# DEVELOPMENT OF BLENDED CEMENTS FOR WATER PROOFING APPLICATION

## (MEMBANGUNKAN SIMEN TERUBAHSUAI UNTUK KEGUNAAN SIMEN KALIS AIR)

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# ABSTRACT

*(Keywords: cement replacement, mineral admixtures, multi-blended pozzolan)*

The application of mineral admixtures as partial cement replacement in concrete leads to a reduction in construction cost. Usually single mixture has limitation and some have contrasting influences on properties of concrete. The combination of more kinds of mineral admixtures is postulated to improve concrete properties. Since RHA is highly reactive pozzolan, it has led to the idea of focusing the study on the performance of Multi-blended pozzolan as partial cement replacement in mortar. Over 8 different mixes were produced in which four mixes contained varying percentages of admixtures (Multi Blended Cement, MBC) and the remainders were single mix (Binary Blended Cement, BBC) containing optimum percentages (based on literature study) of 20% PFA, 20% RHA, 50% SLAG, and 10% POFA. Three samples for each mix, curing period and parameter tests were prepared. This work initially deals with compressive strength characteristics, water absorption, and total porosity on mortar cured (standard curing) for 7, 28, 60 and 90 days. The performance of optimum MBC mortar was studied in terms of ultimate compressive strength, water absorption and total porosity. The strength properties of the optimum mixes of MBC mortars was also examined at different curing regimes. This research also focuses on studying some durability aspects of the optimum mix of MBC mortars namely acid attack, and carbonation. Besides, the effects of saline seawater were investigated for short term exposure. Finally attempt in brief study on suitability of the optimum mixes of MBC mortars as face sheets to produce lightweight non-load bearing sandwich block was conducted. From the results obtained, it was found that the strength of control and BBC mortars at early age on average were 20% higher than MBC mortars, and at final age both were comparable with MBC mortars. The strength of all mortars at 90 days on average was 59MPa. However, the MBC system produced low permeability mortar compared to control, and BBC mortars at all ages. The total porosity and water absorption of control and BBC were 28% and 21%, and 9% and 14%, respectively. The strength of MBC mortar after 45 cycles of wet and dry curing in seawater exhibited 24% higher than control mortar. The initial water curing for 7 and 14 days and continuous air curing also exhibited 13% and 19%, and 21% and 26%, higher early strength than continuous water and air curing, respectively. The strength and durability properties of MBC mortar are more pronounced than control when it is provided with adequate curing. After exposure to chemical attack, the MBC mortar exhibits better resistance than control mortar. With adequate curing the MBC mortar was higher in durability than control mortar when subjected to chemical attack.

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# ABSTRAK

Prestasi mortar berasaskan pelbagai bahan tambah mineral dan sisa industri sebagai bahan gantian separa simen merupakan fokus utama dalam kajian ini. Dalam kajian ini, terdapat 8 jenis campuran bahan tambah (terdiri daripada beberapa peratus campuran) untuk dibandingkan prestasinya dengan mortar yang mengandungi 100 peratus simen (mortar kawalan). Empat campuran daripadanya terdiri daripada pelbagai peratus campuran bahan tambah dengan simen (pelbagai bahan tambah, PBT). Manakala empat jenis campuran lagi adalah campuran simen dengan satu jenis bahan tambah (satu bahan tambah, SBT), di mana peratus kandungan PFA, RHA, SLAG dan POFA yang optimum digunakan dalam kajian ini (berdasarkan kajian ilmiah terdahulu). Bahan buangan ini adalah diperolehi dari sumber tempatan. Pada peringkat awalnya, kajian ini menumpukan kepada ciri-ciri kekuatan bahan, kadar penyerapan air dan jumlah peratus keliangan sesuatu campuran mortar. Mortar diawet dengan air selama 7, 28, 60 dan 90 hari dan diuji bagi mendapatkan campuran PBT yang optimum. Mortar PBT juga diuji kekuatannya dengan pelbagi jenis pengawetan. Kajian juga mengambilkira aspek kebolehtahanlasakan mortar PBT seperti serangan asid, pengkarbonatan, dan kesan terhadap air laut (perubahan tercepat) pada tempoh dedahan yang singkat. Kajian secara umum kesesuaian penggunaan mortar PBT sebagai lapisan yang mengapit blok ringan juga dikaji. Hasil daripada keputusan ujikaji, kekuatan mortar SBT dan kawalan adalah lebih tinggi dari mortar PBT pada awal umur, tetapi kekuatan semua mortar adalah setara pada peringkat akhir umur. Namun, mortar PBT menghasilkan peratus kadar penyerapan air dan jumlah keliangan yang lebih rendah berbanding mortar SBT dan kawalan. Mortar PBT menghasilkan kebolehlasakan yang tinggi sekiranya diawet dengan sempurna. Mortar PBT yang diawet dengan permulaan 7 atau 14 hari di dalam air dan kemudian di udara menghasilkan kekuatan mortar yang tinggi pada awal umur berbanding dengan awetan secara terus di dalam air mahupun udara. Blok konkrit ringan berudara terapit dengan lapisan mortar PBT lebih berprestasi berbanding dengan blok sediada di pasaran dan blok konkrit ringan berudara.

## CONTENTS

# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

Pozzolanic materials are widely used in concrete and mortars for various reasons, particularly for reducing the amount of cement required for making concrete and mortar which lead to a reduction in construction cost. Moreover most pozzolanic materials are by-product materials and the use of these materials leads to reduction in waste and save in energy consumption to produce cement. Most recently blended and multi-blended cement by incorporating industrial by-products/pozzolanic materials is becoming an active area of research because of their improved properties such as workability, long-term strength and durability. The common blending agents used are fly ash (PFA), rice husk ash (RHA), palm oil fuel ash (POFA), Slag, silica fume (SF), calcined clay etc. The improved properties such as rheology and cohesiveness, lower heat of hydration, lower permeability and higher resistance to chemical attack are reported in the literature (Khan *et al.*, 2000; and Mehta P.K., 1989).

In general, each of these materials possesses different properties and reacts differently in the presence of water (Toutanji *et al.*, 2004) and usually has limitations while some have contrasting influences on properties of concrete and mortar (Khan *et al.*, 2000). The combination of two or more kinds of mineral admixtures has emerged as a superior choice over single admixture to improve concrete and mortar properties (Bagel, 1998; Khan *et al.*, 2000; and Pandey *et al.*, 2000). The development of ternary (containing two types of pozzolans) and quaternary (containing three types of pozzolans) blended cement is relatively rare. Though the binary blended cements BBC (containing one type of pozzolans) are commonly nowadays in use and further studies to investigate and improve the performance of BBC are in progress but even then those are not used at larger scale. Whereas, the research to develop the multi-blended cement containing three or more pozzolanic materials to replace cement partially is rather rare.

PFA normally results in lower early strength but improved workability, whereas SF causes downturn in workability due to high specific surface but higher reactivity than PFA. The effect on combination of SF and PFA showed increase in early strength due to the balancing effect in reactivity and water demand. Incorporation of Slag and PFA in OPC remains a common practice (Bagel, 1998) because Slag is widely applied in high performance concrete (Huiwen *et al*., 2004). A few researches have demonstrated the suitability of the use of combination of Slag and SF as pozzolanic material by replacing cement partially. The combination of SF, Slag and PFA is reported to produce high strength and resistance to wet-dry exposures and freeze-thaw as experimentally demonstrated by Toutanji *et al*. (2004).

Since RHA is similar to SF in terms of pozzolanic activity because the former also contains significant amount of Silicon dioxide and a highly reactive pozzolanic material (Paya *et al*., 2001; and Qijun *et al*., 1999), thus the replacement of SF with RHA is one of the potential options to be considered. Also the research findings show POFA, as another pozzolanic material to be added in mortar to achieve its better performance (Salihuddin, 1993).

Recently there has been a growing trend towards the use of supplementary cementitious materials, whether natural, waste or by-products, in the production of blended cements because of ecological, economical and diversified product quality reasons (Noor *et al*., 2006). One of the major options adopted for economic reason is to utilize local resources especially waste materials that would provide cost effectiveness and also a potential utilization of hazardous waste which would other wise causes environmental pollution.

Since Malaysia is the largest producer of Palm Oil in the world and also has a large milling paddy capacity, hence the agricultural fly ash is locally available in huge quantity as waste material. This has led to the idea to investigate the suitability of these materials to be incorporated in MBC as partial cement replacement. Also this may lead to resolve the open burning issue in the disposal of these waste materials which causes hazardous effects on the country’s environmental conditions.

## 1.2 Research problems

In Malaysia the pace of development and construction activity achieved since last three decades was beyond expectations. It has spurred the demand for fast, cost-effective and quality residential buildings. Cement is an expensive constituent of construction materials. Thus to reduce the cost of the construction material thereby reducing the over all cost of the project is becoming an active area of research and the need of the present time in almost all countries in general and in developing countries like Malaysia in particular.

Various strategies are being adopted to achieve the cost effectiveness. Nevertheless, the application of agricultural and industrial by-products and wastages to replace expensive conventional materials fully or partially is being considered as major technique in this regard.

The utilization of agricultural and industrial by-products offer triple benefits namely: conservation of fast declined natural resources, planned gainful exploration of waste materials, and release of valuable land for more profitable used. As the performance of mortars depends upon the admixtures added as cement replacement whereas the properties of these cement replacement admixtures are dependent on the sources from where those are obtained. It is therefore recommended that experimental studies to be carried out to examine the performance of blended or multi-blended mortars containing agricultural and industrial wastes/by products.

This is why the present study is aimed at investigating the suitability of local agricultural and industrial by products as partial replacement of cements in order to produce MBC which is not only potentially cost effective but also exhibits high performance against aggressive environmental conditions.

## 1.3 Aim and objectives

The main aim of this study is to produce MBC mortar of adequate strength and durability which can sustain the internal and external effects of aggressive environment of a tropical region like Malaysia. The relative objectives to achieved the aim of study are as follows:

1. To establish the optimum binder to sand ratio of mortar mix.
2. To establish the optimum mix proportion of Multi Blended Cement in a mortar regarding strength, porosity and water absorption.
3. To determine the durability performance of the mortar with MBC in terms of chemical attack such as carbonation, acid attack, and the effect of seawater.
4. Ultimately, to brief study on the application of the MBC mortar as the face sheets to produce lightweight non-load bearing sandwich block.

## 1.4 Research hypothesis

The MBC system can be utilized to produce high performance mortar. The low early strength of PFA and Slag in MBC mixes can be improved by the incorporation of high reactivity of RHA and POFA. On the other hand, incorporation of RHA and Slag generally will cause a downturn in workability. Whilst, incorporation of PFA in the system can enhance workability hence reduced the water binder ratio. Subsequently low water binder ratio (wbr) of MBC system would achieve low porosity and low absorption mortar compared with control OPC and BBC mortar. Therefore, MBC systems can potentially reduce or eliminate limitations inherent in individual materials (BBC systems). This MBC system is low in alkalinity that contain less amount of CH and also more homogenous and dense mortar, which can potentially withstand chemical attack when exposed to hostile environment compared to control OPC mortar.

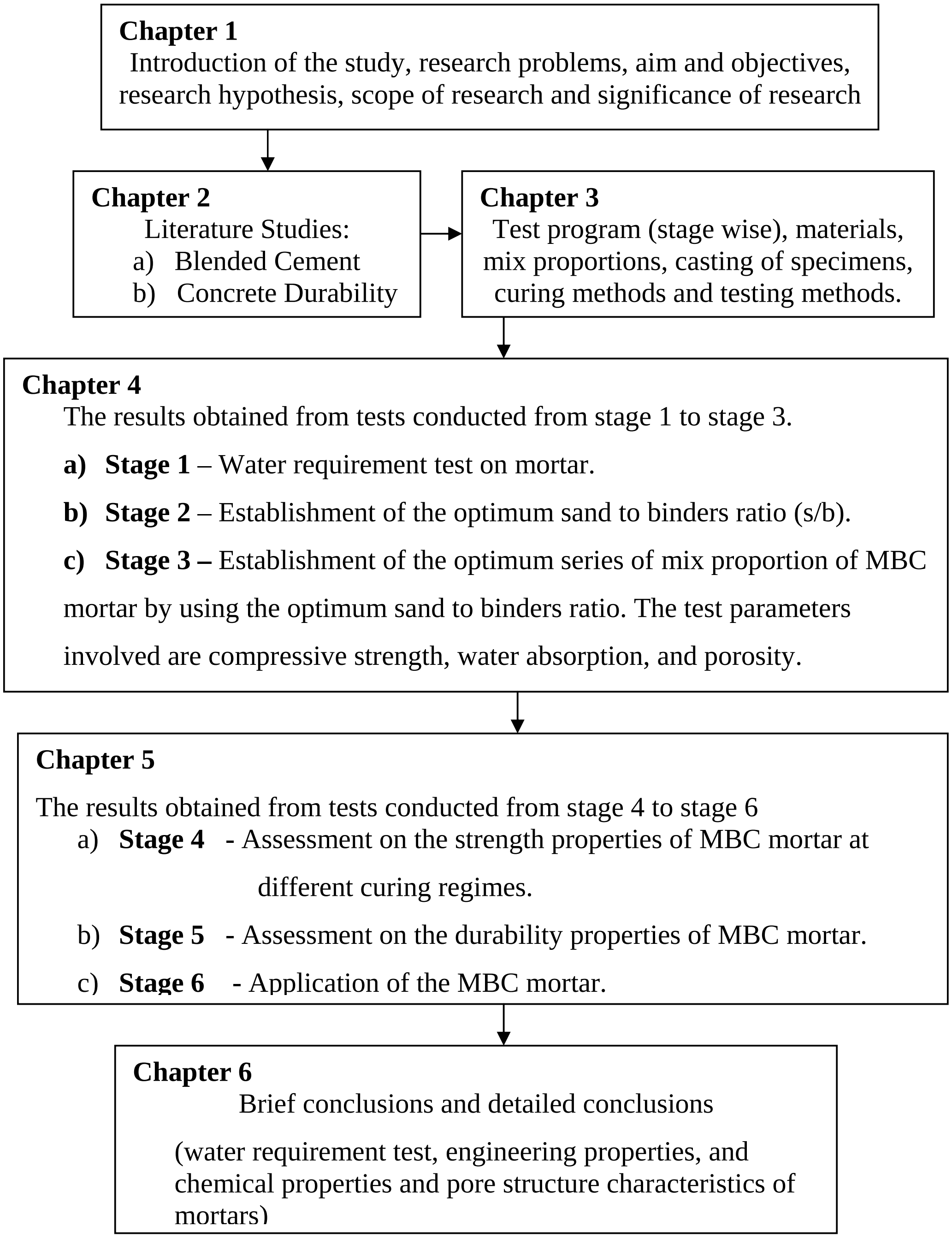
## 1.5 Scope of research

The study is fully experimental in nature and focuses on the development of multi-blended cement (MBC) mortar of optimum mix (sand: binder). The study specially emphasizes to investigate the appropriate proportion of constituents of MBC. The constituents adopted as partial replacement of cement to produce MBC were GGBFS (slag), PFA, RHA, and POFA along with the principal constituent, cement. The content of cement, slag, and POFA was kept constant through out the experimental study. The performance of optimum MBC mortar was studied in terms of ultimate compressive strength, water absorption, total porosity and durability.

The durability of MBC mortar produced was tested in terms of its resistance to acid attack, carbonation, and the saline water from sea. Finally attempt in limited extent was made to investigate the suitability of MBC mortar developed, as the face sheets to produce lightweight non-load bearing sandwich masonry unit with lightweight aerated concrete as core. The thickness of the face sheet provided was kept constant at 10 ± 2mm. The performance of the sandwich masonry unit was examined in terms of its ultimate compressive strength, physical failure pattern, and the apparent composite behavior of the two materials at their interface.

## 1.6 Significance of Research

The study is significant to produce high performance MBC mortar by using the agricultural and industrial waste/by-products. The MBC mortar exhibited the compressive strength of at least at par with the OPC mortar and also better performance in aggressive environment of Malaysia by withstanding the internal and external effects of both short term and long term as well. This is expected due to the low permeability and low porosity of MBC mortar mixes. The ultimate product of MBC mortars would be economical. The study is also important in the effort to resolve the burning issue with regard to the disposal of the huge quantity of waste material from Palm Oil and Paddy industry in Malaysia. MBC mortar can be applied as face sheets to produce lightweight sandwich masonry units in order to reduce over all weight and cost of the building and also a step towards industrialization of the building system.



**Chapter 1**
Introduction of the study, research problems, aim and objectives, research hypothesis, scope of research and significance of research

**Chapter 2**
Literature Studies:
a) Blended Cement
b) Concrete Durability

**Chapter 3**
Test program (stage wise), materials, mix proportions, casting of specimens, curing methods and testing methods.

**Chapter 4**
The results obtained from tests conducted from stage 1 to stage 3.

**a) Stage 1** – Water requirement test on mortar.

**b) Stage 2** – Establishment of the optimum sand to binders ratio (s/b).

**c) Stage 3 –** Establishment of the optimum series of mix proportion of MBC mortar by using the optimum sand to binders ratio. The test parameters involved are compressive strength, water absorption, and porosity.

**Chapter 5**

The results obtained from tests conducted from stage 4 to stage 6

a) **Stage 4** - Assessment on the strength properties of MBC mortar at different curing regimes.

b) **Stage 5** - Assessment on the durability properties of MBC mortar.

c) **Stage 6** - Application of the MBC mortar.

**Chapter 6**
Brief conclusions and detailed conclusions

(water requirement test, engineering properties, and chemical properties and pore structure characteristics of mortars)

**Figure 1.1** Report Organization

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

The consumption of cement according to CEMBUREAU started to increase during the second half of the 20th century at a very rapid pace as seen in Figure 2.1. Although Malaysian apparently is coping with the demand of cement and the cement supply is considered abundant, nevertheless recently the cost of cement has increased. On the one hand, cement is the most expensive constituent in the concrete therefore it exerts pressure on contractors and other parties involved in the construction industry. Like wise, the process for manufacturing of cement also leads to the emission of large quantity of $CO_2$ and $NO_x$ to the environment due to the large quantity of limestone used as a raw material, which required to be burnt at high temperature. The production of every tonne of Portland cement releases approximately one tonne of carbon dioxide, which is the major contributor to the greenhouse effect, which is responsible for global warming (Mehta, 1994). The cement industry is required to restructure into an environmentally compatible industry by utilizing industrial waste as cement replacement. Otherwise, the time is over when concrete could be considered a low-priced commodity product.

The idea to introduce industrial and agricultural by-products in the making of concrete is not new in itself. It has been standardized in Italy since 1929 and has been manufactured in Europe for over five decades. Asian countries are also producing blended cements for quite sometime. Recently, the emphasis has shifted to the development of ternary and quaternary blended cement but the information pertaining to the use of multi-blended cement is still relatively scarce.

There is considerable volume of literature on the use of Silica Fume (SF) in binary and ternary cement in producing concrete. SF due to its high pozzolanicity and its extreme fineness is very effective in producing low permeability and high strength concrete but, generally has the drawback of low workability as a result of its high specific surface area (Bagel, 1998; and Khan *et al*., 2000). In one hand, for SF concrete the incorporation of Superplasticizer (Sp) is essential for maintaining high workability but this normally results in an increase in the cost of production. On the other hand, due to high cost and superfine particles of SF (median size 0.1µm), field applications are limited to a maximum dosage of

15% SF by weight of cement (Mehta, 1994). That is consuming another 85% of OPC constituents, thus hardly helpful in the reduction of cost and environmental pollution.

Rice Husk, an agricultural waste, constitutes about one fifth of the 500 million metric tons of rice produced annually in the world (Mehta, 1992). The pozzolanic effect of RHA has been reported by several researcher (Cook, 1986; Zahairi, 1990; Mehta, 1992; and Salihuddin, 1993). At present, Malaysia produces more than half of the world's total output of palm oil. There are more than 300 palm oil mill plants operating in the country (Tan, 2000). In Malaysia it has been estimated that the total waste generated by the industry is more than 8.1 million tons a year as reported in 1993 (Awal and Hussin, 1996a). Although it is a hazardous material, it has been identified that POFA has pozzolanic properties and highly reactive and can be used as a unique cement replacement for the production of construction materials (Tay, 1990; Zahairi, 1990; Salihuddin, 1993; and Awal and Hussin, 1996a).

Agricultural waste can be used as low cost construction material such as cement replacement materials, in fibre-reinforced concrete as well as aggregate for concrete production. The exponential growth rate of population, development of industry and technology, and the growth of social civilization can be considered as the underlying factors that have caused the increase in waste production in the recent years, which has impact upon environment. This agricultural fly ash is locally available in huge quantity as waste material and the application as cement replacement material have engineering potential and economic advantage.

POFA and RHA have potential to be used in multi-blended cement (MBC) by incorporation of PFA and Slag. PFA normally results in lower early strength but improved significantly in workability and bleeding (Ravindra, 1986; and Khan *et al.*, 2000). Whilst, Slag has advantages like low heat of hydration, high sulfate and acid resistance (Hanifi and Orhan, 2006) and widely applied in repairing material (Sobolev and Yeginobali, 2005) and high performance concrete due to an active additive (Huiwen *et al.*, 2004).

## 2.2 Blended cement

Blended cement is defined as Portland cement containing other finely divided particles in different but well-defined proportions (Shondeep and Bonen, 1994). Most recently blended cement based on industrial and agricultural waste, are well known for their improved long-term strength and durability. The blending agents are such as fly ash (PFA), ground granulated blast furnace Slag (Slags), rice husk ash (RHA), palm oil fuel ash (POFA), SF (SF), calcined clay etc. It is reported to improve rheology and cohesiveness, lower heat of hydration, lower permeability and higher resistance to chemical attack (Khan *et al.*, 2000). In some cases, a boost in early strength becomes apparent, while in others, an increase in late strength occurs (Toutanji *et al*., 2004).

In recent years, the applications of blended cements have been further extended to the manufacture of building elements and the production of concrete pipes and precast products (Sagoe and Mak, 1994). In general, each of these blending materials possesses different properties and reacts differently in the presence of water (Toutanji *et al*., 2004) and usually has limitations and some have contrasting influences on properties of concrete and mortar (Khan *et al*., 2000). The combination of two or three kinds of mineral admixtures has emerged as a superior choice over single admixture to improve concrete and mortar properties (Zhang *et al*., 1996; Jones *et al*., 1997; Bagel, 1998, Khan *et al*., 2000; Isaia *et al*., 2003; Pandey *et al*., 2003; Toutanji *et al*., 2004; and, Sobolev and Yeginobali, 2005). The details information pertaining the multiple binder combinations will be discussed later in this chapter.

### 2.2.1 Pozzolanic materials

The use of industrial and agricultural by-products as mineral admixture is known to possess pozzolanic properties. The word pozzolan is derived from Romans civilization, when volcanic soil in Italy was found to be suitable for producing hydraulic mortar. American standard, ASTM C 618-94 (1994) defines pozzolans as “siliceous or siliceous and aluminous materials which on themselves posses little or no cementitious value but will in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compound possessing cementitious properties”. Slag content hydraulic properties and can also be defined as pozzolan but in countries like United Kingdom (U.K) and United States (U.S), it is normally specified under a stand alone standard such as BS 146:1991 and BS 4246:1991 in UK and ASTM C989-89 in U.S.

To confirm other materials either they possess pozzolanic properties or not, a series of the tests as per the standards are required to analyses and determine the chemical composition and physical properties as recommended in ASTM C618-94.

### 2.2.2 Pozzolanic reaction

A pozzolanic reaction takes place when a siliceous, or siliceous and aluminous material is in contact with calcium hydroxide in the presence of moisture to form compounds possessing cementitious properties. Silica of amorphous form react with lime more readily than those of crystalline form. In the cement hydration process, the calcium silicate hydrate (C-S-H) and calcium hydroxide (Ca $(OH)_2$, which is also written as CH) is released in the hydration of two major compounds of cement namely tricalcium silicate ($C_3S$) and dicalcium silicate ($C_2S$). So as a pozzolanic material in mortar or concrete mix, the pozzolanic reaction will only take place when CH is released. As a result from this reaction the pozzolanic material will produce a C-S-H altogether with calcium aluminate hydrate (C-A-H) which are so called cement gels, that form the hardened cement paste.

Qijun *et al*. (1999), who studied the reaction between RHA and CH, observed that the amount of CH by 30% RHA in cement paste begins to decrease after 3 days, and by 91 days it reaches nearly zero, whereas in the control paste, it significantly increased with hydration time as viewed in Figure 2.2. This phenomenon reveals that the reaction between RHA and CH, could also occur in blended cement containing other pozzolanic materials. The lowering effect of CH indicates that there exists the CSH gel formed in the pozzolanic reaction. El Aziz *et al*. (2004) investigated the hydration and durability of sulphate-resistance and slag cement blends in Caron’s Lake water as the aggressive medium. It also found the same trend in the XRD patterns of the blended cements containing Volcanic Ash hydrated at 12 months which shows that the amount of CH decreased with curing time increases due to hydration process, as presented in Figure 2.3.

Pozzolan can accelerate the early hydration rate within one hour, by stimulating the dissolution of $C_3S$ by the absorption of $Ca^{2+}$ ions on the surface of the pozzolanic particles and also by providing increased sites for the precipitation of C-S hydrates. Hence, the surface of pozzolan acts as a precipitation sites that is preferable to the precipitation of hydrates and secondly can lower the concentration of $Ca^{2+}$ ions that can accelerate the rate of dissolution of $C_3S$. The primary pozzolanic reaction during the early curing is with alkali hydroxides.

Secondly, the main and long-term reaction is with calcium hydroxide. The behaviour of the delay in pozzolanic reaction will result in more permeable concrete at early age and gradually becomes denser than plain concrete with time. This behaviour is due to two reasons, firstly as mention before, PFA or pozzolan particles become the precipitation sites for the early hydration C-S-H and CH that hinders pozzolanic reaction. Secondly, the strong dependency of the breaking down of glass phase on the alkalinity of the pore water which could only attain the high pH after some days of hydration. Pozzolan can partially replace cement in mortar or concrete mix without affecting strength development. The effect of the pozzolanic reaction will produce more cement gel which is the C-S-H and C-A-H, reducing the pore size, blocks the capillary and produces denser concrete thus making it stronger and more durable.

The small particles of pozzolans are less reactive than Portland cements (Mehta and Aitcin, 1990). Nevertheless they generate a large number of nucleation cites for the precipitation of the hydration products when it dispersed in cement pastes. Thus, this mechanism makes the paste more homogenous and dense as for the distribution of the finer pores due to the pozzolanic reactions between the amorphous silica of the mineral addition and the CH (Isaia *et al.*, 2003). According to Mehta (1987), the finer particles of PFA and RHA compared to Portland cement will cause a segmentation of larger pores and increased the number of nucleation sites and will accelerate the reactions and form smaller CH crystal. Berry (1994) discovered that high volume of PFA particles in the cement paste that are not completely reacted may fill the voids and increase paste density.

### 2.2.3 Types of pozzolans

Pozzolans can be classified into two types, may be natural or artificial types. The natural pozzolans are formed from volcanic activity. While artificial pozzolans are produced by the combustion of traditional materials such as calcined clay and shale, silica stone, fly ash and agricultural ashes. During this research study two types of fly ashes namely pulverized fuel ash (PFA) and agricultural ashes, which consist of rice husk ash (RHA) and palm oil-fuel ash (POFA) and also by-product of steel industry namely ground granulated blast furnace slag (Slag), are applied as pozzolans.

#### a) Rice Husk Ash (RHA)

Rice Husk is an external covering of rice, which is generated during dehusking of paddy rice. The rice husk accounts for 20% weight of the paddy (Asavapisit and Ruengrit, 2005). The residue itself cannot be used as a cement replacement and it is the ash obtained from preprocessing the residue (Cook, 1986). The RHA is rich in silica content, obtained by burning rice husk to remove volatile organic carbon such as cellulose and lignin. It is estimated that, one tonne of rice yields 200kg of husk and about 40kg of ash (Cook, 1986). As an agricultural product RHA contains considerable amount of silicon dioxide, which contains about 90% silica by mass similar to SF (Qijun *et al.*, 1999). The silica present in the ash can be amorphous or crystalline and its reactivity depends primarily on burning conditions. The burning method and the fineness of the particles are two major factors that primarily affect the reactivity of RHA (Cook, 1986). The fineness of ash with most of its silica in an amorphous will significantly affect the reactivity of RHA in mortar or concrete mix.

According to Mehta (1979), the totally amorphous silica can be produced by maintaining the combustion temperature below 500ºC, under oxidizing conditions up to 680ºC provided the hold time is less than one minute will results in an amorphous and with a porous structure. Thus, the specific surface can be high as 50 000 $m^2$/kg. Weight loss occurs up to 100ºC due to evaporation of absorpted water. From 400 to 500ºC, the residue carbon oxidizes, and majority of the weight loss occurs in this period. The silica in the ash still remains in the form of amorphous form.

Above 600ºC, probably it may detect formation of quartz. As the temperature increased, the conversion to other forms of crystalline silica will occur, which is first as the crystobalite and at higher temperatures, trydimite. Prolonged heating at temperature beyond 800ºC produces essentially, crystalline silica (Cook, 1986). The lower temperature ashes gave higher reactivity with peak value around 500ºC because the amorphous form could only be obtained at low temperature burning. According to Mehta (1979), the amorphous silica powders with high surface area are more reactive than the crystalline form of silica. In fact, the lower temperatures and retention times resulted in higher specific surface and the pore structure is less damaged. As the temperature of processing becomes higher, the ashes become progressively white. The ash gradually loses its pozzolanicity as the temperature of incinerator is increased at a given fineness.

Kapur (1981) has studied the influence of temperature on husk incinerated for 12 hours, which is the X-Ray diffraction analysis as presented in Figure 2.4. Up to 1000ºC burnt temperature showed that the ash was mostly crystobalite and trydimite in silica, which is indicated that the ash is crystalline silica. Even at 15 hours heating at temperature 300ºC also was detected formation of quartz. The XRD pattern shown in Figure 2.5 indicates that the ash is completely crystalline in silica (Cook, 1986). Whilst, the study conducted by Coutinho (2003) showed RHA as mainly amorphous in silica as shown in Figure 2.6. Thus the burning temperature and duration affects greatly the ash product.

The fineness of ash will significantly affect the reactivity of RHA in lime, mortar or concrete mix. Grinding of ash is a necessary because the raw ash immediately recovered from furnace are coarse in nature. These ashes should be complying with the standard for PFA such as ASTM C 618-84 (1994). The ash has to achieve a maximum of 34% retained on 45µm sieve, when wet sieve analysis is done as per specifications of ASTM C 618-84

1994. Table 2.1 shows the physical and chemical analysis of RHA. It is clearly seen that the major component of RHA is silica. The silica content is higher than 80%, which is similar with SF. Meanwhile the content of CaO is less than 10% and it is classified into class F pozzolan. Unlike SF, the particles of RHA possess a cellular structure that responsible for the high surface area even the particles are not very small in size. An example of RHA particle shape is shown in Figure 2.7.

### b) Palm Oil Fuel Ash (POFA)

Malaysia and Indonesia are the biggest producers of palm oil and palm products in the world. It has been estimated that more than 8.1 millions of total waste generated from this industry is in Malaysia as reported in 1993. The palm oil is not grown in many parts of the world. POFA is a by-product of palm oil industry. The ash is produced as a result of the burning of palm oil shell and husk (in equal volume) as fuel in palm oil mill boiler to produce steam for electricity generation and palm oil extraction process. POFA is hazardous materials and is simply disposed without any commercial returns. The literature study about POFA is relatively limited contrasting with RHA. Various researchers reported that POFA has pozzolanic properties and highly reactive and can be used as a unique cement replacement for building construction materials (Tay, 1990; Zahairi, 1990; Salihuddin, 1993; and, Awal and Hussin, 1997).

POFA is greyish in colour that becomes darker with increasing proportion of unburned carbon. The quality is highly dependent on the efficiency of the mill boiler system. The whitish grey ash is produced with well maintained boiler up to complete combustion of the fuel. The fine ashes are obtained at the foot of the flue tower as trapped after escaping from the burning chamber of the boiler (Zahairi, 1990; and Salihuddin, 1993). The ash produced is rather coarse with approximately 30% passing 45μm sieve. Further grinding is necessary to act in accordance with the fineness of the ASTM C 618-84 standard. The chemical and physical properties of POFA are shown in Table 2.1. It shows that the sum of three significant oxides namely $SiO_2$, $Al_2O_3$ and $Fe_22O_3$ are slightly above 70% while CaO content is low.

### c) Pulverized-Fuel Ash (PFA) or Fly Ash

PFA is a by-product of burning pulverized (finely ground) coal to generate electric power. Temperature are usually around 1500°C on entry furnace, the carbonaceous content of the coal suspension is burnt immediately. The shales and clays (contents of silica, alumina and iron oxide) and the other matters in coal, melt whilst in suspension, and then with rapid cooling they are carried out by the flue gases and form into fine spherical particles. Only 80% of the coal ash is carried out of the furnace with the flue gases is called the PFA and must be removed before the flue gases are discharged to the atmosphere. Whilst, the remainder of the coal ash is called furnace bottom ash (coarser material), which falls to the bottom of the furnace.

The method to remove PFA from the flue gases can affect the quality of PFA being produced at power stations. PFA obtained from cyclone separators is comparatively coarse and contains a large proportion of unburned fuel. While PFA that obtained from electrostatic precipitators is relatively fine having a specific surface of about 3500 $cm^2/g$ or as high as 5000 $cm^2/g$. The shape is generally of spherical particles and some of which may be like glass and hollow and irregularly shaped of unburned fuel or carbon. The colours may vary from light grey to dark grey or even brown.

PFA can be divided into two distinct categories that are generally associated with type of coal used at the power station. The categories namely are low-lime and high lime PFA (Ravindra, 1986). Low lime PFA contains CaO content less than 10% and usually produced from anthracite and bituminous coals, classified into class F fly ash. Whereas high lime PFA with CaO content greater than 10% and are usually produced from sub-bituminous and lignite coals, roughly corresponds to ASTM class C fly ash. The sum of three significant oxides namely $SiO_2$, $Al_2O_3$ and $Fe_2O_3$ for class F have a minimum value of 70% and 50% for class C fly ash. Class F should be defined as truly pozzolanic and Class C as having some cementitious properties itself. In UK references for specification is given by BS 3892: Part1 (1982) whilst the similar document produced by the American as ASTM C 618-94 (1994).

The chemical and physical properties of PFA are as in Table 2.1. In the low lime PFA, the glass is siliceous or alumino-silicate composition, whilst in high lime PFA is calcium aluminate composition. The low-lime PFA generally conforms to ASTM class F due to high portions of silica and alumina, consists principally aluminosilicate glasses. This will convert in the crystalline aluminosilicates if the molten glass do not get cooled rapidly, sillimanite and mullite may crystallize as slender needled in the interior of the glass sphere, becoming non-reactive at ordinary temperature it tends to reduce the reactivity of the PFA.

The high lime PFA is more reactive because it contains most of calcium in the form of reactive crystalline compounds such as $C_3A$, CS and $C_4A_3S$. The evidence is also there that the principal constituents contain enough calcium ions to enhance the reactivity of the aluminosilicate glass.

The reactivity of PFA depends on the nature and proportion of the glass phase. The major range of phase is illustrated in Figure 2.8**.** In general, the greater fineness and lower LOI of PFA have been found to be a great potential to enhance the performance of PFA concrete. PFA normally results in lower early strength but improved workability. The reduction in water requirement incorporation PFA in cement is due to the spherical shaped particles and their smooth surface which also roll in fresh paste thereby reduce the fraction resistance of cement particles and improve the fluidity of the mixture (Sun *et al*., 2003). Figure 2.9 illustrates the difference between the shape of PFA and OPC particles.

