructure. According to Kanadasan & Razak (2015), the packing level of the mortar get enhanced as the voids present within the specimens are diminished. Besides, the author also urged that SCM can grant the enhancement of the specimens’ structure because the self-compatibility characteristic shown by supplementary materials can interface better between aggregate and paste.

Moreover, the result of UPV has the relationship with the replacement level of the RePOFA. From the UPV result showed by Kanadasan & Razak, as the replacement level was increased from 0 % to 50 %, the UPV result is fluctuating. The positive relationship between UPV and replacement percentage was displayed from the replacement of 15 % to 30 % while the UPV was reduced as the replacement level continued to increase until 50 %. The result of the UPV against RePOFA is shown in Figure 2.7 below. The same result was retrieved from the experiment done by Awal & Shehu (2015). As the authors replaced the cement with 50 % to 70 % of RePOFA, the UPV seemed to reduce. Furthermore, the UPV value of 50 % to 70 % RePOFA cement concrete is also lower than the value obtained from the ordinary Portland cement. This also reflects the concept that the replacement ratio of the SCM should not exceed the satisfied limit. According to Hwang et al. (2012), the UPV result which falls between 3.66 km/s and 4.575 km/s indicate a good quality. Even though the UPV value was decreased as the replacement ratio increased from 50 % to 70 %, the value of UPV still remained above 3.66 km/s. Meanwhile, the UPV value of above 4.5 km/s was obtained from 5 % to 50 % of RePOFA replacement level (Kanadasan & Razak, 2015; Awal & Shehu, 2015). Therefore, it can be concluded that the RePOFA can help to enhance the microstructure properties plus the compressive strength of the specimens as shown in Figure 2.8.

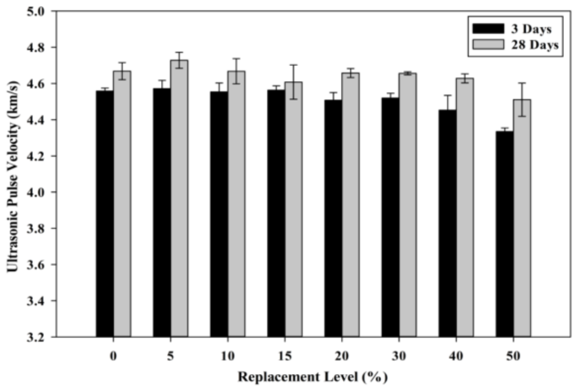

Figure 2.7 Relationship between UPV and replacement percentage (Kanadasan & Razak, 2015)

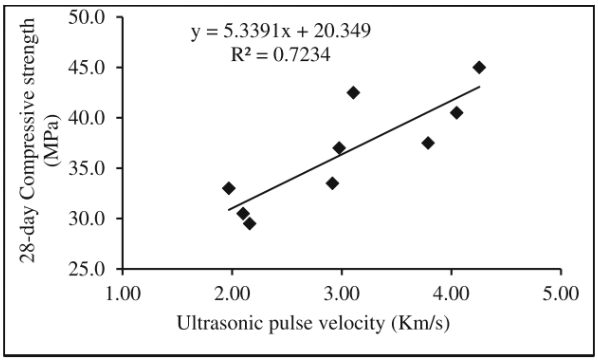

Figure 2.8 Strength versus UPV (Mohammadhosseini et al., 2015)

2.5.4 Scanning Electron Microscope (SEM) Examination

The SEM result between the thermal treated POFA and untreated POFA is first discussed in this subsection before moving forward to the SEM result of different replacement ratio POFA. As observed in Figure 2.9, the unburnt carbon which was porous and irregular shaped found in the untreated POFA but was absent in the SEM result of thermal treated POFA (Chandara et al., 2010). This clearly indicates that the thermal treatment of the POFA can aid in removing the unburnt residue. Furthermore, the absence of agglomeration of particles in the untreated POFA was also discovered from the Figure 2.9.

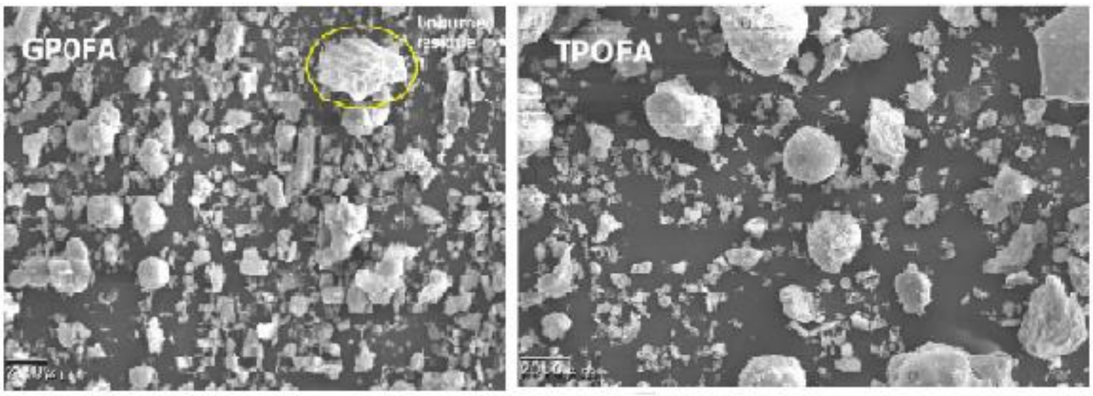

Figure 2.9 SEM of untreated and treated POFA (Chandara et al., 2010)

From the SEM result retrieved from the previous researchers, the image confirmed the pozzolanic reaction and the forming of the C-S-H gel. For example, as refer to Figure 2.10, little pores were noted in the structure including the presence of C-S-H which mostly covered the fracture surface existed within the structure of the POFA concrete. Moreover, the author, Altwair et al. (2013) also concluded that numerous large pores had been filled with the gel and this resulted in the formation of denser structure. However, as discussed above, the increasing replacement ratio of the RePOFA causes the degradation of the performance of the specimen due to the amount of the increasing unreacted particles. In addition, Altwair et al. (2013) also commented that the unreacted POFA particles were increased as the result of the escalating of POFA replacement level by observing the result of SEM. The idea was the same as what Tonnayopas et al. (2006) generated after the author conducting the SEM test regarding the effect of increment ratio of replacement on the microstructure of POFA concrete. As displayed in Figure 2.11, as the author levelled up the replacement ratio from 15 % to 20 %, the voids existed within the structure were growing and this incurred the reducing strength of the product. In short, the result of SEM amplify the effect of over replacement ratio of POFA in concrete or mortar and this issue should be taken with concern. From the another research done by Altwair et al. (2011), high amount of gel was formed as the POFA/cement used was 0.3 but the unreacted POFA particles which were found when the POFA/cement ratio increased to 0.8.

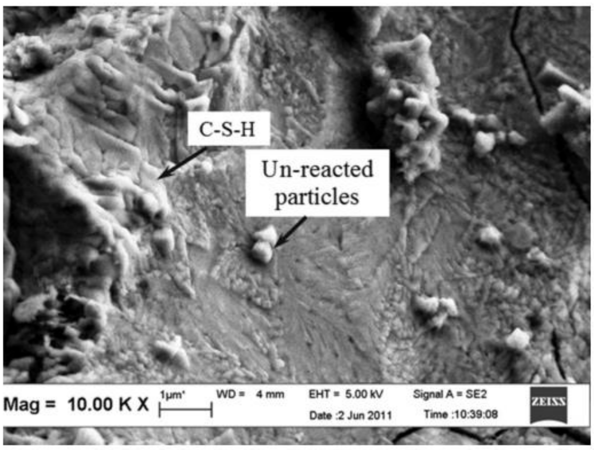

Figure 2.10 SEM of mortar with POFA as SCM (Altwair et al., 2013)

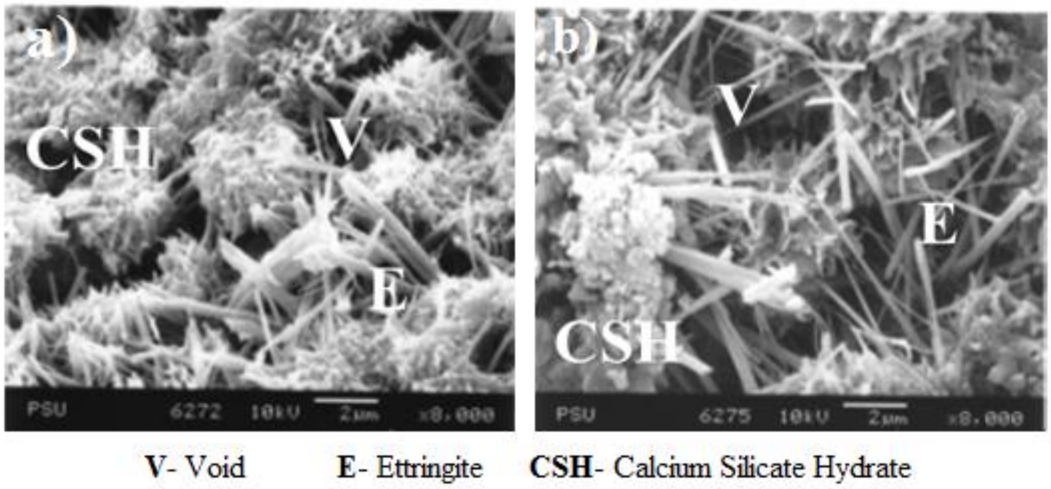

Figure 2.11 SEM With (a) 15% and (b) 25% of POFA replacement (Tonnayopas et al., 2006)

2.5.5 Workability

First, for the workability of the mortar with different size of thermal treated POFA as the SCM will exert different effects on this properties. According to Asrah et al. (2015), the treated POFA with bigger size of particles will suffer from a reduction of its workability. From that research, the replacement of POFA with an increasing number of bigger particles leads to a lower flowability of the fresh mortar. However, when the particles size of the POFA was ground to fine or ultrafine, a better workability of the mortar was observed. The rationality is that the fine particles of the POFA show low porosity and this will avoid the excess absorption of the water added while mixing the mortar. Besides, it is agreed by Megat Johari et al. (2012) that the POFA with fine particles provide a lubrication effect to the mix and this result a good flowability of the fresh mortar.

Furthermore, the untreated POFA also causes the reduction of the workability of the concrete as the substitute percentage is increasing. The statement is proved by the experiment done by Oyejobi et al. (2016) as the author found that the height of the slump was reduced when the replacement of POFA was from 10 % to 30 %. The

RePOFA with thermal treated will not have these consequences because of the lower LOI value for the RePOFA. According to Chandara et al. (2010), the POFA with a high value of LOI will absorb more water and this will cause the diminishing of the flowability. The reason for the treated POFA assists in the flowability of the fresh mortar or concrete is that the extra paste volume resulted by RePOFA enhances the packing effect between the aggregates. The paste acts as a filler to fill into the space present between the particles and this provides a coating to the particles which help in developing their flowability characteristic(Alsubari et al., 2016). The Figure 2.12 shows the increasing workability with the increasing POFA content.

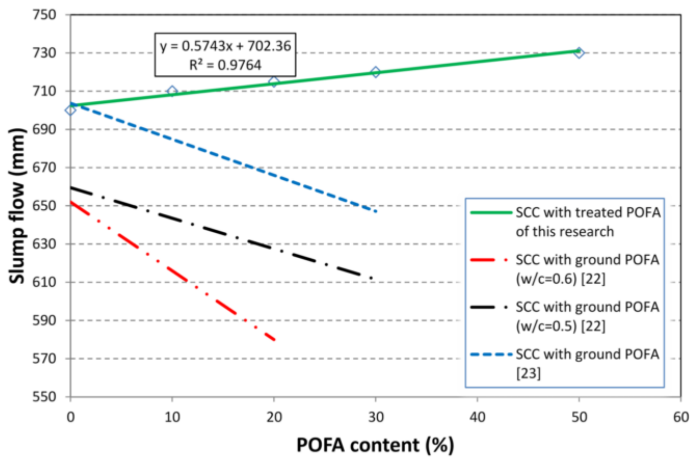

Figure 2.12 Slump flow against POFA percentage (Alsubari et al., 2015)

2.6 INFLUENCE OF REPOFA ON DURABILITY PROPERTIES OF MORTAR

Similar to the engineering properties, a different replacement ratio of the RePOFA leads to the development of a different performance of either the concrete or mortar. In this section, the durability properties that are going to be deliberated are the porosity and water permeability of the concrete or mortar.

2.6.1 Porosity

The porosity of the mortar or concrete is influenced by the usage of the RePOFA as the SCM. In general, the porosity of the mortar will be reduced if compared to the ordinary Portland cement. The rationale behind is that the pozzolanic reaction occurs in between the SiO_2 and $Ca(OH)_2$ plus the role of the POFA as the filler effect (Usman et al., 2015). Meanwhile, when the factor of the replacement ratio of RePOFA is considered, the porosity of the specimen is found to be reduced as the replacement level of the RePOFA is raised. According to the information gathered from the research conducted by Megat Johari et al. (2012), the porosity of the concrete was reduced by 20 % as the substitute percentage is altered from 20 % to 60 %. The Figure 2.13 displays the porosity of the concrete as the replacement level increases. In addition, a similar result of the reduction of porosity by the increment replacement ratio of POFA was also obtained by the researcher, Hussin et al. (2015). The author commented that the porosity of POFA mortar lessens as the period increases due to the hydration process which occurs during the period. However, the inverse relationship between the porosity with POFA content starts to change when the replacement ratio is beyond a certain limit. According to the result obtained by Usman et al. (2015), the trend shows that the porosity decreased as POFA content increased but a growing curve was then discovered after the POFA content exceeds 25 %. When comparing the pore volume of paste with increasing content of POFA, Kroehong et al. (2011) experimented that the paste with 20 % of POFA content had the finer pore volume to the paste with 40 % of POFA content. The reading for the 90 days pore volume of paste with 20 % and 40 % POFA content was 31.0 nm and 35.8 nm respectively. Furthermore, the porosity of the mortar has an influence on its strength. The diminishing result of the porosity will improve the compressive strength and make it denser (Hussin et al., 2015). Figure 2.14 displays the relationship among the compressive strength and porosity of the mortar with 80 % of POFA content.

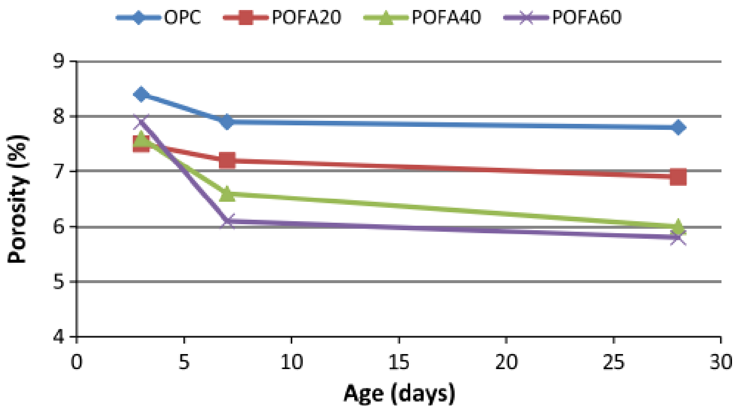

Figure 2.13 Relationship between porosity and POFA content (Megat Johari et al., 2012)

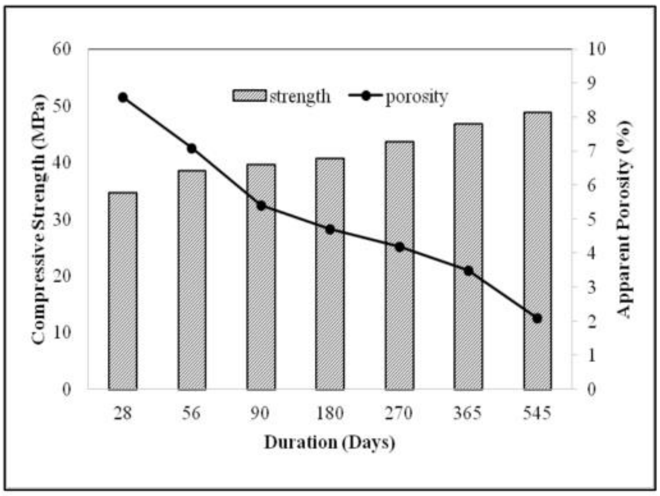

Figure 2.14 Relationship between strength and porosity of 80% content of POFA mortar (Hussin et al., 2015)

2.6.2 Permeability

According to Chindaprasirt et al. (2007), the permeability of the concrete was higher than the POFA-cement concrete. The POFA content also influences the permeability of the concrete. As resulted by the mentioned author, the permeability of the concrete was reduced when the replacement level of the POFA was elevated. The permeability values of the concrete with 20 % of POFA content to 40 % of content were 0.59×10^{-12} m/s and 0.41 x $^{-12}$ m/s respectively. However, when the replacement level was increased to 55 %, the permeability of the POFA concrete was increased to 3.30×10^{-12} m/s. This shows that the POFA content in replacing the cement requires careful thinking as a promising result of mortar needs to be collected. Meanwhile, the result of the permeability test with a different replacement ratio of POFA shown by Tangchirapat et al. (2009) pictured that the permeability of the specimen decreased when the POFA replacement percentage rose from 10 % to 20 % but an increased permeability was shown as the replacement percentage reached 30 %. Hossain et al. (2016) performed the permeability test with the high replacement level of POFA which is from 55 % to 70 %. Eventually, an increment permeability of the specimen resulted. Therefore, it can be said that the higher replacement ratio of the POFA content will contribute to the reducing of permeability but as the limit is reached, the additional of the POFA content will cause the result to be opposed to the initial trend. The Figure 2.15 shows the general trend of the permeability as the replacement ratio increases.

