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DURABILITY OF HIGH STRENGTH CONCRETE CONTAINING PALM OIL FUEL ASH OF DIFFERENT FINENESS

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Abstract: The use of palm oil fuel ash (POFA) as a pozzolanic material for cement replacement in concrete will reduce the cost of concrete and environmental problems. POFA used in this study was ground to increase its degree of fineness to improve its reactivity in the mixture thus enhance the concrete properties. The present study is designed to determine the effect of POFA fineness towards durability of high strength POFA concrete in aggressive environment specifically in terms of increasing its resistance towards chemical attacks namely sulphate, acid and chloride penetration. Two types of mixes were prepared using ash possessing different fineness namely 45 µm and 10 µm and a control mix with OPC. The entire high strength POFA concrete specimens prepared consist of 20% POFA as partial cement replacement material. Conclusively, integration of POFA as partial cement replacement, especially very fine POFA increase the resistance of high strength POFA concrete in chemical environment towards chloride penetration, acid and sulphate attack .

Keywords: *High Strength Concrete; Palm Oil Fuel Ash; Fineness; Durability; Aggressive Environment*

1.0 Introduction

One of the most significant current studies in construction field is the use of supplementary cementitious materials of Portland cement to produce concretes. The generation of large quantities of industrial by-products every year by chemical and agricultural process industries such as fly ash, ground granulated blast furnace slag, silica fume, palm oil fuel ash (POFA), rice husk ash (RHA) and others has created environmental pollution as well as increasing the expenditure of the industry for disposing this waste. These issues have initiated researchers globally to study on the possibility of converting this waste into a useful product for the benefits of human civilization.

The continuous researches carried out become fruitful when these wastes have been discovered to be containing pozzolanic properties enabling it to be used as a mineral admixture in concrete material. As a result, the abundantly generated by-product known as slag (Hogan *et al.*, 1981; Arreshvhina, 2002), fly ash (Mehta, 1985; Chindaprasirt *et al*., 2004), palm oil fuel ash (Abdul Awal and Hussin, 1996), rice husk ash (Salihuddin, 1998) has been added as partial cement replacement material in concrete production. Thus, it is widely recognized that pozzolanic cements increase the concrete durability by affecting the chemical and structural properties of cement paste (Massazza, 1993; Koh *et al.*, 2008). Hence, innovation of various types of concrete manages to assist the industries to be more environmental friendly besides reducing the cost spent for disposing the waste.

2.0 Background

Malaysia being the largest palm oil producing country generates millions of tons of solid wastes known as palm oil fuel ash (POFA) which disposed annually by palm oil mills all over the country. POFA which is generated in the form of coarse and larger size than OPC (Hussin *et al*., 2008) is a by-product obtained from burning the remaining of extracted palm oil fibers and shells in the palm oil mill. It varies in tone of colour from whitish grey to shade depending on the operating system in the palm oil factory. This ash which does not have sufficient nutrients to be used as fertilizer is dumped in open fields in the vicinity of the palm oil mills (Tay and Show, 1995). Similarly, POFA produced in Malaysian palm oil mill also dumped as waste without any profitable return (Salihuddin and Hussin, 1995) thus became one of the pollutants to environment. This has initiated Malaysian researcher to conduct studies on exploring the possibility of using this ash to produce a new construction material.

The continuous research carried out was rewarded at the end of 20th century, when Salihuddin and Hussin (1993) found this ash has high potential to be used as a cement replacement material. This revelation has lead Abdul Awal and Hussin (1997) and Hussin and Abdullah (2009) attempts to produce blended cement concrete and lightweight concrete respectively integrating POFA as one of the ingredient, which eventually results in innovation a new agro cement based concrete performing better in terms of strength and durability compared to normal concrete. Since then, within the past twenty years of studies in POFA utilization in concrete making, researchers (Sata *et al.*, 2004; Mat Yahaya, 2003; Hussin *et al*., 2008) agrees that only certain percentage of POFA can be added as mineral admixture replacing ingredients in concrete in order to produce new type of modified concrete consisting POFA having enhanced properties. Although, there are development in the amount of literature (Sata *et al.*, 2004; Jaturapitakkul *et al.*, 2007,) on the positive contribution of the finer POFA towards advancement concrete properties but there is much more area of studies that remain to be investigated. Realizing that, the present paper focuses on discovering and providing data on durability of high strength POFA concrete.

At the same time, this country being the largest producer and exporter of palm oil in the world in year 2006 (Sumathi *et al*., 2008) is predicted to maintain its lead position over the next one and a half decade (Basiron and Simeh, 2005). Therefore, it is estimated that bigger quantity of POFA will be discarded as environmental polluting waste in future unless this material is processed for other applications. As one of the effort to provide solution to this issue, the aim of present study is to assess the effectiveness of fineness of POFA on the durability aspects of high strength concrete containing POFA. This research is focused on the studying the resistance of the POFA blended cement high strength concrete towards aggressive chemical namely acid and sulphate attack as well as chloride penetration.