#### d) Ground granulated blast furnace slags (Slag)

Slag is a by-product from the manufacture of iron in a blast furnace. A blast furnace slag is a molten material that rises to the top of the pig iron at the bottom of the blast furnace. The temperature close to that iron is between 1400°and 1600°C. A slow cooling of slag melts leads to a stable solid, which consists of Ca-Al-Mg silicates. A granulated glassy material can be formed if they are quenched from the melt. These slags possess latent hydraulic properties. Rapid cooling by spraying large quantities of water jet during the cooling between 900° and 800°C can prevent the crystallization of slag. The water content of slag can be eliminated in dryer mills after the treatment.

The chemical and physical properties of blast furnace slag are shown in Table 2.1. Blast furnace slag is only hydraulic when cooled under conditions that it solidifies as a glass as mentioned earlier. When allowed to crystallize, it has no cementitious properties. Chemical composition influences both the glass-forming properties and the hydraulicity of the slag. Slag neither contain $C_3S$, which is the phase contributing most to the early strength of Portland cements, hence slag cements develop their strength at a slower rate. Nor does slag contain $C_3A$, which is the phase of Portland cement having the greatest heat of hydration.

The early rate of reaction between slag and water is slower than that of Portland cement and water. This indicates that the strength development will also be slower. However, both react at early ages (Regourd, 1986). When slag Portland cement is mixed with water, the Portland cement component begins to hydrate first and there is also small amount of immediate reaction of slag that it releases calcium and aluminium ions in solution. The slag then reacts with alkali hydroxide and followed by reaction with

$Ca(OH)_2$ to form more CSH gel (Neville, 1995). Slag develops its cementitious properties far too slowly to be practical use unless its hydration is activated by the addition of calcium compound. In slag Portland cements, two slag hydration activators are present; the gypsum (sulphate activator) and the portlandite $Ca(OH)_2$ liberated by the hydration of clinker silicates $C_3S$ and $C_2S$ (lime activation).

### e) Silica Fume (SF)

SF is a by-product of the manufacture of silicon and ferrosilicon alloys from high purity quartz and coal in a submerged-arc electric furnace. Microsilica or condensed silica fume are also be referred as SF, but the term most accepted is SF. SF is the gaseous SiO oxidizes and condensates in the form of extremely fine spherical particles of amorphous silica ($SiO_2$). The amorphous silica is highly reactive, and the smallest of the particles speeds up the reaction with CH, which the compound of cement hydrates. The very small particles of SF be able to go through the void between the particles of cement hence improve packing.

The efficient heat recovery system in furnace produce SF virtually free from carbon and is light in colour. On the other hand, the SF may become dark in colour if the furnace without full heat recovery system. The usual ferrosilicon alloys have nominal silicon contents of 50, 75, and 90 percent, which influences the silica content in the resulting SF.

The specific gravity of SF is 2.20, but may become higher when the silica content is lower. The particles are extremely fine and having diameter ranging between 0.03 and 0.3μm. The specific surface of SF determine by nitrogen adsorption is $20{,}000 m^2/kg$ that is 13 to 20 times higher than other pozzolans. It also has a very low bulk density (200 to 300 $kg/m^3$ ) (Neville, 1995). Handling the light powder is difficult and can be added that SF is expensive. The maximum of 3 to 5 percent of SF is used in cement replacement because of its very high reactivity. The high surface area of SF would increase the water demand. Superplasticizer is required when the low wbr is concern in making concrete. The use of SF can reduced bleeding and improved cohesion of the mix. The voids caused by trapped bleed water are also absent. The cohesive of concrete containing SF is good for pumping and for underwater concrete and also for use as flowing concrete.

### 2.2.4 Binary Blended Cement (BBC)

BBC system is Portland cement blended with single mineral admixture in producing cementitious material in well-defined proportions. This system was firstly approached as the basic strategies to restructure the cement industry into environmentally compatible. This section will discuss the influences of BBC system in fresh and hardened concrete and mortar.

### a) RHA / OPC

The grain particles of RHA are irregular in shape, which is in contrast with PFA thus required a higher wbr to produce the paste of same flow (workability). Accordance to Zahairi (1990), RHA cement mortar requires a higher water binder ratio (wbr) than OPC mortar mix to achieve its maximum strength. RHA is cellular and porous in nature, and high specific surface and its addition to a concrete mix will increase its water demand to produce a workable concrete (Cook, 1986). The very fine particles of RHA fill the spaces between the cement grains, thus stabilizing and improving the cohesiveness of the concrete mix but adversely affecting its workability (Mahmud *et al*., 1996). Therefore, an increase in water demand is expected with increasing RHA content because of the water absorbing characteristics of RHA.

The RHA is highly pozzolanic and suitable to use as cement replacement when it is burnt under controlled conditions. Mehta and Folliard (1995) reported that except RHA, no other pozzolanic additions including SF has ability to contribute to the strength of Portland cement concrete at the early ages of 1 and 3 days. Mahmud *et al*. (1996) found that the optimum level for maximum strength gain of RHA concrete was 15%. The optimum level for high strength RHA concrete was 5%. The RHA contributes to strength development much earlier age than SF and OPC, which was similar to the findings of Mehta (1992). High strength concrete (HSC) of 80MPa can easily be obtained by the use of RHA and Sp in combination at 14 days and upward. It concluded that the RHA is a viable alternative material to SF in the production of HSC. Zhang *et al*. (1996) found that the strength of (10% level) RHA concrete exhibited higher than control OPC at all ages but had similar strength at one-day strengths. However, the strength was lower than the strength of (10% level) SF concrete up to 28 days, but similar at 90 and 180 days.

Salihuddin (1993) concluded that the replacement level RHA up to 40% is possible without affecting the strength. However, an optimum replacement of RHA is seen to be lying at about 20% level. It also reported that the RHA replacement up to 30% in mortar produced maximum strength superior than control OPC and 30% PFA mortar.

Nonetheless, the strength at 40% level is comparable to the control strength results. Salihuddin (1993) found that the pozzolanic activity of RHA is to be higher than PFA as confirmed by the TG analysis. The similar results showed by Zahairi (1990) that at 20% cement replacement with RHA at 0.55 wbr gives a better compressive strength compared to OPC. Accordance to Zahairi (1990), RHA cement mortar requires a higher wbr than OPC mortar mix to achieve its maximum strength as mentioned before. However at very high wbr of 0.65 and 0.75 the negative effect is more obvious.

Nevertheless, there is also contrary behavior of both Lime and OPC mixes containing RHA mortar studied by Cook and Suwanvitaya (1981). The strength initially increased rapidly but essentially ceases after 28 days. The strength does not increase significantly beyond 28 days as shown in Figure 2.10. It reported that was probably related to the high reactivity of the RHA and the early completion of the lime-silica reaction.

The pore structure of RHA (30% replacement) mortar is denser than control OPC and PFA (30% replacement level) mortar as confirmed by the mercury porosity analysis (Salihuddin, 1993). Zhang *et al*. (1996) reported that, the higher compressive strength gain and reduction of permeability in concrete incorporating RHA is probably due to the reduced porosity, reduced calcium hydroxide content and reduced width of the interfacial zone between the paste and the aggregate. The formation of more CSH gel and less portlandite in concrete with RHA may improve the concrete properties due to the reaction between RHA and calcium hydroxide in hydrating cement (Qijun *et al*., 1999).

However, Ho (1998) studied 30% replacement of RHA, and PFA in concrete and reported that the porous and high surface area of RHA performed worst than OPC and PFA concrete in terms of absorption however less permeable and showed better results in chloride penetration than OPC concrete. The results on corrosion studied by Singh *et al.* (2002) reveals that the 10% RHA-blended cement is more resistant to the corrosive atmosphere of N/60 $H_2SO_4$. Nehdi *et al*. (2003) reported that RHA reduced the rapid chloride penetrability of concrete from a moderated rating to low or very low ratings as increased the RHA contents (7.5%, 10% and 12.5% replacement level).

It is evident from the literature that mostly RHA blended cement compared to OPC cement exhibited high early strength than OPC. Mehta (1992), Zhang *et al*. (1996), and Mahmud *et al*. (1996), and others all agreed that the performance of RHA blended cement has similarity with SF blended cement due to its considerable silicon dioxide content like SF. RHA is a viable alternative material to SF. But the optimum replacement level of RHA is reported different by the various researchers like, Mahmud *et al*. (1996) concluded with 15% as optimum whereas, Salihuddin (1993) and Zahairi (1990) reported that an optimum replacement of RHA is seen to be lying at about 20% level, whilst, the others recommended ranging between 10% to 30% as optimum replacement of RHA. All these replacement levels of RHA are in percentage by weight of the total binder material.

### b) POFA / OPC

The workability of POFA concrete according to Awal and Hussin (1996a) was found to be slightly lower than control OPC, but the bleeding in POFA concrete was much less than in OPC concrete. Zahairi (1990) reported that at fixed wbr 0.55 the workability would increase with addition of POFA up to 35%. However, the workability reduced with addition of more than that percentage. Whilst, at higher wbr (0.65 and 0.75) addition of POFA up to 35% did not show significant effect on workability but at higher percentage than that, the workability started to decrease.

Zahairi (1990) found that the POFA mortar up to 35% replacement is possible to produce mix having equivalent strength compared to the OPC mortar mix. It also reported that the higher the POFA content the lower the strength than OPC mortar at lower wbr (0.40). At 0.50 wbr, only mix with 35% POFA achieved equivalent strength as OPC mortar. However at high wbr 0.6 the strength of all POFA content was lower than OPC mortar. Salihuddin (1993) reported that the replacement level up to about 20% is possible for POFA mortar without adverse effects on strength. However the optimum replacement of POFA is clearly seen to be lying at about 10% to 15% level. POFA mortar strength is comparable to PFA mortar but both are lower than OPC mortar by approximately 9%.

Awal and Hussin (1996b) investigated that the strength concrete made with 40% POFA is possible to replace without any adverse effect on compressive strength. However, the maximum strength gain occurred at the replacement level of 30% as shown in Figure 2.11. The strength of POFA concrete at early ages was lower than OPC concrete. But during the third week of hydration, the strength of both concrete seems to be equal. However, the strength at 28 days was relatively 10% higher than OPC concrete. As they argued that, this is not unlikely, and is in well agreements with the strength behaviour of other pozzolanic materials like RHA, SF and other class C pozzolans. It was also found that finer ash produced higher strength than the coarser ash as shown in Figure 2.12. This lower development of strength in concrete with coarse ash was possibly due to its lower surface area of the particles that affected the pozzolanic activity and hence its strength.

The pore structure of POFA mortar is more dense than the OPC mortar as confirmed by the mercury porosity analysis. However, POFA samples exhibited a comparable performance in permeability compared to the OPC mortar samples (Salihuddin, 1993). Awal and Hussin (1997) investigated some aspect of durability performances of POFA concrete. They found that POFA concrete exhibited better resistance against acid attack than OPC concrete due to its low CaO content and less amount of $Ca(OH)_2$. The test on resistance to sulphate attack suggests that expansion of mortar bars of POFA concrete are significantly lower than OPC concrete. It was also found that a reduction in expansion due to alkali-silica reaction occurred with the increase in amount of ash content.

From the above findings, it seems that the strength of POFA samples was lower than OPC samples mainly at early ages. The optimum replacement level achieved by Zahairi (1990), and Awal and Hussin (1996b) was 30% whereas, 10% replacement level achieved by Salihuddin (1993). Nevertheless, all researchers have identified POFA as pozzolanic material, which is highly reactive and can be used as a unique cement replacement for building construction materials.

### c) PFA / OPC

It is well documented that the use of PFA increase workability for given water content because of lubrication effect of its spherical particles. The use of PFA can physically disperse the cement flocs, thus freeing more paste to lubricate aggregates and improving workability (Ravindra, 1986). PFA also improves cohesion and plasticity. PFA can restrict the movement of free water in the plastic concrete thus reduces bleeding better than OPC.

However, it is also known that the use of PFA causes delay in the early age strength development. But on later ages PFA concrete goes on progressively to develop higher strength value. This is caused by the delayed pozzolanic reaction. Ho (1998) studied the incorporation of 30% PFA in concrete reported that the 7 days strength of PFA concrete is lower than OPC concrete but at 28 days it achieved higher strength. The results indicated that the early age strength of PFA concrete is contributed by the cement hydration, and at later ages the PFA concrete gained higher strength values than OPC concrete (Ho, 1998).

Naik and Ramme (1989) found the optimum cement replacement levels for PFA less than 40% in terms of strength development when they investigated it with replacement ranging from 0 to 60%. PFA replacements of 35% to 40% have attained 28 days strength of 45-55 MPa and one-year strength about 60-80 MPa (Ravindra, 1986). Besides that, if early strength is not a major aspect, PFA as high as 60% can be used (Naik and Ramme, 1989).

As the strength contributed by the Portland cement slows down, the pozzolanic activity of fly ash contributes the development of the strength at later ages provided that the concrete is properly cured. PFA mixes required longer periods of time to develop strength, which is in contrast with SF. According to Fraay *et al*. (1989), the glass materials in PFA is broken down only when the pH value of the pore water is at least 13.2, and the increase in alkalinity of the pore water requires that a certain amount of hydration of OPC in the mix has been taken place (Neville, 1995). PFA mixes made without additives exhibited outstanding performance at 91 days. However, PFA mixes with too much dosage of Superplasticizer may cause segregation, resulting in lower strength (Toutanji *et al*., 2004).

Generally, total porosity of blended cement is higher than plain cement paste however, their permeability is less than plain cement paste. It is because, in blended cement, the continuity of large pore is less than plain cement and after 28 days of hydration these large pores were essentially isolated. The radial growth of Portland cement products in PFA particles would have a pore refinement effect hence reduce the interconnected between pores (Cook and Cao, 1987). Ho (1998) found that the PFA concrete performed best among RHA and OPC concrete in terms of water absorption, lower absorption rate at covercrete and chloride penetration test. The phenomenon can be linked to improvement on the interfacial transition zones between the cement matrix and aggregate (Toutanji *et al*., 2004). Based on the findings and recommendations of earlier researchers, it is found that replacement level up to 30% by weight was proven to be satisfactory.

### d) Slag / OPC

Slag normally is of greater fineness confers resistance to bleeding in the fresh state and lower permeability when hardened. The glassy surface of the slag may give slightly reduced water requirement, however it depends upon the fineness of grind (Day, 1995). Slag makes the mix more mobile because improves workability but cohesive. This is because of the surface characteristics and better dispersion of slag particles, which are smooth and absorb little water during mixing (ACI 226,1994). There is also reported that slag exhibited an early loss of slump and low rate of slump loss (ACI 226,1994).

High-slag-cements have low strength at early ages. The early strength of slag concrete is likely to be lower than OPC concrete, however at later ages to be higher as shown in Figure 2.13. The initial hydration of slag is very slow because it depends upon the breakdown of the glass by the hydroxyl ions. Generally, the higher the slag contents the slower the development, but the higher the long-term gain (Wrainwright, 1986). The progressive release of alkalies by slag and together with the formation of calcium hydroxide by Portland cement resulting a continuous reaction of slag over a long period. However, the later rate of hydration is accelerated.

A 50% slag replacement in the cementitious material is the highest medium-term strength but gives lower early strength than OPC (Dubovoy *et al.*, 1986). Roy and Idorn (1982) also suggested that the optimum slag content is about 50% from a strength point of view as shown in Figure 2.14. Sivasundaram and Malhotra (1992) reported that a remarkable strength development of 50% to 75% of slag with a total content of cementitious material between 300 and 420kg/m$^3$. However Bagel (1998) found that the replacement of 50% cement by slag caused significant reduction in the 90 days strength of mortar regarding to OPC mortar.

Bagel (1998) also discovered that the use of slag as the partial cement replacement in mortars results in a material with a slightly higher water permeability than OPC mortar by the same workability. Nevertheless Bagel (1998) concluded that the low and medium strength slag mortars cast without water reducing admixture is possible to produce with relatively high density and acceptable permeability, even when the slag activity is very low.

Pigeon and Regourd (1983) reported that with increasing slag percentage the pores become much smaller, which is at 66% slag they found most pores to be less than 20x10$^{-3}$μm. Smolczyk (1980) also reports comparable results, which is the hydrated slag paste contains more gel pores and fewer capillary than OPC paste. Bakker (1980) reported that in addition to the hydrate formation around the slag and clinker particles there are additional (identical) hydrate precipitations in the “gap” between adjacent particles as shown in Figure 2.15. Slag normally has a greater resistance to chemical attack thus suitable for marine works.

### e) Silica fume/OPC

SF due to its high pozzolanicity and its extreme fineness is very effective in producing low permeability and high strength concrete but, generally has the drawback of low workability as a result of its high specific surface area (Bagel, 1998; and Khan *et al*., 2000). The action as a filler through improvement in packing and interface effects probably contributes the early strength development (up to 7 days) of SF (Neville, 1995). The strength of concrete containing SF at 28 days increase with an increase of SF content in the mix (up to certain limit). Strength development of concrete containing SF end much earlier than OPC alone as shown in Table 2.2, which there was no increase in strength beyond 56 days. However, the concrete containing SF increase in strength higher than OPC alone in early strength. The optimum field applications are limited to a maximum dosage of 15% SF by weight of cement (Mehta, 1994).

The continuity of pozzolanic activity of SF results in reduction in the pore size in the hydrated cement paste. Table 2.3 shows that the concrete containing SF small reduction in total porosity of hydrated cement paste as compared with sulfate-resisting (Type V) cement. However, the main effect of SF is to reduce the permeability. 10 percent of SF content in the mix has large effect on the pore system. Whereas, there is no beneficial effect of further increase of SF content in the mix (Neville, 1995). Concrete containing SF is good in sulphate, magnesium, sodium and calcium chloride resistance partly because of a lower permeability and lower CH content. The presence of SF in concrete also has beneficial effect upon resistance to abrasion due to a better bond between the hydrated cement paste and the aggregates.

Usually in the BBC system, some has limitations and contrasting influences on properties of concrete such as workability, and early strength however at later ages possess remarkable strength and durability characteristics because of the additional hydrate precipitations in the “gap” between adjacent particles between the clinkers and pozzolans. Enhancement of workability, strength and durability are among the major benefits associated with the use of multi-blended mineral admixtures in OPC concrete. Many researchers found that the use of agricultural by-product is a viable alternative material to SF in cement replacement due to their engineering potential and economic advantage. It is now a common practice to use agricultural and industrial wastes into OPC.

### 2.2.5 Multi blended cement

#### a) Introduction

Over the years extensive research have been carried out and the relative literature reveals the BBC system. It has become increasingly conventional application in hostile environment structures due to improve in strength and durability of concrete (Khan *et al*., 2000). As mentioned earlier, the combination of two or three kinds of mineral admixtures has emerged as a superior choice over single admixture to improve concrete properties. Currently, the information pertaining to the multi and ternary blended systems and their practical used is rather limited. However, according to Jones *et al*. (1997), the multiple binder combinations is now an option which can be seriously considered for conventional structural concrete.

The use of ternary binder concrete has been implemented in major infrastructure project such as the Stoerbelt bridge/tunnel in Denmark and the Chek Lap Kok bridge, linking to the new Hong Kong airport (Jones *et al*., 1997). The common additional binder materials such as PFA, SF, slag, and RHA are now well established. Usually these individual pozzolanic materials possess different properties and reacts differently in the presence of water (Toutanji *et al*., 2004). Each of these materials has limitations and some have contrasting influences on properties of concrete (Khan *et al*., 2000) as discussed before.

#### b) The incorporation of PFA / SF into OPC

It is known that the incorporation of PFA causes delay in the early age strength development but improve the workability. SF possess a highly reactive pozzolan, increases the early-age strength but downturn in workability**.** Khan *et al.* (2000) investigated the use of binary and ternary blended cementitious systems for the development of high performance mortar based on OPC, PFA and SF. Incorporation of 8-12% SF as cement replacement showed the optimum performance, resulting in the highest compressive strength and the lowest permeability and the lowest porosity values for all levels of PFA. However, PFA on its own did not show significant improvement in permeability and porosity of mortar. The results also showed that the slow early-age strength development of PFA can be compensated with the inclusion of SF but restricted to low level of PFA. The inclusion of 35% of PFA and above, with or without SF were not able to achieve the strength equal to that of OPC as control.

### c) The incorporation of Slag / SF into OPC.

Incorporation of PFA and slag into OPC is a common practice (Bagel, 1998) because slag is an active additive and widely used in high performance concrete (Huiwen *et al*., 2004). Nonetheless, the incorporation of slag and SF into OPC has shown suitability, which have demonstrated as contributions from several researchers. Sobolev and Yeginobali (2005) studied to improve a slag cement binders for used as repairing material in the chemical industry when high thermal or acid resistance is required. It was found that the enhancement of slag cement binders could be achieved with addition of SF and superplasticizer.

Bagel (1998) found that the obtained results in binary system of slag showed slightly higher water permeability and reduced strength than OPC mortar mainly in 50% replacement. However, the incorporation of high portion of SF in binary system leads to increase in considerable water requirement thus affected the strength in the system. But significantly a finer pores structure exists in blends with SF. Whereas, the behaviour and properties of ternary binding systems with high portion of slag and SF of mortar provided further impermeability and durability improvement whilst reached relatively satisfactory level of compressive strength. The addition of SF into OPC/slag mixes in mortar leads to formation of finer and discontinuous pores or to increase in the fraction of the fines pores (Bagel, 1998).

Jones *et al.* (1997) studied the properties of ternary binder systems in concrete with inclusion of PFA and SF, PFA and slag, as well as slag and SF into OPC. The obtained results showed that the chloride resistance of all the ternary binder systems is significantly higher than corresponding OPC and OPC/PFA mixes. Carbonation depths however were generally greater in the ternary systems. The degree to which this occurred was found to relate to the amount of OPC replaced. Whilst, McGrath and Hootan (1997) studied the chloride ingress resistance of concrete containing SF, slag, PFA class C, and PFA class F cements and also blends of OPC/slag/SF and OPC/slag/PFA. Of all these concrete, the ternary blends yielded the best results.

### d) The incorporation of PFA / RHA in OPC

According to Isaia *et al.* (2003), when less reactive pozzolan is employed in ternary mixtures together with another more reactive such as SF or RHA, there is a synergy between these pozzolans, thus the obtained results are higher than those verified in the respective binary mixture. It was found that the binary mixtures of RHA showed better performance than PFA materials, however the ternary mixtures have exhibited overall better results. RHA was also similar to SF, which contains considerable amount of silicone dioxide and highly reactive pozzolanic materials (Paya *et al*., 2001).

### e) The incorporation of SF / Slag / PFA into OPC

Collins and Grace (1997) reported on using quaternary blend of OPC/PFA/slag/SF to build a concrete structure exposed to seawater. Chloride diffusion coefficients ranging from $4x10^{-13}$ to $6x10^{-13}$ $m^2/s$ were reached. Soeda *et al*. (1997) studied the properties of high flowing concrete also containing OPC/PFA/slag/SF. When water-cured provided, this concrete exhibited good resistance to freeze-thaw cycles. Toutanji *et al*. (2004) focussed on studying the strength and durability of concrete cured for short period of time using the binary system containing different percentage of OPC/SF, OPC/PFA, and OPC/slag as well as three mixes made of combination of SF, slag and PFA. The combination of 10% SF, 25% slag, and 15% PFA produced high strength and high resistance to freeze-thaw and wet-dry exposures as compared to other mixes.

Amjad and Salihuddin (1999) investigated the strength, porosity and oxygen permeability between OPC/PFA/SF and OPC/PFA/SF/Slag with respect to OPC concrete. Both blended cements achieved strength values of 60MPa. However both mixes achieved low early strength (1 and 3 days) than OPC. At 7 days all these mixes achieved a comparable magnitude of strength. At 28 days, mix without Slag content achieved 23% higher than OPC, whereas mix with Slag achieved 10% higher than OPC. They reported that at all ages up to 364 days mix without Slag content obtained higher strength than mix with Slag followed by OPC mix.

They found that the both blended cements contributed to produce additional hydration products to fill up the voids, hence produced more dense structure. The total porosity of OPC/PFA/SF and OPC/PFA/SF/Slag reduced significantly that is 2.9 and 3.8 times larger reduction than OPC concrete, respectively from 63 to 182 days. They also found that both systems showed 40% and 50% lower permeability than OPC concrete at 182 days and one-year hydration respectively. They reported that both systems showed similar trend in all parameters when subjected to seawater curing exposed to tidal zone with respect to OPC concrete.

### f) The incorporation of POFA / Timber Industrial Ash (TIA) into OPC

Nisyurman (2002) investigated the strength, water absorption and total porosity of OPC/POFA/TIA concrete. The strength at early ages was lower than OPC control. However the strength improved at 28 days and beyond that was comparable with OPC strength. Although, the water absorption and total porosity showed significant improvement, which is remarkably, lower than OPC even at early ages. The absorption of the blended cement at early ages was 2%, whereas for OPC that was 7% absorption. Nevertheless at 7 and 28 days the absorption of OPC concrete was reduced significantly that was within 2.5% to 4% water absorption, whilst the blended cement achieved within 1% to 2% absorption.

The blended cement showed 13.5% total porosity, whereas OPC concrete has 15.4% at 28 days. The used of POFA/TIA as cement replacement is possible to produce mix having equivalent strength compared to the OPC mix. The delayed pozzolanic reaction contributed to produce additional hydration products to fill up the voids and segmented the capillary pores, hence produced more dense structure.

### 2.2.3 Concrete durability

According to ACI Committee 201 (1991), durability of hydraulic cement concrete is defined as its ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration. The concrete should be designed, without deterioration, over a period of years. High performance concrete is characterized by its excellent durability rather than high strength concrete. It is known that not only the strength of concrete, but also its durability is important to increase the service life of the structure (Chindaprasirt *et al.*, 2004). Two ways to obtain the high performance are; to reduce the flocculation of cement grains and widen the range of grain size (Malier, 1992). As a matter of fact porosity and permeability are the governing parameters, which account for the concrete performance (Pliskin, 1992).

Durability of concrete largely depends on the ease with which, fluids and gases can enter and move through are referred as permeability of concrete. The movement of various fluids through concrete take place not only by flow through the porous system but also by diffusion and absorption (Neville, 1995). Deterioration of concrete is directly related to presence of aggressive solutions in water and the porosity and permeability of the concrete as well as the presence of cracks. Higher early strength can be achieved in some modern cements due to more $Ca(OH)_2$ formation, but this may adversely effect the durability and cost of concrete (Chan and Wu, 2000). By the use of cement replacement of siliceous by-product such as fly ash, agricultural ash, slag, SF in making mortar or concrete may improve durability of the concrete to various types of chemical attack, mainly due to its reduced permeability arising from a pore refining process (Mehta, 1989; Cook, 1987; Salihuddin, 1993; Zhang *et al.*, 1996; Bagel, 1998; Khan *et al.*, 2000; and Amjad and Salihuddin, 1999).

## 2.3 Pore Structure

Porosity is one of the major components of the microstructure of the cement paste. The pore structure development in the cement pastes tends to reduce in the volume of large pores during the initial stage of hydration. This reduction in large pores is due to the hydration products to fill the space of least resistance and also to the increase in the volume of small pores. The increase of small pore volumes has been attributed to the formation of hydration products around the large pore necks. Pore structure of blended cement is different to that of plain cement paste as referred by Mehta and Manmohan (1980).

Generally total porosity of blended cement is higher than plain cement paste, but their permeability is significantly less than plain cement paste. In plain cement, although the total porosity is less than blended cement, however the pore structure tends to be continuous (Feldman, 1983). According to Feldman, 1981, the continuous nature of plain cement paste has been attributed to the high CH content present, mainly as large crystal. Different with blended cement in which the continuity of large pore is lower than plain cement and after 28 days of hydration these large pores are essentially isolated. The rate of reduction in total porosity of blended cement is less, but the rate of large pores (>0.05um) reduction was higher than plain cement paste and contained mainly finer pores. (Cook and Cao, 1987).

### 2.4.1 Definition of Porosity

According to Concrete Society Technical Report 31 (1988), porosity is defined as, the *volume property that represents the content of pores, which are not necessarily inter-connected and may not therefore allow the passage of a fluid.* Pore structure appears to consist basically of two classes of voids, the capillary pores and gel pores as follows.

### a) Capillary pores

It is generally larger in size in which the formation depends on the evaporation of the water used in the pastes. The volume of the capillary system will reduce with the progress of hydration. In any stage of hydration the capillary pores filled the part of the gross volume, which has not been filled by the products of hydration. The average volume and size of the pores decreases, and the network progressively breaks down (segmentation of the capillaries). Figure 2.16 illustrates capillary and gel pores, where as the voids as those marked as C in the space are called the capillary pores and the solid dots represent gel particles but within the gel itself there exist interstitial voids called gel pores.

### b) Gel pores

Gel pores basically are smaller in size and numerous, created by existing cavities in the hydration products of the cement. The gel pores are really interconnected interstitial spaces between gel particles. Although the gel pores constitute a network of communicating pores, it seems that the permeability of this network, by calculation of Power's Law, it is very low: $7.10^{-16}$ m/s (Perraton and Aitcin, 1992). The gel pores are very small between 15 and 20Å and much smaller than capillary pores. The gels are formed in all stages and the continuous does not affect the products already in existence.

The actual value of pore gel is largely independent of water cement ratio and the progress of hydration. The total volume of gel and gel pores increase with the progress of hydration. It is in contrast with the capillary pores that the volume decreases with the progress of hydration. The gel pores occupy about 28% of the total volume of gel. The particles are mostly fibrous, and bundles of such fibrous from a cross-linked network containing some more or less amorphous interstitial material. The gel practically the same specific surface (approximately 200,000$m^2$/kg) is formed throughout the progress of hydration and do not grow in size.

### 2.4.2 Porosity governed by wbr

Wbr significantly affects the microstructure of the hardened cement paste. The initial wbr and the degree of hydration govern the capillary volume. The wbr actually determines the porosity of the hardened concrete at any stage of hydration. As the time of hydration increased, the capillaries may become blocked by gel and segmented so that they turn into capillary pores connected only by the gel pores. Concretes with low porosities must therefore have a low wbr such as equal or less than 0.5 (Loedolff, 1987). Excess of water can cause internal or external bleeding as well as increased porosity. Excess of water held in concrete or which has collected due to internal bleeding will left the concrete by process of evaporation that can forming voids and remains porous and also increased shrinkage (Loedolff, 1987). The addition of superplasticizer can reduce the wbr as they make concrete more flowable and easier compacted hence allow the capillary porosity to be reduced.

### 2.4.3 Pore Structure Measurement Techniques

The measurement techniques of determination of porosity do not always give the same value mainly if it involves removal or addition of water that affects the structure of the hydrated cements (Neville, 1995). The results from Nitrogen adsorption technique could determine the pore size distribution (PSD) for pore size less than 200nm radius, and more suitable than mercury porosimetry for pores of this size. Mercury intrusion porosimetry (MIP) involves forcing the mercury by pressure into porous sample. The force pressure can be converted to equivalent pore size using Washburn equation. MIP also could provide relative patterns of PSD for various specimens. Helium porosity could give an estimate of the amount of pore structure that is interconnected, which employs the gas law to determine solid volume by displacement principles.

There are a few reasons that impossibility of obtaining reliable results by MIP and nitrogen adsorption according to Costa and Massazza (1987). The value of the contact angle between mercury and pore walls, used in calculations for the PSD, can be inexact, the MIP damages and alters the sample microstructure, the hot drying of the samples before the porosimetric analysis can modify the cement hydrates phases, the rapid free water evaporation when the sample is dried under vacuum can break the thinner walls of capillaries (Costa and Massazza, 1987). However, this damage as mentioned above could otherwise blocked by hydration products (Salihuddin, 1993). Only very fine pore structure (less than 200A) will be affected. Nonetheless, the large PSD (> 500A) such as the capillary pores will not be affected.

Evaporable water content, vacuum saturation porosities and Solvent Exchange porosities could only provide approximate porosity of materials due to the associated limitation (Salihuddin, 1993). The PSD patterns of the samples could not be determined. It will be an overestimate of the volume of water-filled pores due to the hydrate water, which is lost when it is heated up to 105ºC. Some solvent may react with calcium hydroxide since from the termogravimetri data obtained for samples using methanol solvent that give more marked compared to Propanol-2-o1 solvent (Salihuddin, 1993).

From the above it seems that the MIP and Nitrogen adsorption are the suitable pore structure measurement techniques since more reliable data can be obtained, which could provide the PSD patterns. However, lately in our lab those machines have some device and software problems require repairing and maintaining. So in this study, the vacuum saturation technique is available in the lab used to determine the total porosity of the material investigate. However, this method is also widely used since it is relatively cheap and easy, furthermore also could provide an aid in speculating the nature of pore structure of hardened cement paste (Salihuddin, 1993).

## 2.5 Permeability and Water Absorption

As mentioned earlier, the movements of various fluids through concrete take place not only by flow through the porous system but also by diffusion and absorption. The permeability of the concrete is perhaps more important than its strength (Orchard, 1958). Penetration of concrete attack by aggressive liquid, gasses or when calcium hydroxide leached out may adversely affect its durability. This penetration is largely dependent on the permeability of concrete. The more impermeable the concrete, the greater will be its resistance to deterioration. The higher permeability permits the ingress of liquids, ions and gases or removal of dissolved reaction products out of concrete. The permeability will decrease rapidly with the progress of the hydration. It is important to assess this water transport mechanism in offshore structure. The water absorption is a major source of damages in structure through its affects on durability of the reinforcement embedded in the concrete and also because of risk of alkali aggregate reactions (Ithuralde, 1992)

### 2.5.1 Definitions of Permeability

Accordance to Concrete Society Technical Report 31 (1988), permeability is a *flow property* and defined as, *that flow property of a porous medium, which characterizes the ease with which a fluid will pass through it, under the action of a pressure differential* (Concrete Society Technical Report 31, 1988). Water absorption is defined as, *the process where by the concrete takes in a fluid to fill spaces within the materials* (Concrete Society Technical Report 31, 1988).

### 2.5.2 Permeability dependency on continuity of pores, and pore size distribution

Porosity in itself does not lead to it being permeable to fluid even though the concrete is porous material. It is permeable to the extent it has interconnecting void spaces. Figure 2.17 shows an illustration on porosity and permeability. Although the cement gel has a porosity of 28% its permeability is only about $7 \times 10^{-16}$m/s. The pores are very small and numerous. While, although in capillaries pore are fewer in number, are much large than gel pores and leads to a higher permeability. Water can flow more easily through the capillary pores than through the much smaller gel pores. It does pursue that; the permeability of cement paste is controlled by the capillary porosity of the paste.

The volume of large pores and the continuity of pore structure affect the permeability of cement paste. The permeability and absorption of mature blended pastes is expected to be low due to the discontinuous nature of pores. The time of curing required in capillary segmented is dependent upon the initial wbr as shown in Table 2.4. Wbr less than 0.5, the cement hydrate in concrete has potential to overgrow and to close capillaries in concrete since the volume of the hydration products is approximately 120% higher than the original cement grains (Loedolff, 1987). For wbr above 0.7, even complete hydration would not produce enough gel to block all the capillaries.