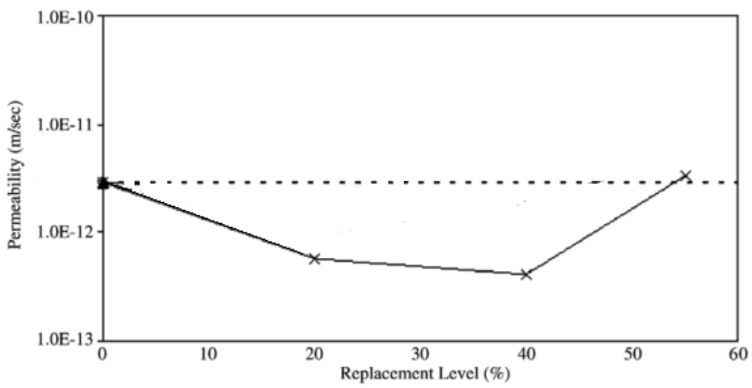

Figure 2.15 Relationship between permeability and replacement level of POFA (Chindaprasirt et al., 2007)

2.7 SUMMARY OF CRITICAL REVIEW

After reviewing the researches done by other researchers, it reflects that the result of the mortar or concrete that use POFA as the SCM showed inconsistency. The reason behind is acknowledged to the uncontrolled burning temperature of the POFA. Moreover, the unburnt carbon exists within the POFA also influences the result. Therefore, the POFA is decided to be treated with thermal and term it as RePOFA. The untreated POFA is decided to be burned under the temperature of 700^{o}C with the duration of 180 mins. The temperature is set as above because there is research supported that the burning of POFA with 500^{o}C cannot completely remove the unburnt carbon. Moreover, the RePOFA is selected as the SCM because the research about the thermal treated POFA mortar or concrete is limited. As this research concerns the optimum replacement ratio of the RePOFA in mortar, the percentage of replacement that is going to be tested is set as 10 %, 20 %, and 30 %. The reason is that most of the studies reflected that the performance of the concrete or mortar will be degraded as the replacement percentage is beyond 20 %. The water/cement ratio is then decided to set as 0.4 as the research with POFA as the SCM designed the w/c ratio as 0.4 showed the satisfied result.

In addition, as this research is concerned on the optimum ratio of the RePOFA on the properties of the mortar, the early strength development of mortar with replacement ratio of 10 %, 20 % and 30 % is investigated first by using steam curing. After indicating the optimum range, the further experiment is conducted to investigate the optimum ratio of the mortar. The mortar consists of the replacement of RePOFA is compared with the controlled mortar to observed the difference and investigate whether the properties of the mortar is influenced or not. In addition, after determining the optimum ratio, the ANOVA test is then carried up to observe the significance of the variation of the RePOFA ration on the engineering as well as durability performance of the RePOFA mortar.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 INTRODUCTION

This chapter is discussing the materials that are used for this research. The details about the materials used are deliberated including the function of the materials used. The design of the mix proportion for the mortar is provided in the following section too. In addition, the tests that were conducted for this research are also listed in this chapter including the explanation of the function of the tests and the procedures to carry out the tests.

3.2 MATERIALS

The aim of this research is to determine the optimum ratio of the RePOFA in mortar, hence the most important material used was palm oil fuel ash (POFA). The other materials that were used in this research were cement, water, and the sand or fine aggregate.

3.2.1 Reincinerated Palm Oil Fuel Ash (RePOFA)

The POFA used for this research was collected from Kilang Minyat Sawit Tg. Tualang. The POFA collected was dried in the microwave oven for 24 hours to remove the moisture content. Then, it was sieved through the 300μm to remove the unburnt residue and the larger size of particles. The ash was then ground to a finer size in order to improve the performance of the mortar as the unground POFA will cause the degradation of the performance of POFA (Altwair et al., 2013). As this research focuses on the performance of RePOFA on the mortar, the ground POFA was then sent for thermal treatment. The POFA was heated under 700^{o}C with the duration of 180 minutes to remove the unburnt carbon. The process for managing the POFA was summarized in Table 3.1. The RePOFA was found different in colour from POFA after incinerating. This is due to the removal of the unburnt carbon which can affect the pozzolanic activity of the constituents in POFA.

Table 3.1 Process for managing POFA

Step 1	Step 2	Step 3	Step 4	Step 5
Collection of POFA	Heating of POFA for 24 hrs	Sieving POFA through 300 μm	Grinding POFA into finer particles	Incinerating POFA to become RePOFA at 700^{o}C for 180 minutes

Figure 3.1 POFA before reincinerating

Figure 3.2 RePOFA after reincinerating under 700°C for 3 hours

Figure 3.3 Furnace used for reincinerate POFA

Figure 3.4 Grinder used for grind RePOFA

3.2.2 Cement

The cement was used in this research as the cement is recognized as the most common binding material in the construction sector. As this research is concentrated on the SCM, the other materials used was set constant especially the usage of cement. The cement used for this research was Hume Cement's Ordinary Portland Cement as displayed in Figure 3.5. The cement was stored off the ground in a dry place. Moreover, the cement bags were wrapped by sheets to provide double protection to the cement.

Figure 3.5 Hume Cement's OPC

3.2.3 Fine Aggregate

The mining sand with a fine modulus of 2.87 was used as the fine aggregate. According to BS EN 12620:2002, the aggregate size less than or equal to 4mm considered as a fine aggregate. The fine aggregate was dried in a microwave oven to get rid of the moisture content. This is due to the fact that the moisture existing within the fine aggregate will influence the other controlled factors. The result of the sieve test for the fine aggregate was tabulated in Table 3.2.

Table 3.2 Sieve analysis for mining sand

Sieve Size Range	**Sieve Fraction**		**Nominal Aperture Size**	**Cumulative Undersize**
mm	gram	% by mass	mm	% by mass
5.000 – 2.360	153	16	2.360	84
2.360 – 1.180	207	21	1.180	63
1.180 – 0.600	169	17	0.600	46
0.600 – 0.300	310	31	0.300	15
0.3.00 – 0.150	101	10	0.150	5
< 0.150	55	5		
Total	995	100		

$$\text{Fineness Modulus} = \frac{(16 + 37 + 54 + 85 + 95)}{100} = 2.87$$

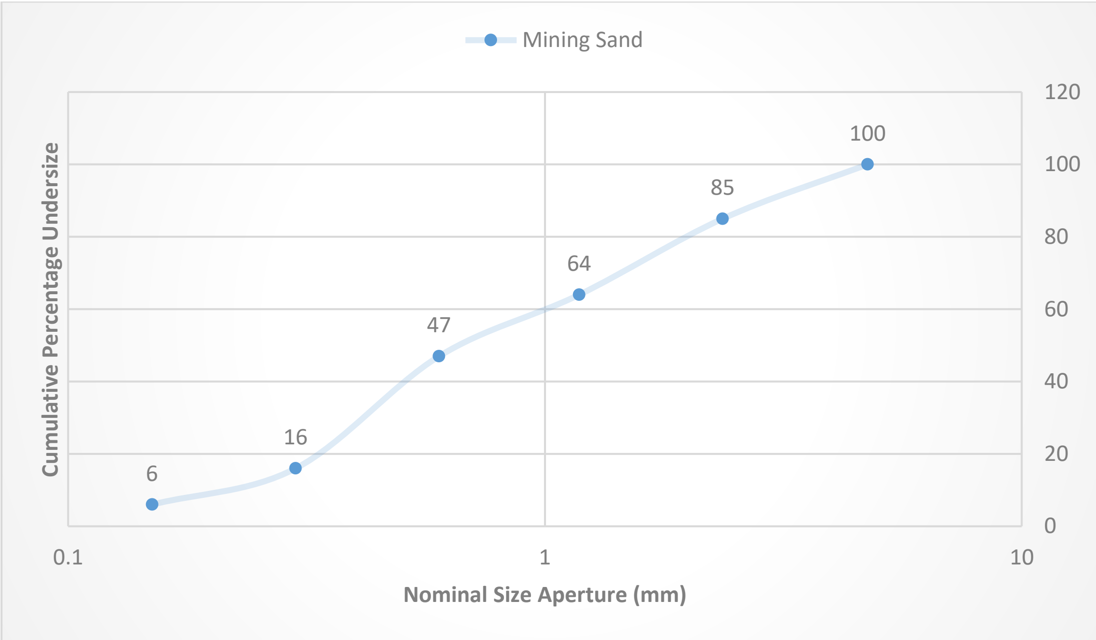

Figure 3.6 Particle size distribution chart

Figure 3.7 Mining sand used for this research

3.2.4 Water

Normal tap water was used for this research. The water plays an important role in the hardening of cement as it aids in the hydration process of the cement. The water to binder ratio was set as 0.40 in this research. This is due to the fact that the increase in water to binder ratio will cause the diminishing performance of the mortar. However, the very low water to binder ratio will influence the workability of the fresh mortar. After reviewing the researches done by previous researchers, the water to binder ratio was set at 0.40.

Figure 3.8 Water source

3.3 MIX PROPORTION OF REPOFA MORTAR

In this study, the replacement percentage of RePOFA was set to be 10 % to 30 % at phase one. The cement to aggregate ratio was set as 1:2.75 based on the information gathered from previous researcher, Noorvand et al. (2013) and also according to ASTM C109/C. Table 3.3 illustrates the mix proportion of the RePOFA at phase one. After determining the optimum range for the RePOFA replacement, the mix proportional was designed as tabulated in Table 3.4.

Table 3.3 Mix proportion of RePOFA at phase one

Mix Code	Ordinary Portland Cement, %	RePOFA, %	Water to binder ratio, w/b	Sand to binder ratio
RePOFA10	90	10	0.40	2.75
RePOFA20	80	20	0.40	2.75
RePOFA30	70	30	0.40	2.75

Table 3.4 Mix proportion of RePOFA at phase two

Mix Code	Ordinary Portland Cement, %	RePOFA, %	Water to binder ratio, w/b	Sand to binder ratio
Control Mortar	100	0	0.40	2.75
RePOFA15	85	15	0.40	2.75
RePOFA20	80	20	0.40	2.75
RePOFA25	75	25	0.40	2.75

3.4 MORTAR MIXNG PROCESS

The materials used were weighed by using the electronic weight balance available in the workshop in Block J according to the mix design before mixing. The portion of RePOFA and cement were mixed according to Table 3.3 at phase one and Table 3.4 at phase two before making mortar mixture. The mixing of materials was then performed by using the concrete mixer. Some portion of the sand was mixed with partial water before adding the cement with RePOFA. After the mixing process, the fresh mortar was casted into the mould prepared. Before casting, the mould was coated with oil to prevent the pasting of the fresh mortar to the mould. Then, the moulds were vibrated using vibration table and the compactor to compact the fresh mortar. The moulds were then placed in the workshop for the setting purpose.

Figure 3.9 Preparation of RePOFA mortar

3.5 CAST, MOULD AND DEMOULD MORTAR

As different tests were carried in this research, the different size and shape of the mould were selected for usage. The cube mould which is sized 50 × 50 × 50 mm plus the cylinder mould with the size of 45 mm diameter and 40 mm height were used in this research for different tests. The mortars that were casted in the cube mould were used to test for the engineering test. Meanwhile, the mortars that were casted in cylinder shape were used to test the durability properties of the mortar.

When pouring the mortar into the mould, half of the fresh mortar was poured first and then compacted by the compactor before adding the remaining mortar. This process was conducted to remove the air trapped within the mixture of mortar. Then, the cement trowel was used to remove the excess fresh mortar present on the moulds. The moulds of the mortar were demoulded after 24 hours and been marked. After that, the specimens were inserted into the water tank for curing purpose.

Figure 3.10 50 × 50 × 50 mm mortar cube mould

Figure 3.11 45 × 40 mm mortar cylinder mould

Figure 3.12 Cube moulds with fresh RePOFA mortar

3.6 CURING

The specimens were cured to ensure the mortar consists of sufficient moisture amount for the hydration of the cement and the strength developing. In this research, the specimens were cured at the ambient temperature. According to BS EN 12390-2:2009, the specimens need to be cured till immediately before conducting the testing on them. Besides, as the standard stated, the temperature should be around 20 ± 2ºC with the relative humidity of more than 95 %. The curing ages for the specimens in this research were 7 days, 14 days, 28 days and 56 days. For this research, the RePOFA mortar was cured under hot water bath as pictured in Figure 3.14 at phase one. After obtaining the optimum ratio, the RePOFA mortar was the cured under ambient temperature water as shown in Figure 3.15.

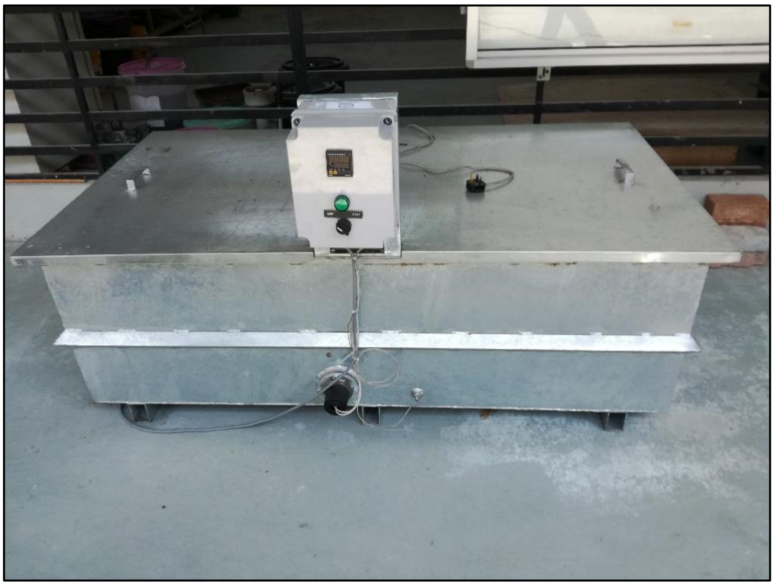

Figure 3.13 Hot water bath curing used at phase one

Figure 3.14 RePOFA mortar cured under hot water bath at phase one

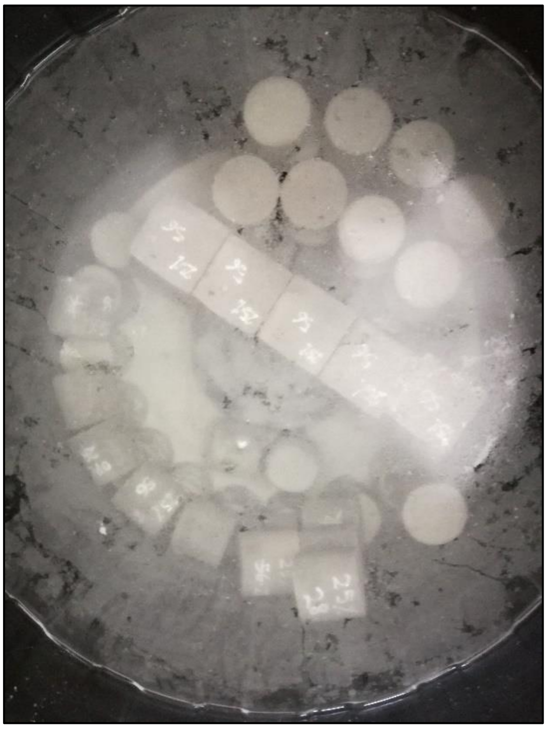

Figure 3.15 RePOFA mortar cured under ambient temperature water at phase two

3.7 EXPERIMENTAL PROGRAM

Table 3.5 tabulates the details on the test program such as the types of the tests carried, testing age of the specimen and the type of the specimens used for different tests. In phase one, only the compressive strength test was conducted in determine the performance of RePOFA mortar to obtain the optimum range. This is because the compressive strength test can result the performance of the mortar significantly. In phase two, all the tests mentioned in Table 3.5 were executed to evaluate the performance of the RePOFA mortar. Moreover, the Figure 3.16 and Figure 17 illustrate the flow of the experimental program at phase one and two respectively. This provides a clearer pictures on the sequence in conducting the experiment. It also helps to give the direction on the flow in conducting the experimental programme.