## 2.6 Influence of Pozzolans on Permeability and Porosity

A numerous researchers agreed that the substitution of pozzolans for part of the cement reduces both parameters in concrete. At 28 days pozzolans concrete may be three times as permeable as ordinary concrete but that after 6 months it may be less than one quarter as permeable. (Information supplied by the Central Electricity Authority of Great Britain. (Orchard, 1958). The amount of reduction is depends on the reactivity of the pozzolans. The pozzolanic materials is used as cement replacement due to produce more identical products of hydration, which can potentially contribute to the filling and segmentation of the capillary voids, thus can be produced dense and impermeable concrete and ultimately more durable concrete.

The pore structure of blended cements is relatively discontinuous after approximately 28 day of curing. The continuous nature of pores in ordinary Portland cement pastes continues with age, which is discussed earlier. Continued moist curing can also reduce permeability because of it promotes and continues the cement hydration. The addition of pozzolan such as PFA in concrete should help to reduce the permeability of concrete judging from the influence of PFA in hydration concrete such as reduction of water content, the dense packing, the increased hydration of cement, as well as its pozzolan reactions.

The presence of pozzolan leads to a greater precipitation of cement gel products than occurs in Portland cement alone, which more effectively block the pores more effectively and therefore helping to reduce permeability. The water-soluble calcium hydroxide liberated by hydrating cement may leach out of hardened concrete and leave voids for the ingress of water. In the pozzolanic reaction, by combining with the Calcium hydroxide (CH) directly reduces the amount of CH, which can reduce the leaching of CH. The additional products by pozzolanic reaction, C-S-H will close the voids, which result in more dense concrete, and consequently reduce the permeability of concrete arising from a pore refining process.

## 2.7 Chemical Attack

It is necessary to understand the phenomena involved in the chemical processes of concrete deterioration. Chemical attack of concrete occurs by way of decomposition of the products of hydration to forms a new compounds which, if soluble it may be leached out and may disruptive in situ if not soluble. Beside CH, the CSH gel can also be attacked but the most vulnerable cement hydrate is CH. The chemical attack occurs mainly through the action of aggressive ions such as chlorides, sulphates, carbon dioxide as well as industrial liquids and gasses through the open pores and cracks available in concrete, which are explained in detail as follows.

### 2.7.1 Acid attack

Concrete containing Portland cement is not resistant to acid attack because cement is highly alkaline that when the cement are attack by strong acids or compounds, it may convert to acids. Concrete can be attacked by liquids with pH value below 6.5 and it may very severe when the pH is below 4.5. However, it is not only pH but also the ability of aggressive ions to be transported that influence the progress of the attack. The rate of attack decreased when the exposed surface is smaller and the aggregates may become exposed thus the attacking substance has to travel around the particles. Table 2.5 shows the list of some materials, which may cause severe chemical attack of concrete.

Acid rain may cause surface weathering of exposed concrete due to its contents of sulfuric and nitric acid which has pH value between 4.0 and 4.5. Sulfuric acid is predominantly aggressive because besides to the sulfate attack of the aluminate phase, the acid attack on CH and CSH gel also can takes place. The microbiological attack is high pH but does not encourage the acids to attack. However, under certain environment such as in tropical conditions like Malaysia, some algae, fungi and bacteria can use atmospheric nitrogen to form nitric acid that can attacks exposed concrete.

Such in domestic sewage which containing high alkaline, when sulfur compounds become reduced by anaerobic bacteria to form $H_2S$, which itself is not a destructive agent but will dissolve in moisture films in exposed surface of the concrete and undergoes oxidation by aerobic bacteria and ultimately to produce sulfuric acid. The acid attack can also exists when the lubricating oils and hydraulic fluid sometimes split on concrete, break down when heated by exhaust gases and react with CH thus causing leaching. There is no standard procedure to test on the resistance of concrete to acids. In this research, the test method on acid attack by Awal and Hussin (1996b and 1997) is adopted.

Use of blended cements provided by good curing is advantageous in reducing the ingress of aggressive ions. In blended cement, the pozzolanics reaction takes place when CH is released which can potentially lowering the alkalinity in cement paste thus exhibit good resistance to acid attack. In addition, the results of pozzolanics reaction with CH produced more CSH gel thus, the pores become filled and the resistance of the concrete to acid attack is also increased probably due to the formation of more CSH gel. The inadequate curing in blended cements can results in less dense microstructure hence more area in contact of acid attack. Its can lead to progressive neutralization of the alkaline nature of cement paste (Huang *et al*., 2005). The elimination of alkalies and dissolving of portlandite and CSH gel may increase in porosity and permeability.

### 2.7.2 Carbonation

**A**ir contains $CO_2$, which, in presence of moisture, reacts with hydrated cement. Actually the actual agent is carbonic acid because the gasses $CO_2$ is not reactive. The rate of carbonation of concrete increases with an increase in the concentration of $CO_2$, especially in high w/c ratio concrete. The most hydrated product that reacts readily with $CO_2$ is CH, which produce $Ca\ CO_3$ on reaction but other hydrates are decomposed such as hydrated silica, alumina, and ferric oxide.

The carbonation can reduce the pH of the pore water in hardened Portland cement paste from between 12.6 to 13.5. The value can be reduced to 8.3 when all CH has become carbonated. When the low pH reaches the surface of the reinforcing steel, the protective oxide film is removed and corrosion can take place providing the presence of oxygen and moisture. So, the depth of carbonation is the important factor to know whether it has reach the surface of embedded steel. Even in presence of cracks in the surface concrete, the carbonation can ingress through cracks by penetration.

The rate of carbonation is slow, if the pores in hydrated cement are filled with water because the diffusion of $CO_2$ in water is four times slower than in air. Carbonation is controlled by the diffusivity of the hardened cement paste, which is function of the pore system of hardened cement paste during the period when the diffusion of $CO_2$ takes place.

The types of cement, the w/c, and the degree of hydration and curing conditions are also the relevant factors influencing the carbonation. The high w/c ratio could produce high porosity and late capillaries segmentation as discussed before. The open pores could potentially influence the diffusion of $CO_{2.}$

Concrete containing blended cements providing an adequate curing can potentially improve the depth carbonation attack through the pore system in concrete. Firstly, the pozzolan reacts with CH resulting from the hydration of Portland, which leads to lower CH content in the hardened cement so that a smaller amount of $CO_2$ is required to remove all the CH by producing $CaCO_3$. The pozzolanics reaction resulting in a denser structure of hardened cements paste as mentioned earlier. Hence, that may reduce and slow down the diffusivity of carbonation into concrete. Concrete containing blended cements is more sensitive to inadequate curing. It is necessary to apply water curing to the concrete containing blended cements at least 7 days to expose the delayed pozzolanic activity.

The continuation of hydration is important to ensure that the hydrated compound contribute to filling and segmentation of the capillary voids. Figure 2.18 shows the effect of curing on carbonation of concrete. The carbonation is more pronouns in samples with absence of wet curing, due to result in high porosity. Other researchers reported that increasing the period of wet curing from 1 day to 3 days reduces the depth of carbonation by about 40% (Neville, 1995).

### 2.7.3 Effects of seawater on concrete

Salts in seawater represent 77% of dissolved salts that leads to various chemical actions of seawater on concrete such as salt weathering, chloride induced, abrasion by sand in suspension and by ice. The chemical reaction of seawater on concrete due to presence of $MgSO_4$, $MgCl_2$ with NaCl and other dissolved salt are common. Table 2.6 shows the ion concentrations for the individual salts. Seawater contains also some dissolved $CO_2$, which can react with CH to form $CaCO_3$ in the form of aragonite (Neville, 1995).

Ion sulphate as well as chloride in seawater are the most aggressive ions, which on reaction between cement constituent can lead to dissolution of CH and the formation of Sulphoaluminate and chloroaluminate hydrates thus causing expansion and softening of concrete respectively (El Aziz *et al*., 2004). The results of Calcium Chloride ($CaCl_2$) from the reaction of $MgCl_2$ with liberated lime can increase the solubility of CH that can allow leaching. Thus the $Mg(OH)_2$ dissociates CSH and produces $Ca(OH)_2$ and silica gel (El

Aziz *et al*., 2004). The latter may react with $Mg(OH)_2$ to form Magnesium Silicate hydrates. While, the CSH are also decomposed by magnesium sulphate in aggressive solutions to give gypsum, hydrated silica and magnesium silicate hydrates, which have little or no binding power properties like CSH gel. All the reactions mentioned above contribute to the decrease in strength.

However the chemical reaction of seawater on concrete shown below has good advantage to concrete properties.

$MgSO_4 + Ca(OH)_2 \rightarrow CaSO_4 + Mg(OH)_{2}$$_{85}$..

The magnesium ion present in the seawater substitutes from the calcium ions. The $Mg(OH)_2$ is also known as brucite, which precipitates in the pores at the surface of the concrete, thus forming a protective surface layer at about 20 to 50µm thick formed rapidly as observed in a number of fully submerged sea structures. The layer can potentially obstruct further reaction. However, the blocking nature of brucite is in limited extent, that if abrasion can remove the surface deposit, then the reaction by the magnesium ion freely existing in the seawater continues.

The synergistic wave action enhances the chemical attack, by way of forming and crystallization of salts, thus make the concrete more exposed to erosion by wave action and to abrasion by sand suspended in seawater. When concrete is repeated wet and drying periods, while the pure water evaporates, the dissolved salts in seawater are left behind in the forms of crystal mainly sulfates. It will re-hydrate and grow upon following wetting and therefore exert an expansive force on the surrounding hardened cement paste, which is known as salt weathering. Chloride can ingress into concrete by diffusion, adsorption and transportation. Thus results in higher concentration if the ingress is prolonged or repeated with time.

There will be no corrosion when concrete permanently submerge in seawater, unless oxygen is present at the cathode. The ingress of chlorides is progressive when the concrete is alternately exposed to seawater and sometimes dry. However, the movement of salt depends on the length of the wetting and drying periods. The water in the outer zone of the concrete evaporates and while the remaining water in the interior will become saturated with salt and the excess salt will precipitate out as crystal.

Blended cements are known to produce concrete with a dense microstructure. The diffusivity of chloride through concrete depends on the microstructure of the concrete. The addition of pozzolan decreases the formed CH by the pozzolanic reaction to produces more CSH gel that can improve the strength and durability of concrete. Sodium chloride ($NaCl_2$) acts as accelerator to both cement hydration and pozzolanic reaction. The glassy particles of PFA are easily attacked by $Na^+$ to convert into soluble silicates, which further combine with CH and produce more CSH gel thus; the mass becomes more impermeable to foreign ions (Pandey *et al*., 2003). The use of PFA as cement replacement can potentially reduce the water demand, as Jensen *et al*. (1999), studied the chloride ingress in cement paste and mortar observed that, an increased w/c ratio is seen to increase the chloride ingress. This is due to the more open pore and coarse pore structure at higher w/c ratio.

## 2.8 Factors influencing the Strength and Durability

The strength and durability of concrete is normally to be governed by such factors as water binder ratio (cementitious content), the efficiency of curing, compactness, admixtures and also content of cement in the mix.

### 2.8.1 Water Binder ratio (wbr)

The wbr is actually determines the porosity of the hardened cement paste at any stage of hydration, which have mentioned earlier in section 2.4.2. Concrete that have a low wbr will have a low porosity; therefore will have a very high durability and strength as well because there is enough gel to produce to discontinuity in pore structure. As discussed earlier in section 2.5.2, for wbr above 0.7, the volume of gel is not sufficient to fill all the space available so that leaving some volume of capillary pores even after the process of hydration has been completed. Insufficient water content will cause the composition of the materials that are not uniformly mixed hence the bonding is totally weak. On the other hand, the excessive of water content will cause the segregation and internal and external bleeding too.

### 2.8.2 Curing Process

To obtain a good and quality concrete, curing in appropriate environment during the early stages of hardening is very important factor that influences the concrete strength. The objective of curing the concrete is to keep concrete saturated or nearly saturated until the original water-filled space in the fresh cement paste has been filled to the desired level by the products of hydration cements (Neville, 1995). The necessity for curing the concrete is due to the hydration of cement, which can take place only in water-filled capillaries. Usually minimum of seven days are necessarily for curing OPC. A longer curing period is required with slower hardening cements.

High strength concrete should be cured at an early age as partial hydration may make the capillaries discontinuous and the renewal of curing water would not be able to enter the interior of the concrete and no further hydration would result. For Pozzolan concrete, at least initial of seven days water curing is necessary to allow the pozzolanic activity and reaction. The strength of OPC concrete that cured varying initial water curing period is lower than pozzolan concrete. For mortar 7 and 14 days initial water-cured specimen exhibited higher strength than the corresponding continuously water-cured specimens. The higher strength of partly dried specimens with respect to continuous wet ones was attributed to the increase in the secondary forces between the surface of cement gel and also the reduction in the disjoining pressure due to the drying (Ozer and Ozkul, 2004).

In contrast, OPC concrete has higher rate of strength than pozzolan concrete in air curing. According to Feldman, it is known that drying evaporates the pore solution and shrinkage results in cracks that change the microstructure. Drying the cement paste would increase the permeability, possibly because shrinkage may rupture some of the gel between the capillaries and therefore will open new passages to the water.

### 2.8.3 Compactness

The presence of voids can reduce the strength of concrete. Voids in concrete are in fact either bubbles of entrapped air or spaces left after excess water has been removed. The volume of the later is largely dependent on the w/c of the mix. The need to compact the concrete is essential to eliminate the entrapped air. Besides that, it provides a good and strong bonding between the cement paste and aggregate. 5% of voids can lower the strength by as much as 30% and even 2% voids can drop the strength more than 10% (Neville, 1995).

### 2.8.4 Water reducing agent (Superplasticizer, Sp)

The quality and properties of concrete are governed by its flow behaviour, which is controlled by the dispersion of cement particles. The additions of Sp provide the possibility of a better dispersion of cement particles, thereby producing paste of higher fluidity. The Sps becoming essential due to their contribution to the development of strength concrete remarkably larger than that of cement. The Sps are absorbed by cement particles, which deflocculates and separate, releasing trapped water from cement flocks. The deflocculation of cement grains by Sp can be seen as in Figure 2.19. For a given w/c, this dispersion will increase the concrete workability.

A variety of Sps have been developed belongings to different basic group, namely lignosulfonic (LS), melamine formaldehyde sulfonic acid (SMF), naphthalene formaldehyde sulfonic acid (SNF) and Polycarboxylic acid (CE). SNF may be more effective than the others Sp in dispersion of cement particles. Figure 2.20 shows the schematic representation of SNF.

One effect of dispersion is to expose a greater surface area of cement to hydration, which progresses at a higher rate in the earlier stages. For this reason, there is an increase in the strength of concrete, compared with a mix of the same w/c but without the admixture. The use of Sp is also to produce concrete at normal workability nevertheless having a high strength concrete due to high reduction in w/c. The use of Sp in concrete has no significant effect in long-term strength as reported from 13 years of study. Generally, the Sp with a given workability can facilitate the reduction in water content up to 25 to 35% and increase strength up to 24 hours, which will increase up to 50 to 75%. Beside that, the high increment of strength can be achieved at early age of the concrete. The Sp can be used with cement replacement material such as Fly Ash or Slag when the early strength is the matter of great concern due to delayed pozzolanic reaction. The reaction of Sp happens in short period approximately 10 minutes after mixing the water and just after 30 to 90 minutes the workability of concrete paste turn back to be normal.

### 2.8.5 Influence of richness of the mix on strength

An extremely rich mix that is high cement content (above 530 kg/m$^3$) with a very low w/c showed retrogression of strength, mainly when large size of aggregate is used. Therefore, at later ages, in this type of mix, a lower w/c would not lead to a higher strength. This behaviour is due to the stress induced by shrinkage, whose restraint by aggregate particles causes cracking of cement paste or loss of the cement aggregate bond. High aggregate/cement ratio for a constant w/c, leads to a higher strength (Neville, 1995). High cement content will causing the high early temperature developed from the heat of hydration that can have detrimental effects on the performance of concrete. It can cause the differential expansion due to the large tensile stresses on the surface and leading to cracking. Thus leads to reduction in strength and durability at the later ages.

## 2.9 Correlation between Engineering properties and Microstructural characteristics

### 2.9.1 Relationship between Strength and Porosity

The presence of entrapped air, capillary pores, gel pores, and entrained air in concrete could influence the strength properties of hardened concrete. Besides, their volume, the shape and size of pores are also factors influence the strength. Rossler and Odler (1985) have shown a linear relationship existing between strength and porosity based on volume of pores larger than 20 nm in diameter referred in Figure 2.21. Whereas, the effect of pores of size smaller than 20mm in diameter was found to be insignificant. Commonly, at a given porosity, smaller pores lead to a higher strength of the cement paste (Neville, 1995).

Feldman and Beaudoin (1991) also produced a linear relationship between the two parameters of hardened cement pastes as shown in Figure 2.22. It concluded that porosity is a primary factor influencing the strength of Portland cement systems. Marsh (1984) studied the relationship between strength and mean-volume pore radius (MVPR) for 30% PFA cement paste hydrated until one year at varying temperatures. It was found that the PFA and OPC control samples lie in a single curve as can be referred in Figure 2.23 and 2.24. MVPR is a measure of the average pore size.

Whilst, according to Salihuddin (1993), his results showed quite different behaviour compared to Marsh's results, that the relationship between strength and MVPR of RHA and POFA samples curves lie well below the OPC control curve except for the young PFA samples. At early ages PFA mortar tends to approach to the OPC control curve. It concluded that for any given strength, the MVPR values for OPC/ASH mortar are smaller than the OPC control except for the young PFA samples as shown in Figure 2.25. It seems that, the pozzolanic reaction of RHA and POFA has resulted in the filling up of the pores much earlier than the PFA. However, it found that the PFA performs best in terms of the reduction of MVPR at later ages (Salihuddin, 1993).

### 2.9.2 Relationship between Porosity and Permeability

As mentioned before porosity in itself being permeable to fluid to the extent it has interconnecting void spaces even though the concrete is porous material. If the porosity is high and the pores are interconnected, they contribute fluid to transport through the capillary pores, which will results high permeability in concrete. On the other hand, the discontinuous pores structure in concrete will results in low permeability due to the fluid will ineffectively able to transport even its porosity is high. The permeability of hardened concrete is controlled by its capillary porosity. Powers (1958) has shown the relation between both quantities referred in Figure 2.26. Small pores carry very little permeability water compared to the maximum continuous pore radius. Marsh (1984) found that a significantly reduction in permeability in PFA cement paste. It explained the reduction in permeability as the results of pore blockage due to the pozzolanic reaction of the PFA.

Salihuddin (1993) also studied the relationship between the permeability and the volume of pore radius greater than 200Å of RHA and POFA mortar. It found that almost all OPC/RHA samples tested show permeability results within the low permeability region as shown in Figure 2.27. However, OPC/POFA has five high permeability mortars compared to only one for OPC/RHA specimens as can be referred in Figure 2.28. However, it found the direct relationship between two parameters but very poor in nature. The lines drawn are just indication of general trends.

The trends show a general rise in permeability as percentage of volume of pores of radius greater than 200A increased (Salihuddin, 1993). It suggested that for OPC containing pozzolan mortar, there is a critical volume of large pores, which they show high permeability that lies between 10 and 11% of specimen volume. It defined the large pores as those of radius greater than 200A. However, It found that the OPC control mortar did not show the similar trend to that of OPC/ASH mortar. The volume of pores greater than 200A for OPC control mortar varies from about 8 to 13% of the specimen value, but the permeability is defined as lying within low permeability regions.

## 2.10 Conclusions

From literatures covered in this chapter the use of multi blended systems exploiting the potential synergy between these pozzolanic materials provided by constituents of amorphous in silica or glass content and sufficient curing time. Each of these materials operates in a different but co-operative way (Isaia *et al.*, 2003). Recently from the literature point of view it seems that a number of researchers had studied the use of SF into OPC/PFA/Slag in MBC system. RHA is a highly reactive pozzolanic material, which contains considerable amount of silicon dioxide that is similar with SF. Several researchers also have studied RHA by incorporating it in binary and ternary system. However the application of this material in the construction industry is non existence.

There is also very limited study on cement pertaining to incorporation of palm oil waste (POFA) into multi-blended system.

It is reported elsewhere that the blended cement has a great potential to improve the concrete quality and properties. All researchers agreed that the microstructural characteristics such as porosity and permeability which governed the quality and durability of concrete. As a matter a fact, the permeability is dependent on the continuity of pores and pore size distribution. However, both characteristics are associated with the wbr, the contribution from hydrated compounds to fill up the voids and closing of the capillary pores, and provision of a suitable and adequate curing. High cement contents in some modern concrete can adversely affect the strength and durability at later ages due to high content of $C_3A$. The exothermal compound can cause the differential expansion due to the large tensile stresses on the surface and leading to cracking

From the literature studies it is also found that the use of pozzolans as cement replacement is viable and has engineering potential and economic benefits. On one hand the additional products from pozzolanic reaction, results in more dense concrete. Consequently reduce the permeability of concrete arising from a pore refining process. Whilst on the other hand, the blended cement which is low in alkalinity because of the main and long-term reaction with CH that directly reduces the amount of CH. Therefore it can reduce the leaching of CH and obstruct further reaction from the chemical ingress. Besides, in blended cement the amount of $C_3A$ can be reduced resulting from the partial replacement of OPC in the blended cement.

The MBC using agricultural waste (RHA and POFA) that is abundant in agro-based country such as Malaysia presents a potential alternative to the conventional blended system. Whilst, the enhancement of workability and durability characteristics of PFA and slag has major technical benefits associated with the use of RHA and POFA into the MBC system. This approach as cement replacement materials has engineering potential and economic benefits for many developing countries such as Asia, Africa and South America due to the increase in the population and standard of living and increasing cost of raw materials as well as the continuous reduction of natural resources. The increase in cement demand will not be met by expanding cement clinker production capacity but by increasing the use of supplementary cementing materials. The use of waste by-product as raw material is the basic strategy to decrease solid waste problems.

POFA and RHA has vast potential to be used in MBC by incorporation of PFA and Slag with the aim of exploiting the potential synergy between these materials, thus reducing or eliminating limitations inherent in individual materials. If these agro wastes (RHA and POFA) could be used as cement replacement in Portland cement rather than the use of high cost and extreme fineness of SF, it can leads to considerable cost savings to the manufacturer and also reducing environmental impact and landfill use. Limited effort had been carried out in the past to exploit the economic benefits from these wastes as construction materials in concrete. Contractors and owners have to realize that what is important is not the cost of $1m^3$ of concrete but rather the cost of 1 MPa or 1 year of life cycle of a structure (Aitcin, 2000). The behavior and synergic effect of MBC should be emphasized and more efforts are needed for rapid implementation in adopting this technology to date. In order to save resources and energy, it is now a common practice in the use of industrial wastes into OPC but not the case yet with agricultural wastes and by-products. To realize this vision and objective the current research was undertaken to enrich the literatures and enhance the developing and advancement of knowledge in this field.

Table 2.1 : **Chemical constituents and physical properties of OPC, PFA, Slag, RHA and POFA**

| **Chemical constituents** | **OPC (%)** | **PFA (%)** | **Slag (%)** | **RHA (%)** | **POFA (%)** | Requirements of ASTM C 618-84 **Class F** |
|---|---|---|---|---|---|---|
| Silicon dioxide ($SiO_2$) | 20.1 | 48.7 | 28.2 | 87.2 | NA | |
| Aluminium oxide | 4.9 | 27.8 | 10.0 | 0.2 | NA | |
| Ferric oxide ($Fe_2O_3$) | 2.5 | 9.2 | 1.8 | 0.2 | NA | |
| ($SiO_2 + Al_2O_3 + Fe_2O_3$) | 27.5 | 85.7 | 40.0 | 89.4 | 75.9 | 70 |
| Calcium oxide (CaO) | 65 | 3.0 | 50.4 | 0.6 | NA | |
| Magnesium oxide (MgO) | 3.1 | 1.9 | 4.6 | 0.4 | NA | |
| Sulphur oxide ($SO_3$) | 2.3 | 0.9 | 2.2 | 0.2 | 1.0 | 5.0 |
| Sodium oxide ($Na_2O$) | 0.2 | 1.3 | 0.1 | 1.1 | NA | |
| Potassium oxide ($K_2O$) | 0.4 | 2.4 | 0.6 | 3.7 | NA | |
| Titanium oxide ($TiO_2$) | 0.2 | 1.1 | - | <0.1 | NA | |
| Phosphorous oxide | <0.9 | 0.3 | - | <0.1 | NA | |
| Loss on ignition (LOI) | 2.4 | 3.9 | 0.2 | 5.9 | 3.7 | 6.0 |
| Fineness: | | | | | | |
| Specific Gravity | 3.2 | 2.7 | | 2.1 | 2.1 | 5.0 |

OPC, PFA, RHA : after Ho (1999)
POFA : after Salihuddin (1993)
Slag : from YTL Cement Sdn. Bhd

**Table 2.2:** Strength development of test cylinders of concretes containing Silica Fume (Hooton, 1993)

| Age | Compressive strength (MPa) of mixes with a Silica Fume content of (percent) | | | |
|---|---|---|---|---|
| | 0 | 10 | 15 | 20 |
| 1 day | 26 | 25 | 28 | 27 |
| 7 days | 45 | 60 | 63 | 65 |
| 28 days | 56 | 71 | 75 | 74 |
| 56 days | 64 | 74 | 76 | 73 |
| 91 days | 63 | 78 | 73 | 74 |
| 182 days | 73 | 73 | 71 | 78 |
| 1 year | 79 | 77 | 70 | 80 |
| 2 years | 86 | 82 | 71 | 82 |
| 3 years | 88 | 90 | 85 | 88 |
| 5 years | 86 | 80 | 67 | 70 |

**Table 2.3:** Pore characteristics of mortars containing Sulfate-Resisting Cement and Silica Fume (Hooton, 1993)

| Period of moist curing, days | Total porosity, percent of mixes with a Silica Fume content of (percent) | | | |
|---|---|---|---|---|
| | 0 | 10 | 15 | 20 |
| 7 | 16.0 | 14.3 | 13.7 | 13.0 |
| 28 | 14.7 | 13.4 | 12.9 | 11.7 |
| 91 | 14.3 | 13.3 | 11.7 | 10.6 |
| 182 | 10.8 | 10.8 | 9.6 | 8.6 |
| 365 | 10.7 | 9.5 | 10.5 | 9.1 |
| | Volume of pores with a diameter smaller than 0.05um, percent | | | |
| 7 | 8.5 | 3.0 | 2.7 | 2.0 |
| 28 | 6.3 | 2.8 | 2.2 | 2.3 |
| 91 | 7.5 | 2.8 | 1.8 | 1.7 |
| 182 | 5.3 | 3.2 | 2.4 | 2.3 |
| 365 | 5.1 | 2.1 | 2.5 | 2.0 |

**Table 2.4:** Time required for capillaries to segmented (Neville, 1995)

| Water to cement ratio by weight | Required age |
|---|---|
| 0.40<br>0.45<br>0.50<br>0.60<br>0.70<br>0ver than 0.70 | 3 days<br>7 days<br>14 days<br>6 months<br>1 years |

**Table 2.5:** List of some substances that cause severe chemical attack of concrete (Neville, 1995)

| ***Acids*** | |
|---|---|
| **Inorganic** | **Organic** |
| ***Carbonic*** | Acetic |
| Hydrochloric | Citric |
| Hydrofluoric | Formic |
| **Nitric** | Humic |
| Phosphoric | Lactic |
| Sulfuric | Tannic |
| ***Other substances*** | |
| Aluminium Chloride | Vegetable and animal fats |
| Ammonium salts | Vegetable oils |
| Hydrogen Sulfide | Sulfates |

**Table 2.6:** Ion concentration of individual salts (Neville, 1995)

| **Ions** | **%** |
|---|---|
| Chloride | 2.0 |
| Sulfate | 2.8 |
| Sodium | 1.11 |
| Magnesium | 0.14 |
| Calcium | 0.05 |
| Potassium | 0.04 |

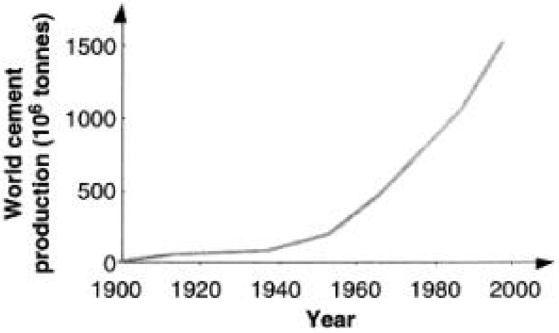


**Figure 2.1 :** World production of cement according to CEMBUREAU (Aitcin, 2000)

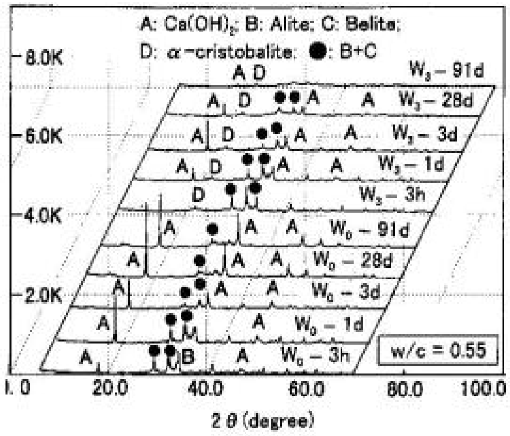


**Figure 2.2:** XRD patterns of pastes OPC, $W_o$ and 30% RHA, $W_3$ at w/c ratio 0.55 and hydrated at 20 ± 1ºC for different ages. (Qijun *et al*., 1999)

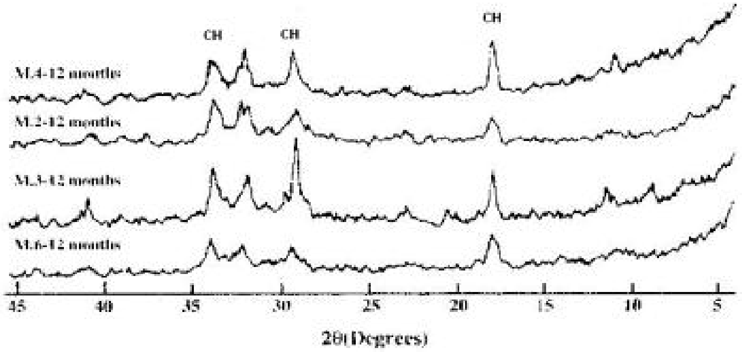


**Figure 2.3:** XRD patterns of various mixes at 12 months (El Aziz *et al*., 2004)

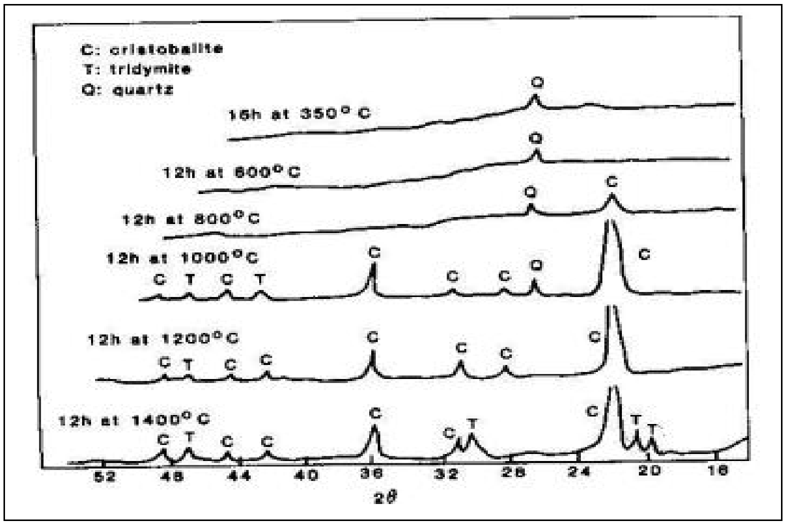


**Figure 2.4:** XRD pattern for RHA burnt at different temperatures (Kapur, 1981)

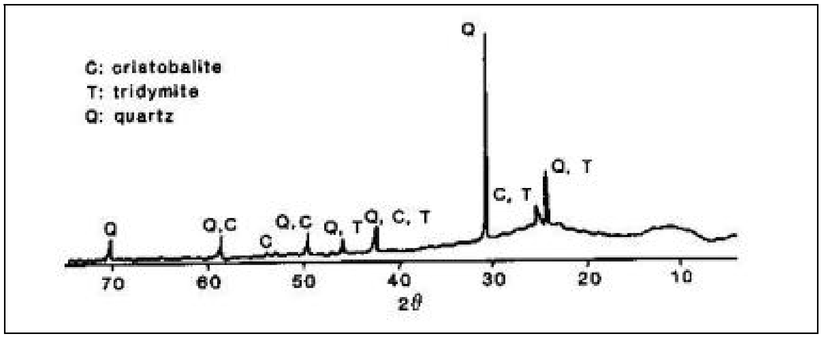


**Figure 2.5:** XRD pattern for RHA containing crystalline silica (Cook,1986)

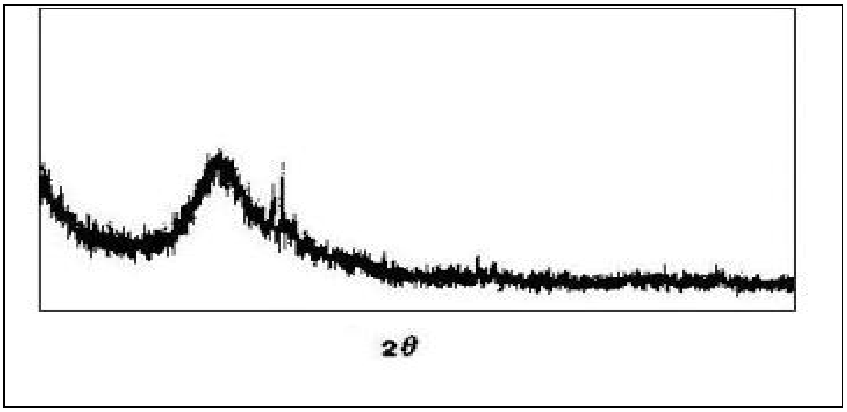


**Figure 2.6:** XRD pattern for RHA mainly amorphous silica (Coutinho, 2003)

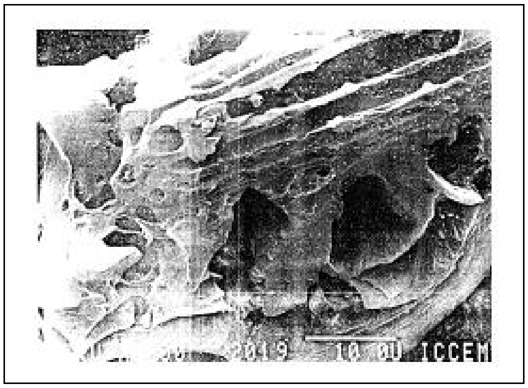
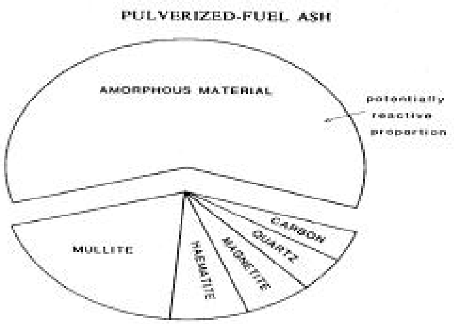


**Figure 2.7**: Skeletal structure of RHA particle



| Phase | Mean (%) | Min. (%) | Max. (%) |
|---|---|---|---|
| Amorphous | 59 | 30 | 78 |
| Mullite | 19 | 7 | 46 |
| Haematite | 7 | 2 | 15 |
| Magnetite | 6 | 2 | 10 |
| Quartz | 5 | 1 | 12 |
| Carbon | 4 | 1 | 13 |

**Figure 2.8:** Phase composition of UK PFA

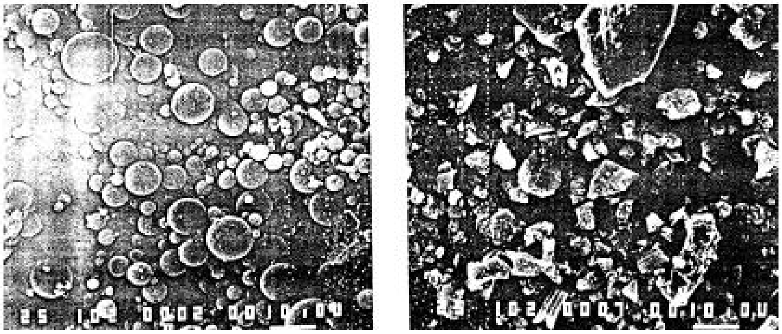


**Figure 2.9:** Photomicrographs of PFA (left) and OPC (right)

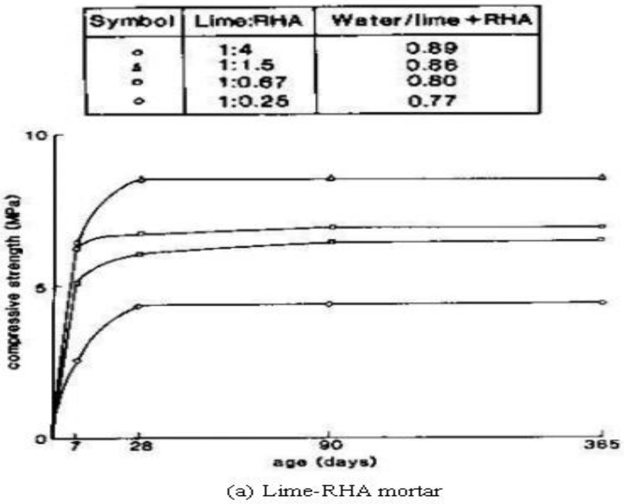
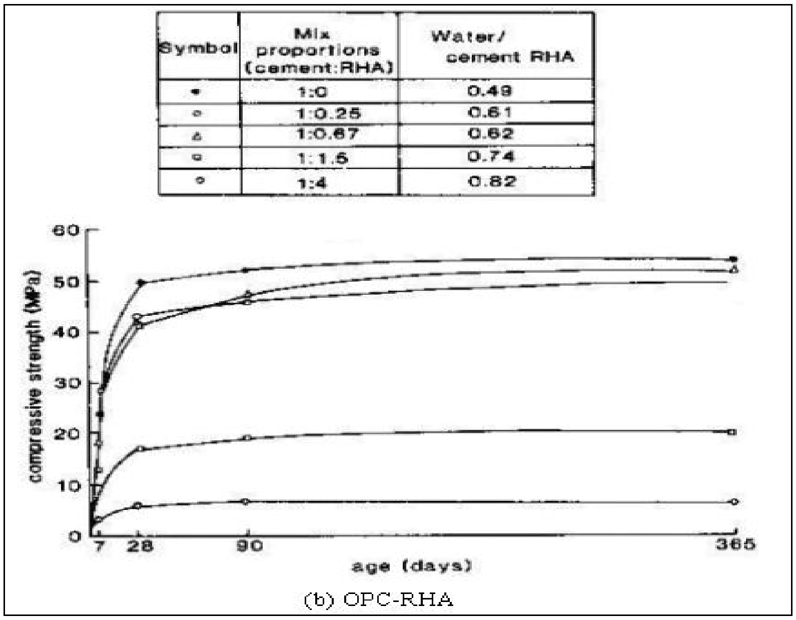


**Figure 2.10:** Strength development of RHA mixes (Cook and Suwanvitaya, 1981)



| Symbol | Mix proportions (cement:RHA) | Water/ cement RHA |
|---|---|---|
| ● | 1:0 | 0.49 |
| ○ | 1:0.25 | 0.61 |
| △ | 1:0.67 | 0.62 |
| □ | 1:1.5 | 0.74 |
| ○ | 1:4 | 0.82 |

**Figure 2.10:** (cont.)

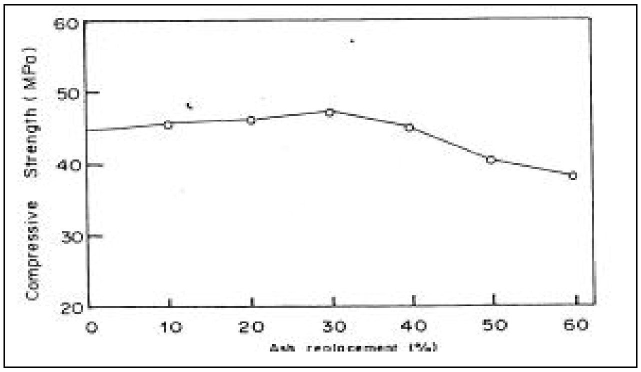


**Figure 2.11:** Effect of POFA content on compressive strength of concrete (Awal and Hussin, 1996b)

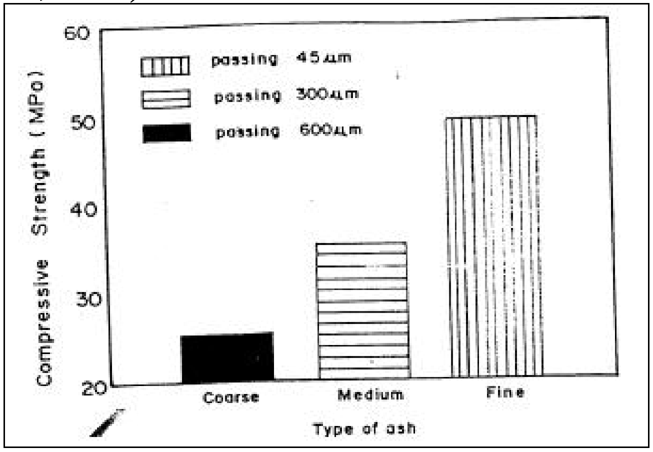


**Figure 2.12:** Effect of fineness of ash on compressive strength of concrete (Awal and Hussin, 1996b)

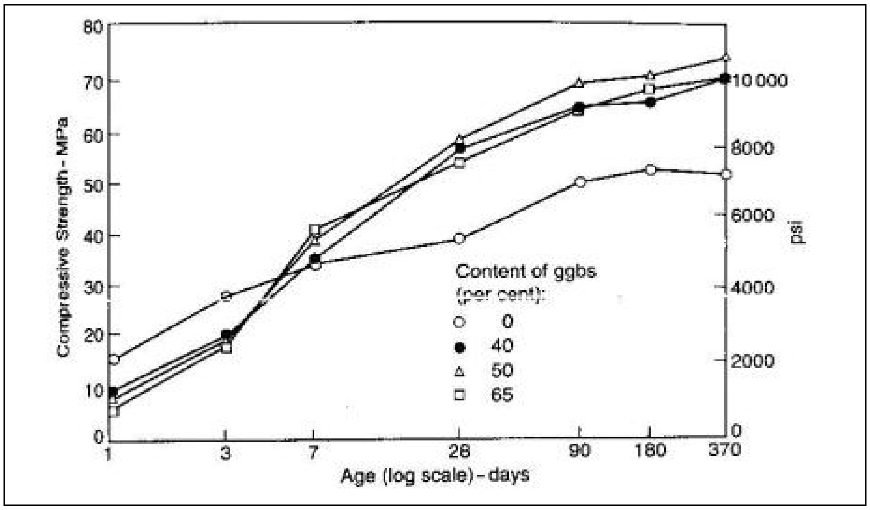


**Figure 2.13:** Strength development of various Slag content (Hogan and Muesel, 1981)

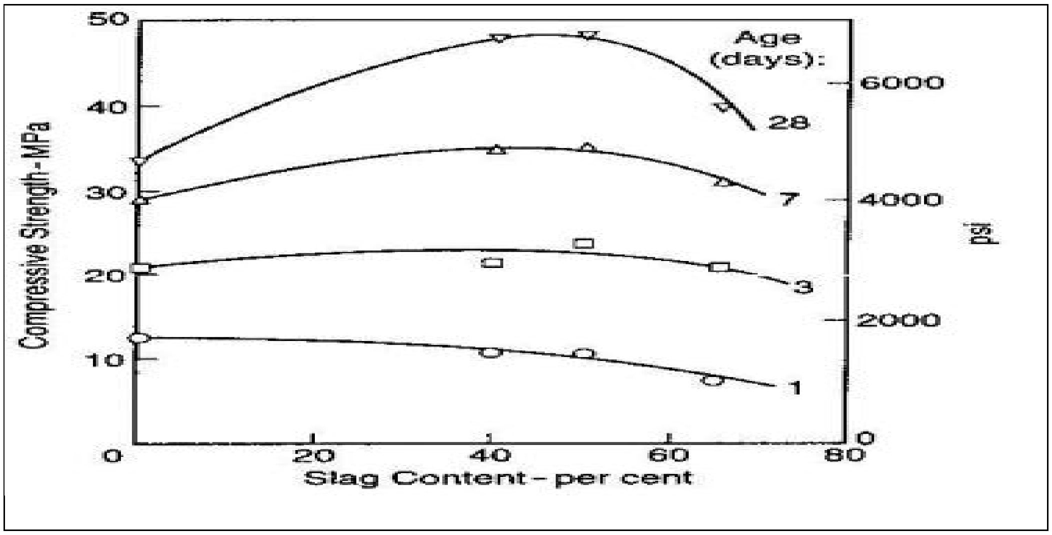


**Figure 2.14 :** Strength development of various Slag content (Roy and Idorn, 1982)

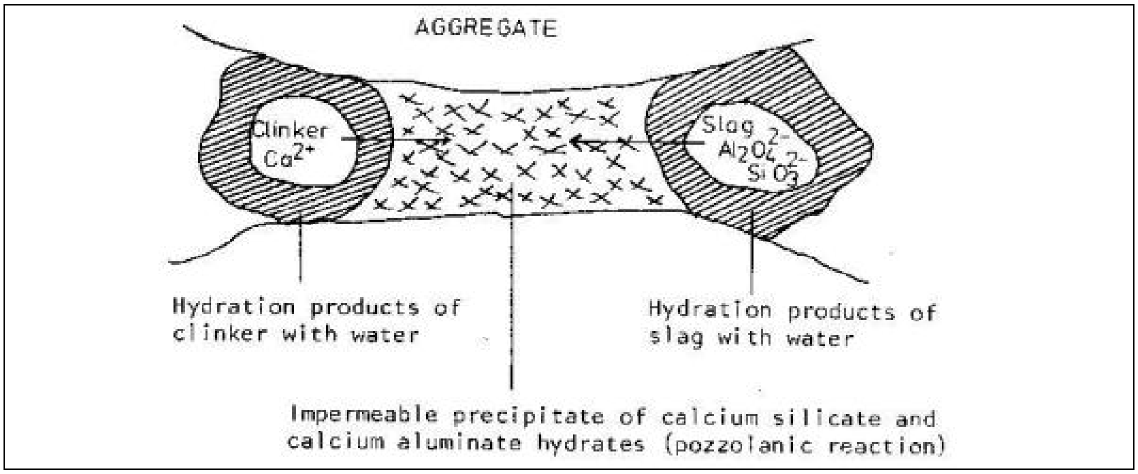


**Figure 2.15:** Hydrates between adjacent particles in Slag (Bakker, 1980)

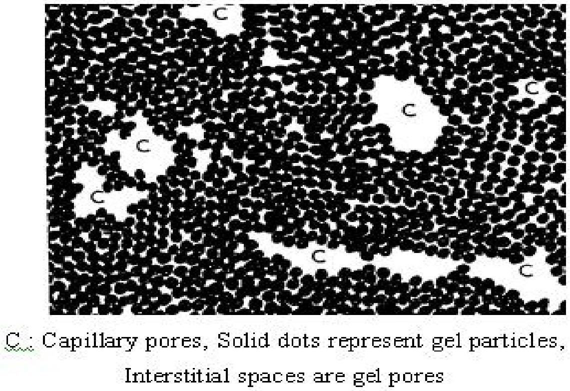


**Figure 2.16:** Simplified model of paste structure (Powers, 1958)

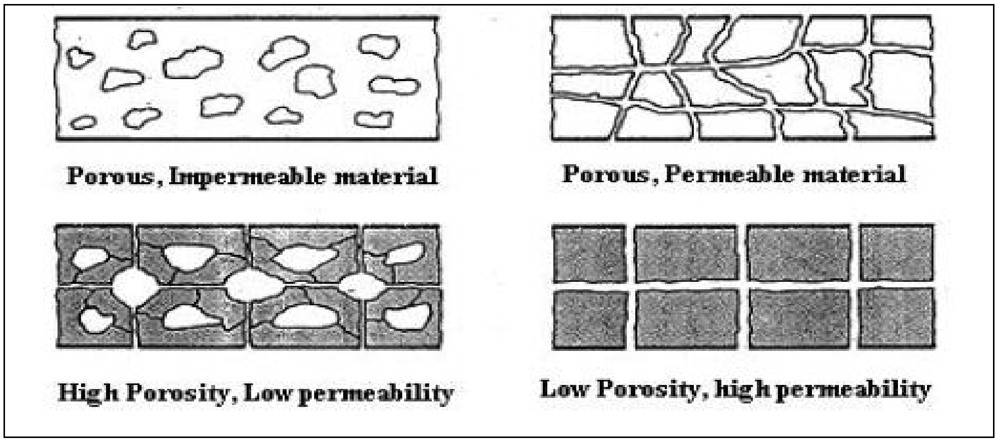


**Figure 2.17:** Illustration of Permeability and Porosity (From Concrete Society Technical Report no.31, 1988)

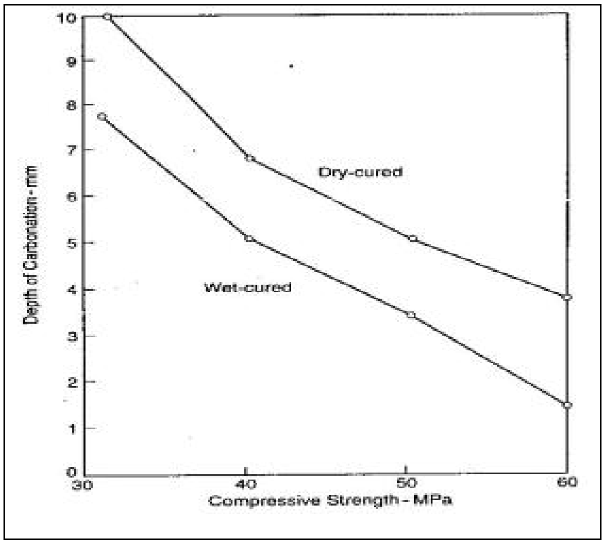


**Figure 2.18**: Relation between the depth of carbonation and compressive strength of concrete after 2 years (Neville, 1995)

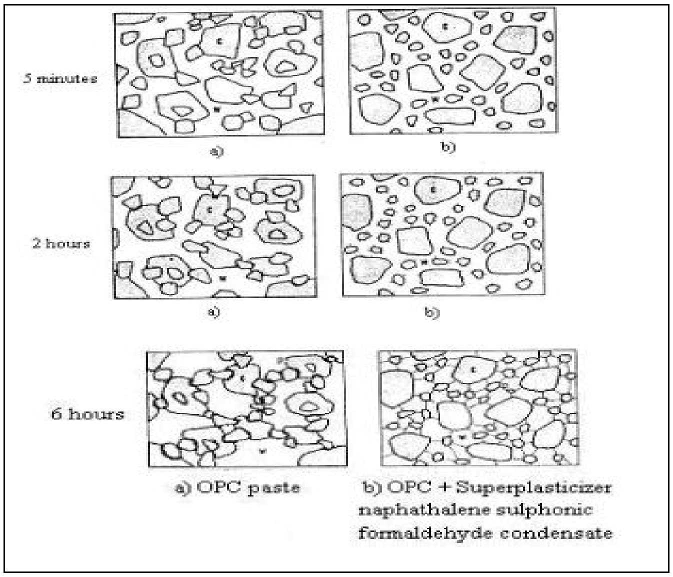


**Figure 2.19:** Deflocculation of cement grains by superplasticizer (Uchikawa, 1986)

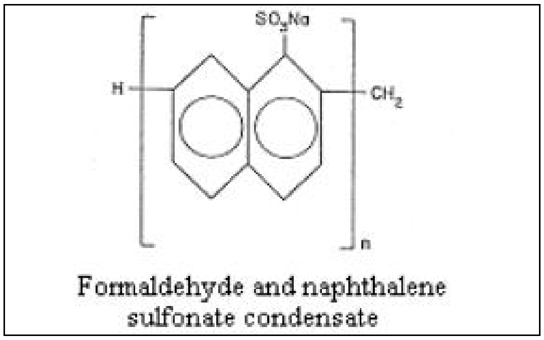


**Figure 2.20** Schematic representation of molecules of naphthalene sulfonate condensate (Aitchin, 1992)

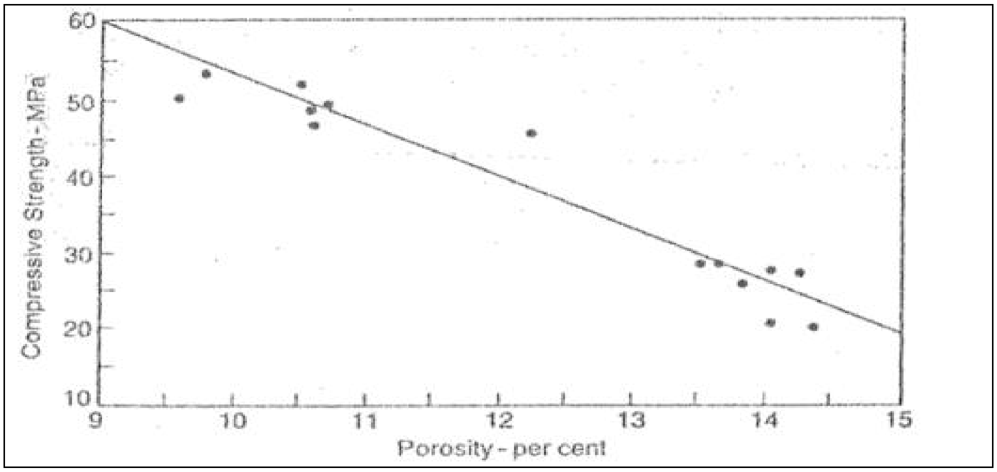


**Figure 2.21** Relation between compressive strength of mortar and porosity calculated from the volume of pores larger than 20nm in diameter (Sersale *et al.*, 1991)

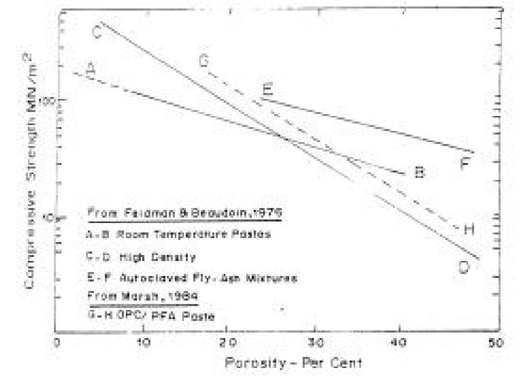


**Figure 2.22:** Relationship between compressive strength and porosity (Feldman & Beaudoin, 1991)

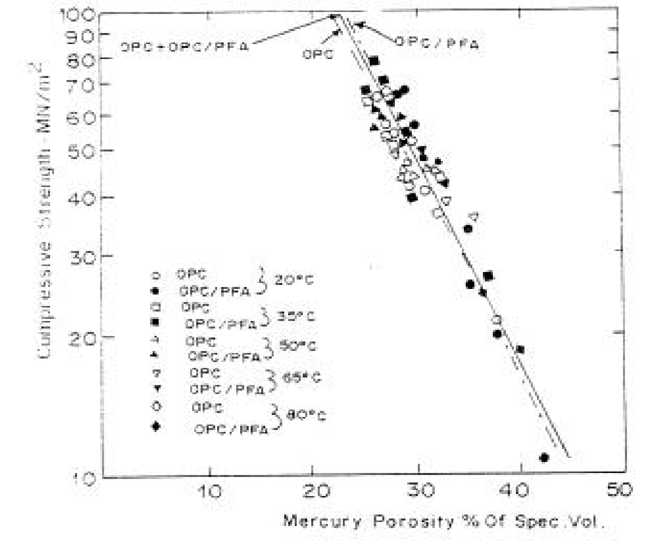


**Figure 2.23:** The relationship between compressive strength and Mercury Porosity of OPC and OPC/PFA pastes. (Marsh, 1984)

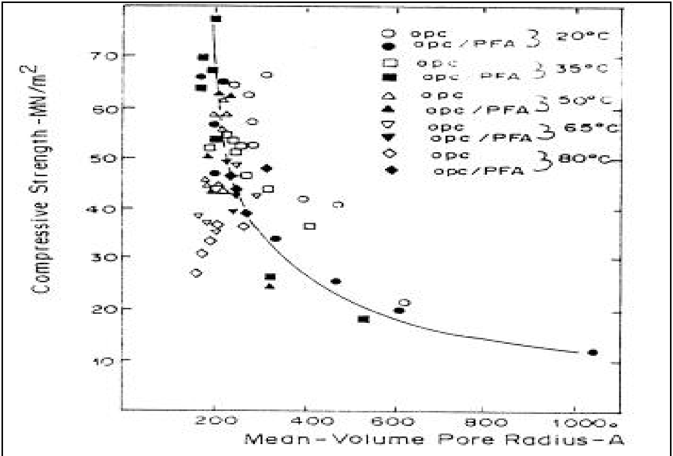


**Figure 2.24:** The relationship between compressive strength and mean-volume pore radius (Marsh, 1984)

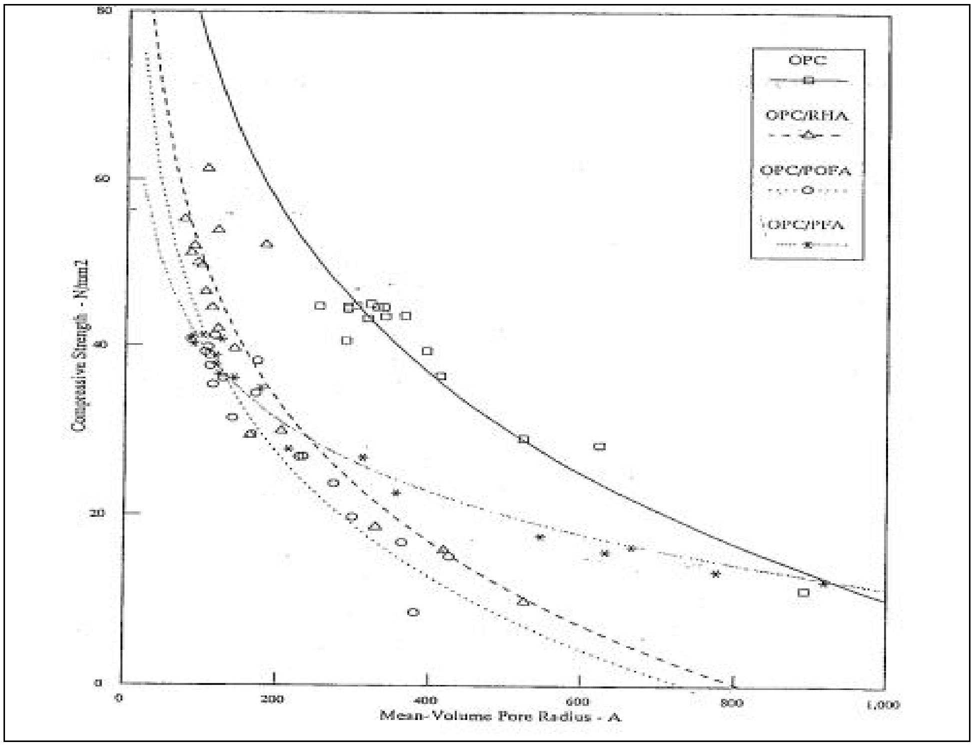


**Figure 2.25:** The relationship between compressive strength and mean-volume pore radius of control OPC and 30% replacement OPC/ASH mortar pastes (Salihuddin, 1993)

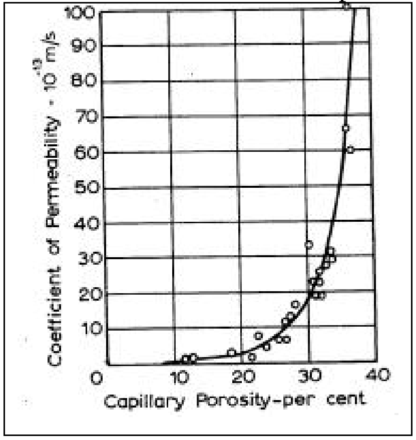


**Figure 2.26:** Relation between permeability and capillary porosity of cement paste (Power, 1958)

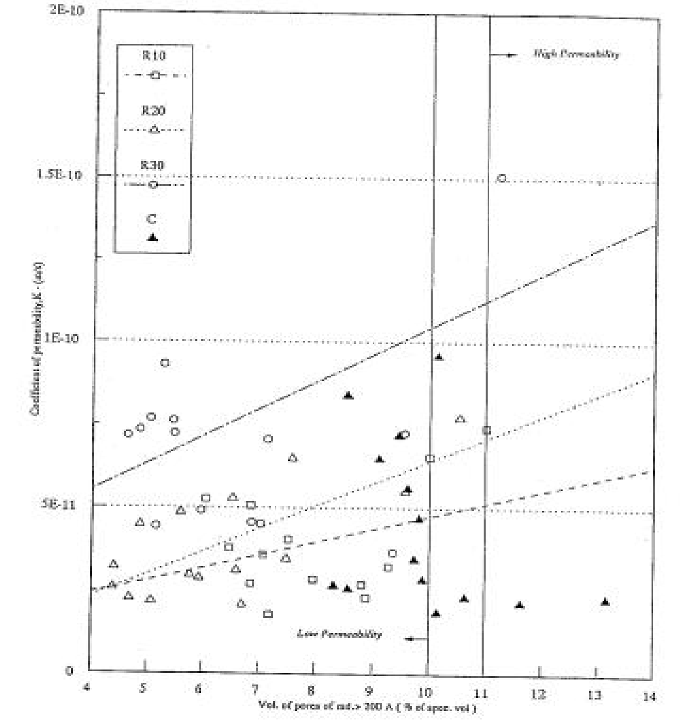


**Figure 2.27:** The relationship between permeability and the volume of pores of radius greater than 200A for OPC/RHA mortar containing 10-30% replacement (Salihuddin, 1993)

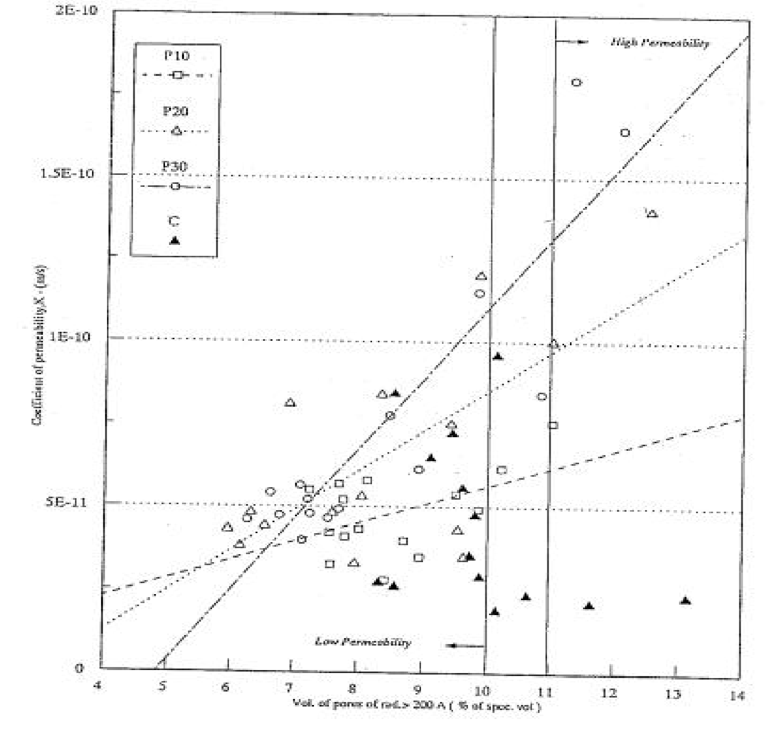


**Figure 2.28:** The relationship between permeability and the volume of pores of radius greater than 200A for OPC/POFA mortar containing 10-30% replacement (Salihuddin, 1993)

# CHAPTER 3
# RESEARCH METHODOLOGY

## 3.1 Introduction

This chapter includes the details of the following.

- Test program (stage wise)
- Materials
- Mix proportions
- Casting of specimens
- Curing methods and
- Testing methods

## 3.2 Test programme

The entire experiments conducted during this study were carried out in the laboratory of Structures and Materials, Faculty of Civil Engineering, UTM Malaysia. The laboratory experimental program covers the following stages:

a) Stage 1 – To determine water/binder (w/b) ratio of mortar mixes at flow value of 105%-115% as recommended by ASTM C109-92 (1992).

b) Stage 2 - To establish the optimum sand: binder proportion applying the w/b ratio determined during stage 1 on the basis of the compressive strength at 28 days.

c) Stage 3 - To evaluate the optimum mix proportion of MBC mortar on the basis of compressive strength, water absorption and porosity.

Where the optimum sand: binder ratio determined in stage 2 is considered as the principal mix proportion for MBC Mortar.

d) Stage 4 - To investigate the effects of the different curing regimes on the compressive strength of MC mortar developed.

e) Stage 5 - To study the durability properties of MBC mortar developed in terms of its resistance to acid attack, carbonation, and the exposure to saline water (Seawater).

f) Stage 6 - To examine the suitability of MBC mortar to be applied as face sheets of lightweight aerated concrete masonry sandwich block.

Figures 3.1 and 3.2 show the flow chart of the test programme and the supplementary tests conducted during the entire experimental program of this study. Table 3.1 shows the test parameters covered during the experimental program. Table 3.2 shows the category of tests.

### 3.3.1 Materials

Materials used during this experimental study comply with the standard specifications of various standards like ASTM, BS, and MS. The details of the materials are as follows:

#### a) Cement

Ordinary Portland Cement (OPC) of 'SELADANG' brand from Holcim Cement Manufacturing Sdn. Bhd. in Pasir Gudang, Johor was used. The OPC used complies with the Type I Portland Cement as in ASTM C150 (1994) specifications. The chemical and physical composition of the cement used are presented in Table 3.3.

#### b) GGBFS (Slag)

Ground Granulated blast furnace slag was obtained from YTL Sdn. Bhd. located at Pasir Gudang, Johor. It was kept in airtight container before its use. The GGBFS used complies with the specifications of ASTM C989 (1993). The slag activity index is 100. The chemical composition of slag as compared with OPC is shown in Table 3.3. The composition of silica, alumina and iron oxide of slag is 40%, which is the lowest content among the pozzolanic materials. But it has high content in CaO, approximately 50.4%. Thus, the slag is considered as cementitious material instead of a pure pozzolan.

#### c) PFA

The PFA used throughout the study was obtained from MAJU PERKASA Sdn. Bhd. The source of PFA used is a coal-power station located in Sepang, Selangor, Malaysia. It was supplied in the bags of 50 Kg. Table 3.3 shows the chemical composition of PFA used. The oxide content (silica, alumina and iron oxide) is approximately 97.8% of the total composition. This content is somewhat comparable with RHA but higher than POFA. Whereas the content of CaO is less than 10% that classifies the PFA used as Class F in accordance with ASTM C 618-84(1992). The fineness of PFA complies with the specifications of ASTM C 618-84(1992), which is less than 34% retained in the 45μm sieve as shown in Table 3.7.

**d) RHA**

The RHA used was obtained from a rice mill located in Kedah and supplied by Maju Perkasa Sdn. Bhd. It was packed in 20 kg bags. The chemical composition of RHA is given in Table 3.3. The combined oxides content (silica, alumina and iron oxides) is approximately 97.7% of the total composition. The content of CaO in case of RHA is also less than 10% which places itself in Class F. The ashes obtained undergone a grinding process to achieve their fineness as per the specifications of ASTM C 618-84. It is mentioned that the pozzolanic materials ought to have fineness of at least 66% of the ash passes through the 45µm sieve. While the percentage of fineness of RHA reported in the literature is referred in Table 3.3. In fact, the fineness of the ashes significantly affects the reactivity of the ash in mortar or concrete (Cook, 1986). Hence the RHA obtained was ground until the required fineness was achieved. Los Angelas Abrasion test (LAAT) equipment as shown in Figure 3.3 was used for the grinding purpose. Initially the material was sieved in 300µm sieve to remove the coarse and foreign particles (if any) form the material.

Before grinding it was observed that the percentage of passing of RHA through 45µm was found to be 12% of the total material. The references used to determine the % of fineness for RHA can be referred in Table 3.4. The grinding time for RHA and the wet sieve analysis test results are given in Table 3.5 while Figure 3.4 presents the pictorial view. Based on the test results, the optimum grinding time for RHA to achieve the specific fineness was determined as about one and half-hours by using 15 numbers of 12mm diameter and 800mm long stainless steel bars as grinding media. This is in coincidence with the recommended time reported in the literature. The grinding media is depicted in Figure 3.5.

**e) POFA**

POFA was also supplied by MAJU PERKASA Sdn. Bhd, in the bags of 50 kg per bag. The chemical composition is shown in Table 3.3. The oxides analysis shows the 93% combined oxides content (silica, alumina and iron oxides). The content of CaO of POFA was found to be less than 10%, hence it is also classified as class F. According to Awal and Hussin (1996b), the finer the POFA, the greater is the strength development. Initially the percentage passing of the POFA through 45micron sieve achieved was only 2%. Hence the POFA was also ground by adopting the similar method used for RHA. After grinding the percentage passing through 45 micron sieve obtained is 94%. The optimum time to grind the POFA is observed to be two and half hours. Table 3.6 and Figure 3.6 present the grinding time and wet sieve analysis test results of POFA.

It is important to mention here that in common practice generally OPC is not ground to achieve more fineness than the fineness at its manufacture. Hence during this study OPC was not ground. Whereas the Slag and PFA used were also in ground form and hence both materials required no grinding. The samples of OPC, Slag and PFA were tested for the fineness, the results of which are presented in Table 3.7. From the table it is evident that the ashes are finer than that of the OPC. After grinding, the ashes were kept in airtight plastic bags and placed in a suitable container to avoid any atmospheric effect on the ashes.

### f) Fine aggregates (Sand)

Quarry sand used was in this study. The sand was dried in a large size oven at 105°C temperature for 24 hours to remove the moisture. It was sieved from the set of sieves according to BS 410: (1986). Figure 3.7 depicts the grading curve of the sand used and it clearly shows that the grading curve is enclosed within the fine aggregate envelope.

### g) Water

Water is one of the most important materials required to produce mortar paste. In general the water acceptable for drinking purpose is suitable for the manufacture of mortar. Impurities in water may influence the setting time of the cement and also can adversely affect the strength of concrete or cause staining of its surface (Neville, 1995). Therefore, tap water was used to cast the specimens during this study.