Table 3.5 Test program schedule

Properties	Type of Test	Age of Specimen	Type of Specimen
Fresh Properties	Flow Table Test	-	-
Engineering Properties	Density Test	7, 14, 28 and 56 days	Mortar cube with 50 × 50 × 50 mm dimension
	Compressive Test	7, 14, 28 and 56 days	Mortar cube with 50 × 50 × 50 mm dimension
	UPV test	7, 14, 28 and 56 days	Mortar cube with 50 × 50 × 50 mm dimension
Microstructure Analysis	SEM test	14 days	-
Durability Properties	Porosity Test	7, 14, 28 and 56 days	Mortar cylinder with 45 mm diameter and 40 mm height
	Permeability Test	7, 14, 28 and 56 days	Mortar cylinder with 45 mm diameter and 40 mm height

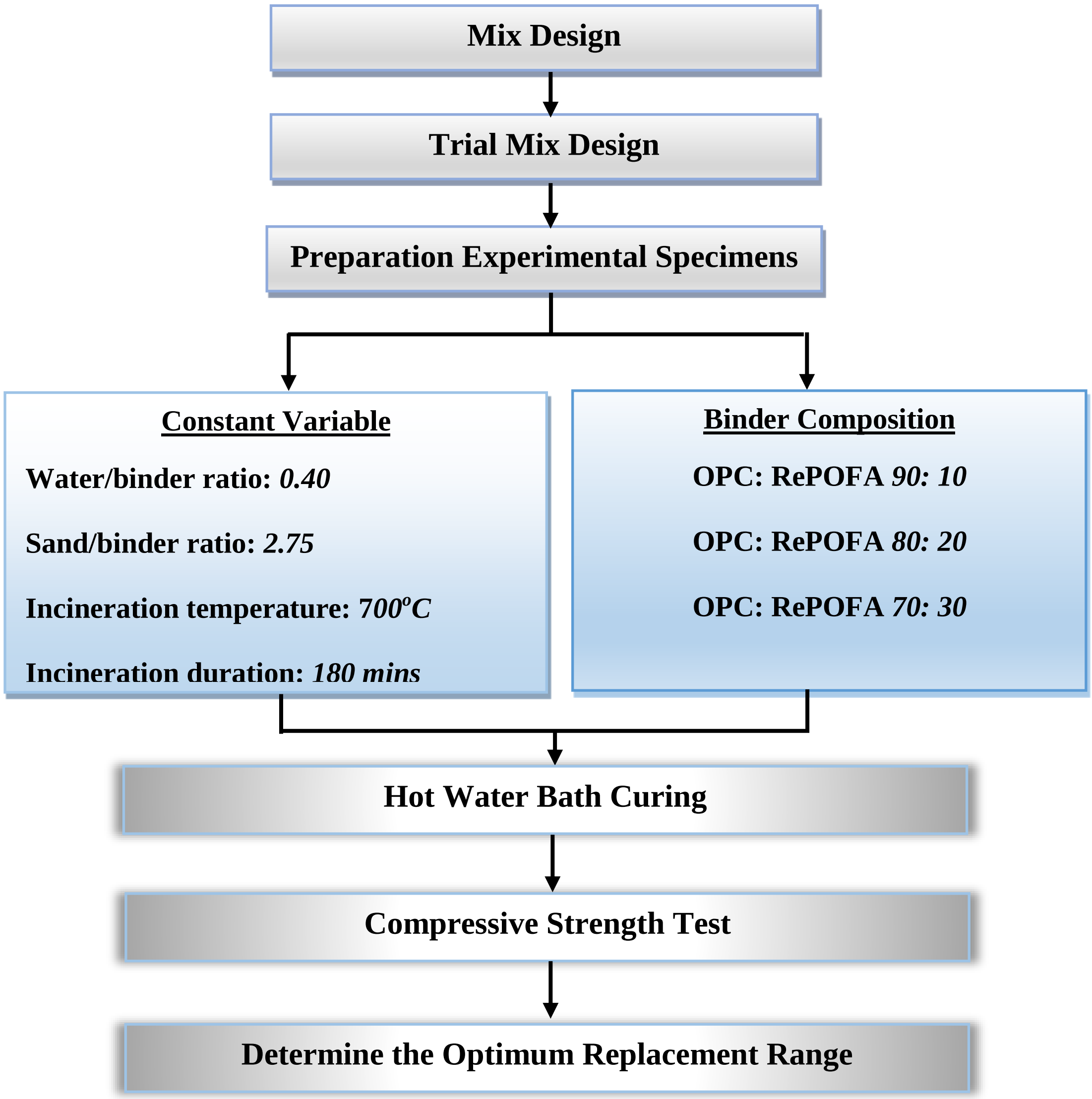

Figure 3.16 Experimental flowchart at phase one

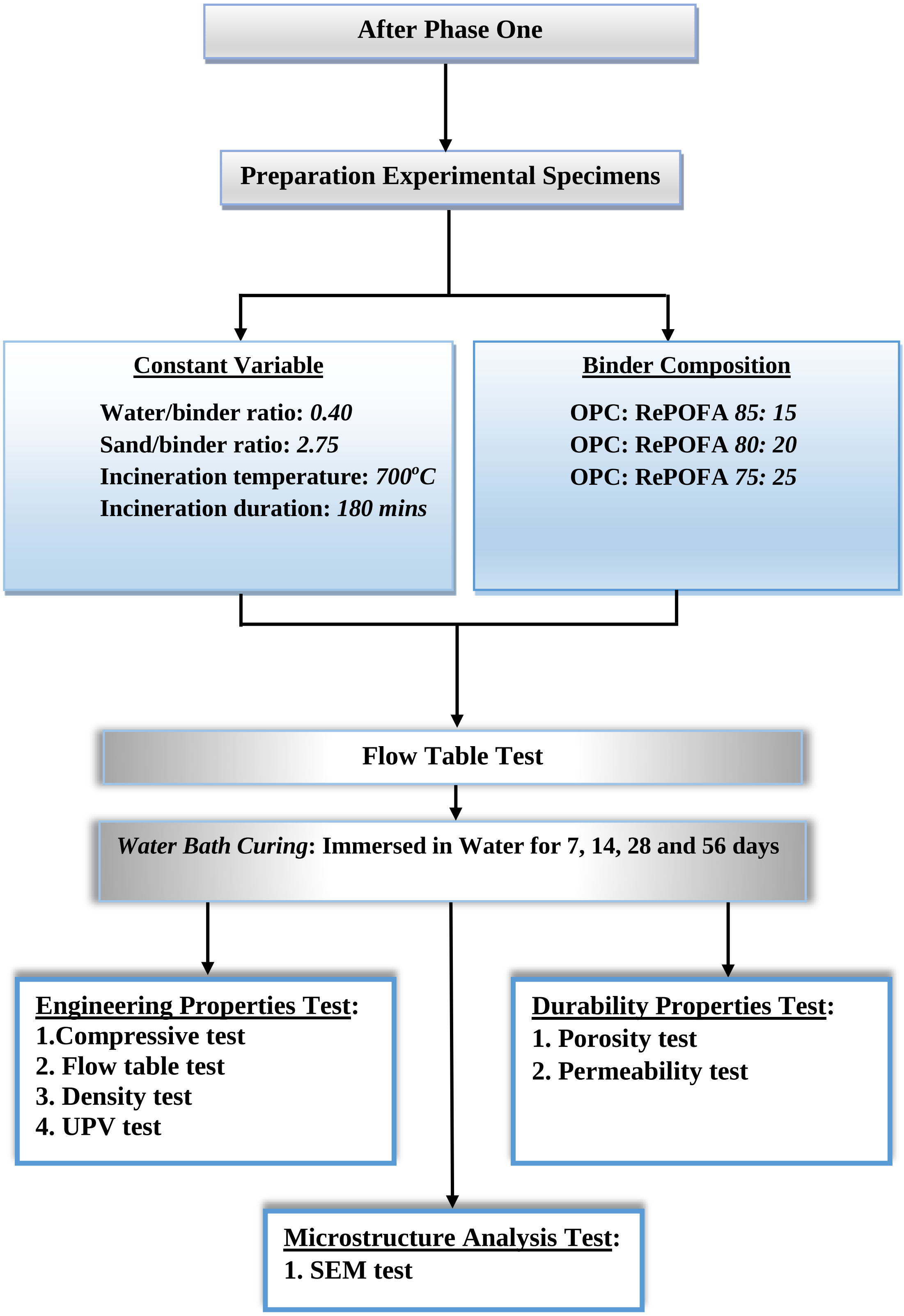

Figure 3.17 Experimental flowchart at phase two

3.8 TESTS ON REPOFA MORTAR

There were 7 tests conducted in this research including both the engineering and durability test and the microstructure analysis. For the engineering tests, the compressive strength, density, flow table and UPV tests were conducted. For the durability tests, the permeability and porosity tests were operated while SEM examination was carried for microstructure analysis.

3.8.1 Flow Table Test (ASTM C 1437-07)

The flow table test was conducted to test the workability of the fresh mortar. The workability for all the fresh mortar listed in Table 3.3 was determined by using the flow table test. The workability of the fresh mortar plays an important role in determining the performance of the mortar. This is due to the fact that the highly workability fresh mortar will help to eliminate or reduce the void in between the particles.

According to ASTM C 1437, the flow table was carefully cleaned to ensure it was dry before placing the flow mould at the center. Then, a layer of mould with the thickness of 25 mm was poured into the mould and tamped with tamper up to 20 times. The second layer was then placed into the mould after ensuring the mould was uniformly filled by the first layer. The mortar was then cut off to ensure the top of the mould was plane surfaced by using the trowel. After that, the table was wiped to confirm the absence of water around the edge of the flow mould. The mould was then lifted one minute after complete mixing the mortar. Later, the table was dropped immediately 25 times in 15 seconds. As there was four lines scribed in the table top, the diameter of the mortar was measured using the lines mentioned. The diameter was recorded to the nearest millimetre. In the last step which was the cleaning process, the table top was wiped by using a wet cloth and the mould was washed to prevent the hardening of mortar on it.

Figure 3.18 Flow table test equipment

3.8.2 Compressive Strength Test (ASTM C109/C-07)

The compressive strength of the mortar is the capacity of the mortar to withstand the maximum stress without fracture under an applied load. As stated in ASTM C109/C, the purpose of this test is to indicate the compressive strength of the mortars and the result may be used to determine compliance with specifications. In this study, the specimens were tested immediately after removal from the water tank. The specimens were wiped to ensure the surface were in dry condition. Moreover, the cross-sectional area of the specimens was checked to ensure the surface was in good condition. The specimens which had the unsatisfied surface were discarded.

Before the testing, the load was decided to be applied on the faces of the specimen which were in contact to the plane surfaces of the mould. Moreover, it was confirmed that the spherically seated block was free to tilt before contact with the specimens' surface. The specimens were located below the center of the top bearing block in the test machine. During the testing, a load rate with the range of 900 to 1800 N/s was applied on the specimens. No adjustments were made to the load rate before the failure of the specimens was noticed. The maximum load indicated by the machine was then indicated and the calculation of the compressive strength for the specimens was conducted. The formulae used is shown as below:

$$fm = P/A \tag{3.1}$$

Where:

fm = Compressive strength in MPa

P = Total maximum load in N

A = Area of the loaded surface in mm^2

The compressive test of the specimens was conducted in the days of 7, 14, 28 and 56. Furthermore, five sets of the samples were tested for each test age and the average strength was determined. The specimens that were used were the size with 50 mm × 50 mm × 50 mm.

Figure 3.19 Kenco compressive strength test machine

3.8.3 Density Test (ASTM C 642-06)

The density test was conducted to determine the compactness of the mortar. The amount of the air content within the mortar was tested to gauge the density of the specimen. For example, the low density shown if compared with others indicates the high air content or void present in the specimen. According to ASTM C 642, before conducting the calculation for the density, essential information was collected. The information mentioned were the mass of specimen in air (recorded as m_a) and mass of specimen submersed in water (recorded as m_w). The density of the specimens was calculated by using the formula shown below:

$$\rho_m = \frac{m_a - \rho_w}{m_a - m_w} \tag{3.2}$$

Where:

m_a = Mass of specimen in air, g

m_w = Mass of specimen submersed in water, g

ρ_w = Density of water, g/cm^3

ρ_m = Density of mortar, kg/m^3

The specimens used for this test plus the testing age were same as the specimens used and testing age stated for the compressive strength test. The specimens with cube size of 50 mm in length, width, and height were used and tested for 7, 14 ,28 and 56 days. Same specimens were chosen along the 4 testing ages to examine the changes of density within the same specimens.

Figure 3.20 Equipment setup for density test

3.8.4 SEM Test (ASTM C 1723)

According to ASTM C1723, SEM was conducted to trace the chemical constituent changes and also observe the microstructure of the specimens as the SEM can provide images that range from low magnification to very high magnification which is from 15× to 50,000× or even higher. The test was essential for this research as the effect of the microstructure of mortar after substituting the composition of cement need to be clarified by using SEM. The controlled specimen, specimens with 15 % to 25 % of RePOFA with the testing age of 14 days were collected and the SEM test was conducted on the mentioned specimens. The microstructure for the mortar was observed and the differences among the tested specimens were distinguished. The specimens that required the SEM test were sent to the machine operator in UTAR to conduct the test. After the test, the image for different specimens tested was inspected to confirm the influence of the PePOFA replacement percentage in the microstructure of the mortar.

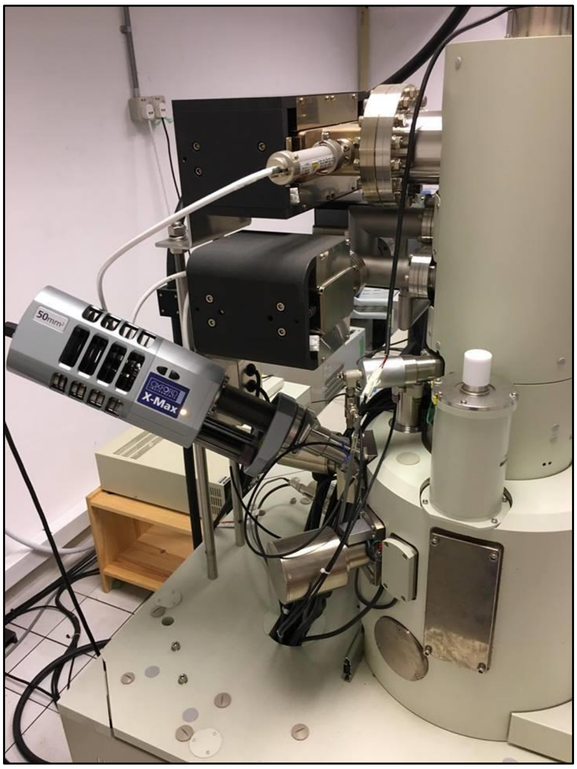

Figure 3.21 Scanning electron microscopy machine

3.8.5 UPV Test (ASTM C597-09)

The purpose of carrying up the UPV test in this research is to examine the quality of the mortar with different replacement ratio of RePOFA. As retrieved from ASTM C597, this test can help to indicate whether any void or crack is present in the mortar. According to Bayan et al. (2015), UPV test can help to inspect the quality and strength of the questionable product. Furthermore, by comparing with the different samples, the UPV assisted in determining the properties of the mortar with different substitution level of RePOFA especially the severity of deterioration. There are 3 basic ways for the arrangement of the transducer which are on opposite faces (direct transmission), adjacent faces (semi-direct transmission) and same face (indirect transmission). In this study, the direct transmission was used as maximum pulse energy was transmitted and received by the transducer for direct transmission. This can improve the reliability of the time measurement. The specimen with the size of 50 × 50 × 50 mm was used in this test. The specimens with the testing age of 56 days were selected for the testing of the quality. The quality of the specimens was determined by examining the pulse velocity. The information required for the calculation of pulse velocity was the path length and the measured travel time. The equation is shown as below,

$$v = {}^{L}/_{t} \tag{3.3}$$

Where:

v = Pulse velocity

L = Path length

t = Measured travel time

Figure 3.22 Ultrasonic pulse velocity testing machine

3.8.6 Porosity Test (RILEM CP 11.3)

The purpose of the porosity test is to determine the bulk volume of the product occupied by voids. It is important as the porosity will affect the durability plus the strength of the mortar. The test was conducted first by drying the specimens for 24 hours at 105°C and cooling the specimens in the desiccator for the next 24 hours. The weight of the specimens was weighed and marked as W_d. The specimens were then located in the desiccator for vacuuming with approximately 15 minutes. After 2 hours, the specimens were vacuumed again for 15 minutes. In order to enable the samples fully submerge in the water, the de-aired and de-ionised water were filled into the desiccator. The samples were then kept for 24 hours before collecting them for weighing in air and water. The weight weighed in air and water were recorded as W_a and W_w respectively. The porosity of the specimens was calculated by determining the amount of water penetrated into the specimens. The equation is as below,

$$Porosity\ (\%) = \frac{\mathrm{Wa - Wd}}{\mathrm{Wa - Ww}} \times 100\% \qquad (3.4)$$

Where:

W_a = Saturated dry weight of specimen

W_d = Oven-dried weight of specimen

W_w = Saturated submerged weight of specimen

The specimens with the cylinder size were used for this test. Furthermore, this test was conducted for the specimen with the testing age of 7, 14, 28 and 56 days.