### h) Water reducing agents (Superplasticizer)

Water reducing admixtures were added to reduce the water/binder ratio of the concrete and mortars by maintaining the workability in order to reduce the voids ratio thereby increasing the strength and decreasing the porosity of the mortar. The addition of superplasticizer also plays significant role to reduce the flocculation of cement grains (Malier, 1992). The superplasticizer of trade name SIKAMENT NN was used as the chemical admixture during this study. It is type F high range water reducing admixture according to ASTM C 494-92 (1992). All the physical requirements of superplasticizer are in accordance with Table 1 of ASTM C 494-92. It is from group Sulphonated Naphthalene Formaldehyde condensates (SNF) in dry powder form.

### 3.4 Mix proportion

In all, nine types of mixes including one control mix without replacement of cement were casted for this study. Two series of the mortar mixes were considered. Four mixes were designed with the binary blended cement as binder material during first series. Binary blended cement (BBC) was prepared by replacing partially with one of the blending constituents in each mix. The blending constituents considered for this series are Slag, PFA, RHA and POFA. Whereas the percentages of partial replacement applied for each blending constituent is the optimum value as reported by the various researchers as refer in the literature review in this thesis. The details of the BBC mortars are given in Table 3.8a.

The second series of the mortars was designed by replacing cement with the combination of all the four blending constituents and the mortars developed are known as Multi-Blended Cement (MBC) mortars. Four mixes were prepared for this series. The replacement level of OPC was fixed at 50% of total binder by weight. Whereas, the content of Slag, and POFA was also fixed at 20% and 5% of the total binder by weight respectively. The remaining 25% replacement of cement was adjusted between the various percentages of RHA and PFA. The details of the MBC mortars are shown in Table 3.8b. Figure 3.8 depicts the pictorial view of all the constituents including fine sand used to produce mortars for this study.

### 3.5 Casting process

All materials including water were weighed prior to mixing of the materials. Initially binders were mixed in an electrically operated mortar mixer at 285 ± 10 rpm for about 2 minutes to ensure proper blending of the OPC and all the blending constituents. Figure 3.9 shows the mixer used. Then sand, and superplasiticizers were added in the blended binder and were mixed in mixer for 1-2 minutes again. Finally, water was added slowly into the dry mix and mixing of the mortar mix continued for about 3 minutes in order to achieve the uniform mix. Then cube specimens of standard size were cast. The moulds and the table vibrator used for the specimen casting are presented in Figure 3.10 and 3.11, respectively. The moulds were covered in a plastic sheet with wet gunnysacks at the top to provide humidity during the hardening process. After 24 hours the specimens were demoulded and cured accordingly.

### 3.6 Curing process

Curing is generally the procedures employed to promote hydration of cement, and consists of a control temperature and the moisture movement from and into concrete or mortar as well (Neville, 1995). The curing procedures adopted for this study were as per the recommendations of the standard methods reported in literatures. Initially the specimens were cured in water for 7, 28, 60 and 90 days and tested accordingly in order to establish the optimum sand: binders proportion and also to select optimum mix proportion for MBC mortars. The specimens prepared from MBC mortars were cured in three curing regimes namely continuous water, air curing, and initial water curing for 7 and 14 days followed by the air curing up to 28, 60 and 90 days to examine the effect of curing regimes.

As per the objectives, the strength of MBC mortars subjected to chloride attack was examined. For this purpose the cube specimens of MBC mortars were subjected to accelerated cyclic curing in seawater by immersing the specimens in seawater for 24 hours and then dried in oven for 24 hours. Prior to the accelerated cyclic curing specimens were cured in water for 7 and 28 days. Seawater was collected and stored in a fibre tank and the specimens were immersed for required time in the tank as per the standard procedures of the curing the specimens in water. It has been reported in a literature that one cycle of the accelerated treatment may roughly correspond to immersion in seawater for 50 to 60 days (Nishibiyashi *et al*., 1990). To investigate the acid attack the specimens were initially cured in water for 7 and 28 days and then immersed in distilled water containing 5% solution of Hydrochloric acid (HCl) till the specific age, a total period of 600 hours of immersion. However, to determine the carbonation, the cube specimens were cured in water, air, natural weather, and the sea water for 7, 28 and 90 days.

## 3.7 Testing Procedures

The laboratory experimental programme was carried out stage wise as mentioned in Section 3.2. The testing methods and procedures adopted are as per the standard procedures reported in the codes and literatures. Details of the testing procedures are described as follows:

### 3.7.1 Stage 1: Water requirements test on mortar

Flow table in compliance with the specifications of ASTM C230-90 (1990) was used to determine the w/b ratio of the entire mixes. The test was conducted in accordance with the procedure described in ASTM C 109-92 (1992). The flow is defined as the resulting increase in the base diameter of a mortar mass expressed as a percentage of the original base diameter after being vibrated on a flow table. The flow value of the mortar specimens is maintained at 105-115% that is to be considered as the application for MBC mortar as the face sheet of Aerated lightweight concrete block. The MBC mortar is designed in such way, which is it can be stick or plastered on the aerated block. The constant flow of the mortar paste will be produced varies wbr for each mortars. Figure 3.12 shows the flow table.

As per procedure of the test, mortar mix is filled in the standard mould placed on the base plate of the flow table in 2 layers. Each layer was compacted with a 25mm diameter mild steel bar by adopting 20 numbers of blows. The tamping pressure should be just sufficient to ensure uniform filling of the mould. Then after, the mould was removed and the flow table was vibrated by dropping it from standard height of 12.5mm at the rate of 25 drops in 15 seconds. Finally, the resulted increase in the base diameter of mortar mix was measured and divided by the original diameter to obtain the flow value. The test procedure was repeated for three times for each mortar mix to obtain the average value.

### 3.7.2 Stage 2: Establishment of sand and binders ratio (s/b)

Only compressive strength test was carried during this stage of the test programme. Initially four mix proportions 1:1, 2:1, 2.5:1 and 3:1(sand: binder) were considered. The details of the mix proportions are given in Table 3.8a, 3.8b and 3.9. Cube specimens of standard size70.6mmx70.6mmx70.6mm were cast and tested at 7 and 28 days to determine the compressive strength. The specimens were cured in water up to the testing age. The compressive strength test was carried as per the test procedure detailed in BS 1881 Part 116 (1983). TONIPAC 3000 testing machine of 3000kN loading capacity, available in the structures and materials laboratory, Faculty of Civil Engineering at UTM was used to conduct the compressive strength test. Figure 3.13 depicts the testing of a cube specimen. The specimens were wiped to a surface-dry condition upon removal from the curing tank just before the test. The specimens were loaded gradually without shock and the loading rate was set at a constant rate of 0.1 N/(mm$^2$)s until ultimate failure of the specimen. The ultimate failure load was recorded and the compressive strength was calculated accordingly.

### 3.7.3 Stage 3: Establishment of the optimum series of mix proportion of MBC mortar by using the optimum sand and binder’s ratio.

In order to establish the optimum mix proportion of MBC mortars, three tests were conducted during this stage of the study. The three tests conducted were compressive strength test, porosity test, and water absorption test. The details of the procedures are given below.

### a) Compressive strength test

Cube specimens of standard size (70x70x70mm) were casted and tested as per the procedure described earlier in section 3.7.2.

### b) Porosity test

The objective of this test was to determine the effect of the blending constituents on the total porosity compared to that of the OPC and BBC mortars. The low value of the total porosity would imply the potential high durability and high density of the mortars. The porosity is generally measured with Mercury Intrusion Porosity and the Nitrogen absorption equipments. However, for this research the test was performed using Vacuum Saturation method. The testing procedure adopted in this study is similar to the one used by Vanisha (2003). Figure 3.14 shows the photograph of the equipment used. The cube specimens of standard size 50x50x50mm (as in Figure 3.15) cut from 100x100x100mm cubes and tested at their ages of 7, 28, 60 and 90 days after curing accordingly. The specimens for this stage of study were cured in water. The stepwise testing procedure is described below.

1. The specimens at their specific age were removed from the curing tank and dried in oven for 24 hours by maintaining the temperature at 105 °C.

2. The specimens were removed from oven and put in vacuum flask (Desiccator) and closed tightly to avoid the specimens from absorbing air and moisture. The specimens were left to cool in the vacuum flask for 24 hours as in Figure 3.16.

3. Then after the vacuum pump is set on to suck the entire air from the flask and the specimens. This process was continued for 3 hours.

4. The vacuum pump was then switched off and distilled water channel was opened directly to the vacuum flask until the specimens were totally immersed in the water with water level 10mm over the top of the specimen. Subsequently the vacuum pump was restarted to suck the air inside (if any) in order to achieve complete saturation of the specimens for 3 hours, meanwhile the specimens remained submerged in the water.

5. Again the vacuum pump was switched off followed by the opening the air channel so that the pressure in the vacuum flask was in equilibrium with the atmospheric pressure and the specimens were left submerged in water for further 24 hours. This was to ensure that the specimens were saturated with the distilled water.

6. After 24 hours, the specimens were removed from the flask and weighed by placing in the water (Wsw) and air with surface condition (Wssd). The weight of the specimens were recorded carefully.

7. Finally the specimens were dried in oven at a temperature of 105°C for 24 hours in order to ensure complete drying. The completely dry specimens were weighed to determine the dry weight (Wd) followed by the calculation of the percentage of total porosity using following formula:

$$P_T = \frac{Wssd - Wd}{Wssd - Wsw} \times 100\% \qquad (3.1)$$

Where,

$P_T$ = percentage of total porosity

Wd = weight of dry specimen

Wsw = weight of specimen in water

Wssd = weight of saturated specimen in air

**c) Water absorption test**

The objective of this test was to determine the percentage of water absorbed into the interconnectivity capillary pores in mortar pore structure, This test was conducted as per the specifications of BS 1881: Part 122 (1983). This test method is known as ‘water immersion method’. The size of cube specimens used was 70x70x70mm. The test was carried on three specimens to achieve average value, taken from each mix and cured in water for 7, 28, 60 and 90 days; the age of the testing. Figure 3.17 depicts the pictorial view of the specimens immersed in water. Accordance to Concrete Society Technical Report No. 31 (1988), the typical values of the water absorption of concretes rating the type of concrete cured in water and tested at 28 days as per the recommendations and test procedures of BS 1881 BS 1881: Part 122 (1983), are defined as:

| | |
|---|---|
| Low absorption concrete | < 3% |
| Average absorption concrete | 3 – 4% |
| High absorption concrete | > 4% |

The stepwise testing procedure is as follows:

1. The specimens were taken out from the curing tank at their specific age of testing and weighed to record the initial weight. Then the specimens were dried in oven at a temperature of 105 ° C for 72 ±2 hours.

2. Then after the specimens were placed in a an airtight desiccator for 24 ± 0.5 hours in order to cool the specimens followed by weighing the specimen to determine dry weight (Wd).

3. Immediately after weighing, the specimens were immersed in a water tank with a water level 30 ± 5 mm above the top of the immersed specimens. The specimen were left immersed for 30 ± 0.5 min before their removal from the tank. The surface of the specimens was wiped with clean cloth and were weighed again to obtain the wet weight (Ww) of the specimens.

4. The percentage of water absorption (WA) is calculated as follow:

$$WA = \frac{Ww-Wd}{Wd} \times 100\% \tag{3.2}$$

Where,

WA= percentage of water absorption

Wd = weight of dry sample

Ww = weight of wet sample

### 3.7.4 Stage 4: Assessment on the strength properties of the optimum MBC mortar at different curing regimes

This phase of study was conducted to investigate the effect of the curing regimes at various ages on the strength properties of MBC mortars. Cube specimens of the standard size (70x70x70mm) were cast and cured under different curing regimes as mentioned before. For wet-dry cyclic curing in seawater, the number of cycles was fixed at 15, 30 and 45 cycle. The specimens were tested for compressive strength at their appropriate age of testing as per the procedure described earlier in section 3.7.2. Three specimens in each case were tested to obtain the average value.

### 3.7.5 Stage 5: Assessment on the durability properties of the optimum MBC mortar

Durability of mortars is considered to be related to porosity and permeability characteristics. Chemical attack occurs mainly through the action of aggressive ions, such as chlorides, sulfates, carbon dioxide, and sometimes because of industrial liquids and gases as well. The movement of water in concrete and mortar takes place not only by flow through the pores of the concrete and mortar but also by diffusion and adsorption. However, it depends on the interconnectivity of the pores within the concrete and mortar mass. Two types of tests namely carbonation test and acid attack test, were conducted during this phase of the study to examine the durability of the MBC mortars. The procedures of the test conducted is described below:

### a) Carbonation test

Carbonation attack is assessed in terms of depth of carbonation in mortars. The test was performed as per the procedure recommended by RILEM (RILEM Committee CPC-18). The depth of carbonation is easily visualised in mortar by spraying a solution of phenolphthalein in alcohol and water on the fresh surface obtained by breaking the specimen in two parts. This solution is preferred to be used due to its alkalinity and colourless regions.

After spaying the solution, the surface being sprayed changes in colour to purple. The depth of carbonation could simply be measured by observing the area which has changed in colour. When the alkalinity of the concrete/mortar is unaffected, a purple colour is observed. But, the surface which is colourless or its colour is not changed, is considered to be affected by carbonation. The depth of colourless area hence indicates the depth of the carbonation occurred in mortar. According to RILEM, the carbonation process can only occur at about 2 mm to 3 mm depth when solution is sprayed over the surface of broken specimen.

### b) Acid attack

The test for resistance to acid attack of mortar cube specimens was carried out by measuring the loss of weight of the specimens caused by continuously submerged in a 5% of hydrochloric acid (HCL) solution. The time of submergence depends upon the percentage of Hydrochloric acid (HCL) solution. The time period to submerge the specimens in HCL solution to measure the weight loss was fixed at 100, 200, 300, 400, 500 and 600 hours during this study. This was based on the time period considered by Awal and Hussin (1996b). Concrete and mortar that are highly alkaline is less resistant to attack by strong acids or compounds that may convert to acids (Neville, 1995).

### 3.7.6 Stage 6: Application of the optimum MBC mortar established in stage 3 as face sheets of lightweight aerated concrete sandwich block.

#### a) Introduction

On the basis of the experimental study, one MBC mortar was to be selected which exhibited high performance in terms of compressive strength, water absorption, porosity, and the other durability criteria. This MBC mortar may have various applications in construction industry. However, MBC mortar can also be applied as face sheets to produce lightweight sandwich element by having lightweight and medium strength and low density material like aerated concrete as core material. The attempt has been made in limited extent to investigate the suitability of the MBC mortar selected as optimum mix to produce lightweight sandwich masonry block in terms of compressive strength, failure mode and the apparent composite behaviour.

One of the applications of MBC mortar is its use as materials for low water absorption. The aerated lightweight concrete is a high porosity concrete due to its foamed and porous nature. The optimum MBC mortar showed only 2-3% water absorption, while the aerated lightweight concrete exhibits values in the ranges of 16-20% depending upon its density. Hence it is expected that the overall water absorption of the block could be decreased significantly if this MBC mortar is adopted as face sheets separated by thick layer of lightweight aerated concrete as core to produce lightweight sandwich block. The enhancement in the overall strength of sandwich block is also expected compared to the block solely made of aerated concrete.

To check the suitability of the MBC mortar mix developed as the face sheets sandwiched with aerated lightweight concrete to produce a lightweight sandwich block in terms of compressive strength is also part and the last phase of this experimental study. The significance of the production of this sandwich block is a step towards the development of precast lightweight sandwich structural panels with sustainable performance to industrialize the building system in Malaysia.

#### b) Lightweight masonry sandwich

Lightweight masonry sandwich block was produced by using two 10mm ± 2mm (thick) layer of the optimum MBC mortar mix as external skin layer and 75± 1mm (thick) of Aerated lightweight concrete layer as core which can be referred in Table 3.10. The total thickness of the block is 100mm. However, the aerated concrete design is not part of this study. Nevertheless the mix design was established with slight modifications made in the aerated concrete produced by previous researchers at UTM (Noor *et al*. 2006; and Areshvinna, 2002).

### c) Casting of core (Aerated concrete)

Six constituents namely sand, cement, slag, water, aluminium powder and superplasticizer were used to produce core. The specifications of cement, slag, water and superplasticizer are the same as described for the preparation of the mortars. However, the sand passing from 600µm sieve was used as fine sand and aluminium powder was added as the aerating agent to produce aerated concrete. The specifications and the chemical composition of the aluminium powder are presented in Table 3.11.

Cement, slag, sand, aluminium powder, and superplasticizer were weighed and mixed for approximately 2 minutes until all the materials were mixed uniformly followed by the addition of water and further mixing of the mix constituents for 2 minutes. Upon achieving consistent flow, the mix was poured into the mould immediately before the reaction of aluminium powder with cement started to expand the volume. Wooden mould was used with inner sides covered by aluminium sheets in order to avoid water absorption by the wood surface. The mix of aerated concrete was prepared and poured in the mould up to 80% of its volume and trimmed after 3 hours when expansion was completed and the core has hardened enough to be trimmed. The specimens were demoulded after 24 hours and were ready to apply face sheets to produce sandwich blocks. The Aerated mix design is as in Table 3.12.

### d) Casting of sandwich block

The size and dimension of the block was based on the typical size of non-load bearing wall including the clear spacing for the services area. Immediately after demoulding of the aerated concrete core, one side of the core was plastered with MBC mortar mix while the other side was plastered on the next day. Approximately after one hour of the casting of each layer, specimen was covered with wet gunny and plastic sheet to conserve humidity for 24 hours. The sandwich blocks were then cured in water for 14 days and subsequently cured in air up to 28 days; the age of the testing. Figure 3.18 show the mould used. Whilst Figure 3.19 presents the sandwich block produced.

**e) Testing of sandwich block**

The sandwich blocks were tested for compressive strength using TONIPACT testing machine. The tests were conducted according to ASTM E 72-80 (1980). The specimens were tested at 28 days. Prior to testing the specimens was wiped with a dry cloth and weighed. The loading speed was maintained 0.5 kN/s until failure. During the test, crack pattern and failure mode of the specimens were carefully observed and recorded.

**Table 3.1:** Test Parameter

| **No.** | **Parameter** | **Unit/test** | **Range** | Requirement |
|---|---|---|---|---|
| 1. | Sand and Binders ratio 1:1, 2:1, 2.5:1 and 3:1 | Compressive strength | Age:<br>7 and 28 days | BS 1881<br>pt 116 (1983) |
| 2. | % Cement Replacement | % Weight of cement replaced | | |
| 3. | Compressive strength | 70.6mm cube<br>Standard curing | Age:<br>7, 28, 60 and 90 days | BS 1881<br>pt 116 (1983) |
| | | Air curing | | |
| | | Initial water curing 7 and 14 days and continuous air curing. | | |
| | | Seawater curing<br>Total salinity: 23.7ppt<br>PH: 7.91 | 24 hours in seawater & 24 hours in oven-dry for 1 cycle.<br>Cycle: 15, 30, 45 | Nishibiyashi et. al, 1990 |
| 4. | Porosity | (% of total porosity)<br>50x50x50mm cube<br>Vacuum Saturation | Age:<br>7, 28, 60 and 90 days | Vanisha (2003) |
| 5. | Water absorption | 70.6mm cube<br>30mins immersion in water | Age:<br>7, 28, 60 and 90 days<br>(Water curing) | BS 1881; pt 122 (1983) |
| 6. | Carbonation | Phenolphthalein solution | Age: 7, 28, and 90 days<br>Curing: Air, water, seawater, natural weather | RILEM Committee CPC-18 (1988) |
| 7. | Resistance to acid attack | Submerge in 5% Acid Hydrochloric | Period :<br>100,200,300, 400, 500 and 600 hours | Awal and Hussin (1996b) |

**Table 3.2 :** Category of tests

| **Category** | **Test** |
|---|---|
| Engineering properties | Compressive strength |
| Pore structure characteristics | Porosity (Vacuum Saturation) |
| Chemical characteristics | Carbonation |

**Table 3.3 :** Chemical and physical properties

| **Chemical constituents** | **OPC (%)** | **PFA (%)** | **SLAG (%)** | **RHA (%)** | **POFA (%)** | **Requirements of ASTM C 618-84 Class F** |
|---|---|---|---|---|---|---|
| Silicon dioxide ($SiO_2$) | 20.1 | 91.2 | 28.2 | 97.5 | 91.1 | |
| Aluminium oxide | 4.9 | 5.84 | 10.0 | 0.02 | 0.73 | |
| Ferric oxide ($Fe_2O_3$) | 2.5 | 0.76 | 1.8 | 0.13 | 1.18 | |
| ($SiO_2 + Al_2O_3 + Fe_2O_3$) | 27.5 | 97.8 | | 97.7 | 93.0 | 70 |
| Calcium oxide (CaO) | 65 | 0.34 | 50.4 | 0.18 | 1.66 | |
| Magnesium oxide | 3.1 | | 4.6 | | | |
| Sulphur oxide ($SO_3$) | 2.3 | 0.35 | 2.2 | 0.49 | 1.11 | 5.0 |
| Sodium oxide ($Na_2O$) | 0.2 | 0.24 | 0.1 | 0.1 | 0.16 | |
| Potassium oxide ($K_2O$) | 0.4 | 1.21 | 0.6 | 1.39 | 3.47 | |
| Titanium oxide ($TiO_2$) | 0.2 | | - | | | |
| Phosphorous oxide | <0.9 | | - | | | |
| Loss on ignition (LOI) | 2.4 | | 0.2 | | | 6.0 |
| ***Physical properties*** | | | | | | |
| Fineness: | | | | | | |
| Pozzolanic activity index<br>- with OPC, min %<br>- with lime, 7D (kPa-min) | | -<br>- | -<br>- | -<br>- | -<br>- | 75.0<br>5500 |
| Water requirement<br>Max % of control | | - | | | | 105 |
| Specific Gravity | 3.2 | 1.18 | 1.30 | 0.90 | 1.18 | 5.0 |

**Table 3.4:** The references used to determine the % of fineness of RHA

| **Reference** | **% Fineness passing 45micron** |
|---|---|
| ASTM C618 – 84, 1984 | 66 |
| BS 3892, 1982 | 87.5 |
| Zahairi Abu, 1990 | 94 – 95 |
| Islam, 1981 | 85 |
| Smith and Freda, 1979 | 90 |

**Table 3.5 :** The time grinding and the % of RHA fineness

Weight of ash: 2kg

Sieve: 45 micron (No. 325)

Grinding Media : 15 numbers of mild steel bars in LAAT machine

| **Time grinding, hr** | **% Retained** | **% Passing** |
|---|---|---|
| 0 | 88 | 12 |
| 1.0 | 12 | 88 |
| **1.5** | **4** | **96** |
| 2.0 | 1.1 | 98.9 |
| 2.5 | 0.7 | 99.3 |

**Table 3.6 :** The time grinding and the % of POFA fineness

Weight of ash : 2kg

Sieve : 45 micron (No. 325)

Grinding Media : 15 numbers of mild steel bars in LAAT machine

| Time grinding, hr | % Retained | % Passing |
|---|---|---|
| 0 | 98 | 2 |
| 1.0 | 46 | 54 |
| 1.5 | 28 | 72 |
| 2.0 | 12 | 88 |
| **2.5** | **6** | **94** |
| 3.0 | 5.6 | 94.4 |

**Table 3.7 :** The summary and comparison of % of ashes fineness

| **Materials** | **% Retained 45 micron** | **% Passing 45 micron** |
|---|---|---|
| OPC | 30 | 70 |
| SLAG | 6 | 94 |
| PFA | 8 | 92 |
| RHA | 4 | 96 |
| POFA | 6 | 94 |

**Table 3.8:** Series of mix proportion

**a) BBC mortar**

| Series | OPC (%) | (%) Replacement | wbr | **SP (%)** |
|---|---|---|---|---|
| SLAG | 50 | 50 | 0.53 | 0.1 |
| PFA | 70 | 30 | 0.43 | |
| RHA | 80 | 20 | 0.52 | |
| POFA | 90 | 10 | 0.51 | |

***b) MBC mortar***

| **Mix** | **OPC (%)** | **SLAG (%)** | **PFA (%)** | **RHA (%)** | **POFA (%)** | **wbr** | **Sp (%)** |
|---|---|---|---|---|---|---|---|
| MA | 50 | 20 | 5 | 20 | 5 | 0.54 | 0.1 |
| MB | 50 | 20 | 10 | 15 | 5 | 0.49 | |
| MC | 50 | 20 | 15 | 10 | 5 | 0.48 | |
| MD | 50 | 20 | 20 | 5 | 5 | 0.46 | |

**Table 3.9 :** Sand and Binders contents for 1m$^3$

| **Mix ratio** | **Binders** Kg/m$^3$ | **Sand** Kg/m$^3$ |
|---|---|---|
| 1:1 | 1100 | 1100 |
| 2:1 | 700 | 1400 |
| 2.5:1 | 600 | 1500 |
| 3:1 | 525 | 1575 |

**Table 3.10 :** Specification of the Sandwich Block

| | |
|---|---|
| Size | 400 x 200 x 100 mm |
| Thickness for Aerated lightweight concrete | 75± 1mm |
| Thickness for MBC mortar | 10 ± 2mm |

**Table 3.11:** Specification of the Aluminium powder

| **Specification** | No. 300 |
|---|---|
| Colour | Silver |
| Particle size | Mesh 220 |
| **Chemical composition (%)** | |
| Aluminium | Min 99.3 |
| Copper | Max 0.1 |
| Iron | Max 0.4 |
| Silica | Max 0.2 |

**Table 3.12:** Aerated lightweight concrete mix design

| **Density** | **1000 – 1100 kg/m$^3$** |
|---|---|
| Cement: Sand | 50:50 |
| Slag replacement | 50% |
| Aluminium Powder | 0.1% |
| Superplasticizer | 0.55% |
| Water of dry-mix | 0.23 |

**Establishment of Sand and Binders ratio**

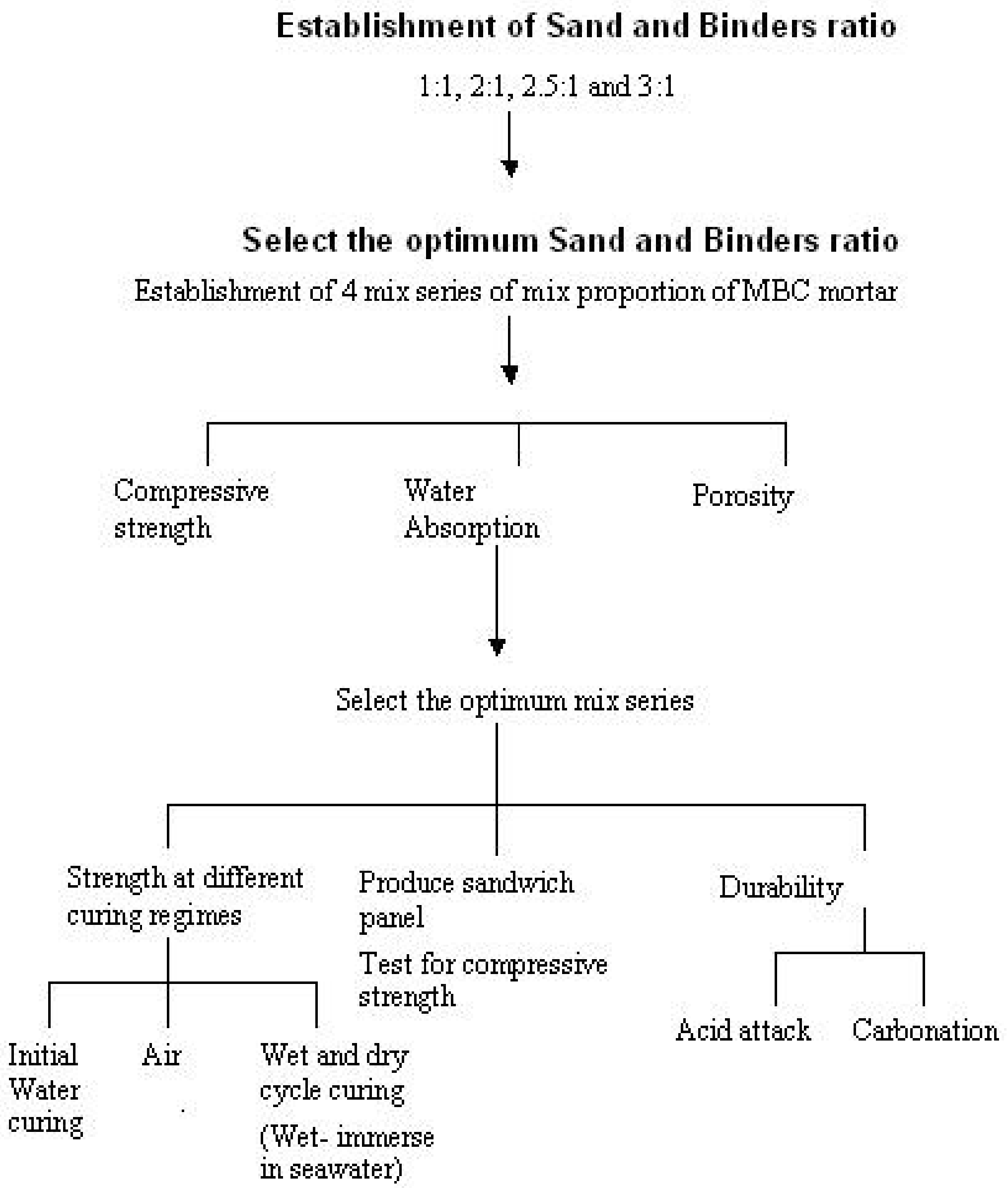


*Figure 3.1:* ***The flow of test program***

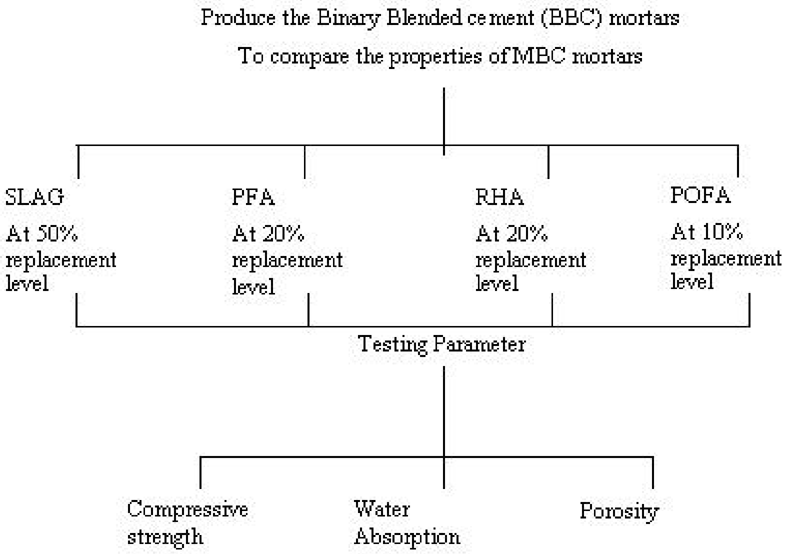


**Figure 3.2:** Supplementary test for comparison between properties of MBC and BBC mortars

**Figure 3.3:** Los Angeles Abrasion Machine (LAAT)

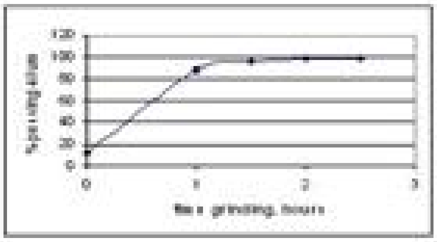


**Figure 3.4:** The optimum grinding time of RHA

**Figure 3.5:** 12mm diameter and 800mm long Mild steel

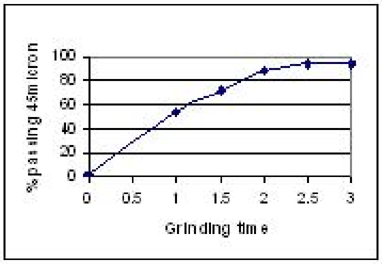


**Figure 3.6**: The optimum grinding time of POFA

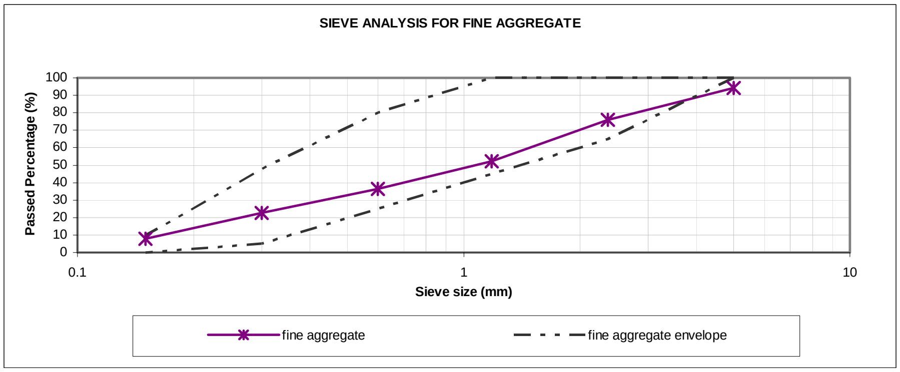


**Figure 3.7:** Sieve analysis

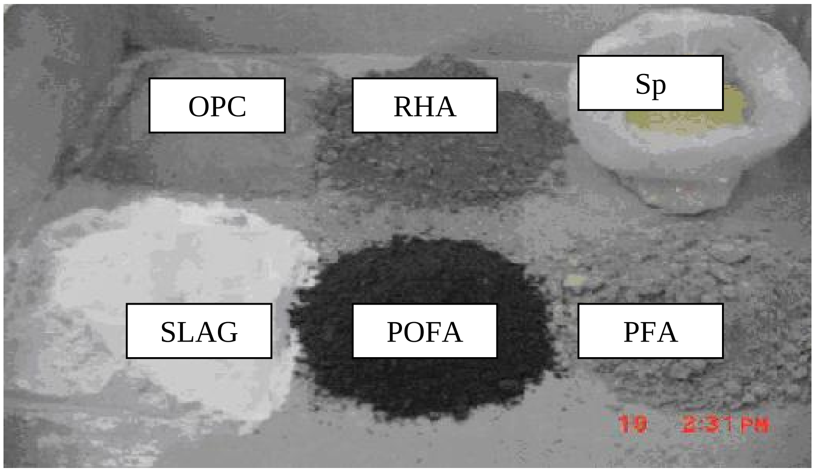


**Figure 3.8**: Materials used

**Figure 3.9**: Mortar Mixer

**Figure 3.10:** Casting into moulds size 70.6x70.6x70.6 mms

**Figure 3.11**: Vibration table

**Figure 3.12**: Flow table

**Figure 3.11**: Vibration table

**Figure 3.12**: Flow table

**Figure 3.15**: 50x50x50mm cubes cut from 100x100x100mm by cutter machine

**Figure 3.16**: Desiccator

**Figure 3.17**: Water absorption test (30 minutes immersion method)

**Figure 3.18**: Mould of Sandwich Block

**Figure 3.19:** Sandwich Block

# CHAPTER 4

# RESULTS AND DISSCUSIONS OF THE DEVELOPMENT OF MBC MORTARS

## 4.1 Introduction

This chapter discusses mainly on the results obtained from tests conducted from stage 1 to stage 3, which focussed on the development of MBC mortars. Whilst, the remaining test results from stage 4 to 6 are discussed in Chapter 5. The three stages discussed here are:

**Stage 1** – Water requirement test on mortar.

**Stage 2** – Establishment of the optimum sand to binders ratio (s/b).

**Stage 3 –** Establishment of the optimum series of mix proportion of MBC mortar by using the optimum sand to binders ratio. The test parameters involved are compressive strength, water absorption, and porosity.

## 4.2 Stage 1 - Water requirement test

### 4.2.1 Effects of wbr on various sand to binders ratio (s/b) of MBC mixes

This section discuses on the trend of water requirement of all MBC mixes whilst section 4.3 concentrates on the discussion of the optimum sand to binders ratio.

**Table 4.1 :** List of various sand to binders ratio to be investigated

| Sand to binders ratio |
|---|
| 1:1 |
| 2:1 |
| 2.5:1 |
| 3:1 |

**Table 4.2:** Series of mix proportion

**a) MBC mortar**

| Series | OPC (%) | SLAG (%) | PFA (%) | RHA (%) | POFA (%) |
|---|---|---|---|---|---|
| MA | 50 | 20 | 5 | 20 | 5 |
| MB | 50 | 20 | 10 | 15 | 5 |
| MC | 50 | 20 | 15 | 10 | 5 |
| MD | 50 | 20 | 20 | 5 | 5 |

**b) BBC mortar**

| **Series** | **OPC (%)** | **Percent Replacement (%)** |
|---|---|---|
| SLAG | 50 | 50 |
| PFA | 70 | 30 |
| RHA | 80 | 20 |
| POFA | 90 | 10 |

**Table 4.3** : Flow values for various s/b with addition of Sp

Sand to Binders ratio : **1:1, 2:1, 2.5:1, 3:1**
Type of mix : **MBC-MC**
% of Sp : **0.1%**

| **item** | **wbr** | **%flow** | **item** | **wbr** | **%flow** |
|---|---|---|---|---|---|
| **1:1** | 0.35 | 80 | **2:1** | 0.47 | 95 |
| | 0.36 | 105 | | 0.48 | 105 |
| | 0.37 | 120 | | 0.49 | 115 |

| **item** | **wbr** | **%flow** | **item** | **wbr** | **%flow** |
|---|---|---|---|---|---|
| **2.5:1** | 0.56 | 103 | **3:1** | 0.65 | 80 |
| | 0.57 | 105 | | 0.66 | 105 |
| | 0.58 | 115 | | 0.67 | 115 |

**Table 4.4 :** Summary of wbr with addition of Sp that produce a flow of 105-115%

Sand to binders ratio : **1:1, 2:1, 2.5:1, 3:1**
Type of mix : **MBC-MC**

| **s/b** | **wbr with Sp** |
|---|---|
| **1:1** | 0.36 |
| **2:1** | 0.48 |
| **2.5:1** | 0.57 |
| **3:1** | 0.66 |

**Table 4.5:**. Flow values for various s/b ratios without addition of Sp

Sand to binders ratio: **1:1, 2:1, 2.5:1, 3:1**
Type of mix: **MBC-MC**
% of Sp: **0%**

| Item | wbr | %flow | Item | wbr | %flow |
|---|---|---|---|---|---|
| **1:1** | 0.40 | 95 | **2:1** | 0.52 | 85 |
| | 0.41 | 105 | | 0.53 | 105 |
| | 0.42 | 120 | | 0.54 | 130 |

| Item | wbr | %flow | Item | wbr | %flow |
|---|---|---|---|---|---|
| **2.5:1** | 0.60 | 85 | **3:1** | 0.70 | 85 |
| | 0.61 | 105 | | 0.71 | 105 |
| | 0.62 | 120 | | 0.72 | 130 |

**Table 4.6 :** Summary of wbr with and without Sp that produce a flow of 105-115%

Sand to binders ratio : **1:1, 2:1, 2.5:1, 3:1**
Based on mix : **MBC-MC**

| s/b | wbr with SP | wbr without SP | % Reduced |
|---|---|---|---|
| **1:1** | 0.36 | 0.41 | 12.2 |
| **2:1** | 0.48 | 0.53 | 9.4 |
| **2.5:1** | 0.57 | 0.61 | 6.6 |
| **3:1** | 0.66 | 0.71 | 7.0 |

### 4.2.2 Effects on wbr of MBC compared with control mortar (with 0.1% Sp)

**Table 4.7 :** Flow values for Control mortar of various s/b ratio with addition of Sp.

Sand to binders ratio : **1:1, 2:1, 2.5:1, 3:1**
Type of mix : **CONTROL MORTAR**
% of Sp : **0.1%**

| Item | wbr | %flow | Item | wbr | %flow |
|---|---|---|---|---|---|
| **1:1** | 0.36 | 85 | **2:1** | 0.50 | 90 |
| | 0.37 | 105 | | 0.51 | 105 |
| | 0.38 | 120 | | 0.52 | 120 |

| Item | wbr | %flow | Item | wbr | %flow |
|---|---|---|---|---|---|
| **2.5:1** | 0.56 | 60 | **3:1** | 0.70 | 95 |
| | 0.60 | 90 | | 0.71 | 105 |
| | 0.61 | 105 | | 0.72 | 120 |

**Table 4.8 :** Summary of wbr of MBC-MC mortar compare with Control mortar

Sand to binders ratio : **1:1, 2:1, 2.5:1, 3:1**

Type of mix : **MBC-MC & Control mortar**

% of Sp : **0.1%**

| s/b | wbr of MBC-MC | Wbr of Control |
|---|---|---|
| **1:1** | 0.36 | 0.37 |
| **2:1** | 0.48 | 0.51 |
| **2.5:1** | 0.57 | 0.61 |
| **3:1** | 0.66 | 0.71 |

### 4.2.3 Effects of wbr on MBC mortar compared to BBC mortar

**Table 4.9:** Flow values for MBC mortars

Sand to binders ratio : **2:1**

Type of mix : **MBC**

% of Sp : **0.1%**

| item | wbr | %flow | item | wbr | %flow |
|---|---|---|---|---|---|
| **MA** | 0.52 | 90 | **MB** | 0.48 | 90 |
| | 0.53 | 105 | | 0.49 | 105 |
| | 0.54 | 125 | | 0.53 | 125 |

| item | wbr | %flow | item | wbr | %flow |
|---|---|---|---|---|---|
| **MC** | 0.47 | 95 | **MD** | 0.44 | 80 |
| | 0.48 | 105 | | 0.46 | 105 |
| | 0.49 | 115 | | 0.47 | 120 |

**Table 4.10 :** Summary of wbr for MBC mortars that produce flow of 105-115%

Sand to binders ratio : **2:1**

Type of mix : **MBC**

% of Superplasticizer : **0.1%**

| MBC | wbr |
|---|---|
| **MA** | 0.54 |
| **MB** | 0.49 |
| **MC** | 0.48 |
| **MD** | 0.46 |

**Table 4.11 :** Flow values for BBC mortars

Sand to binders ratio : **2:1**
Type of mix : **BBC**
% of Superplasticizer : **0.1%**

| **Item** | **wbr** | **%flow** | **Item** | **wbr** | **%flow** |
|---|---|---|---|---|---|
| **RHA** | 0.52 | 105 | **POFA** | 0.48 | 85 |
| | 0.53 | 120 | | 0.50 | 105 |
| | 0.54 | 130 | | 0.52 | 140 |

| **Item** | **wbr** | **%flow** | **Item** | **wbr** | **%flow** |
|---|---|---|---|---|---|
| **SLAG** | 0.52 | 95 | **PFA** | 0.42 | 95 |
| | 0.53 | 105 | | 0.43 | 105 |
| | 0.54 | 140 | | 0.44 | 110 |

| **item** | **wbr** | **%flow** |
|---|---|---|
| **Control** | 0.50 | 90 |
| | 0.51 | 105 |
| | 0.52 | 120 |

**Table 4.12**: Summary of wbr for MBC mortars compared to BBC mortars producing flow of 105-115%

Sand to binders ratio : **2:1**
Type of mixes : **BBC & MBC**
% of Sp : **0.1%**

| **Mixes** | **wbr** |
|---|---|
| BBC (PFA) | 0.43 |
| MBC (MD) | 0.45 |
| MBC (MC) | 0.48 |
| MBC (MB) | 0.49 |
| BBC (POFA) | 0.50 |
| CONTROL | 0.51 |
| BBC (RHA) | 0.52 |
| BBC (SLAG) | 0.53 |
| MBC (MA) | 0.53 |

## 4.3 Stage 2 - Establishment of optimum sand to binders ratio (s/b) in terms of strength and wbr

**Table 4.13**: The wbr and the compressive strength of mortar for all s/b at constant flow of 105-115%

| Ratio | Binders content (kg/m$^3$) | OPC content (kg/m$^3$) (50% cement replacement) | wbr | Compressive strength (MPa) | |
|---|---|---|---|---|---|
| | | | | 7 days | 28 days |
| 1:1 | 1100 | 550 | 0.36 | 41.3 | 56.8 |
| 2:1 | 700 | 350 | 0.48 | 30.6 | 44.7 |
| 2.5:1 | 600 | 300 | 0.57 | 27.0 | 39.6 |
| 3:1 | 525 | 262.5 | 0.66 | 18.7 | 28.1 |

## 4.4 Stage 3 – Establishment of the optimum mix proportion of MBC mortar in terms of Strength, Water Absorption and Total Porosity test results by using the optimum sand to binders ratio (s/b).

During this stage, the optimum mix proportion of MBC mortar was analysed and selected based on three parameters, mentioned earlier namely the strength development, total porosity, and water absorption. The properties of MBC mortars in all parameters studied were also compared with control and BBC mortars. All parameters are discussed in the following sections.

### 4.4.1 Strength development

**Table 4.14 :** The wbr and the compressive strength of mortar without Sp at constant flow of 105-115%

| | | Compressive Strength (MPa) | | | |
|---|---|---|---|---|---|
| Mix | Wbr | 7days | 28days | 60days | 90days |
| OPC | 0.53 | 34.1 | 49.2 | 53.6 | 58.1 |
| MA | 0.57 | 19.3 | 38.2 | 48.2 | 56.3 |
| MB | 0.54 | 26.7 | 42.7 | 49.2 | 58.8 |
| MC | 0.53 | 28.1 | 42.1 | 50.2 | 59.1 |
| MD | 0.50 | 28.3 | 46.1 | 54.4 | 60.3 |
| RHA | 0.55 | 31.3 | 41.3 | 55.3 | 57.1 |
| POFA | 0.53 | 37.5 | 47.2 | 53.0 | 60.5 |
| PFA | 0.47 | 33.3 | 50.8 | 63.1 | 68.9 |
| SLAG | 0.57 | 26.1 | 41.1 | 49.7 | 56.5 |

**Table 4.15 :** The wbr and the compressive strength of mortar with 0.1% Sp at constant flow of 105-115%

| | | **Compressive Strength (MPa)** | | | |
|---|---|---|---|---|---|
| **Mix** | **Wbr** | **7days** | **28days** | **60days** | **90days** |
| OPC | 0.51 | 37.6 | 49.4 | 53.3 | 58.3 |
| MA | 0.54 | 26.1 | 43.1 | 47.8 | 56.0 |
| MB | 0.49 | 30.4 | 46.8 | 48.8 | 58.5 |
| MC | 0.48 | 30.6 | 44.7 | 55.0 | 59.7 |
| MD | 0.46 | 34.2 | 45.4 | 57.6 | 61.2 |
| RHA | 0.52 | 38.4 | 52.5 | 57.8 | 57.8 |
| POFA | 0.50 | 39.2 | 47.7 | 55.4 | 61.1 |
| PFA | 0.43 | 35.1 | 53.4 | 65.3 | 69.4 |
| SLAG | 0.53 | 29.9 | 44.5 | 52.3 | 57.0 |

#### 4.4.1.1 The strength development of BBC Mortars compared to Control mortars

**a) RHA mortar**

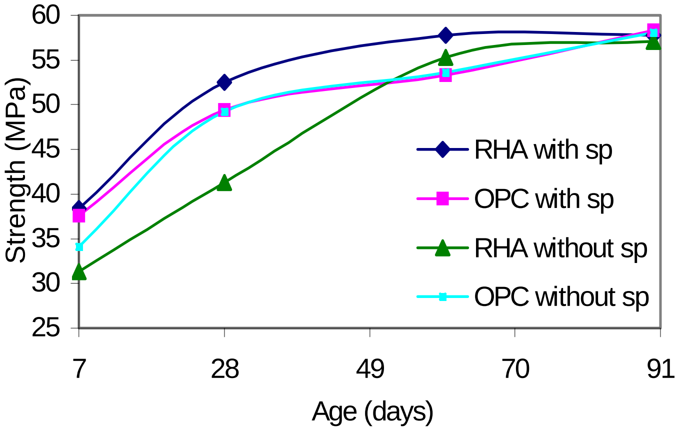


**Figure 4.1:** Strength development of RHA mortar

**b) PFA mortar**

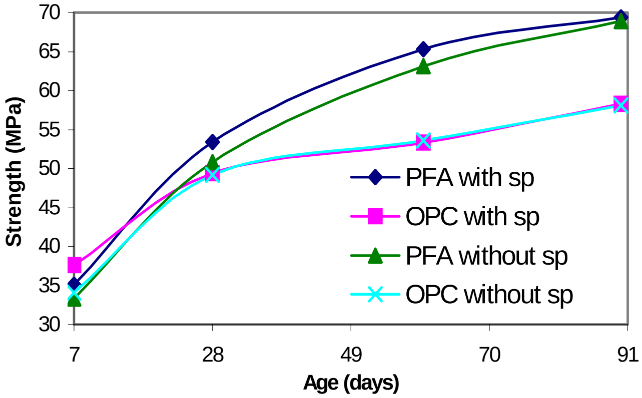
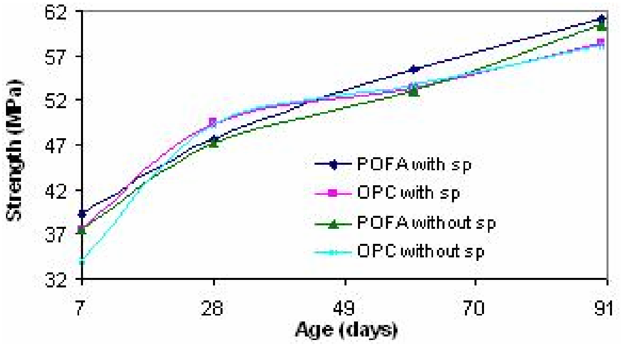


**Figure 4.2:** Strength development of PFA mortar



### c)

### POFA mortar

**Figure 4.3:** Strength development of POFA mortar

### d) Slag mortar

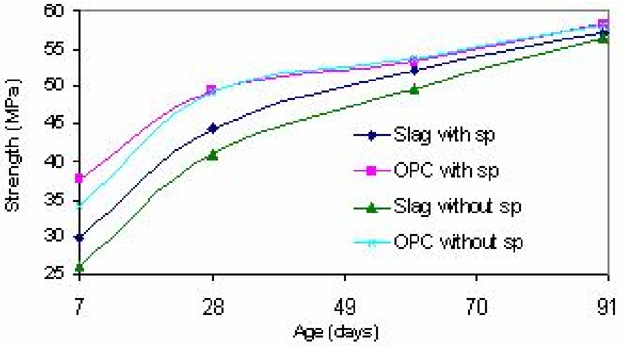


**Figure 4.4:** Strength development of Slag mortar

#### 4.4.1.2 Strength comparisons among all BBC mortars.

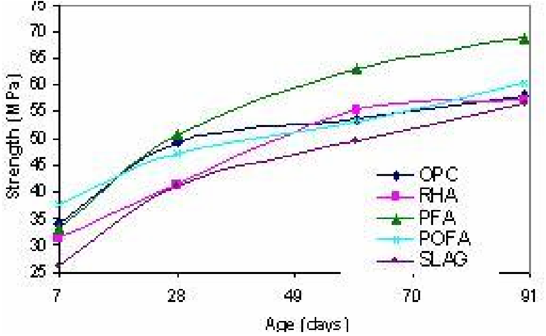


**Figure 4.5:** Strength comparisons among all BBC mortars without Sp

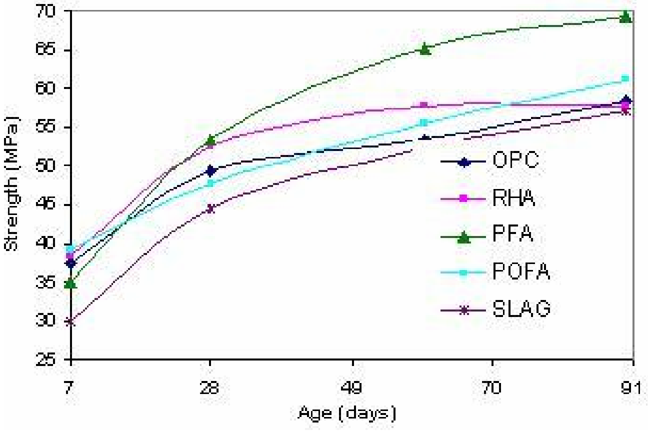


**Figure 4.6:** Strength comparisons among all BBC mortars with Sp

### 4.4.1.3 Strength development of MBC compared to Control mortar.

**a) MA mortar**

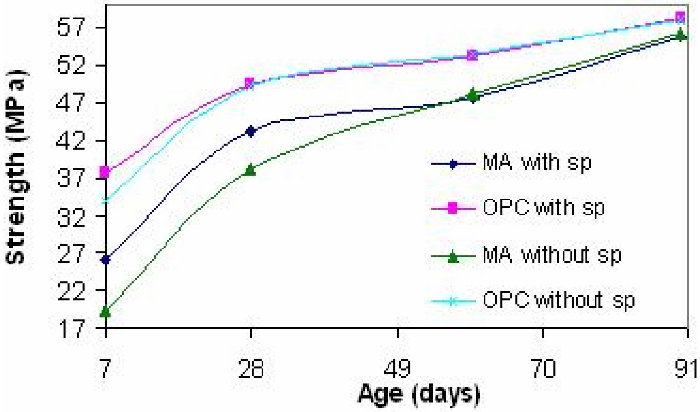


**Figure 4.7:** Strength development of MA mortar

**b) MB mortar**

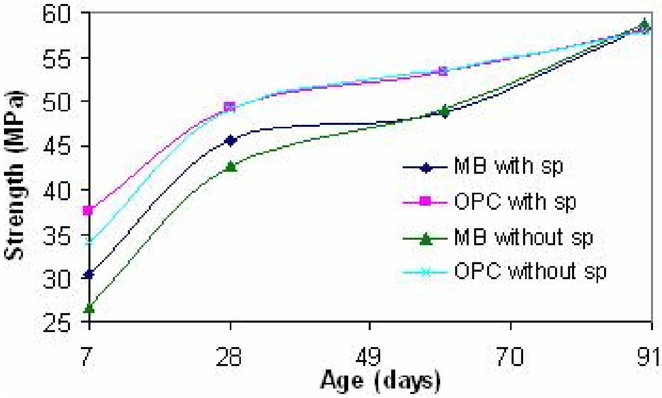
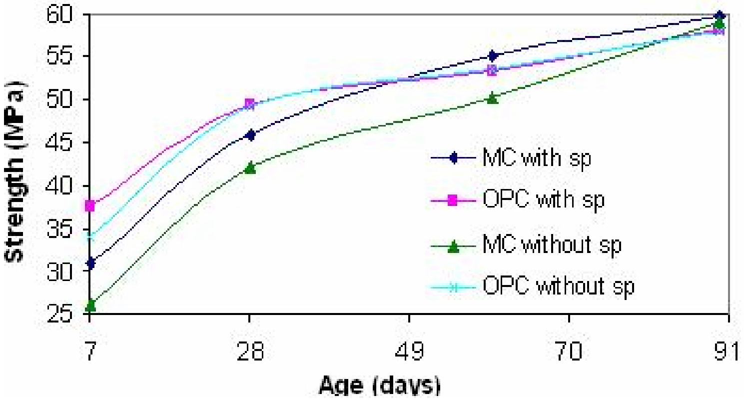
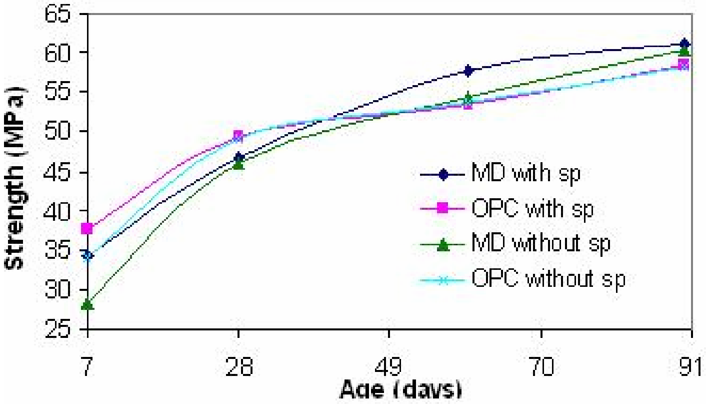


**Figure 4.8:** Strength development of MB mortar



**c) MC mortar**

**Figure 4.9:** Strength development of MC mortar



**d) MD mortar**

**Figure 4.10:** Strength development of MD mortar

### 4.4.1.4 Strength comparisons among all MBC mortars.

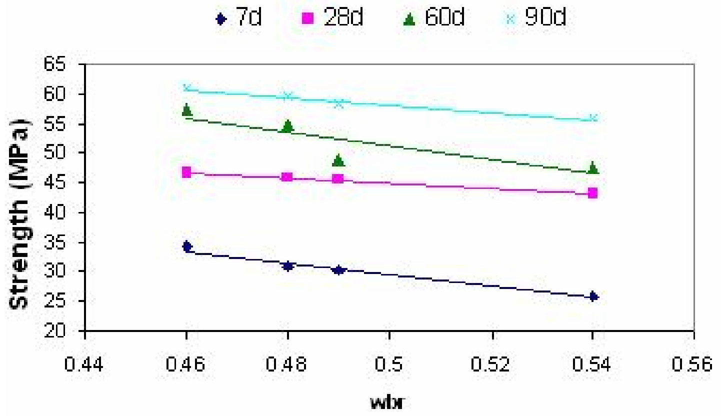


**Figure 4.11:** Strength of MBC mortars with different wbr

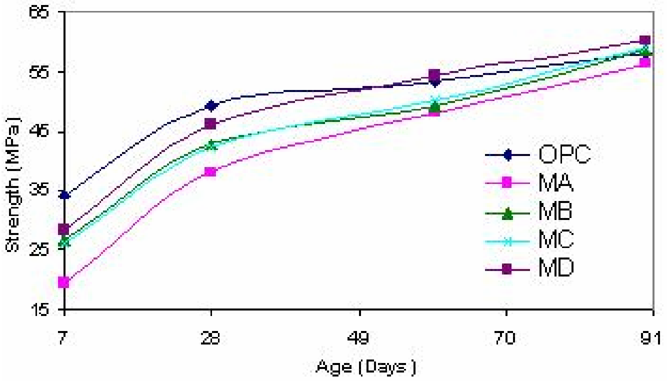


**Figure 4.12:** Strength comparisons among all MBC mortars without Sp

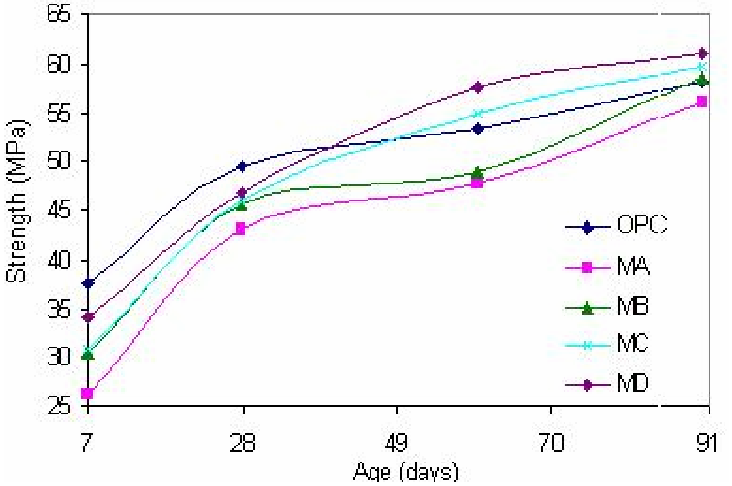


**Figure 4.13:** Strength comparisons among all MBC mortars with Sp

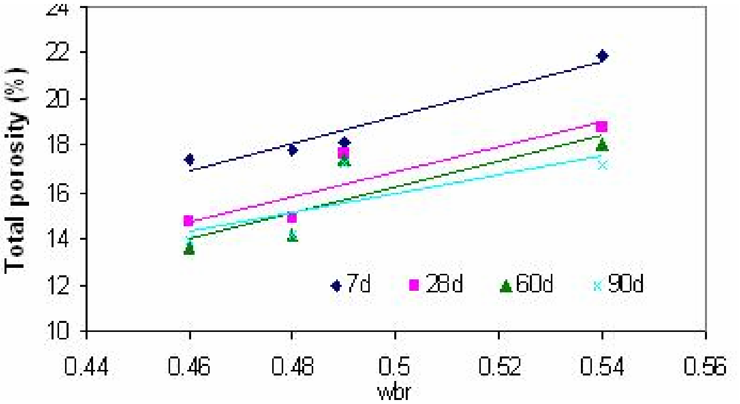


**Figure 4.14:** Total porosity of MBC mortars with different wbr

### 4.4.1.5 Strength comparisons between Control, MBC, and BBC mortars.

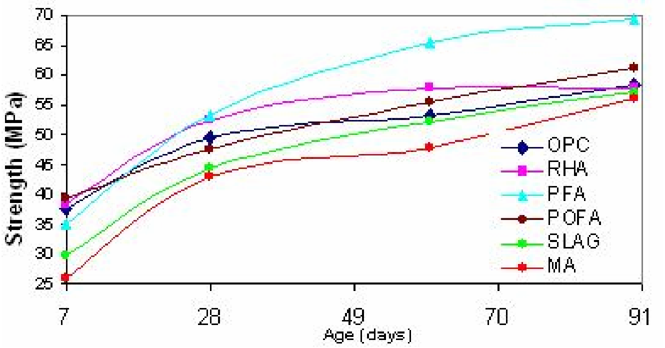


**Figure 4.15:** Strength comparisons between Control, MA and BBC mortars without Sp

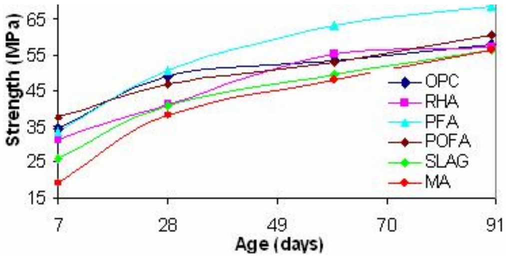


**Figure 4.16:** Strength comparisons between Control, MA and BBC mortars with Sp

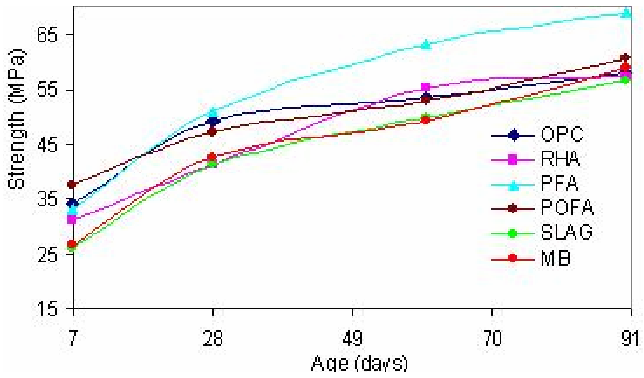


**Figure 4.17:** Strength comparisons between Control, MB and BBC mortars without Sp

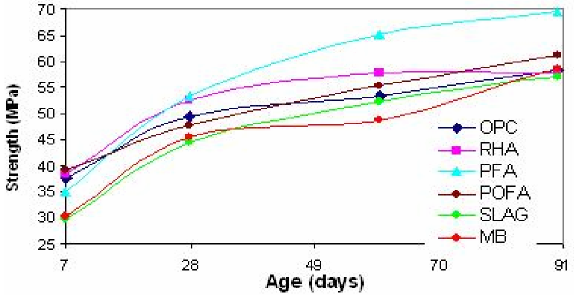


**Figure 4.18:** Strength comparisons between Control, MB and BBC mortars with Sp

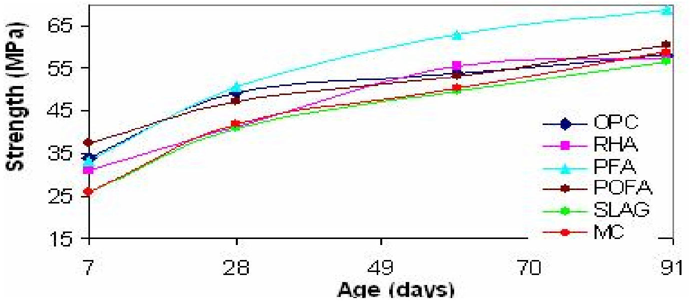


**Figure 4.19:** Strength comparisons between Control, MC and BBC mortars without Sp

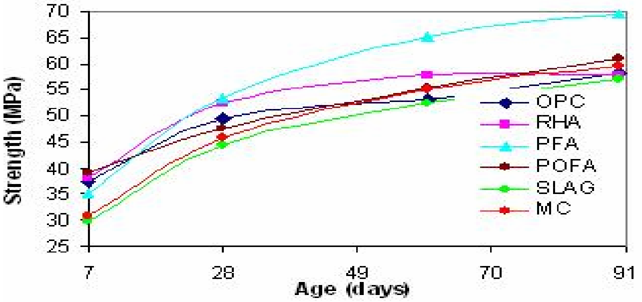


**Figure 4.20:** Strength comparisons between Control, MC and BBC mortars with Sp

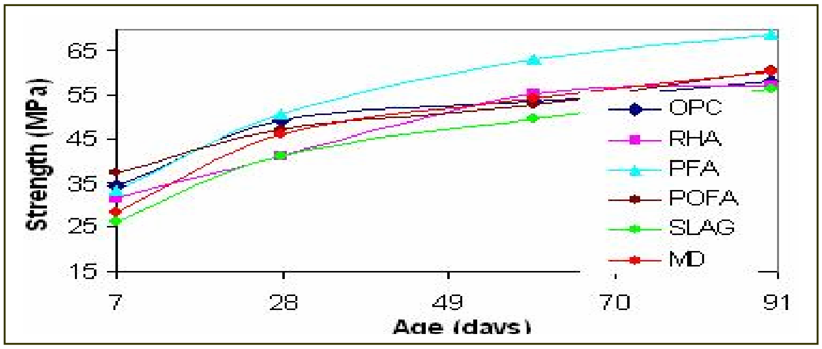


**Figure 4.21:** Strength comparisons between Control, MD and BBC mortars without Sp

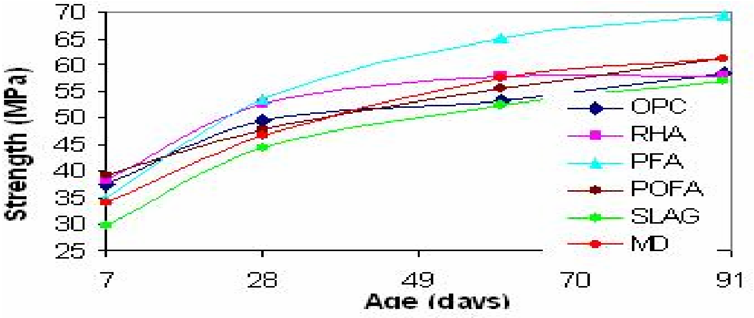


**Figure 4.22:** Strength comparisons between Control, MBC and BBC mortars with Sp

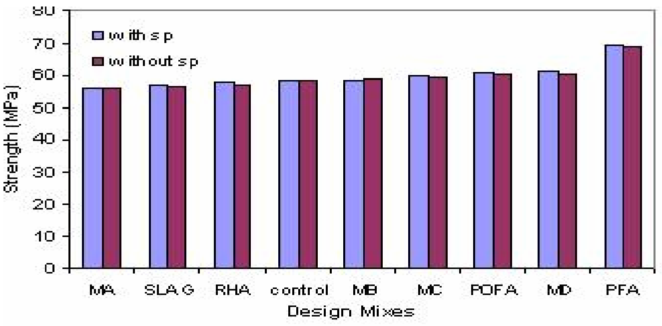


**Figure 4.23a:** Strength comparisons of all mortars at 90 days (generally)

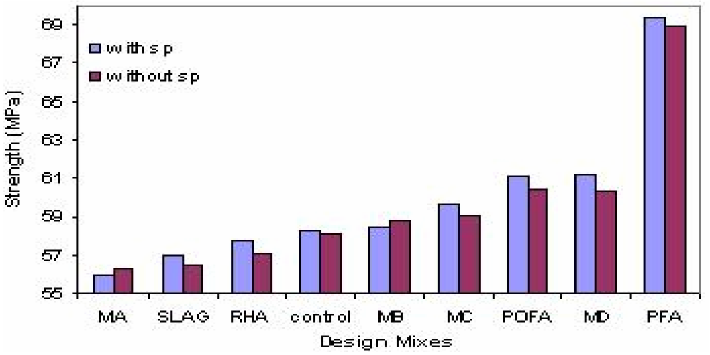


**Figure 4.23b:** Strength comparisons of all mortars at 90 days (precisely)

### 4.4.1.6 Conclusions

This section concludes the performance of mortar mixes on the strength development. From the findings, it can be concluded that there are many factors influencing the strength development of MBC mortars. For the MBC mortar series, it is observed that at the fixed content of Slag and POFA, it seems that the reduction in wbr positively influenced the strength development of MBC mortars. Where as, if seen in the overall performance that is in all systems, the strength of MBC mortars were also influenced by the low reactivity of Slag, and RHA and also enhanced by the physical and chemical characteristics of PFA in the multi-blended mixes.

The strength of BBC mortars significantly depends on the degree of hydration and its chemical properties. The strength values of MBC mortars were lower than Control and BBC mortars at early ages of hydration. PFA mortar showed the highest strength value after 28 days. Whilst, MD and POFA also produced the highest strength besides PFA compared to the rest of mortars. MA, and Slag mortars exhibited the lowest strength values at final ages.

The effect of Sp on strength of control mortar shows, which is containing 100% of OPC, can potentially be prepared without the addition of Sp due to the strength without Sp was only 9% lower than the strength with Sp at early age. PFA and POFA also can be prepared without addition of Sp due to the strength without Sp was only 4% lower through all ages. While slow reactivity RHA, and Slag used in this study required addition of SP to enhance the early strength. Whereas, for the MBC mortars, the addition of Sp was also necessary and was the important factor in order to enhance the strength. It was due to the MBC mixes that require longer periods of curing time to develop strength as discusses before.

Although the strength of BBC mortars was not significantly influenced by the low wbr effect, as far as the durability is concerned, which is governed by porosity and permeability, both parameters are significantly related to low wbr. It is well known that Sp improves workability of mortar or concrete mixes with low wbr. Therefore, in this research all mortar mixes for the studies of Total Porosity and Water Absorption contained a fixed dosage of 0.1% SP. The choice of the dosage was based on the manufacturer's recommendation.