Figure 3.23 Porosity test equipment

Figure 3.24 RePOFA mortars were vacuumed for 15 minutes

3.8.7 Intrinsic Air Permeability test (Cabrera et al., 1989)

This test was conducted to observe the influence of different replacement ratio of RePOFA on the durability properties of the mortar. The permeability plays an important role in ensuring the performance of the mortar as the highly permeable mortar will cause the degradation of the strength of the mortar.

The test was conducted by applying a constant pressure of nitrogen gas. Intrinsic permeability was defined by Klinkenberg as the y-intercept of the line connecting permeability and the inverse of the average pressure. The specimens were dried for 24 hours under 105°C before having the permeability test. After cooling for 30 minutes, the cylinder sized specimens were ready for the test. The RePOFA mortar specimens were surrounded by a thin layer of silicon rubber and insert into the permeability cell, 2 bars of gas pressure was then applied. Precaution need to be taken to disallow leakage happen. The time flow of gas was recorded according to the suitable bubble meter used. The measurement was repeated 4 times to obtain the average result. In order to calculate the permeability of the mortar, several readings need to be taken and the formula below was used.

$$\mathrm{K} = \frac{2P_2(1.76\times10^{-16})VL}{A(P_1^2-P_2^2)} \tag{3.5}$$

Where:

K = Coefficient of intrinsic air permeability, m^2

P_1 = Absolute applied pressure bars (atm. pressure) usually 2 bars

P_2 = Pressure at which the flow rate is measured (atm. pressure) usually 1 bar

A = Cross sectional areas of specimens, m^2

L = Length of specimen, m

V = Flow rate, cm^3/s

$$V = \frac{(\frac{D^2}{4})\pi H}{T} \tag{3.6}$$

D = Flowmeter diameter, cm

H = Length read on flowmeter, cm

T = Average time, s

The permeability between the specimens was then compared and recorded. The value of the water permeability of the mortar was measured at the age of 7, 14, 28 and 56 days. For this test, the cylinder size of the specimen was used.

Figure 3.25 Intrinsic air permeability testing machine

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 INTRODUCTION

The results collected from the laboratory experiments are discussed and analysed in this chapter. The optimum replacement percentage of RePOFA was determined after undergoing two phases which was the determination of the range for the optimum replacement percentage and determination of the optimum ratio by using the tests described in Chapter 3. The performance of the RePOFA mortar was analysed through the results generated from the aforementioned tests. In phase one, the range of the optimum replacement ratio was determined among 10 %, 20 % and 30 % of RePOFA replacement percentage. After the range was set, the further laboratory experiments were conducted to determine the optimum replacement percentage of RePOFA.

4.2 MORTAR PERFORMANCE AT PHASE ONE

As the strength of the mortar unfold the direct information regarding the performance of the mortar, the compression test was conducted to determine the optimum RePOFA replacement range in phase one. The range was determined in between 10 %, 20 % and 30 % of the RePOFA replacement. Besides, as an intention to notice the 28-days strength of the tested specimens without waiting 28 days, the accelerated curing method, hot water bath curing was used at phase one in order to obtain the result. The result was tabulated and analysed in Table 4.1 and Figure 4.1 respectively.

Table 4.1 Compressive strength of RePOFA mortar at phase one

Variables	Compressive Strength (N/mm^2)
RePOFA-10	23.11 ± 0.98
RePOFA-20	37.78 ± 0.78
RePOFA-30	31.02 ± 0.88

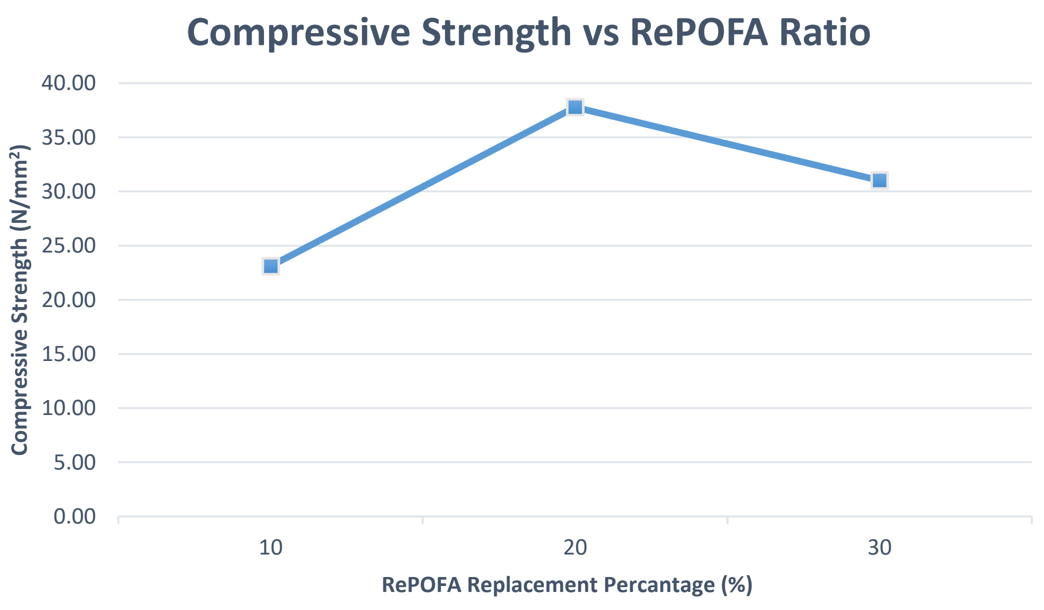

Figure 4.1 Result of RePOFA mortar at phase one

From the result obtained, it is noticed that the strength of the RePOFA mortar reached the peak at the replacement value of 20 % and started to decline after that. Therefore, the phase two laboratory experiments were then conducted by using the RePOFA replacement value of 15 %, 20 % and 25 % to determine the optimum replacement ratio of RePOFA.

4.3 MORTAR PERFORMANCE AT PHASE TWO

In this phase, the optimum replacement ratio of RePOFA on the mortar was determined in between 15 %, 20 % and 25 % by carrying up the tests to examine its engineering properties and durable properties. Moreover, the performance of the RePOFA mortar was also compared with the plain mortar as an intention to acknowledge the ability of the RePOFA as a SCM. In order to achieve the objectives of this research, the engineering properties of the RePOFA mortar were determined by using flow table test, compressive test, density test and UPV test. However, the durability properties of the mortars were examined by conducting the porosity test and air permeability test. For the purpose of analysing the microstructure of the experimented mortars, the SEM test was also executed for better explanation.

4.3.1 Flow Table Test

The workability of the fresh mortar was examined by executing the flow table test. A good workability is required in order to produce a dense product. As the workability of the fresh mortar is maintained in a high workability range, the mortar can be compacted easily and it can aid in reducing the forming of void within the specimens. The test was conducted after mixing the fresh mortar. The results are shown in Table 4.2 and Figure 4.2 as below.

Table 4.2 Flow table test result

Variable	Water/binder ratio	Flow diameter (cm)	Flow (%)
Control	0.4	12.2	22
RePOFA-15	0.4	15.5	55
RePOFA-20	0.4	13.4	34
RePOFA-25	0.4	12.5	25

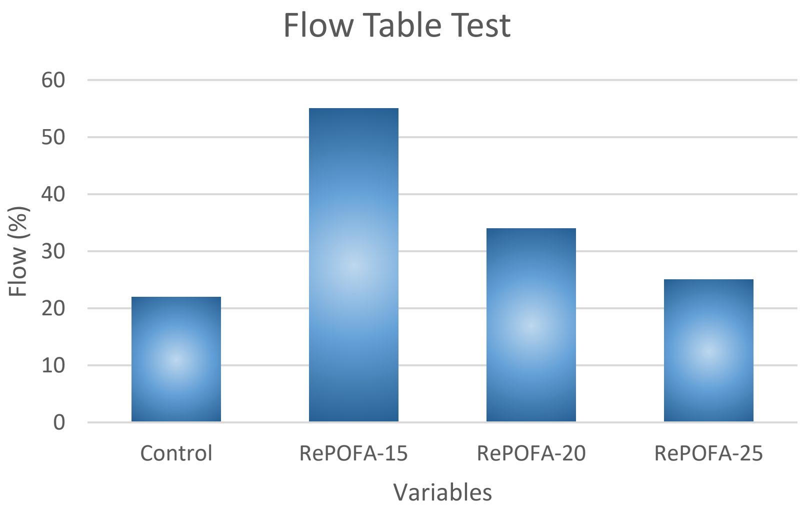

Figure 4.2 Flow percentage of different RePOFA percentage

From the result obtained, it displays the flowability result of the fresh OPC and the RePOFA mortar which were 22 %, 55 %, 34 % and 25 % for OPC mortar, RePOFA-15, RePOFA-20 and RePOFA-25 mortar respectively. At the same time, it also clearly shows that the flowability of the mortars with RePOFA added were higher than the plain mortar. The flow percentages were 33 %, 12 % and 3 % higher than the control variable for RePOFA-15, RePOFA-20 and RePOFA-25 respectively. Therefore, it magnified that the inclusion of treated POFA can help to improve the workability of the plain mortar. The rationale behind is that the treated and ground

POFA contributes to a greater binder paste volume due to the lower specific gravity of POFA compared to OPC. Eventually, the excess paste volume provided better roles of coating the fine aggregate as well as filling the gaps in between the particles. Furthermore, the lubrication effect provided by the treated POFA enabled the aggregates particle to move easily and then improved the workability of fresh mortar (Megat Johari et al., 2012). In addition, the ground RePOFA which provides a high fineness will adsorb on the surface of the oppositely charged cement particles and this prevent the flocculation of the OPC particles which will trap more water (Alsubari et al., 2016).

However, the flowability of the RePOFA mortar reduced as the replacement percentage increased. The agglomeration of the fresh mortar was observed while the replacement percentage escalated. The same result was collected by the researchers, Islam et al. in 2016. This is probably due to the fact that the POFA which has high specific surface area and porous in characteristic absorbed higher amount of water. Safiuddin et al. (2011) claimed that the angularity and irregularity of the treated and ground POFA with some porosity would also lead to a higher water demand of fresh mortar.

4.3.2 Density Test

The density test was conducted at the period of 7, 14, 28 and 56 days of curing days. The purpose of the test is to examine the influence of the RePOFA on the density performance of the mortar as the pozzolanic reaction in between the silicon dioxide and cement hydration by-product will cause the formation of the C-S-H gel which can improve the density of the specimens according to the researches reviewed. The result is tabulated and evaluated in Table 4.3 and Figure 4.3 respectively.

Table 4.3 **Density test result**

Variables	**Density (kg/m^3)**			
	7 Days	**14 Days**	**28 Days**	**56 Days**
Control	2247 ± 9	2252 ± 9	2257 ± 1	2276 ± 9
RePOFA-15	2305 ± 7	2312 ± 10	2318 ± 5	2325 ± 4
RePOFA-20	2274 ± 4	2279 ± 1	2289 ± 1	2308 ± 1
RePOFA-25	2259 ± 8	2261 ± 5	2271 ± 5	2285 ± 7

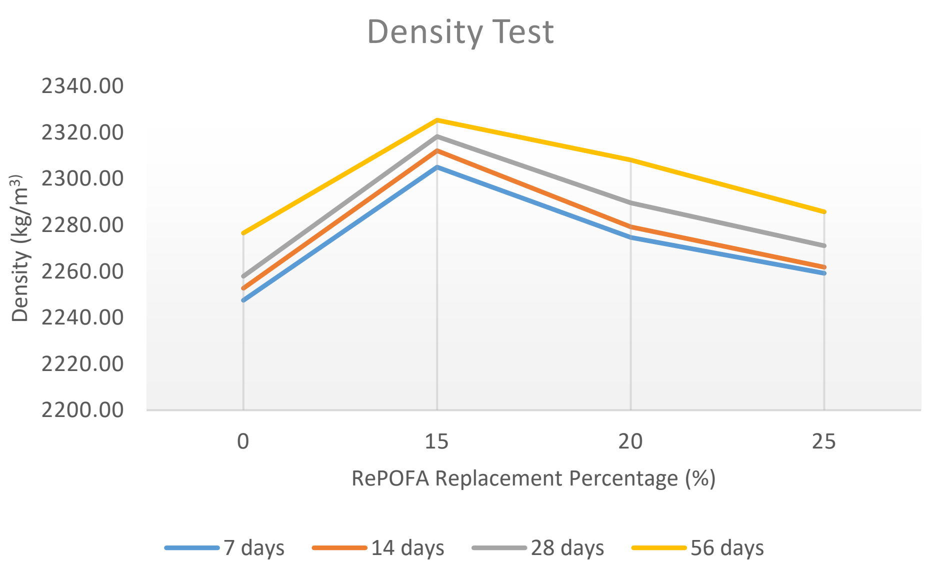

Figure 4.3 Mortar density with different RePOFA ratio

As displayed in Figure 4.3, in considering the overall trend, the density of the specimens increased as the curing time increased. The mortar with the RePOFA as the replacement materials pictured higher density as compared with the plain mortar. Taking the result of 56-days testing age as an example, the density of the RePOFA mortar was 102.1 %, 101.4 % and 100.4 % of the plain mortar for RePOFA-15, RePOFA-20, and RePOFA-25 respectively. The reason is that the RePOFA which was treated and ground provide a better filler effect characteristic which filled up the void in between the pore among the particles and decrease the internal pores (Usman et al., 2014). Besides, the increment of the density also due to the fact that the POFA allow the pozzolanic reaction which consume the by-product of hydration process, $Ca(OH)_2$ produce secondary C-S-H gel (Muthusamy et al., 2015). The large amount of C-S-H gel provides the path for the densification of mortar thus assisting the RePOFA mortar to be higher density than the control mortar.

The RePOFA-15 mortar showed the highest density compared to others along the curing period. The density of the RePOFA mortar commenced to drop as the replacement percentage exceed 15 %. The same result was obtained by Muthusamy and Zamri (2015) that the density of the specimens reduced as the POFA content enlarged. For this research, even though density of the RePOFA-25 is higher than the control specimen, it is believed that the density of the mortar will be lowered as the replacement percentage rises. This is probably because the dilution effect resulted by the excess amount of the cement substituted. As the degree and the rate of hydration is reduced due to the increased amount of POFA in total weight of paste, the amount of the calcium hydroxide is reduced gradually and this leads to the arising issue of the reduction of C-S-H gel (Altwair et al., 2013).

In addition, the significance of the RePOFA ratio to the changes of density was determined by carrying out the Analysis of Variance (ANOVA) test. For the ANOVA test, as the p-value is less than 0.05 with the confidence level of 95 %, it displays a mean that the changes of the variation is significant to its respondent. From the result shown in Figure 4.4, the p-value obtained is 0.00 which is less than 0.05. This means that the variation of the RePOFA ratio have a significant effect on the fluctuations of the density.

```
One-way ANOVA: Density versus RePOFA%

Source    DF    SS    MS      F      P
RePOFA%    3  7455  2485  16.56  0.000
Error     12  1801   150
Total     15  9256

S = 12.25   R-Sq = 80.54%   R-Sq(adj) = 75.68%


                           Individual 95% CIs For Mean Based on
                           Pooled StDev
Level  N    Mean  StDev  --+---------+---------+---------+-------
 0     4  2258.0   12.7   (----*-----)
15     4  2315.0    8.5                        (----*----)
20     4  2287.5   15.0              (----*----)
25     4  2269.0   11.9      (-----*----)
                         --+---------+---------+---------+-------
                         2250      2275      2300      2325
```

Figure 4.4 One-way ANOVA for RePOFA ratio versus density

4.3.3 Ultrasonic Pulse Velocity (UPV) Test

UPV test is considered as one of the non-destructive test to weigh the homogeneity and integrity of concrete or mortar. In order to examine the quality of the RePOFA mortar, the UPV test was executed and the results were compared by evaluate the velocity of the transmitted pulse through the mortar specimen. As the ultrasonic pulse velocity depends on the density of the specimens, the density of the specimens will have positive relationship with the value of pulse velocity. The UPV test results of the RePOFA mortar for 7, 14, 28 and 56 days are presented in Table 4.5 and Figure 4.5. The quality of the mortar was categorized based on the guideline given in Table 4.4 below.