## 4.2 Total Porosity of mortar

### a) BBC mortars

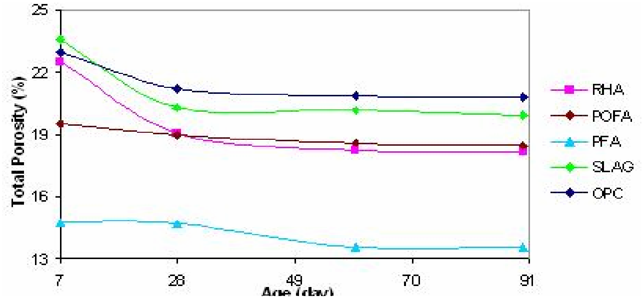


**Figure 4.24:** Total porosity of BBC and Control mortars

### b) MBC mortars

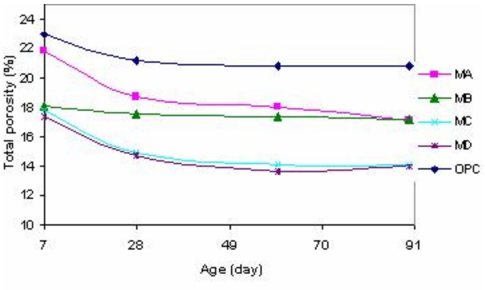


**Figure 4.25:** Total porosity of MBC and Control mortars

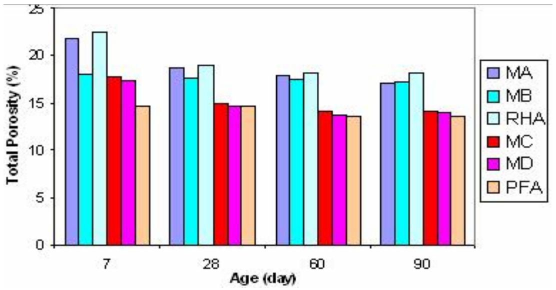


**Figure 4.26:** Influences of PFA and RHA in porosity of MBC mortars

From the test results it can be deduced that the total porosity of MA and MB was affected by the physical properties of RHA. While MC and MD was affected by the physical properties of PFA.

### c) Control, MBC and BBC mortars

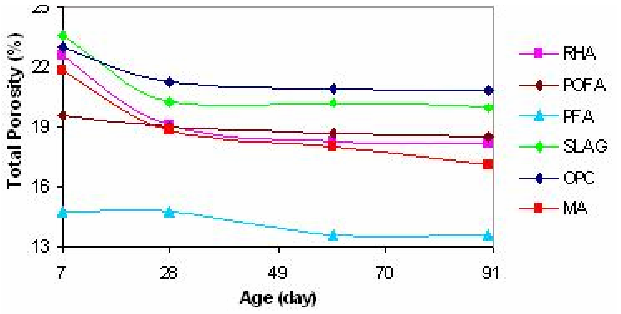


**Figure 4.27:** Porosity of MA, Control and BBC mortars

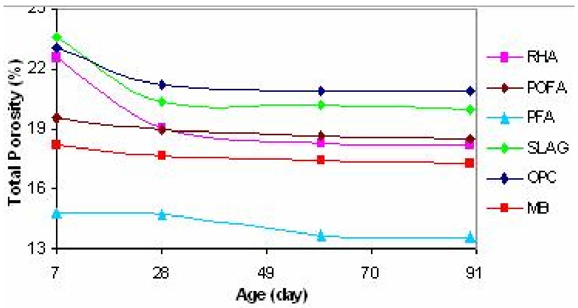


**Figure 4.28:**Porosity of MB, Control and BBC mortars

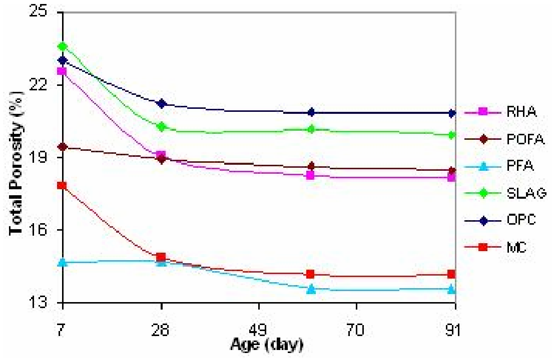


**Figure 4.29:** Porosity of MC, Control and BBC mortars

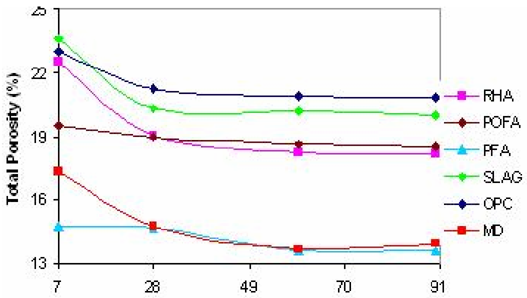


**Figure 4.30:** Porosity of MD, Control and BBC mortars

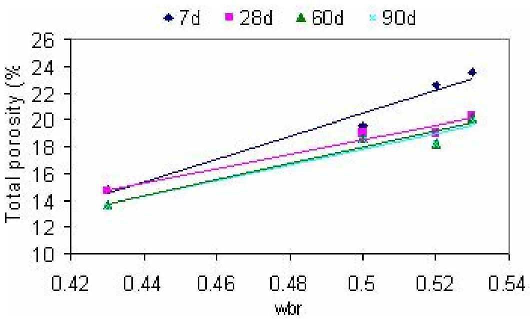


**Figure 4.31:** Total porosity of BBC mortars with different wbr

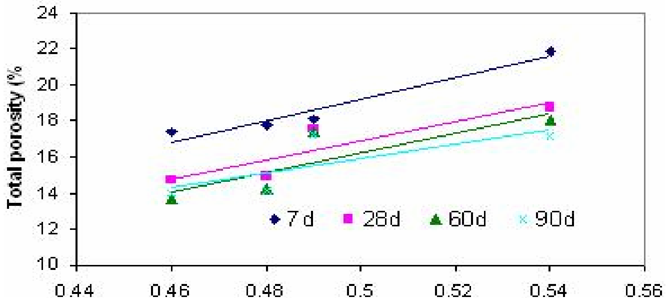


**Figure 4.32:** Total porosity of MBC mortars with different wbr

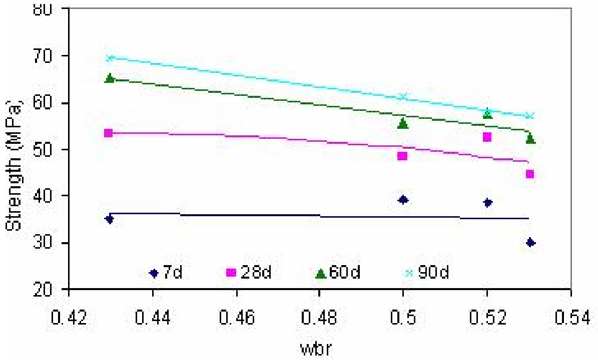


**Figure 4.33:** Strength of BBC mortars with different wbr

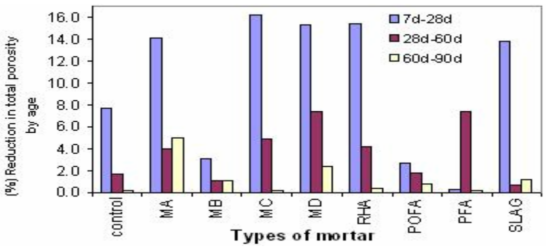


**Figure 4.34:** Percentage of reduction in porosity by age

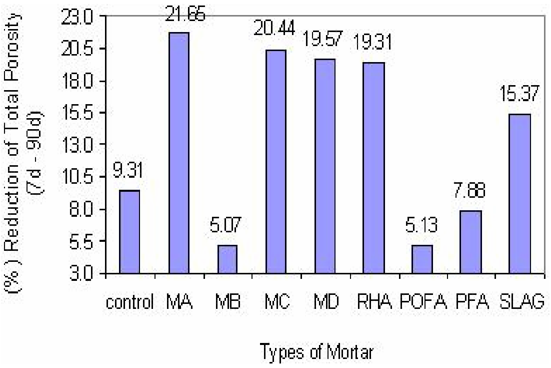


**Figure 4.35:** Percentage reduction in porosity between 7 and 90 days

It can be concluded that the low wbr content of MBC mortars produced considerably lower porosity beside PFA mortars, whilst control, Slag, POFA and RHA mortars (highest wbr) show the highest porosity mortars. It does indicate that the lower content of wbr significantly governed the porosity in hardened mortar. As the wbr increases, the total porosity also increases.

### 4.4.3 Water absorption test results

Water mobility in hardened mortar and concrete is governed by capillary pore. In other words water can flow and be absorbed more easily through the volume of large pores or capillary pores and the continuity of microstructural than through the much smaller pores. Detailed results are as follows:

**a) BBC mortars**

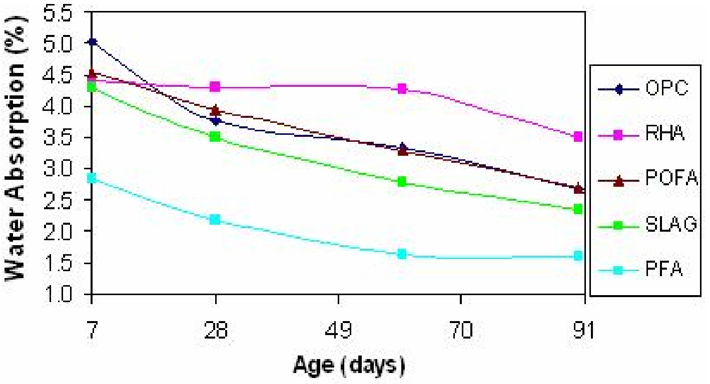


**Figure 4.36:** Water absorption of BBC and Control mortars

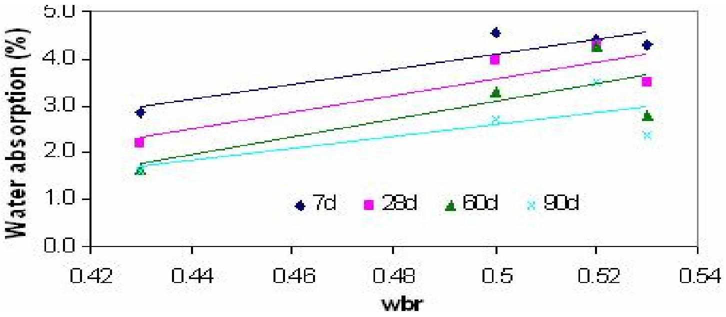


**Figure 4.37:** Water absorption of BBC mortars with different wbr

**b) MBC mortars**

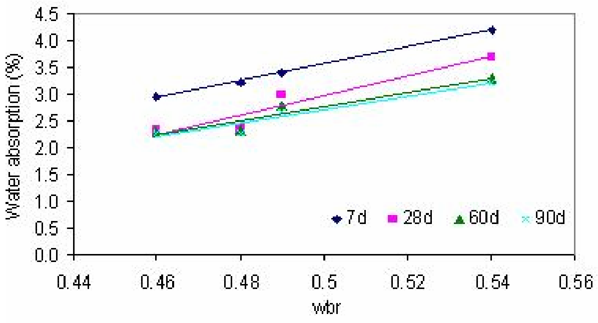


**Figure 4.38:** Water absorption of MBC mortars with different wbr

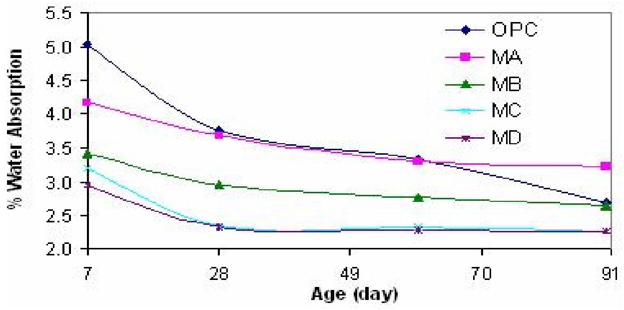


**Figure 4.39:** Water absorption of MBC and Control mortars

### c) Control, MBC and BBC mortars

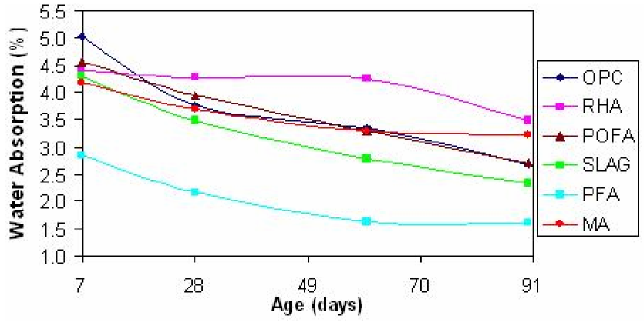


**Figure 4.40:** Water absorption of Control, BBC and MA mortars

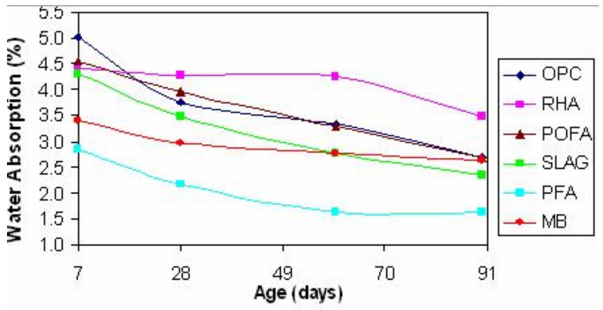


**Figure 4.41:** Water absorption of Control

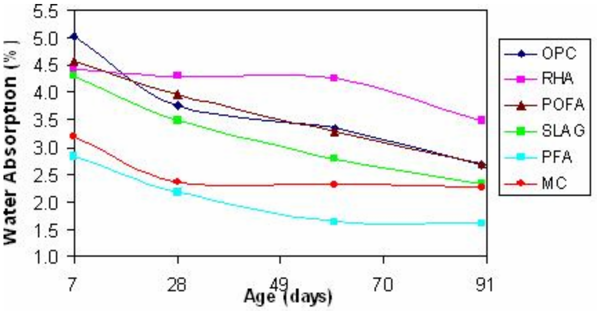


**Figure 4.42:** Water absorption of Control

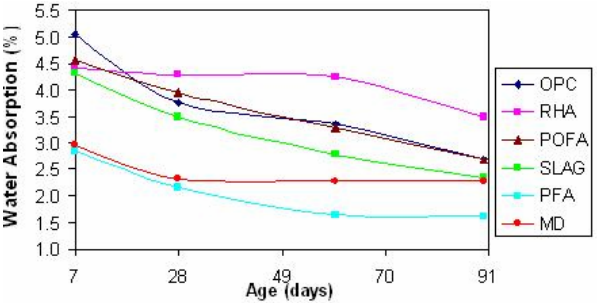


**Figure 4.43:** Water absorption of Control

The low wbr effect was observed to contribute great influence to produce lower water absorption. It was proven by the results of MBC mortars that produced low absorption beside PFA mortar than the rest of BBC and control mortars.

### 4.4.4 Strength and Total porosity relationship

### a) BBC mortars

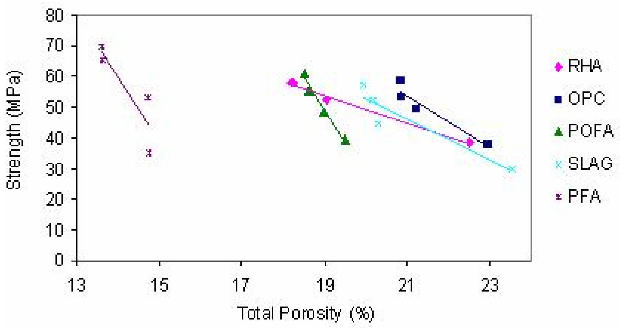


**Figure 4.44 :** The Relationship Between Compressive Strength and Total Porosity of Control OPC and BBC mortars

### b) MBC mortars

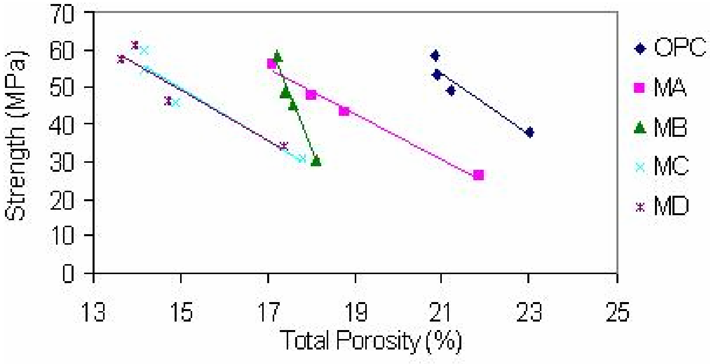


**Figure 4.45:** The Relationship Between Compressive Strength and Total Porosity of Control OPC and MBC mortars

### 4.4.5 The relationships between compressive strength and water absorption

### a) BBC mortars

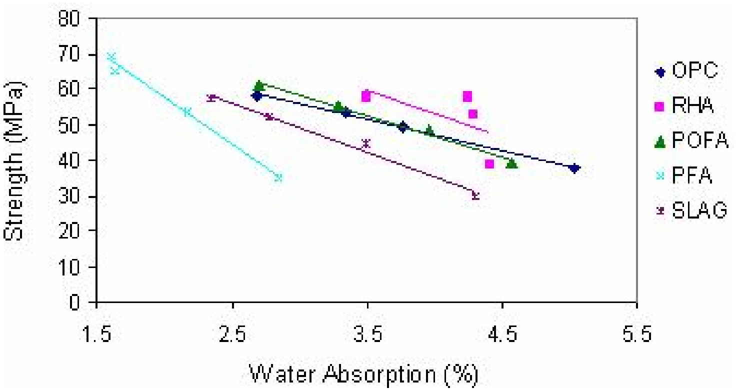


**Figure 4.46:** The Relationship Between Compressive Strength and Water Absorption of Control OPC and BBC mortars

### b) MBC mortars

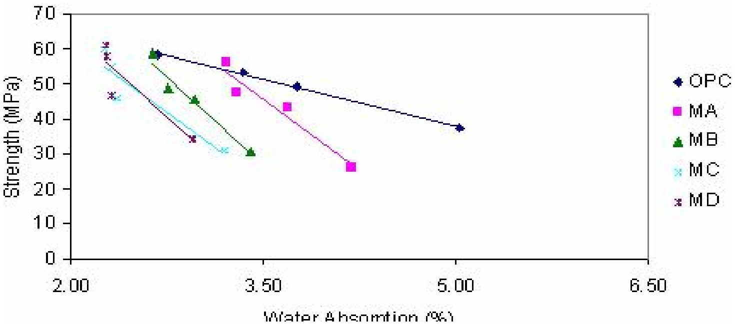


**Figure 4.47:** The Relationship Between Compressive Strength and Water Absorption of Control OPC and MBC mortars

### 4.4.6 Relationships between total porosity and water absorption

a) BBC mortars

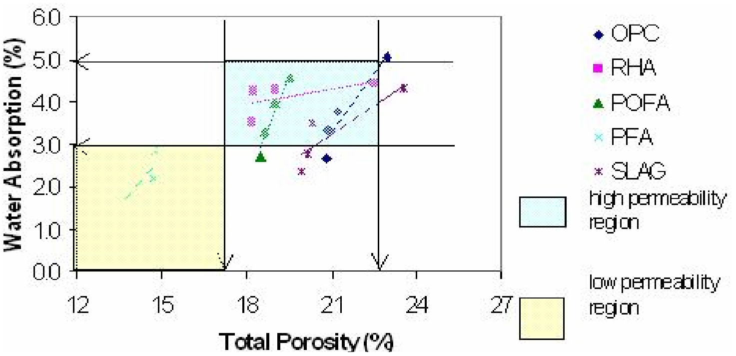


**Figure 4.48: T**he Relationship Between Water Absorption and Total Porosity of Control OPC and BBC mortars

**b) MBC mortars**

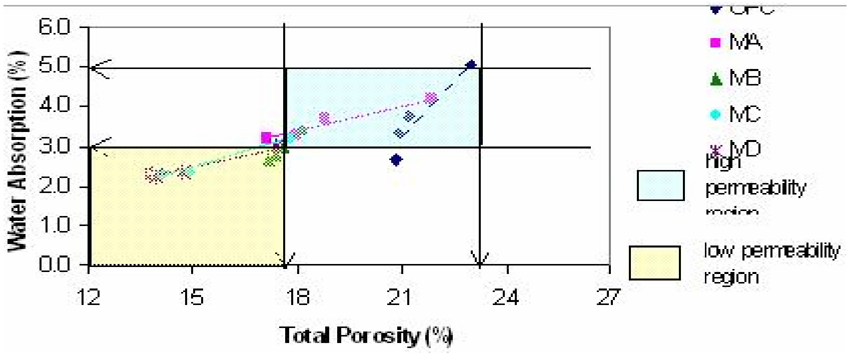


**Figure 4.49:** The Relationship Between Water Absorption and Total Porosity of Control OPC and MBC mortars

### 4.4.7 X-Ray Diffraction analyses (XRD)

All samples of all the mixes were analysed by the XRD to check the reaction with calcium hydroxide (CH), where the decreased amount of CH indicates the existence of the pozzolanic activity. The pozzolanic reaction depends on the CH released by the hydration reactions of calcium silicates (Isaia *et al*., 2003). Nevertheless, the analysis was in terms of qualitative not quantitative values. The analysis was based on the intensity of the peak corresponding to CH in the samples. Figures 4.50 and 4.51, illustrate the XRD patterns of the control, BBC and MBC pastes which were hydrated for 90 days with water curing.

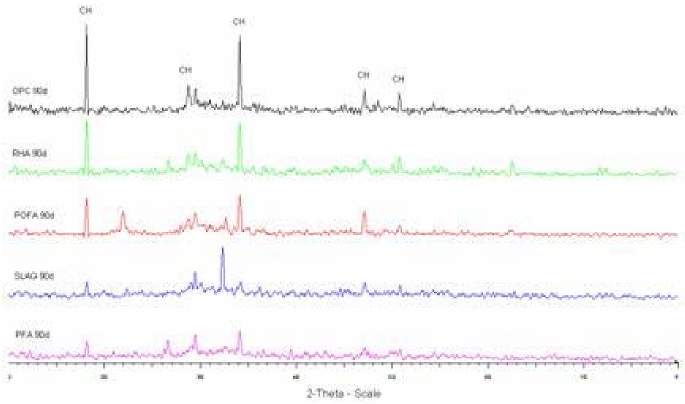


**Figure 4.50**: XRD patterns of BBC pastes hydrated at 90 days

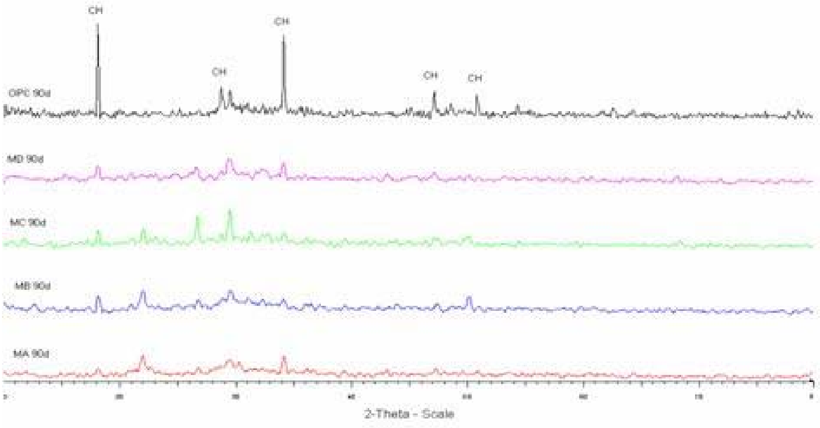


**Figure 4.51:** XRD patterns of MBC pastes hydrated at 90 days

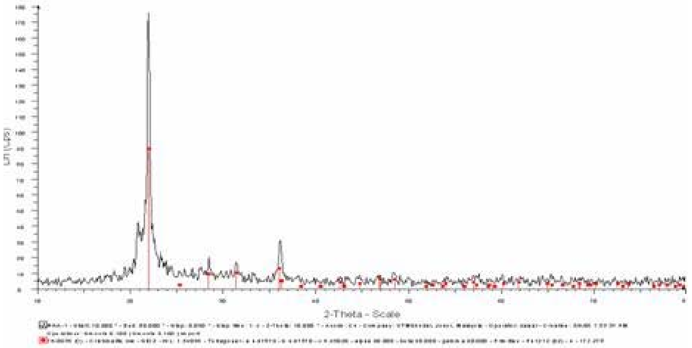


**Figure 4.52:** XRD patterns of unhydrated RHA sample

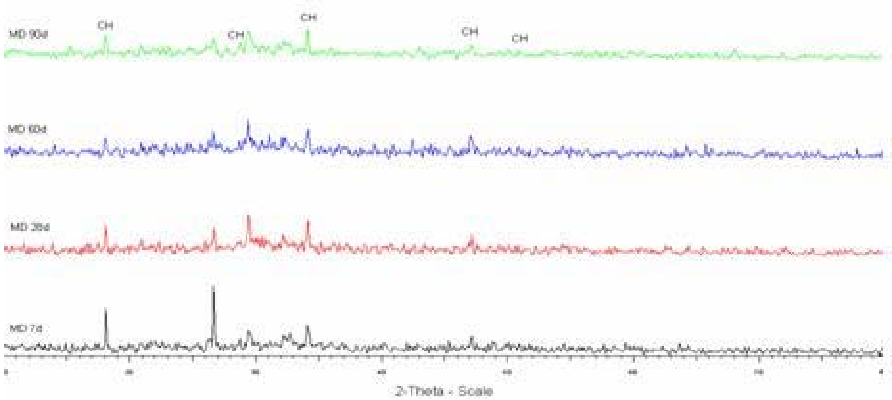


**Figure 4.53:** XRD patterns of MD hydrated at 7, 28, 60 and 90 days

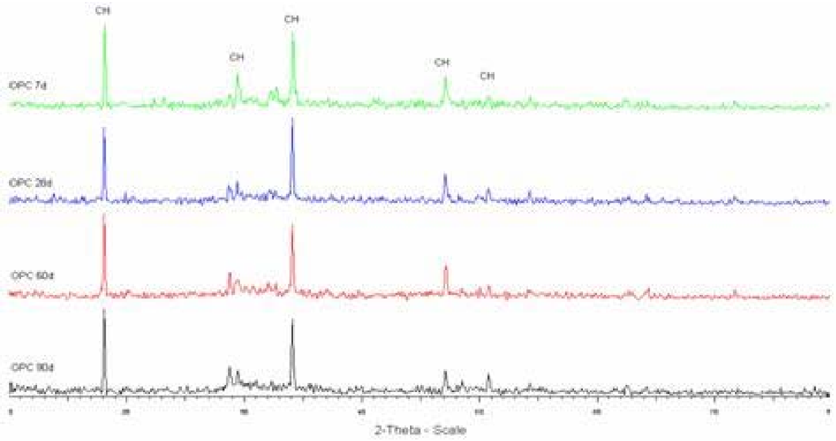


**Figure 4.54:** XRD patterns of OPC hydrated at 7, 28, 60 and 90 days

From the XRD patterns of all pastes, it can be deduced that cement containing multi-blended pozzolanic materials possesses better properties due to its low alkalinity which also contains less amount of CH rather than binary blended cements mainly POFA and RHA, as well as cement containing 100% Portland cement. Concrete having high alkalinity is generally less well resistance to chemical attack. It generally occurs by way of decomposition of the products of hydration and the formation of new compounds, which may leach out or disruptive in situ. The CH is the most vulnerable compound being attacked. The low alkalinity of MBC paste can potentially impedes further reaction of the chemical ingress with CH. Nonetheless, PFA, and Slag also show low alkalinity because of the less amount of CH content.

### 4.4.8 Overall performance of MBC mortars to select the optimum mix

#### a) MA mix

MA mix, which contains higher replacement of RHA produced the highest wbr, exhibited the lowest strength compared to other MBC mixes through all ages. However, the strength at final age was comparable with control mortar with only 3% less than the control. The highest wbr of MA mixes also affected the total porosity in hardened MA mortar, which produced the highest total porosity compared to the rest of MBC mortars. However the total porosity of MA mortars was comparable with MB mortars at the final ages. It was also observed that the total porosity of MA mortars tends to approach RHA mortars mainly at early ages. MA mortars showed lower porosity than control, RHA, POFA and Slag at final ages.

MA mix also showed the highest water absorption compared to all MBC mixes at all ages. It also exhibited the highest absorption compared to BBC mixes mainly after 7 days. The linear correlation between strength and total porosity for MA mixes lie below the control line. It shows that MA mixes were able to reduce porosity compared to control even at early ages. The linear correlation between strength and water absorption for MA mixes was below the control line. However, at final age MA mixes tend to over cross control mix. MA was identified as high permeability mortar that was proven from the linear relationship between water absorption and total porosity, which resulted within the high permeability region. The control mortar could also be placed in the same regions. Although MA mixes resulted in high permeability mortar, it produced average porosity mortar at final ages.

#### b) MB mix

The strength values of MB mixes were higher than MA mixes but were lower than MD mixes through all ages. The strength values were comparable with MC mixes. However, the strength at final ages was comparable with control mortar and slightly higher than Slag and RHA and lower than POFA mortar. The total porosity of MB mortar was higher than MC, and MD mortars. MB mortars produced lower porosity than MA mortar but at final ages it was comparable. However, the total porosity was lower than control and BBC and higher than PFA mortars at all ages. The water absorption of MB mortar also results in similar trend with total porosity. However the absorption of MB mortars at final ages was comparable with control, and POFA mortars and higher than Slag, and PFA mortars.

The linear correlation between strength and porosity of MB mixes lie far below control mortars. It showed that MB mixes were able to reduce porosity compared to control mortars. The linear correlation between strength and water absorption is also below than the line of control mortar. However the sample tends to approach the control mortar at final ages. For the linear correlation between water absorption and porosity at early ages, the MB samples tend to approach in the outermost part in high permeability regions. Nevertheless, the samples at final ages resulted in outermost part in low regions. MB mixes were identified as average permeability with average porosity mortar.

### c) MC mix

As mentioned above the strength of MB, and MC mortars is comparable through all ages. The strength of MC was higher than MA but lower than MD mortar at all ages of hydration. The strength of MC mortars is comparable with control mortars. Its strength is higher than RHA, and Slag but lower than POFA, and PFA mortars. The total porosity of MC mortars tends to approach MD mortars through all ages. However, it was lower than MA, MB and BBC mortars, and higher than PFA mortar. The absorption of MC mortars also showed similar trend with MD mortar mainly after 7 days of hydration. It was also lower than MA, and MB mortars through all ages. The absorption of MC mortars was lower than control, POFA, and RHA mortars but higher than PFA mortar. It was also observed that the absorption of MC mortar was slightly lower than Slag mortar at the final ages.

The linear correlation between strength and porosity of MC mortar slightly approaches to that of the MD mortar line that was far below the control curve. MC mixes were able to perform better in terms of reduction of porosity than control mortar even at early ages. MC mixes also perform in similar trends for the relationship between strength and absorption. The linear correlation between water absorption and total porosity of MC mortars was also below control line, which was placed it into the low permeability regions. However, at early ages it was outside the regions but not in the high permeability regions. MC mixes were identified as low permeable and low porosity mortar.

### d) MD mix

The strength of MD mortars was found to be higher than all MBC mortars through every age of hydration. The strength showed low early strength than BBC mortars, except for slag mortar, which improved at final ages, which is higher than control, RHA, and Slag mortars. The strength was comparable with POFA but lower than PFA mortar at this age.

The total porosity of MD mortars was lower than all other mortars except for PFA mortar. The total porosity of MD mortars as mentioned above was approximately comparable with MC mortars that tend to approach the total porosity of PFA mortars. The water absorption of MD mortars is also comparable with MC mortars that were lower than all mortars except for PFA mortars through all ages.

The linear correlation between strength and porosity of MD mortars as mentioned before slightly approached the MC mortar line, which is far below the control line. MD mixes were also able to perform better in terms of reduction of porosity compared to control mortar even at early ages even though it exhibited low early strength than control mortar. MD mix also performs in similar trends in relationship between strength and absorption as was in the strength and porosity relationship. The linear correlation between water absorption and total porosity of MD mortar also lie below control line, thus could be placed into the low permeability regions. But it is observed that at early ages it was in outermost part of the regions. However, at final ages it was far below the high regions. MD mixes were also identified as low permeability and low porosity mortar similar to MC mixes.

At this juncture, MA mixes tends to produce high permeability and average porosity mortar. MB mixes produced average permeability and average porosity mortar. Whereas, MC, and MD mixes tends to produce high performance mortar that resulted in low permeability and low porosity mortars. Both MC and MD mixes potentially reduce the amount of CH in such cement mortar better than MB and MA mixes as shown in the XRD patterns in Figure 4.51. The summary of the performance of MBC mixes is presented in Table 4.20. From the overall performance of MBC mixes, the optimum multi-blended cement mix proportion seems to be MC and MD mixes. However, as far as durability is concern, MD mix is the optimum mix design due to its lowest wbr requirement, which results in low porosity, low water absorption as well as the medium strength mortar at early age and high strength at final age.

The optimum mixes of MBC mortar (MD mixes) were also tested with others properties such as the strength at different curing regimes, durability and the application of MBC mortar. The test results were further discussed in Chapter 5.

# CHAPTER 5

# RESULTS AND DISCUSSIONS OF THE REMAINING PROPERTIES AND APPLICATION OF THE OPTIMUM MBC MORTAR

## 5.1 Introduction

This chapter discusses mainly on the results obtained from tests conducted from stage 4 until stage 6, which focused on the other properties and the application using the optimum MBC mix. The three stages to be focused in this chapter will be as follows.

g) **Stage 4** - Assessment on the strength properties of MBC mortar at different curing regimes.
h) **Stage 5** - Assessment on the durability properties of MBC mortar.
i) **Stage 6** - Application of the MBC mortar.

## 5.2 Stage 4 : Assessment on the strength properties of the optimum MBC mortar mixes at different curing regimes.

### 5.2.1 Results on the strength of MBC mortars at different curing regimes.

Table 5.1 : **Strength under different curing regimes**

| | **Strength (MPa)** | | | |
|---|---|---|---|---|
| Curing | 7days | 28days | 60days | 90days |
| Water | 34.2 | 46.7 | 57.6 | 61.2 |
| Air | 31.0 | 42.6 | 49.4 | 49.6 |
| Initial 7days water curing and continuous air curing | 35.3 | 53.8 | 66.0 | 60.2 |
| Initial 14days water curing and continuous air curing | 35.3 | 57.9 | 66.8 | 62.6 |

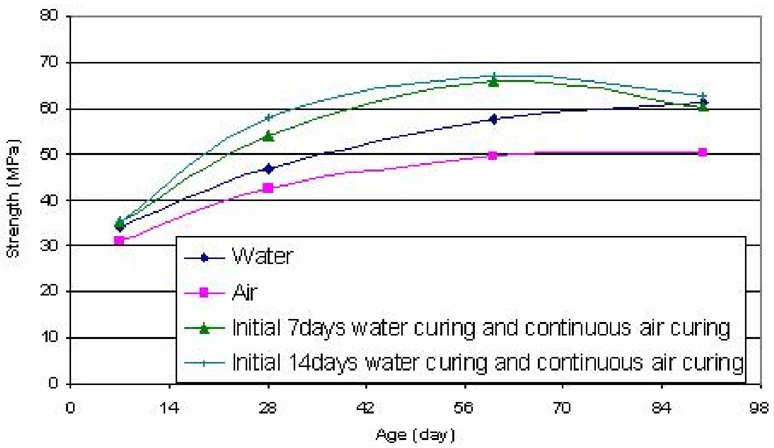


Figure 5.1: **Strength development of MBC mortar at different curing regimes.**

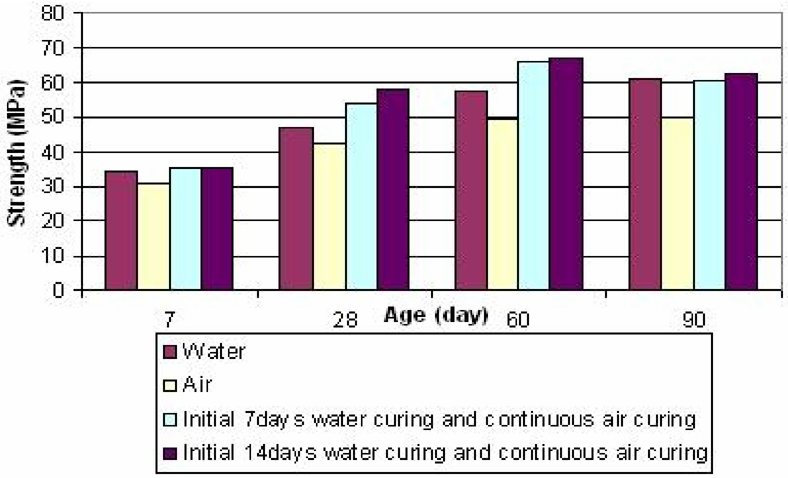


**Figure 5.2:** The strength different on effect of different curing regimes.

### 5.2.2 Results on compressive strength after the wet and dry cycle curing in seawater

The results of the strength of MBC and control mortars after wet and dry cycle curing in seawater after 7 and 28 days of pre-curing (curing in plain water) are given in Table 5.2.

**Table 5.2 :** Results on strength after wet and dry curing in seawater

| Pre-curing | No. of cycle | Compressive strength (MPa) | |
|---|---|---|---|
| | | MD | OPC |
| 7days | 0 | 34.2 | 37.6 |
| | 15 | 49.4 | 52.0 |
| | 30 | 54.2 | 32.1 |
| | 45 | 62.2 | 39.9 |
| 28days | 0 | 46.7 | 49.4 |
| | 15 | 55.0 | 62.2 |
| | 30 | 55.0 | 43.3 |
| | 45 | 49.2 | 37.5 |

### 5.2.2.1 Strength of Control mortar subjected to 7 and 28 days pre-curing

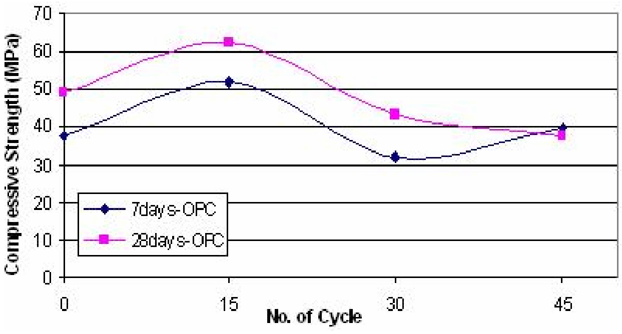


**Figure 5.3:** Effect on periods of pre-curing on Control mortar

### 5.2.2.2 Strength of MBC mortar subjected to 7 and 28 days pre-curing

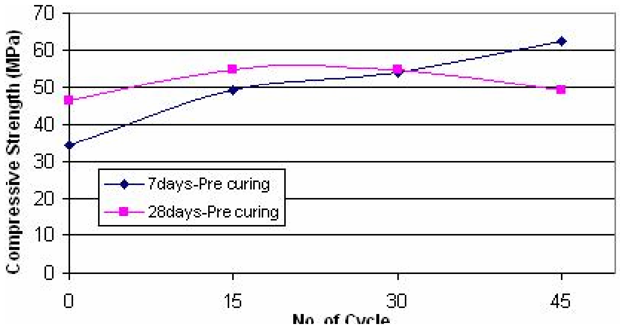


**Figure 5.4:** Effect on periods of pre-curing on MBC mortar

### 5.2.2.3 Strength of MBC vs Control mortar subjected to wet and dry curing

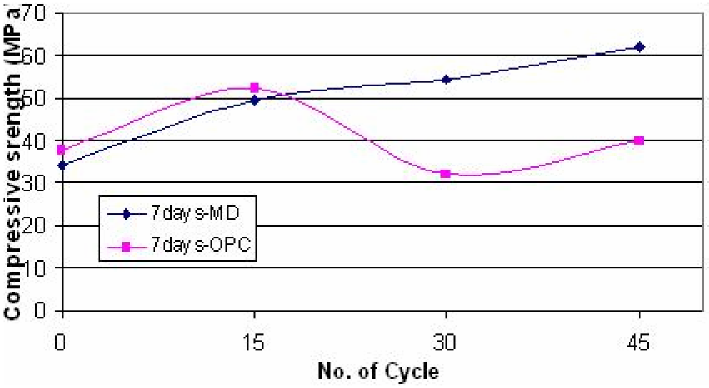


**Figure 5.5:** Strength of MBC and Control mortar subjected to 7days pre-curing

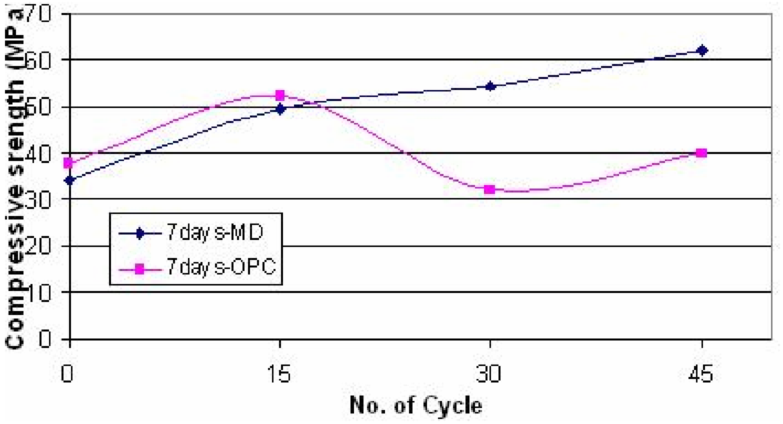
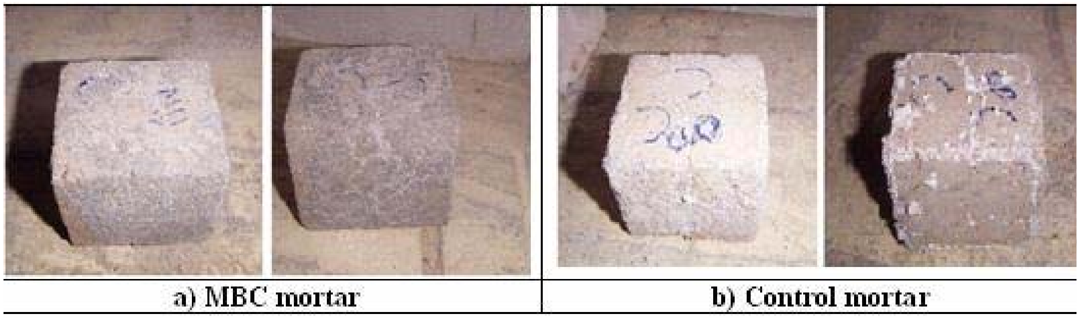


**Figure 5.6:** Strength of MBC and Control mortar subjected to 28days pre-curing



a) MBC mortar

b) Control mortar

**Figure 5.7:** Effect on surface of mortar on the accelerated changes subjected to wet and dry cycle curing in seawater

It can be concluded that the strength of MBC mortar increased with an increase of wet and dry cycles because it contains less amount of CH, which can potentially obstruct further reactions of negative compounds. While, the strength of control decreased with an increase of wet and dry cycles. From the test results it can be seen that, the strength of

MBC mortar after wet and dry curing are significantly improved and better resistance against chloride environment was observed. It is also possible to prepare MBC, which shows better performance than the ordinary Portland cement in terms of compressive strength retention in chloride or corrosive environment.

## 5.3 Stage 5 : Assessment on the durability properties of mortar.

### 5.3.1 Results on carbonation of mortar.

In this study it was found that, both the investigated and control mortar were less affected by carbonation when subjected to air, water, seawater and natural weather curing, where the depth of carbonation was less than 2mm in all tested ages. Table 5.3 and Figures 5.8 to 5.11 show the results obtained for the carbonation test. While, Figures 5.12 to 5.15 present the conditions of the broken specimens. The specimens were tested using phenolphthalein, which the purple colour in the figures indicates that the specimens have not been affected by carbonation. Whereas, the transparent colour around the outmost depth of specimen, indicates the region was affected by the carbonation.

*Table 5.3 :* ***Depth of carbonation of MBC and Control mortar at different curing regimes***

| | **Depth of Carbonation (mm)** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Water curing | | | Seawater | | | Air curing | | | Natural weather | | |
| Age (days) | 7 | 28 | 90 | 7 | 28 | 90 | 7 | 28 | 90 | 7 | 28 | 90 |
| MD | - | - | - | - | - | - | - | 0.75 | 1.75 | - | 1.25 | 1.85 |
| Control | - | - | - | - | - | - | - | 0.50 | 1.50 | - | 1.20 | 1.60 |

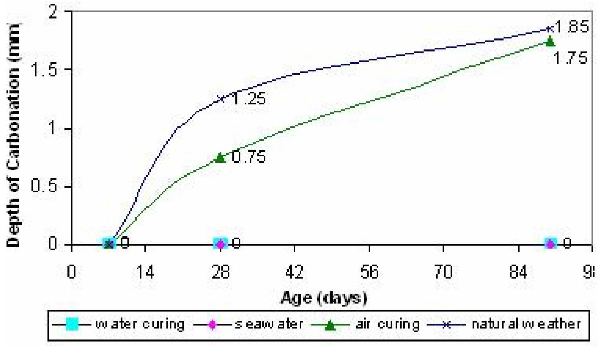


**Figure 5.8:** Depth of Carbonation of MBC mortar at different curing regimes

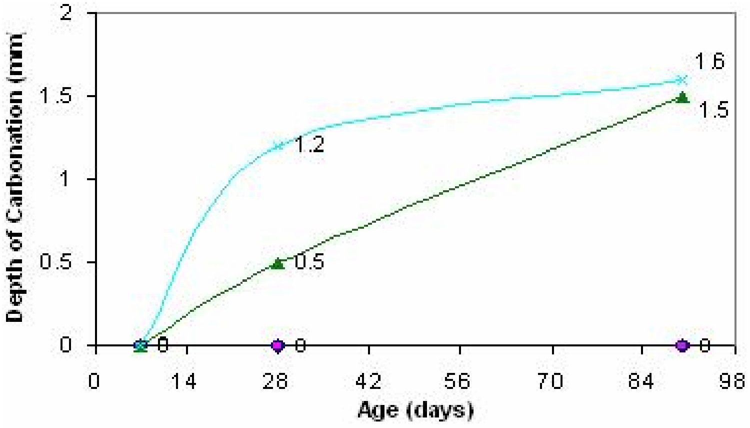


**Figure 5.9:** Depth of Carbonation of Control mortar at different curing regimes

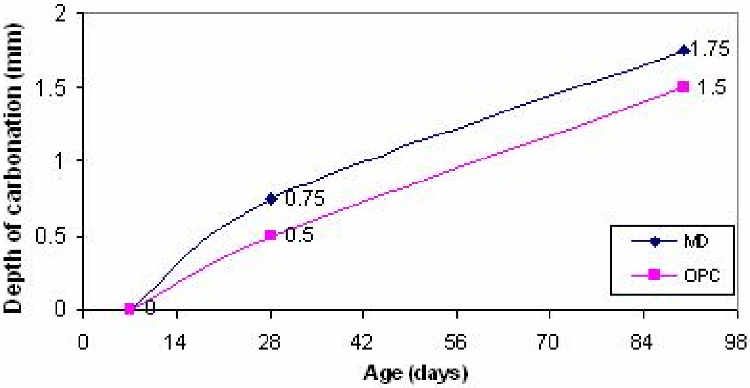


**Figure 5.10:** Depth of Carbonation of MBC-MD and Control mortar in air curing

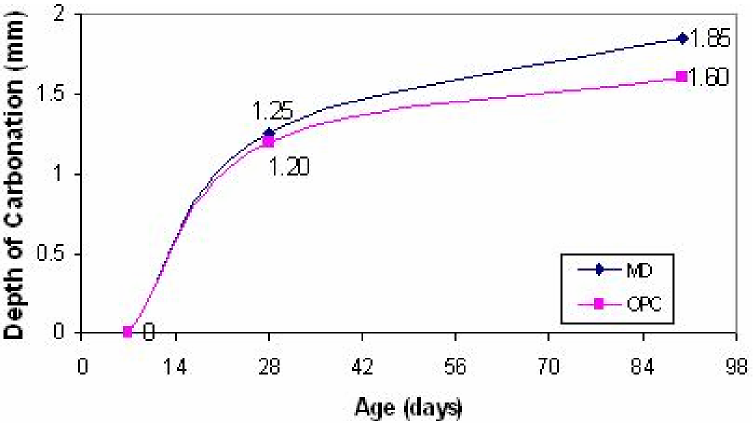


**Figure 5.11:** Depth of Carbonation of MBC-MD and Control mortar in natural weather

a) Carbonation of MBC (left) and control (right) mortar at 7days

b) Carbonation of MBC (left) and control (right) mortar at 28days

c) Carbonation of MBC and control mortar at 90days

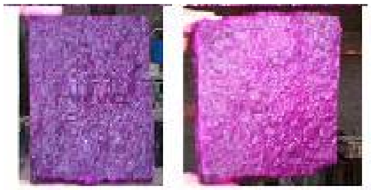
**Figure 5.12:** Carbonation of mortar at different age subjected to water curing

a) Carbonation of MBC (left) and control (right) mortar at 7 days

b) Carbonation of MBC (left) and control (right) mortar at 28 days

c) Carbonation of MBC and control mortar at 90days

**Figure 5.13:** Carbonation of mortar at different ages subjected to Seawater curing

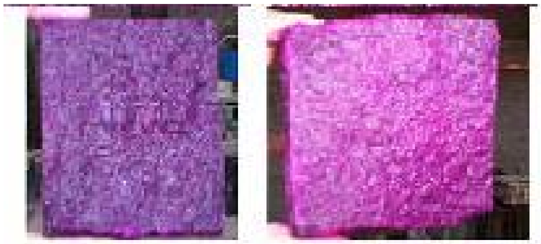


a) Carbonation of MBC (left) and control (right) mortar at 7 days

b) Carbonation of MBC (left) and control (right) mortar at 28 days

c) Carbonation of MBC (left) and control (right) mortar at 90days

**Figure 5.14:** Carbonation of mortar at different ages subjected to air curing



a) Carbonation of MBC (left) and control (right) mortar at 7 days

b) Carbonation of MBC (left) and control (right) mortar at 28 days

c) Carbonation of MBC (left) and control (right) mortar at 90 days

**Figure 5.15:** Carbonation of mortar at different ages subjected to natural weather

### 5.3.2 Acid Attack

The results of the weight loss of mortar specimens subjected to 5% hydrochloric (HCL) acid solution is presented in Table 5.4 and Figure 5.16. All the specimens were pre cured in plain water for 7 and 28 days before being immersed into the acid.

**Table 5.4:** Percentage of weight loss after immersed in 5% HCL solution

| | | | % Weight loss after immersed in Acid Hydrochloric (hours) | | | | | | Strength at 600hrs Immersed in 5% HCL | |
|---|---|---|---|---|---|---|---|---|---|---|
| Period of hydration | | 0 | 100 | 200 | 300 | 400 | 500 | 600 | | |
| | | | | | | | | | | |
| 7day | MBC | 0 | 3.5 | 4.2 | 4.8 | 5.2 | 7.0 | 7.2 | 24.1 | 7.5% |
| | OPC | 0 | 3.4 | 4.6 | 4.9 | 5.5 | 8.4 | 9.1 | 22.3 | |
| | | | | | | | | | | |
| 28day | MBC | 0 | 2.2 | 2.4 | 2.5 | 4.0 | 4.7 | 4.8 | 38.3 | 15.7% |
| | OPC | 0 | 2.0 | 2.2 | 2.4 | 4.5 | 4.9 | 5.2 | 32.3 | |

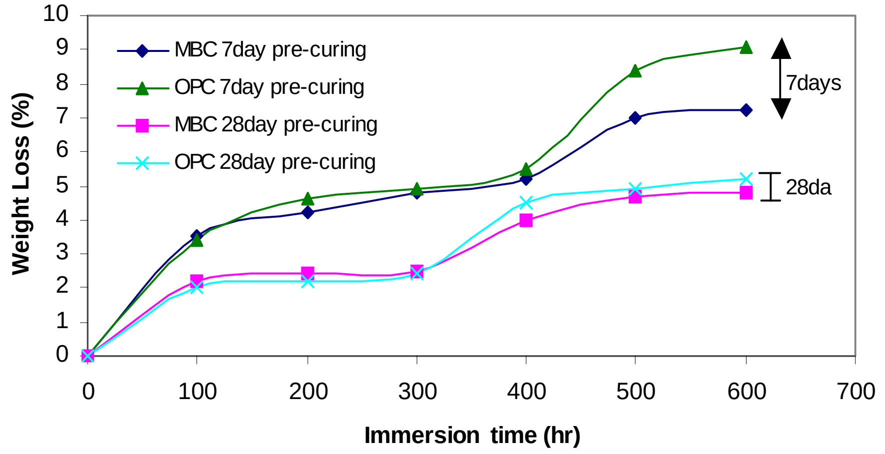


**Figure 5.16:** Comparative weight loss of Control and MBC mortar continuously immersed in 5% HCL solution

### 5.3.2.1 Performance of MBC vs control mortar on acid attack.

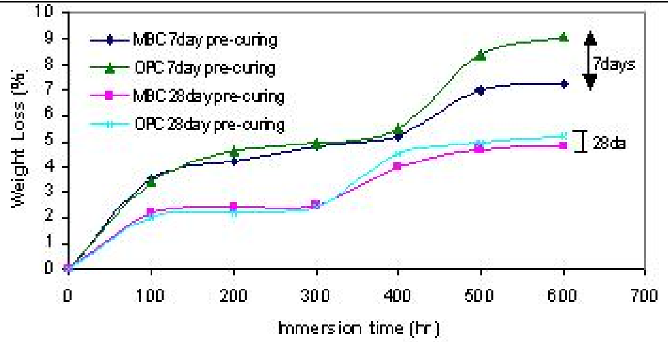


**Figure 5.17:** Strength of mortar after 600hrs immersed in 5% HCL solution

From the test results it is deduced that concrete properly cured can potentially improve the engineering properties and reducing the ingress of aggressive substances. It clearly shows that the strength and microstructure of the mortar before exposure is important in order to withstand the chemical attack. Figures 5.18 and 5.19 show the effect on mortars when exposed to HCl solution after 600 hours of immersion. The control mortar is more adversely affected compared to MBC mortar. The MBC mortar can be potentially better resistant to acid attack provided it is adequately cured.

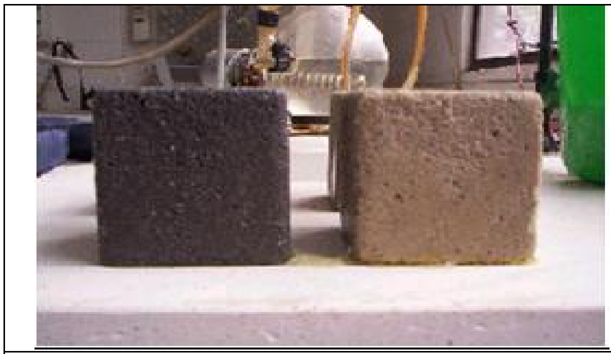


**Figure 5.18:** Effect on MBC (left) and control (right) mortar subjected to acid attack after 600hours of immersion

(a) MBC (left) and OPC (right)

(b) OPC (left) and MBC (right)

**Figure 5.19:** Effect penetration of acid HCL into mortar after 600hours of immersion

## 5.4 Stage 6 : Application of the MBC mortar

### 5.4.1 Introduction

This stage discusses the suitability of MBC mortar mix developed as face sheets covering a layer of lightweight aerated concrete as core to produce lightweight sandwich block. All the parameters of study namely strength, density, and mode of failure were compared to block solely made of aerated lightweight concrete and also a typical commercial block.

### 5.4.2 Manufacturing of product

### a) Aerated Lightweight concrete

a) Aerated concrete cast vertically

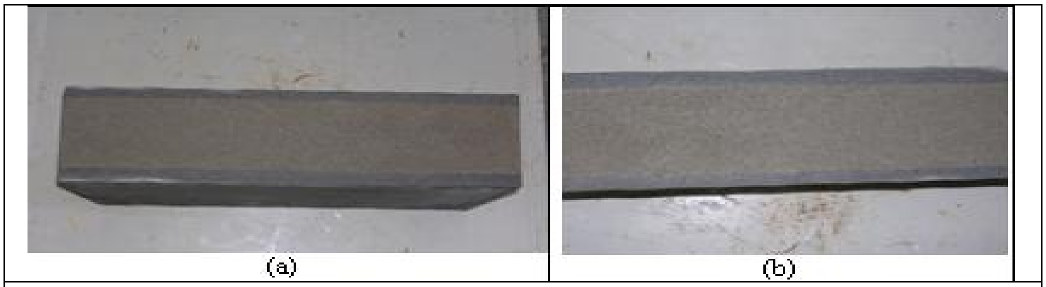
b) Aerated concrete cast horizontally

**Figure 5.20:** The expansion of 0.1% aluminium powder for both methods

### b) MBC mortar – as the face sheet of the Sandwich Block (SB)

The MBC mortar paste was prepared using the technique to produce mortar as in previous stages. The vertical casting was also found to be inappropriate method for producing the face sheet of the SB. It is mainly because of the difficulty in pouring the MBC mortar paste into the thin thickness of the mould, which is 10 ± 2mm thick. It also required more materials to cast into the mould with prolonged vibration, which ultimately increased the density and the segregration as well as bleeding of the specimens. The MBC mortar design here is considered to be applicable for plaster or such application. Hence, the flow of MBC mortar was maintained at 105 ± 10%, which gave the optimum workability.

It is suggested that for ease of pouring into thin layer, the paste has to be designed at flow value of 130 ± 10%. Nevertheless, it leads to increase in wbr, which could affect the overall properties and performance of MBC mortar mainly in porosity and permeability, which govern the durability of the mortar. Therefore, the samples were cast horizontally for easy pouring and plaster the MBC mortar on the top surface of the core material and besides to maintain the properties of MBC mortar. Figure 5.21 presents the complexion of the sandwich panel.



(a) (b)

**Figure 5.21:** The surface of sandwich block

### 5.4.3 Strength performance of sandwich block (SB)

As mentioned before, the sandwich block (SB) produced in stage of preliminary studies, the strength performance was only evaluated at the age of 28 days. Three samples were used and an average value was recorded as the compressive strength of the SB compared to Aerated Lightweight block (AB), having the same dimension and method of casting as the SB. Besides that, both specimens were also compared to commercial block (CB). CB is commonly used as construction material for internal and external wall that is commonly available in market. Even though the size of CB is slightly different from SB and AB, the CB was tested for a comparison purpose because of the block is currently and practically used in the construction industry. The results on the strength performance of all blocks are presented in Table 5.5. The load applied to the block was perpendicular to 400mm length of the block.

**Table 5.5 :** Strength of Investigated blocks

| Sample | Strength (MPa) |
|---|---|
| SB | 14.13 |
| AB | 8.29 |
| CB | 5.23 |

**a) The strength of SB compared to AB**

The strength of SB was expected to be higher than AB that by 41%. The strength of the composite block and AB was 14.13 MPa and 8.29 MPa, respectively. According to Areshvinna (2002), the strength of Aerated lightweight concrete was approximately at grade 8, which is similar with the strength results of AB obtained in this research. Whilst, the strength of the material used (MBC mortar) as for the face sheet of the SB was grade

40 (Lenny *et al*., 2005). Hence, it shows overall increased strength of SB compared to the block solely made by the Aerated lightweight concrete (AB).

However, in terms of the density, the SB gave higher density than AB. The density of SB (1578.8 kg/m$^3$ at 28 days) was 23% higher than AB (1222.5 kg/m$^3$). The enhancement in strength of SB was expected due to high density of SB than AB. The properties of the face sheet material were established after conducting the comprehensive tests to the MBC mortar as described in previous stages. The low wbr effect of MBC mortar has significantly governed the formation of total porosity of hardened mortar as well as time required for capillary segmentation which depends on the initial wbr. The 0.48 wbr of MBC mortar required less than 14 days to block and close the capillaries in MBC mortar, thus produced the dense microstructural mortar that would probably explained for the higher strength of the block after the Aerated concrete being sandwiched with MBC mortar. The strength of AB was expected to be lower than the composite blocks due to the formation of air pores in the aerated concrete which definitely affect the strength of the aerated concrete block. The air pores structure would give the lightweight effect to the concrete.

### b) The strength of SB compared to CB

Although the weight of CB was approximately the same as SB, the strength was not influenced by the weight per meter cube. The strength of CB was only 5.23 MPa compared to the strength of SB, which was 14.13 MPa. The strength of SB was 63% higher than CB. Whilst, the density of CB was only 4.3% higher than SB, which was 1650.5 kg/m$^3$ and 1578.8 kg/m$^3$, respectively. The strength of CB was influenced by several factors. As discussed earlier the low wbr effect and the delayed pozzolanic reaction of MBC mortar has significantly influenced the formation of total porosity thus produced the dense microstructural mortar.

From physical observation the commercial block was brittle and crispy. The block was easily broken and damage. One of the factors potentially influenced the strength of CB probably was the mix design. According to the manufacturer, it was manufactured with high sand to cement ratio. However, the specific mix ratio, wbr, and other properties were not given. From author’s point of view and observation from previous experiment, the high ratio of sand has significantly influenced for the higher water demand to produce the optimum workability of the paste. Thus, the higher water to cement ratio was primarily responsible for the lower strength of CB compared to SB.

### c) The strength of AB compared to CB

The strength of AB was also higher than CB by approximately 37%. The density and weight of CB was 25.9% higher and heavier than AB. Although the AB produced air pores thus gave more lightweight than CB, nevertheless AB was stronger than CB. As discussed earlier the lower strength of CB was probably due to the poor mix design.

Generally the strength of all specimens (SB, AB and CB) were well matched with the standard requirement as referred to ASTM C129-85 (1990), which the strength required for non-load bearing units is 3.45 MPa at the 28 days. Specifically, the CB produced lower strength and more dense than AB and SB. AB produced more lightweight and medium strength materials, whilst SB gave stronger and medium weight. However, the strength obtained for all specimens indicate that the blocks can be used as a precast lightweight component for non-load bearing units, which produced the strength and density of lightweight materials ranging from 5 to 14 MPa and 1200 to 1600 kg/m$^3$, respectively. Nevertheless, the sandwich block was designed for low absorption material and low alkalinity that gave better resistance to chemical attack. It can potentially be applied in aggressive and severe environment such as in seawater or beach area, industrial building, and also in the area exposed to lubricating oils or hydraulic fluids.

### 5.4.4 Effect of curing on density of the blocks

This section discusses the effect of curing on density of SB compared to AB. CB was not compared because of the block was not produced in laboratory. The blocks were bought from supplier and as mentioned earlier the specifications of CB were unknown.

As discussed earlier in chapter three of the thesis, all the samples were cured by an initial of 14 days water curing and followed by 14 days of air curing. The purpose of the curing method applied was discussed earlier in chapter three. It was observed that the weight and density of SB after demoulding were 12.05kg and 1506.3 kg/m$^3$, respectively, and after subjected to 14 days water curing and 14 days air curing, both parameters increased by 4.8% at the age of 28 days. Meanwhile, the aerated block showed an increase of 10% for both weight and density as seen in Table 5.6. It was expected that the MBC mortar as for the face sheets of the block would give low water absorption compared to the macro pores formed in aerated lightweight concrete. However, the density of the SB after demoulding and after curing process was 27% and 23% higher than AB, respectively. Nevertheless, both blocks are considered as lightweight concrete since the density of lightweight concrete should be within the range of 700 to 1800kg/m$^3$. Therefore, both blocks have met the designed purpose.

**Table 5.6 :** Weight and Density of investigated blocks

| Sample | Size (mm) (Lxhxt) | Weight (kg) | | Density (kg/m$^3$) | |
|---|---|---|---|---|---|
| | | 1day | 28days | 1day | 28days |
| SB | 400x200x100 | 12.05 | 12.63 | 1506.3 | 1578.8 |
| AB | 400x200x100 | 8.89 | 9.78 | 1111.25 | 1222.5 |
| CB | 390x190x100 | - | 12.23 | - | 1650.5 |

### 5.4.5 Cracks and failure mode of blocks

The crack patterns and the mode of failure were also observed and recorded during the compressive strength test. From the test results, most of the failure occurred at the aerated concrete portion, which was mostly at the outermost part of the SB such as in Figure 5.22. Figures 5.23 and 5.24 showed the crack patterns at both sides of core layer. There is no failures occurring neither at the side of the face sheets nor at the bonding area between the face sheets and the core layer. Figure 5.25 reveals that there was good bonding of MBC mortar with the aerated concrete. The samples also did not indicate any cracks failure on the face sheets surface. It is presumed that the loading was more concentrated on the core material which is the weaker part of the block. However a detailed study is required in this regard.

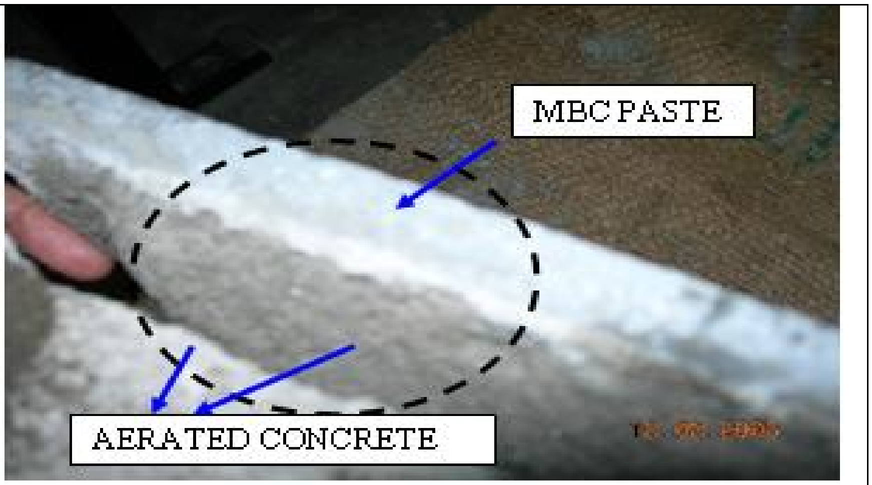


**Figure 5.22:** Failure occurred at outermost part of aerated concrete

**Figure 5.23:** Crack pattern at aerated concrete

**Figure 5.24:** Cracks at the side of aerated concrete

(a) (b)

**Figure 5.24:** Good bonding between face sheet and core layer

## 5.5 Conclusions

From the discussions covered in this chapter, the continuity of progress of hydration is an important factor, which relates to adequate curing particularly for concrete containing pozzolanic materials to enhance the concrete performances. It was observed that MBC mortar provided with initial 14 days water curing and continuous for 14 days air curing achieved high early strength than continuous water curing. It is suggested that the strength and microstructure of concrete before being exposed to severe environment ought to be properly taken care of.

The low alkalinity of MBC mortar gives better performance towards chemical attacks compared to highly alkaline OPC. It is also observed that MBC mortar exposed to saline water was found to be sufficient with 7 days or extended to 14 days rather than 28 days pre-curing. It is because the $NaCl_2$ acts as accelerator to pozzolanic reaction. The sodium ions convert to soluble silicates and easily attacked the pozzolanic particles, which further combined with CH, hence increased the CSH gel. The formation of protective layer of brucite impedes further reactions. Thus the MBC mortar improved significantly against the chemical reaction of seawater. Concrete should be designed in such a way that it has to be compatible with the conditions of the environments. Hence, the sandwich block was designed for better resistance to chemical attack that can potentially be applied in aggressive environments.

# CHAPTER 6

# CONCLUSIONS AND RECOMMENDATIONS

## 6.1 Conclusions

Detailed conclusions have been discussed in the end of Chapter 4 and 5. Therefore, in this chapter, the author will be summarized the finding conclusion and its significance.

The Chapter 4 is mainly focused on the development of the MBC mortar. From the results, it observed that the MD mortars achieved the highest strength value, and lowest percentage of total porosity and water absorption compared to control and other MBC mortars. Whilst, in the BBC system, PFA mortars exhibited the highest strength value, and lowest percentage of total porosity and water absorption among all BBC and control as well MBC mortars. The MBC mortars mainly MD and MC mix were higher strength value than control and BBC mortars such as RHA and Slag mortar. MBC system was also exhibited greatly lower percentage of total porosity and water absorption than BBC system and control mortar. Based on the results obtained, The MBC system has reduced limitations inherent in individual materials (BBC system). From the overall performance of MBC mortar, MD mixes (which contains 5% of RHA, 20% of PFA, 5% POFA and 20% of Slag) achieved the objectives of study to establish the optimum mix proportion of MBC mortar.

Whilst, Chapter 5 studied the other properties and application using the optimum MBC mixes. The strength values of MBC mortar when subjected to initial 7 days and 14 days water curing and continuous air curing until age of 28 days showed higher early strength values than continuous water and air curing. The strength values of MBC mortars for both 7 days and 28 days pre-curing increased after 30 cycles after wet and dry curing, which was higher than control mortar. After 200-300 hours until total 600 hours immersed in HCL acid, the MBC mortar showed better performance than control mortar. Poor curing of MBC mortars exhibited bad performance on effect of carbonation when exposed to air curing and natural weather condition. Application of the MBC mortar as the face sheet of sandwich block exhibited higher strength than aerated lightweight block and commercial block. Whilst, the density of sandwich block was found higher than aerated block but much lower than the commercial block.

Based on the test results obtained in Chapter 5, it can be summarized that the strength and durability properties of MBC mortar are more pronounce when it is provided with an adequate curing. After certain of time of exposure to chemical attack, the MBC mortar performs better resistance than OPC mortar. The main objective of the study to produce MBC mortar of adequate strength and durability is achieved. The production of MBC mortar as face sheet of sandwich block can be used in aggressive environment. It can be utilized as low cost construction materials and reduce the volume of waste generated. POFA and RHA potentially to be used in MBC by incorporation of PFA and Slag.

1% reduction in OPC causes 0.16% strength reduction, however, 0.62% lower in porosity and 0.76% lower in absorption in the MBC system. The multiple binder combinations will have twice over benefit of reduction in the cost of construction material and also as a mean of disposal of waste. Material recovery from the alteration of agricultural wastes and industrial wastes into constructive materials has not just environmental achieves, but may also conserve natural resources.

## 6.2 Recommendations for further studies.

### 6.2.1 Materials

**a)** The studies on the strength, pore structure and durability characteristics of MBC mortars by using the quality and reactive RHA (amorphous silica)

**b)** Detail properties of production of RHA in terms of burning method and fineness of the particles must be properly taken care in order to enable better performance of MBC mortars and help to improve the early strength of MBC mortars.

### 6.2.2 Engineering and chemical / microstructural characteristics.

**a)** Concentrating on varies the dosage of superplasticizer into MBC mixes (with fixed wbr) and choose the optimum dosage that exhibit better properties especially to improve the early strength as the same time the cost of production ought to be economical.

**b)** Further studies on the similar durability test as the current research but the MBC specimens should be provided by initial water curing and continuous air curing before exposed to the severe condition as to enhance the current findings.

**c)** Further studies on others durability aspect such as alkali silica resistance, shrinkage and sulphate resistance.

**d)** Studies on the mechanical properties of MBC mortar such as the flexural and modulus of elasticity.

**e)** Focus on the microstructural studies such as the pores size distribution and termogravimetri and permeability test.

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