Table 4.4 Assessment on quality of concrete (Civil Engineering Portal, 2014)

Pulse Velocity (km/s)	Concrete Quality (Grading)
Above 4.5	Excellent
3.5 to 4.5	Good
3.0 to 3.5	Medium
Below 3.0	Doubtful

Table 4.5 Result of UPV test

Variable	Pulse Velocity (km/s)							
	7 days	Std. dev	14 days	Std. dev	28 days	Std. dev	56 days	Std. dev
Control	4.01	0.02	4.17	0.01	4.18	0.02	4.39	0.01
RePOFA-15	4.45	0.04	4.50	0.04	4.51	0.03	4.62	0.04
RePOFA-20	4.29	0.03	4.31	0.02	4.31	0.04	4.51	0.06
RePOFA-25	4.23	0.05	4.25	0.01	4.28	0.04	4.45	0.05

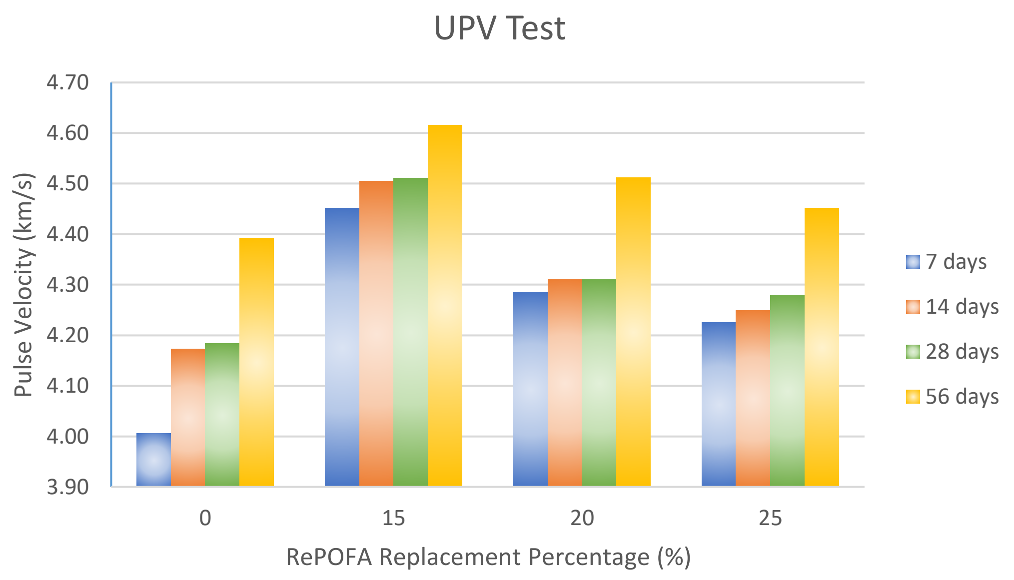

Figure 4.5 Pulse velocity result with different RePOFA ratio

Table 4.5 shows the UPV test result for all the specimens. All of the specimens portrayed a "good" quality according to Table 4.4. From the displayed result, the pulse velocity value was raised for all variables along the period time. The increment of the UPV value is because of the continuous water curing of the specimens which allow the better hydration process for the cement and the pozzolanic reaction to be occurred and resulting the forming of C-S-H gel. The production of the gel aids in filling the existing pores and enables the reduction of travel time of the transmitted pulse (Muthusamy et al., 2015).

Moreover, it is observed that the UPV values of all the RePOFA mortars were higher than the plain mortar. For 56-days curing, the UPV values of the RePOFA mortars were 1.40 % to 5.14 % higher than the plain mortar's UPV value. The same experimental result which the treated POFA concrete exhibited higher UPV value than control concrete was obtained by Safiuddin et al. (2012). The reason behind is that the treated ground POFA which is fine in size enhancing the POFA particles to act as the filler in filling the existing pores. The fineness of the RePOFA particles also enables the resulting of the appropriate arrangement of the small particles and reducing the formation of pores eventually (Jaturapitakkul et al., 2011). Furthermore, the formation of C-S-H gel resulted from the pozzolanic reaction helps in filling the void in between the particles and this elevated the velocity of the pulse transmitted.

According to the result revealed in Figure 4.5, the peak UPV value for this research was 4.62 km/s resulted from the RePOFA-15. The pulse velocity was started to decline for the variable of RePOFA-20 and RePOFA-25. In short, there was an inversely proportional relationship in between the RePOFA replacement percentage and the UPV value. The rationale is that there was a reduction of the void been filled up by the calcium silicate hydrate due to the dilution effect. Same as the explanation mentioned in Section 4.3.2, the reduction of the cement components, calcium oxide, CaO caused the dilution of the calcium hydroxide which is essential for the forming of the C-S-H gel (Altwair et al., 2011). As the amount of gel was reduced, the micro-filling ability of the RePOFA mortar was downgraded and reflected the lower UPV value.

On the other hand, it is noticed that there was a relationship between the density of the mortar and the pulse velocity transmitted. According to Kanadasan and Razak (2015), the density of the mortar influences the UPV value of the specimens in the sense that the higher density mortar will have a better UPV result. The correlation among the density and UPV of the RePOFA mortar is then illustrated in Figure 4.6 as below.

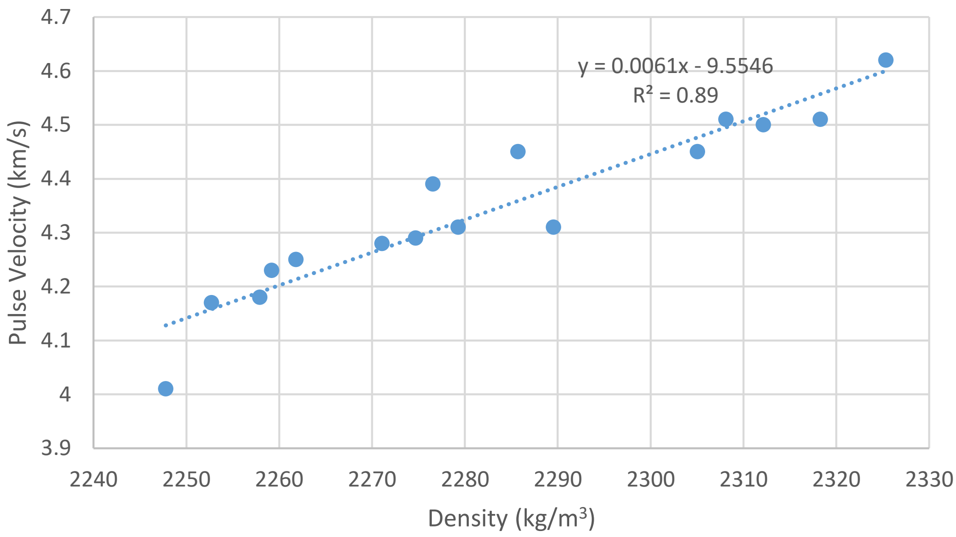

Figure 4.6 Correlation between density and pulse velocity

As displayed in Figure 4.6, a direct relationship between pulse velocity and density can be obviously observed where the pulse velocity was higher in the denser mortar. A linear regression method was applied to correlate the data and the coefficient of determination with the value of $R^2 = 0.89$ was obtained for all the specimens. The denser mortar exhibited better UPV value mainly due to the packing system. Since the particle was well-packed, the voids which existed in between the particles were then diminished. Eventually, the reduction of the pores enabled the specimens to show increment in their density. As stated by Andalib et al., (2014), a higher velocity was achieved as the concrete quality is high in terms of density and uniformly. In short, the void present among the particles which was occupied by the fine particles or the secondary gel will be lessened in quantity, thus allowed the mortar to be denser and thus escalated the velocity of the transmitted ultrasonic pulse.

In order to examine the significance of the changes in RePOFA ratio to the UPV value, the Analysis of Variance (ANOVA) test was conducted. With reference to Figure 4.7, the ANOVA showed that the variation of the RePOFA ratio had a significant effect on the pulse velocity on the RePOFA mortar as p value obtained was 0.009 which is less than 0.05.

One-way ANOVA: UPV versus RePOFA%

```
Source   DF      SS      MS     F      P
RePOFA%   3  0.2291  0.0764  6.08  0.009
Error    12  0.1508  0.0126
Total    15  0.3800

S = 0.1121   R-Sq = 60.30%   R-Sq(adj) = 50.38%


                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level  N    Mean   StDev  ---------+---------+---------+---------+
 0     4  4.1875  0.1559  (-------*-------)
15     4  4.5200  0.0716                       (-------*-------)
20     4  4.3550  0.1038             (-------*-------)
25     4  4.3025  0.1005          (-------*-------)
                          ---------+---------+---------+---------+
                                4.20      4.35      4.50      4.65
```

Figure 4.7 One-way ANOVA for UPV value versus RePOFA ratio

4.3.4 Compressive Strength Test

The compressive strength of the RePOFA mortars and plain mortars were tested and compared along 7, 14, 28 and 56 days of curing. This test is essential as it bookmarks the performance of the RePOFA mortar and the possibility for the RePOFA as the SCM. The RePOFA is considered as an astounding SCM if its compressive strength performance is higher or less difference with the plain mortar. The result of compressive strength test is portrayed in Table 4.6 and Figure 4.8.

Table 4.6 Compressive strength test result

Variable	Compressive Strength (N/mm^2)							
	7 days	Std. dev	14 days	Std. dev	28 days	Std. dev	56 days	Std. dev
Control	23.80	1.34	26.70	2.05	33.47	1.83	36.08	0.24
RePOFA-15	27.81	0.80	29.18	0.55	38.49	0.67	48.48	1.33
RePOFA-20	25.30	1.20	26.26	0.26	34.12	1.17	40.36	0.44
RePOFA-25	22.47	0.77	24.75	1.16	31.92	0.45	38.86	0.66

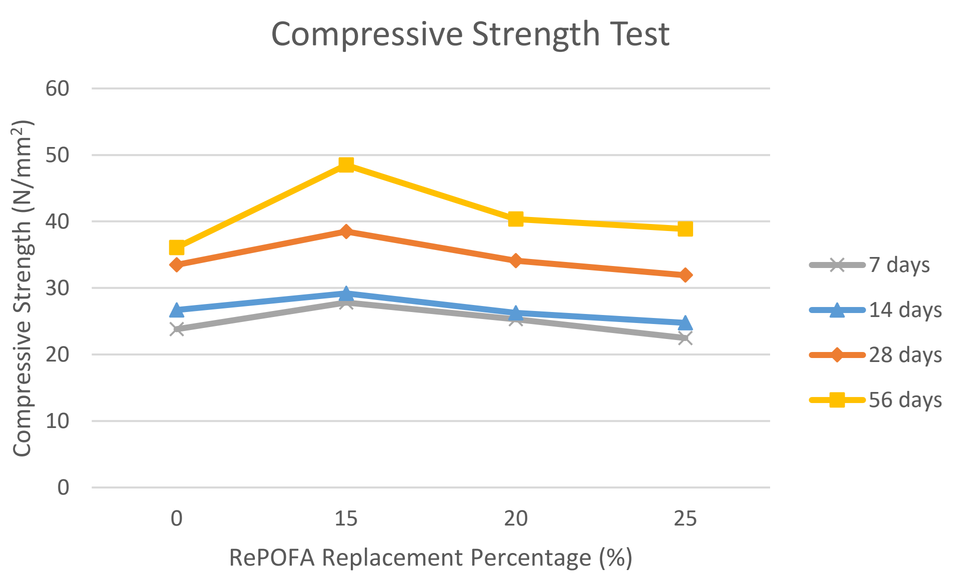

Figure 4.8 Compressive strength result with different RePOFA ratio

From the results presented in Figure 4.8, the inclusion of the RePOFA reflected different trend patterns of RePOFA mortars' compressive strength depending on the age and the quantity of cement replaced. At 7-days and 14-days curing period, the strength of RePOFA-25 was the lowest compared to the control specimen, RePOFA-15 and RePOFA-20. The strength activity index of RePOFA-25 for 7-days and 14-days were 94.43 % and 92.72 % of the control specimen respectively. The similar result was obtained by Altwair et al. (2011) where the specimens with high amount of POFA added showed lower strength at the earlier stage. This is because the pozzolanic reaction of the POFA is slow at the earlier stage and this caused the lack amount of the generation of C-S-H gel which is important in strength development (Mujah, 2016). The statement can be proved in this research as the strength of RePOFA-25 commenced to be 7.72 % higher than the control specimens after 56 days of curing. The continuous curing of the RePOFA mortar allowed the pozzolanic reaction to be occurred and forming of the secondary C-S-H gel which lead to the strength development at later stage.

Moreover, as referred to Figure 4.8, the strength of RePOFA-15 pictured the highest value in either the earlier stage or the later stage. The strength activity index of the RePOFA-15 was 116.85 %, 109.30 %, 115 % and 134.37 % for 7-days, 14-days, 28-days and 56-days respectively. At the earlier stage, the strength of the RePOFA-15 mortar appeared to be the highest among all. There could due to two reasons behind the scenario; (1) The RePOFA which is high fineness can act as the filler to fill in between the cement and the aggregates, thus producing a dense specimen and increase the early strength (Tangchirapat et al., 2009). (2) Besides the aid of the filler effect shown by the RePOFA, the low substitution cement also helped in the early strength development. According to Zeyad et al (2016), the hydration reaction of alite (C_3S) and belite (C_2S) of OPC composition allows the early strength development of the concrete. As the low substitution of the cement in RePOFA-15, it allowed the hydration among the composition mentioned and sufficient amount of the portlandite to aid pozzolanic reaction and the formation of the C-S-H gel. In addition, the highest strength with the value of 48.48 N/mm^2 developed at later stage for RePOFA-15 was probably due to the formation of the secondary C-S-H gel resulted by the pozzolanic reaction of silicon dioxide with the calcium hydroxide. The generated secondary gel assisted in occupying the existing pores and allowed the formation of dense product.

On the other hand, the strength of the RePOFA mortar happened to be reduced as the replacement percentage exceeding 15 %. This could be the reason of the resulting dilution effect. As the cement replacement ratio increased, the lack of cementitious material caused the lack of releasing by-product after hydration reaction. It then affected the performance of the pozzolanic reaction contributed by the POFA. As stated by Muthusamy and Zamri (2015), the lower quantity of calcium hydroxide produced due to lack cement amount would be insufficient for the available silica component to transform it into C-S-H gel. The increment of the pozzolan contents caused the emerging consequences where the surplus of the small sized fraction moved apart from cement grains and lead to the unpacking system. The unpacking system was then induced the reduction of density of the mortar and so then the strength as the POFA replacement ratio increased.

As aforementioned, as the additional calcium silicate hydrate was formed, the secondary gel will help to improve the interfacial bonding between the aggregates and paste. The enhancement of the bonding allow the formation of a denser product which increased the ability of the mortar to withstand the massive force applied (Karim et al., 2011). In order to study the relationship between the density and the compressive strength of the RePOFA mortar, the correlation graph was plotted and displayed as Figure 4.9.

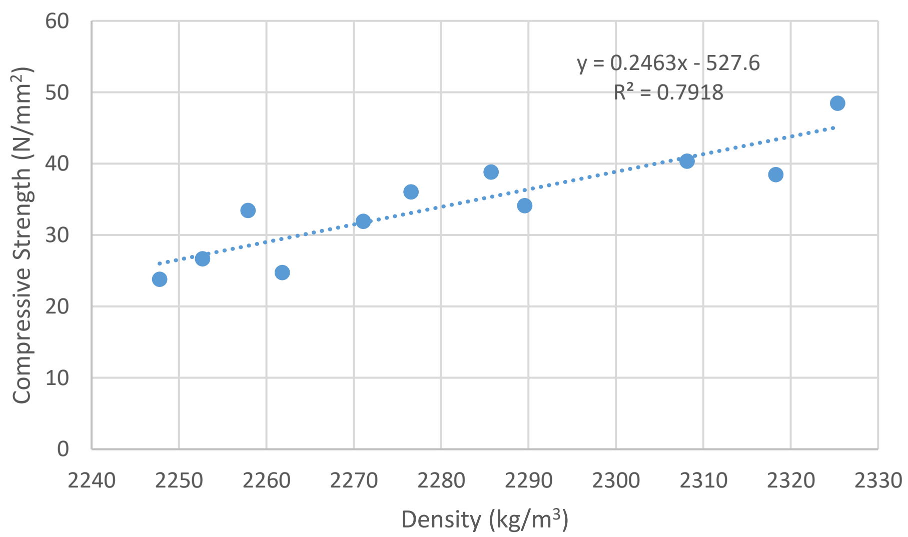

Figure 4.9 Relationship between RePOFA compressive strength and density

A positive relationship was obtained between the density and compressive strength of the RePOFA mortar. Moreover, the linear regression method was applied to correlate the data obtained and the coefficient of determination, R^2 of 0.79 was achieved. The figure illustrated that the denser mortar portrayed a higher compressive strength. The RePOFA mortar which showed pozzolanic reaction produced the secondary gel to interlock the bonding between the particles and enabled a production of denser mortar which was high in compressive strength. Furthermore, Sata et al. (2007) explained that the fineness of the RePOFA boosted the pozzolanic properties and the packing density of the particles. The mentioned characteristics was then assisted in improving the mortar density as well as the mortar strength.

The relationship in between the RePOFA ratio, compressive strength and density was evaluated through the surface plot drafted in Figure 4.10. As represented in Figure 4.10, the compressive strength have the relationship with density as described above. As the RePOFA ratio increased, the density of the RePOFA mortar increased as well as the compressive strength. RePOFA-15 exhibited the highest strength, with the value near 50 N/mm^2 and density, with the value near 2325 kg/m^3. The RePOFA mortars were denser than the control mortar while the density deflated as the RePOFA ratio raised.

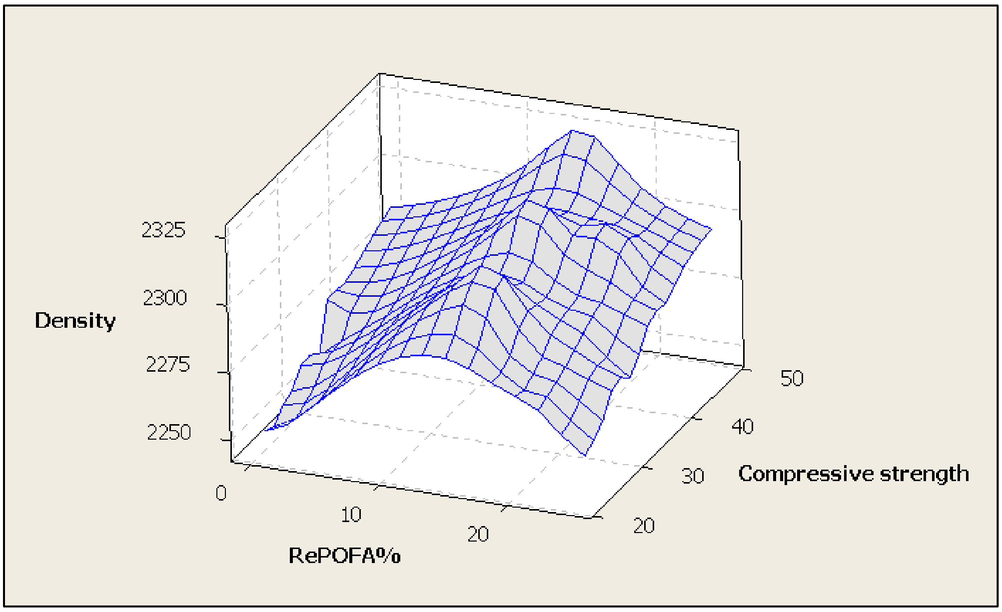

Figure 4.10 Surface plot of RePOFA ratio versus density and compressive strength

4.3.5 Porosity Test

The porosity test was carried out to examine the durable properties of the RePOFA mortar. The porosity of the tested specimens was evaluated at 7, 14, 28 and 26 days of ambient water curing. In order to confirm the filler effect shown by the RePOFA as suggested by previous researchers, the RePOFA mortar was also compared with the plain mortar. Table 4.7 and Figure 4.11 illustrates the result of the porosity test.

Table 4.7 Porosity test result

Variable	**Porosity (%)**							
	7 days	**Std. dev**	**14 days**	**Std. dev**	**28 days**	**Std. dev**	**56 days**	**Std. dev**
Control	21.49	0.49	20.61	0.82	18.91	0.68	18.03	0.52
RePOFA-15	20.61	0.82	19.60	0.17	16.41	1.25	14.79	0.45
RePOFA-20	21.20	1.07	19.90	0.81	17.49	0.51	15.08	0.27
RePOFA-25	21.50	0.79	20.60	0.61	18.68	0.38	16.67	0.43

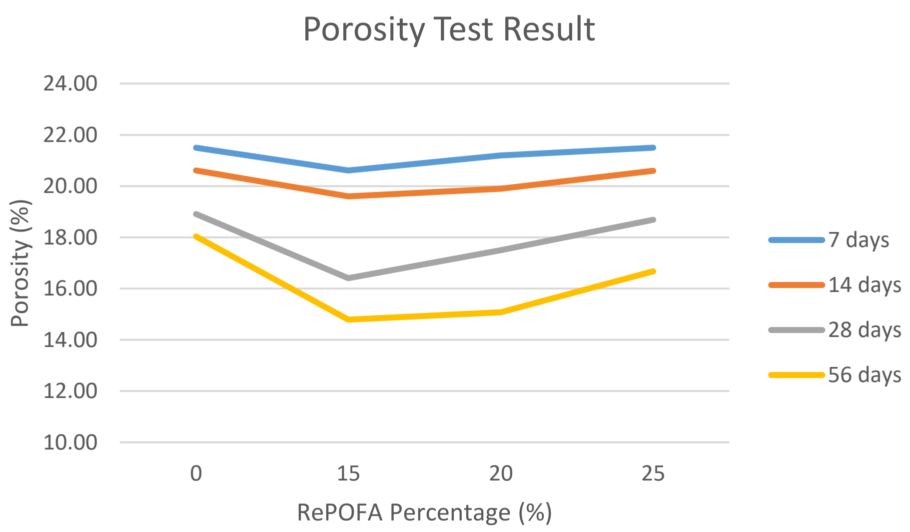

Figure 4.11 Porosity result with different RePOFA percentage

As published in Figure 4.11, the porosity of all the specimens was reduced as the curing time increased. This was because the hydration reaction and the pozzolanic reaction resulted the formation of the gel which was the fill up the corresponding void existed in between the particles. Meanwhile, it is noticed that all the RePOFA replaced mortar displayed the lower porosity as compared to the plain mortar. According to Table 4.6, the porosity of RePOFA-15, RePOFA-20, and RePOFA-25 was 18.01 %, 16.40 % and 7.54 % lower than plain mortar respectively. This was probably due to the fact that RePOFA which act as the filler or microstructural reinforcement contributed to the refinement of the pores and reduce the air volume (Zeyad et al., 2016).

In addition, the porosity values of the RePOFA mortar reduced drastically from the resulted obtained at 14-days and 28-days. For example, the porosity value reduced 16.29 %, 12.09 % and 9.32 % for the specimens RePOFA-15, RePOFA-20 and RePOFA-25 respectively. As compared with control specimen with the reduction of 8.25 % in porosity, the RePOFA mortar showed a better reduction in air volume within the specimens after increment of curing period. The better reduction of the porosity can be linked to the pozzolanic reaction which was occurred at late stage. The secondary gel produced due to the late pozzolanic reaction aided in refining the pore structures of the hardened mortar (Usman et al., 2015).

Furthermore, from the result obtained, even though the porosity of the RePOFA mortar was lower than the plain mortar, the porosity value seemed to be increased once the replacement percentage exceeding 15 %. For instance, the porosity of the RePOFA-15 was 14.79 % while the porosity value for RePOFA-20 and RePOFA-25 were 15.08 % and 16.67 % respectively. The result was same with the result obtained by Kroehong et al. (2011) where the porosity increased as the POFA replacement ratio raised. The increment ratio of POFA caused reduction in the cement amount and atlas the downsized in quantity of the hydration product. The absence in the sufficient gel resulted the increment of the porosity as the RePOFA percentage elevated.

As suggested by Jaturapitakkul et al. (2011), the reduction of the porosity POFA replaced mortar was mainly due to the reason of the diminishing of the void amount present among the particles. The filling of the void by the fineness particle and the secondary gel produced after pozzolanic reaction increased the density of the RePOFA mortar. The correlation relationship in between the porosity and the density was plotted shown in Figure 4.12.

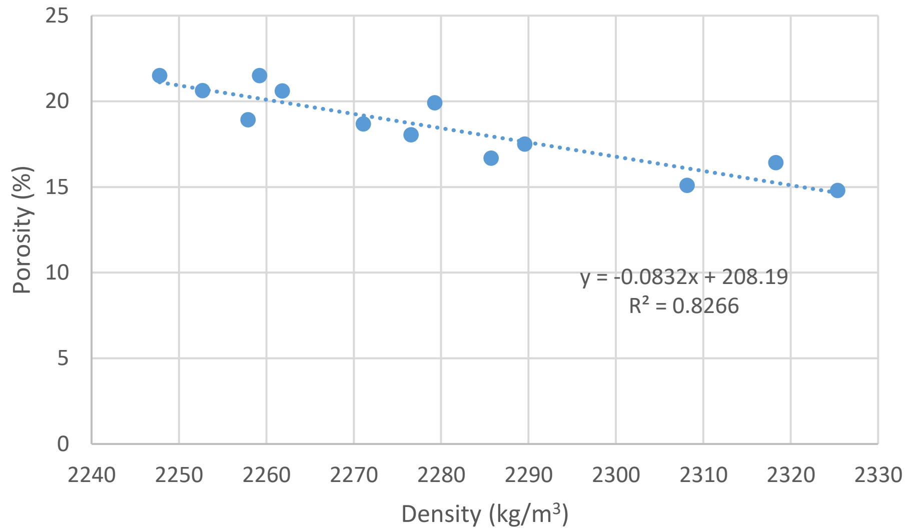

Figure 4.12 Correlation relationship between density and porosity

The Figure 4.12 shows that the density of the RePOFA mortar increased as the porosity reduced. The reducing in porosity enabled the denser mortar to be produced as the air volume was lessened and filled by the secondary gel. The result also magnified the fact that the durability properties have the significant relationship with the engineering properties. The drop in the porosity of the RePOFA mortar emerged a better mechanical performance of the RePOFA mortar. The R^2 value of 0.82 was obtained for this regression analysis with the equation of $y = -0.0832x + 208.19$.

On the other hand, the significance of the RePOFA to the porosity performance of the RePOFA mortar was examined. From the result displayed in Figure 4.13, the obtained p-value was 0.044. This shows that the increasing of the RePOFA ratio influenced the porosity performance of the RePOFA mortar significantly.

One-way ANOVA: Porosity versus RePOFA%

```
Source   DF     SS     MS     F      P
RePOFA%   3  35.25  11.75  7.10  0.044
Error     4   6.62   1.66
Total     7  41.88

S = 1.287   R-Sq = 84.18%   R-Sq(adj) = 72.32%


                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level  N    Mean  StDev  ------+---------+---------+---------+---
 0     2  21.050  0.622                  (-------*--------)
15     2  15.600  1.146  (-------*-------)
20     2  16.285  1.704    (-------*--------)
25     2  17.675  1.421        (--------*-------)
                         ------+---------+---------+---------+---
                            15.0      18.0      21.0      24.0
```

Figure 4.13 One-way ANOVA for RePOFA ratio versus porosity

4.3.6 Intrinsic Air Permeability Test

Intrinsic air permeability test is one of the test to determine the durable properties of the specimens. If the concrete compound is permeable, it will cause the penetration of the corrosive agents which will lead to the consequences of deterioration of concrete properties. Besides, the concrete with huge amount of void affect the permeability properties of the concrete as the interconnection of the voids will make the concrete permeable. According to Chindaprasirt et al. (2007), the POFA that acted as filler can minimize the presence of void which result the impermeability of the concrete. Therefore, in this research, the RePOFA specimens were tested and compared with the plain mortar. The specimens were examined at the curing ages of 7 days, 14 days, 28 days and 56 days. The result is tabulated in Table 4.8 and illustrated in Figure 4.14.

Table 4.8 Intrinsic air permeability test result

Variable	Gas Permeability ×10^{-16}, K (m^2)							
	7 days	Std. dev	14 days	Std. dev	28 days	Std. dev	56 days	Std. dev
Control	2.20	0.02	1.51	0.03	1.18	0.03	0.56	0.05
RePOFA-15	0.89	0.03	0.65	0.02	0.30	0.08	0.22	0.04
RePOFA-20	1.03	0.02	0.73	0.05	0.39	0.02	0.29	0.01
RePOFA-25	1.13	0.02	0.84	0.05	0.42	0.01	0.32	0.05

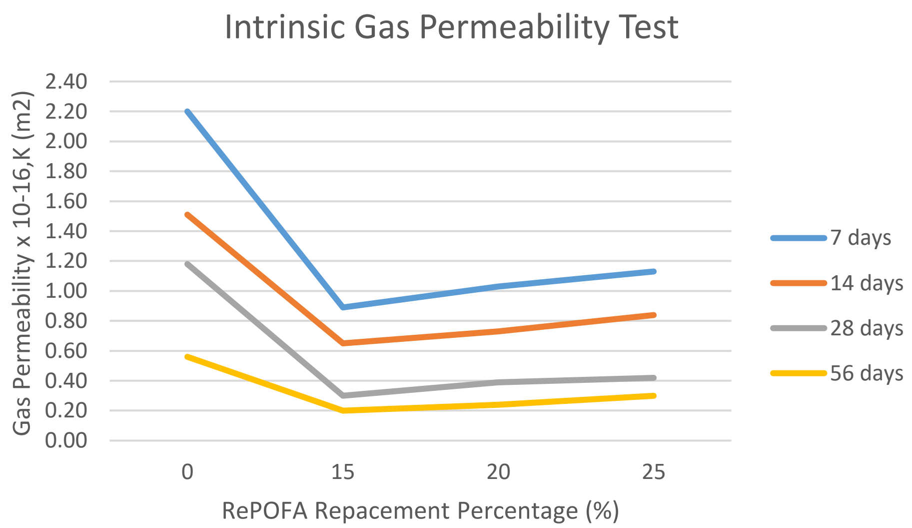

Figure 4.14 Gas permeability result against different RePOFA percentage

As projected in Figure 4.14, same as the result of porosity test, the gas permeability value was decreased as the curing period prolonged. This reflected that the pores among the specimens were reduced as the curing ages increased. However, the plain mortar showed higher permeability value compared to the RePOFA mortar in all the curing periods. The permeability result of 0.56 to 2.2 ×10^{-16} m^2 was obtained by the plain mortar. The reason could be the huge amount of carbon content which was irregular in shape causing the situation of irregular arrangement and lead to the huge formation of pores in between the particles compared to the RePOFA mortar. As explained by Chindaprasirt et al. (2007), the RePOFA particles which are finer in size compared to the cement particles allow the RePOFA to fill in the void between the aggregates. The void that been occupied by the POFA particles inhibited the passing of the gas thus reduce the travel time.

On the other hand, it is clearly showed that the permeability value was reduced remarkably from 14-days to 28-days which was same as the result of porosity. The permeability value of RePOFA-15 reduced 53.84 % compared to the result in 14-day. Reduction of 46.6 % and 50 % in permeability value also shown by RePOFA-20 and RePOFA-25 respectively. The extremely reduction of the permeability could due to the reaction of the pozzolan with the hydration by-product which was occurred in late stage. The forming of the secondary gel aided in filling up the pores existing between the particles and resulted denser structure. Meanwhile, the formation of the gel due to the pozzolanic reaction of RePOFA enhanced the impervious ability of the mortar and it was supported by Tangchirapat and Jaturapitakkul (2010). The author reflected that the pozzolanic reaction encourages the formation of the secondary gel which can help to upgrade the packing effect of the particles and produce a product with denser matrix and low permeation.

In addition, the RePOFA-15 manifested the highest impermeability characteristic along the different curing ages. For example, the gas permeability of RePOFA-15 was 0.89×10^{-16} m^2 which was the lowest among the others mortar specimens at the testing age of 7 days. The value continued to decline until 0.22×10^{-16} m^2 which is 60.7 % lower than the control specimen. The reason could due to the fact that the filler effect of the RePOFA and the early hydration reaction of the portlandite which helped to fill up the void at the early stage. The permeability value remained the lowest at 56-days was because the formation of the secondary gel which enhanced the packing effect of the particles (Mehta and Monteiro, 2006). However, there was a positive effect of the permeability against the replacement percentage. The permeability value increased as the replacement ratio raised. For instance, the gas permeability value commenced to climb from 0.22×10^{-16} m^2 to 0.32×10^{-16} m^2 at the testing age of 56 days as the replacement percentage was enlarged from 15 % to 25 %.

As deliberated by Islam et al., (2016), the increment of the substituted percentage of cement caused the reduced amount of by-product to react with the silicon compound. This inflated the situation of the excess amount of unreacted silica which weakened the packing system of the particles.

Last but not least, there was a relationship between the porosity and the permeability of the RePOFA mortar. The correlation graph was illustrated in Figure 4.15. From the displayed figure, it is witnessed that the porosity had the positive effect with the permeability. As the porosity raised, the value of the permeability will also increase. This is because the huge amount of the void within the specimens eased the penetration of the gas and made the specimen to be permeable. As the high permeability of mortar resulted in the bad performance in the quality, the porosity of the mortar played a critical role in achieving a satisfied result.

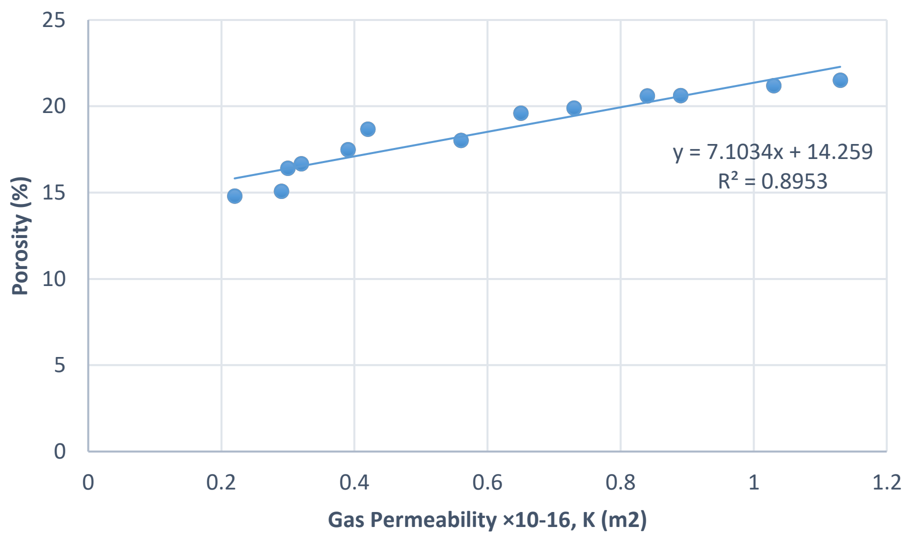

Figure 4.15 Relationship between porosity and permeability of RePOFA mortar

Figure 4.16 is then illustrates the significance of RePOFA ratio on the permeability performance of the RePOFA mortar. The one-way ANOVA indicated that the variation of the RePOFA ratio has significant effect on the permeability of the

RePOFA mortar as displayed by the p-value which was noticed to be 0.046 which is less than 0.05. The relationship between engineering and durability properties with the variation of the RePOFA ratio was also evaluated by plotting the surface plot among RePOFA ratio, compressive strength and the porosity percentage. As interpreted in Figure 4.17, the low porosity of RePOFA resulted a high compressive strength as a dense specimen was formed. Meanwhile, RePOFA-15 showed the lowest porosity and the highest in compressive strength compared to others. The surface plot also deliberated that the variation of the porosity was significant for RePOFA mortar compared to the plain mortar.

One-way ANOVA: Permeability versus RePOFA%

```
Source   DF     SS     MS     F      P
RePOFA%   3  1.780  0.593  3.59  0.046
Error    12  1.984  0.165
Total    15  3.764

S = 0.4066   R-Sq = 47.30%   R-Sq(adj) = 34.12%


                          Individual 95% CIs For Mean Based on Pooled StDev
Level  N    Mean   StDev    +---------+---------+---------+---------
 0     4  1.3125  0.6043                     (--------*--------)
15     4  0.4275  0.2012    (--------*-------)
20     4  0.6100  0.3374       (--------*--------)
25     4  0.6775  0.3765         (--------*-------)
                            +---------+---------+---------+---------
                          0.00      0.50      1.00      1.50
```

Figure 4.16 One-way ANOVA for RePOFA ratio versus permeability

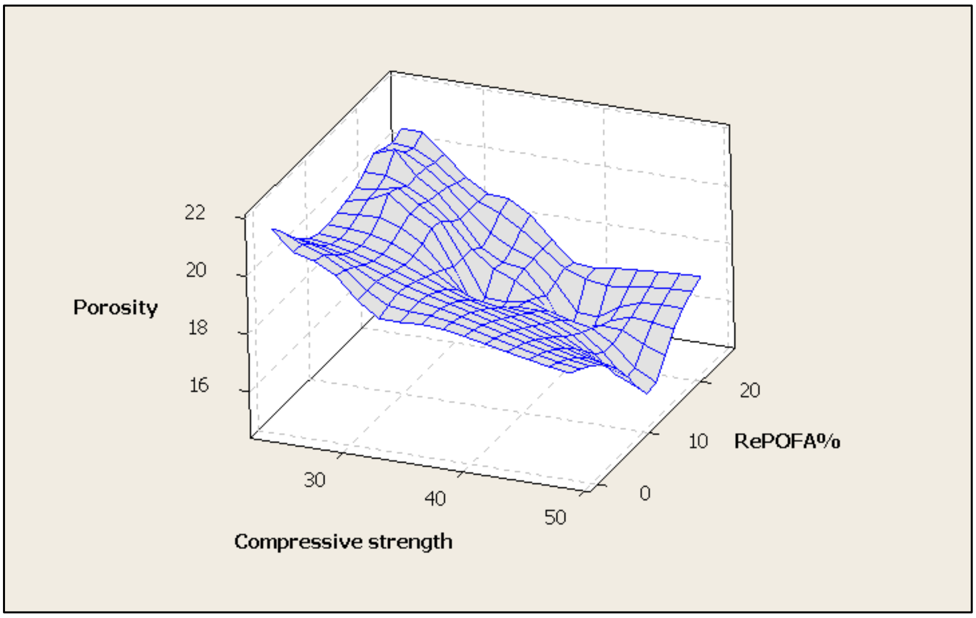

Figure 4.17 Surface plot of RePOFA ratio versus porosity and compressive strength

4.3.7 Scanning Electron Microscopy (SEM) Examination

The SEM test was performed to analyse the shape and size of the microstructure of the specimens. In order to examine the microstructure development of the RePOFA mortar, the pieces of mortar specimens were collected and sent for analysis after 14 days of curing. The RePOFA mortars' performance after 14 days curing were evaluated by observing the microstructure of the mortars. Moreover, the microstructure of the RePOFA mortars and plain mortar were compared based on the SEM images. The results of the SEM test were pictured as below.

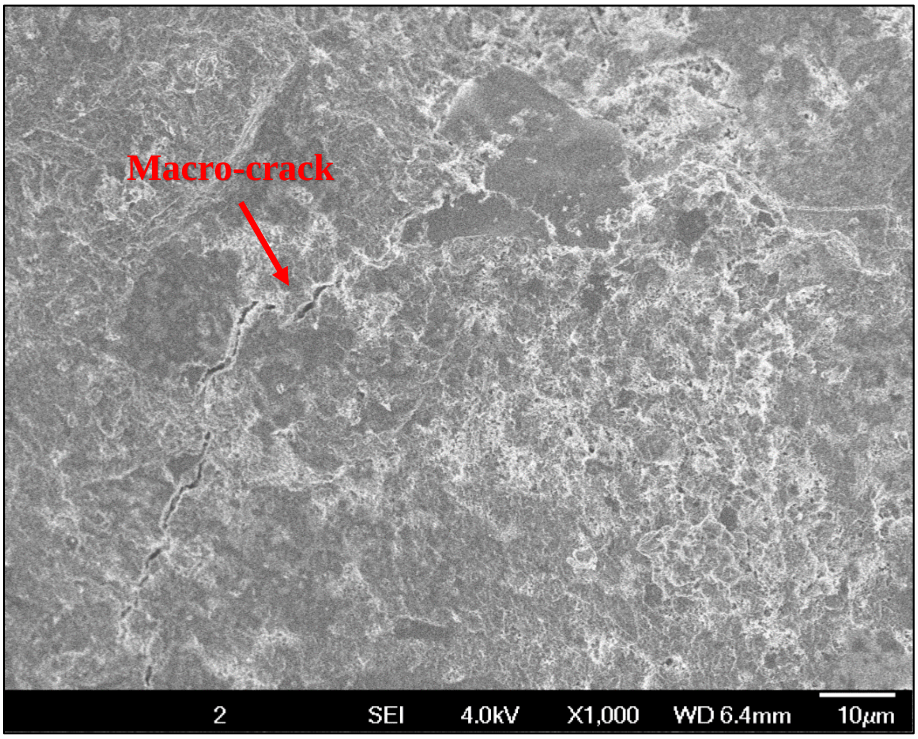

Figure 4.18 SEM image of plain mortar (×1000 magnification)

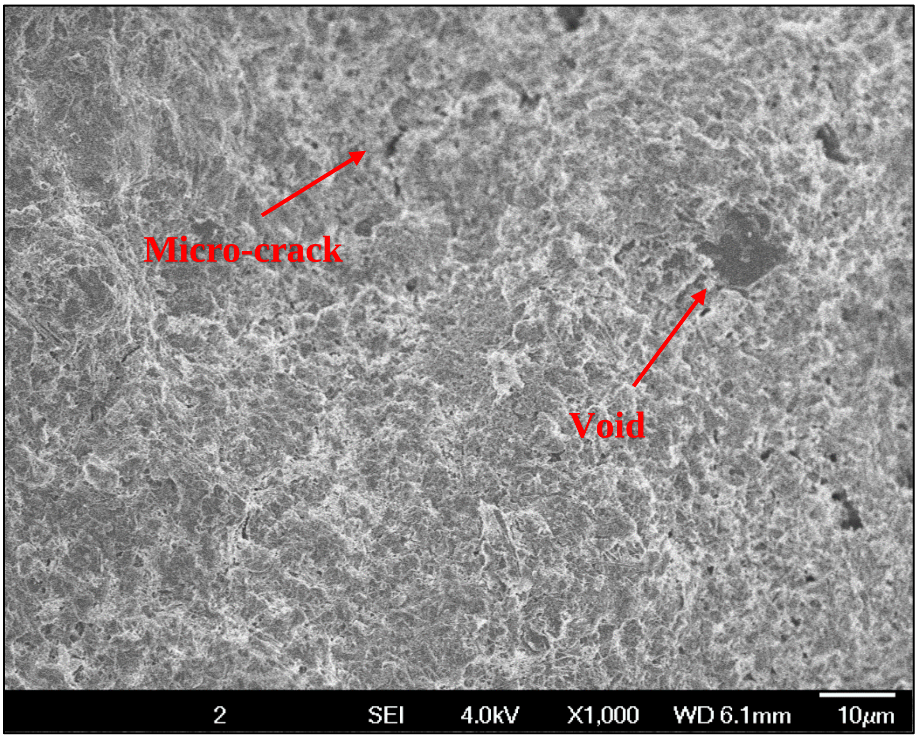

Figure 4.19 SEM image of RePOFA-15 (×1000 magnification)

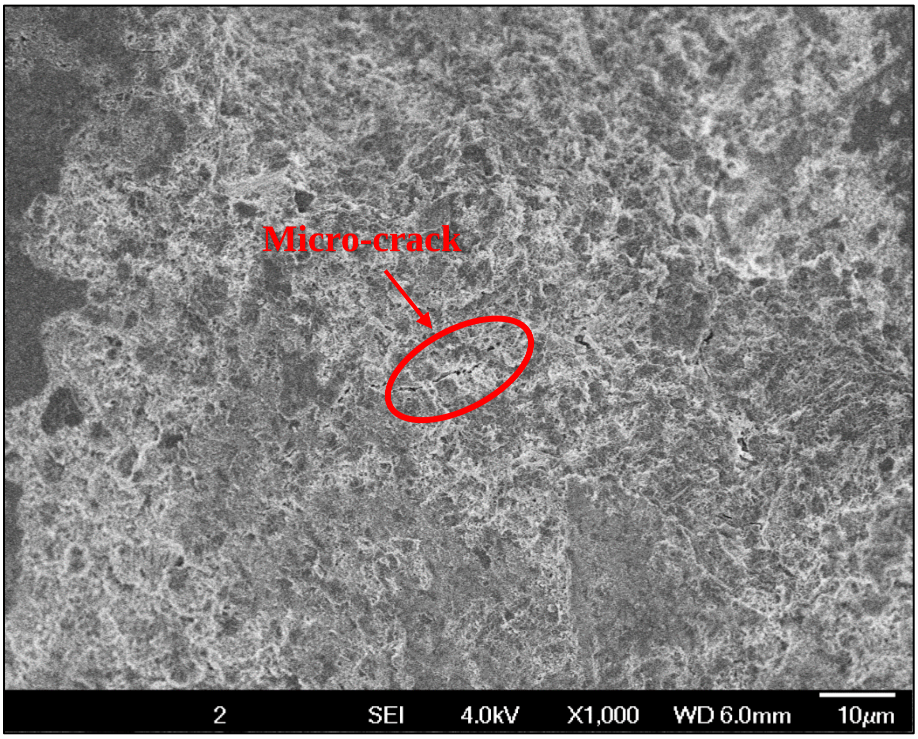

Figure 4.20 SEM image of RePOFA-20 (×1000 magnification)

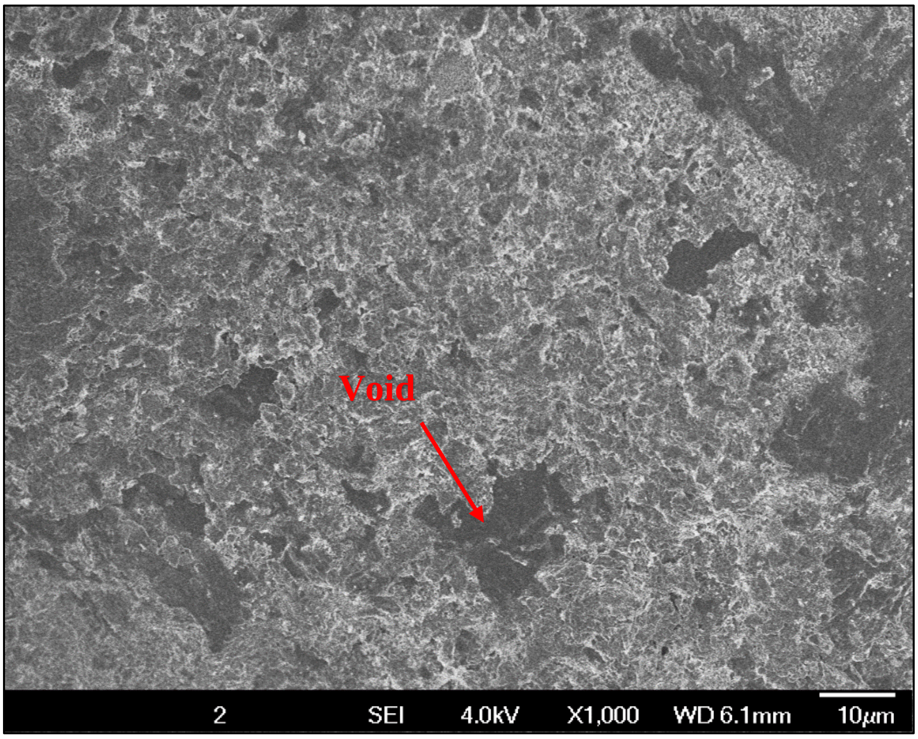

Figure 4.21 SEM image of RePOFA-25 (×1000 magnification)

The Figure 4.18 to Figure 4.21 indicated the SEM image with 1000 magnification for plain mortar, RePOFA-15, RePOFA-20 and RePOFA-25 respectively. As displayed in the figure, different denseness and porousness of the microstructure for the RePOFA mortar and plain mortar were demonstrated. In term of compactness, the RePOFA-15 presented the highest denseness compared to other specimens followed by RePOFA-20, plain mortar and RePOFA-25. Moreover, there was a macro-crack been observed in the plain mortar and this could be the reason of the low compressive strength achieved. Micro-cracks were also been discovered in RePOFA-15 and RePOFA-20. The porousness of the specimens were also clearly signposted from the image. The RePOFA-25 indicated the high porousness as high amount of air void was observed from the image. A clearer identification of the air void can refer to Figure 4.22 to Figure 4.26. The presence of the C-S-H gel was also be confirmed based to the figures. However, as the Energy Dispersive X-Ray Analysis (EDX) was not conducted for this research, the amount of the secondary gel cannot be confirmed and quantified.

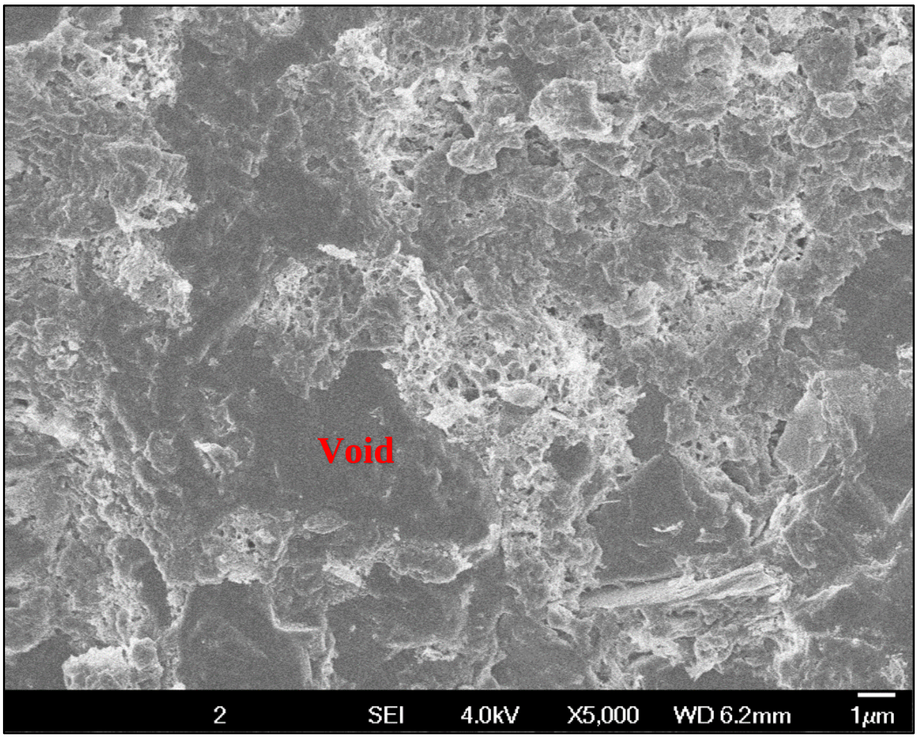

Figure 4.22 SEM image for plain mortar (×5000 magnification)

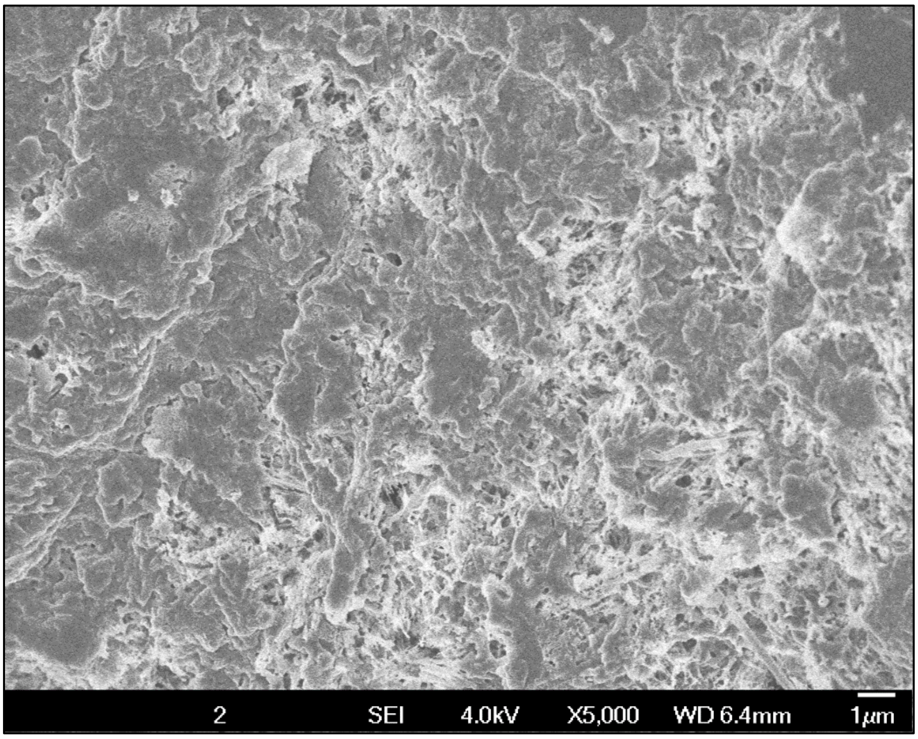

Figure 4.23 SEM image for RePOFA-15 (×5000 magnification)

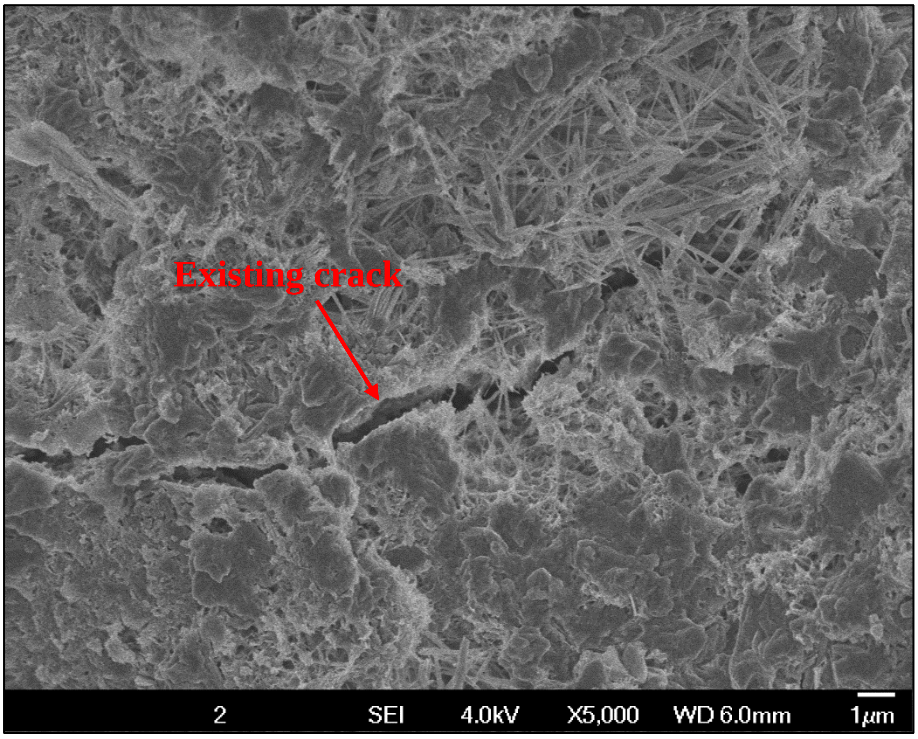

Figure 4.24 SEM image for RePOFA-20 (×5000 magnification)

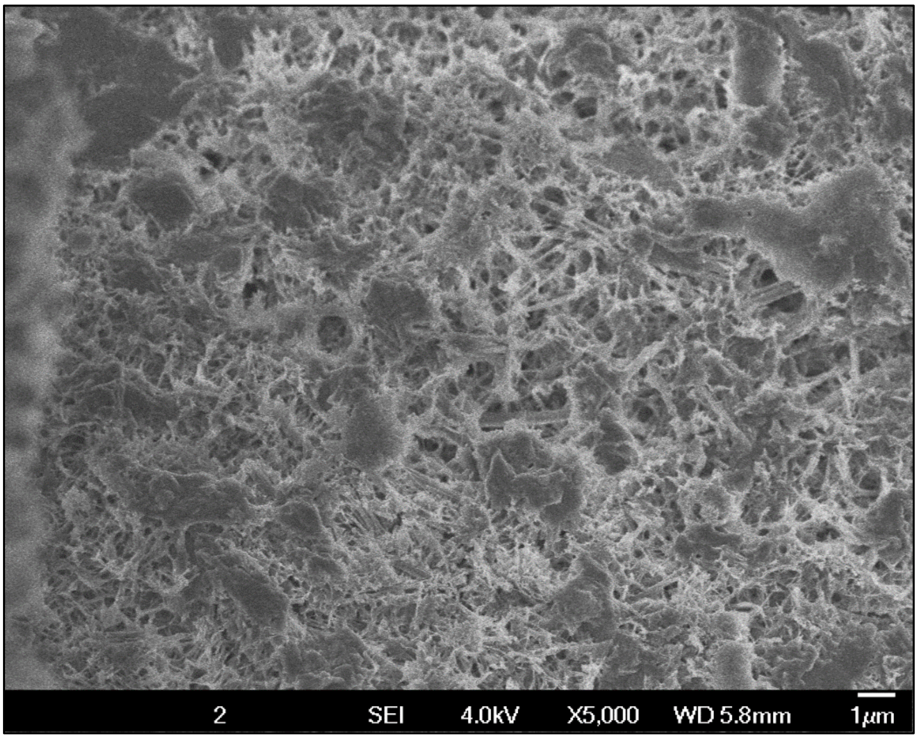

Figure 4.25 SEM image for RePOFA-20 (×5000 magnification)

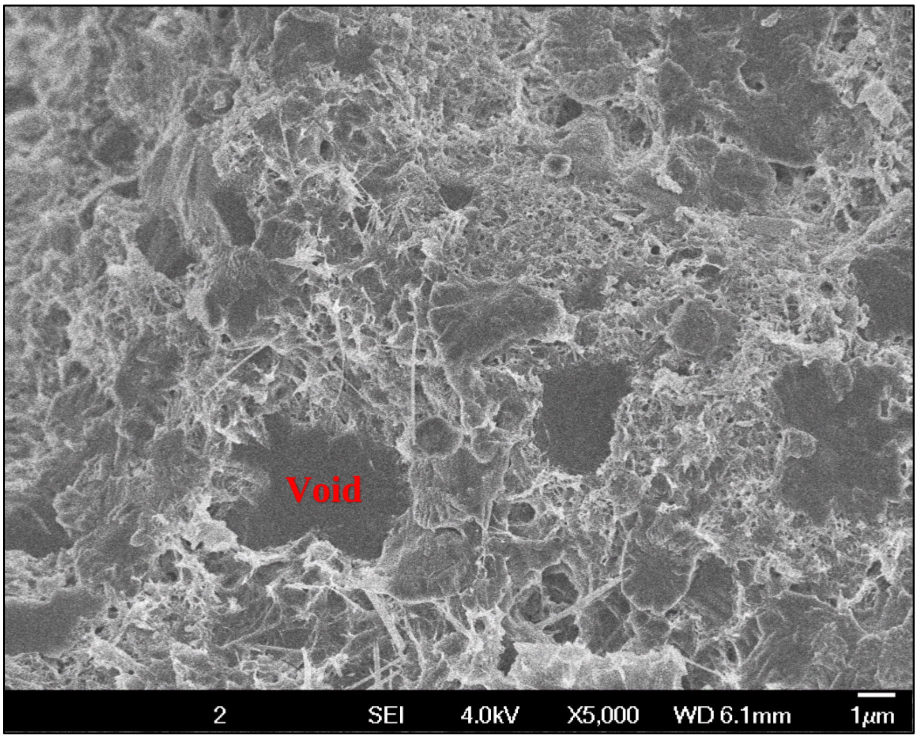

Figure 4.26 SEM image for RePOFA-25 (×5000 magnification)

In a nutshell, for the SEM results, it was noticed that all the specimens had the loose structure at the age of 14 days. Due to the loose structure formed, the compressive strength of the plain mortar and the RePOFA mortar was low at the testing age of 14 days. In addition, the porousness of the mortar was found high in RePOFA-25. The high porousness of RePOFA-25 caused the mortar to exhibit the lowest strength among the variables. On the other hand, it is recommended that the SEM test needed to be carried up again at the later stage in order to discover the microstructure packing system of the RePOFA mortar as the pozzolanic reaction which assists in the strength development occur at the later stage. Furthermore, the EDX test is suggested to be executed to provide elemental identification and quantitative compositional information in order to discover the formation of C-S-H gel resulted by the pozzolanic reaction.

4.4 CONCLUDING REMARK

After the tests were conducted, the performance of the RePOFA mortar was determined. In term of the workability, the flowability of the fresh RePOFA mortar was better than the plain mortar. This is due to the fact that the RePOFA was treated and ground which reduced the carbon content that are porous and high water-absorption eventually. However, the workability was reduced as the RePOFA content increased due to the high fineness of RePOFA which was high surface area can absorb more water.

In term of engineering and durability properties, the tests executed were density test, UPV test, compressive strength test, porosity test and gas permeability test. From the result obtained, the RePOFA mortar exhibited better performance than the plain mortar in sum. The rationale behind was the filler effect shown by the RePOFA particles and the pozzolanic reaction which occurred at the later stage. However, the performance of the RePOFA mortar seemed to be declined as the POFA replacement ratio escalated. This was probably due to the fact that the emerging of the dilution effect. As the replacement of the SCM compound enlarged, the amount of the cement will diminish and caused the less amount in hydration product. Eventually, the secondary C-S-H gel cannot be formed through pozzolanic reaction in the situation of lacking in hydration product. In a nutshell, the concern need to be paid on the replacement percentage of the SCM otherwise retard effect will be inflated and the performance of the SCM concrete or mortar will be diminished. In addition, after conducting the ANOVA test on the variation of the RePOFA ratio on the durability and engineering, it was observed that the changes of the RePOFA ratio can significantly affect the engineering and durability performance of the RePOFA mortar. Regarding the aim of this research, the RePOFA-15 was determined as the optimum replacement ratio for reincinerated POFA without scarifying the properties of the mortar.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 GENERAL CONCLUSION

This research concerns on the optimum replacement ratio of the reincinerated palm oil fuel ash (RePOFA) without omitting the properties of the mortar. All the literature review and the laboratory experiments were conducted in the effort to discover the influence of the RePOFA replacement percentage on the performance of the RePOFA mortar. Throughout the experimental works, the RePOFA-15 was recognised as the optimum replacement ratio for RePOFA mortar. However, the performance of the RePOFA mortar commenced to decline as the replacement ratio elevated. Thus, more effective alternative need to be brainstormed to overcome the issue as an effort to reduce the cement usage while utilizing the waste that caused environmental issues.

5.2 ENGINEERING PERFORMANCE OF REPOFA MORTAR

After conducting the mechanical tests on the RePOFA mortar, the performances of the RePOFA mortar were evaluated, analysed and compared among each other. Then, several conclusions can be drawn after the processes, such as:

1. The RePOFA mortar illustrated a better workability compared to the plain mortar. The retard in flowability was discovered as the RePOFA replacement percentage increases.
2. Denser mortars were produced compared to the plain mortar as the RePOFA was used as the SCM.
3. “Good” concrete quality was obtained for plain mortar, RePOFA-20 mortar and RePOFA-25 mortar as the pulse velocity is ranged in between 3.5 to 4.5. The “excellent” concrete quality was obtained for the RePOFA-15 with the pulse velocity of 4.62 km/s.
4. RePOFA-15 achieved the highest compressive strength (48.48 N/mm^2) compared with other variables. RePOFA-25 which displayed lower compressive strength than plain mortar at the earlier stage presented a higher compressive strength than plain mortar at the later stage.
5. The mortar with higher replacement amount of RePOFA exhibited better performance at the later stage which is beyond 28 and 56 days of curing age.
6. RePOFA-15 illustrated a better engineering performance compared to RePOFA-20 and RePOFA-25 in both early stage and later stage.

5.3 DURABILITY PERFORMANCE OF REPOFA MORTAR

Illustrated as below, the summary of the durability performance on the RePOFA mortar after executing the durability tests; porosity test and intrinsic air permeability test was drawn.

1. All of the RePOFA mortars portrayed lower porosity value than the plain mortar. The RePOFA-15 exhibited the lowest percentage of porosity in comparison with the RePOFA-20 and RePOFA-25.
2. The permeability of the plain mortar was the highest among the RePOFA mortar. The permeability reduced as the RePOFA was added into the mortar.
3. The RePOFA mortar pictured in degraded durability performance as the replacement ratio increased.
4. A remarkable changes of the durability performance of RePOFA mortar was observed after 14 days of curing. The rationale behind was due to the late occurrence of the pozzolanic reaction.
5. RePOFA-15 was considered as the optimum replacement ratio as it demonstrated better performance than plain mortar, RePOFA-20 and RePOFA-25.

5.4 RECOMMENDATIONS

As an intention to build a green environment, the practice of utilizing the waste is highly recommended. In order to encourage the utilization of POFA in the construction material, the following recommendations are made to enhance the possibilities in utilizing the industrial waste. Moreover, the recommendations are deliberated for the use of further studies on the RePOFA product.

1. As the pozzolan exhibits better engineering and durability performance at the later stage, the experimental period is suggested to be prolonged. A longer experimental period allow a better evaluation on the performance of the RePOFA concrete or mortar.
2. Since the workability of the RePOFA reduced as the replacement percentage increased, the superplasticizer is recommended to be added. The positive changes of the workability may result a better performance of the mortar though replacement percentage is elevated.
3. An accelerated curing method can be used in further research to investigate the performance of the RePOFA binder under different curing method.
4. As the high percentage RePOFA mortar exhibited better performance at later stage, an alternative materials are recommended to discover in order to allow a better performance of binder with high RePOFA ratio at earlier stage.
5. Energy-dispersive X-ray spectroscopy (EDX) can be executed to analyse the amount of the chemical composition within the product.

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