3.0 Materials and Experimental Program

3.1 Raw Materials

Preparation of materials, laboratory tests, and test procedures were the initial steps of the work. The step after that was the preparation of the test specimens according to standards. First of all, the ash was collected from palm oil mill owned by Yayasan Pembangunan Johor which is located in State of Johor where the material obtained from the burning of extracted palm oil fibres and shells. Then, the ashes were dried in the oven at the temperature of 110ºC ± 5 for 24 hours before sieved through 300 µm sieve. After that, it was ground until achieved the required fineness according to ASTM C 618-05a (2005). Two batches of POFA with different fineness were used in this study that is POFA 45µm and POFA 10µm. POFA 45 µm were obtained through 3.5 hours of grinding of 4 kg ash that was checked by wet sieving through 45 µm and found about 70% ashes pass through. Then, POFA 10 µm was produced after 10-hours grinding, whereby the median particle size was reduced to less than 10 µm.

A single batch of Ordinary Portland Cement (OPC) complies with the Type 1 Portland Cement as in ASTM C150 - 92 (1992) was used in this experiment. The chemical constituent of OPC and POFA is illustrated in Table 1. Based on the chemical composition analysis, POFA used throughout this research is classified as Class F pozzolan, according to the standard specified in ASTM C618-05a (2005). Dry mining sand and crushed aggregate of 10 mm size were used as fine and coarse aggregate respectively. Superplasticizer type F high range water reducing admixture complying with ASTM C494-05a (2005) was incorporated in this study. Tap water has been used throughout the experimental work.

Table 1: Chemical Constituents (%) Of OPC and Palm Oil Fuel Ash (POFA)

Chemical Constituents	**OPC**	**POFA**
Silicon Dioxide (SiO_2)	28.2	53.82
Aluminum Oxide (AL_2O_3)	4.9	5.66
Ferric Oxide (Fe_2O_3)	2.5	4.54
Calcium Oxide (CaO)	50.4	4.24
Magnesium Oxide (MgO)	3.1	3.19
Sodium Oxide (Na_2O)	0.2	0.1
Potassium Oxide (K_2O)	0.4	4.47
Sulphur Oxide (SO_3)	2.3	2.25
Phosphorus Oxide (P_2O_2)	<0.9	3.01
Loss On Ignition (LOI)	2.4	10.49

3.2 Mixture Proportions

Absolute volume mix design was considered to obtain concrete mix proportion. Three types of mixes have been used in this study. The performance of a two mixes produced using POFA of different fineness as partial cement replacement is compared with control mix formed of 100% OPC. POFA high strength concrete mixes produced using POFA 45 µm is labelled as (POFA45) and POFA 10 µm referred as (POFA10) and control specimen known as (Control Po). 20% POFA has been chosen to replace the cement partially since results from previous studies (Hussin *et al*, 2008) indicates that replacement of 20% POFA gives the optimum strength to concrete. The total cementitious material content has been kept constant in all mixes and the only difference in the ash concretes is that 20% OPC has been replaced by POFA. The detail of the concrete mixes used is presented in Table 2.

Table 2: Details of Concrete Mixes

Ingredients	OPC Concrete (kg/m^3) Control Po	POFAConcrete (kg/m^3) POFA 45	POFA 10
Ordinary Portland Cement	400	320	320
Palm Oil Fuel Ash (POFA)	-	80	80
Water	174.5	174.5	174.5
Fine Aggregate	678.7	678.7	678.7
Coarse Aggregate	1090	1090	1090

3.3 Testing Procedure

As an overall view, the tests conducted throughout this experimental programme have been divided to two stages as been tabulated in Table 3 shown below.

Table 3: Tests conducted throughout the experimental program

No.	Test During Initial Stage	Factors Measured
1	Compacting Factor Test and Vebe Test	Compaction Factor Index and Vebe time
2	Compressive Strength Test	Strength Value
No.	**Durability Test At Second Stage**	
1	Chloride Resistance	Depth of chloride penetration
2	Acid Resistance	Percentage of weight loss
3	Sulphate Resistance	Percentage of weight loss, expansion of mortar bar,

At the initial stage, the fresh concrete mixes produced of different design mix were subjected to workability test namely compacting factor test and Vebe test. Measurement of compressive strengths for all design mixes is conducted in accordance to BS1881:116 (1983). All the mixes were cast in the cubes of 100x100x100mm before water cured for 28 days prior to compressive strength test.

At the second stage, all the specimens to be subjected to durability tests were cast into required shape, demoulded after 24 hours before placed in water curing according to the available standards. The studies on the effect of POFA fineness towards chloride attack were investigated by adopting the procedures applied by (Abdul Awal, 1998). Cylindrical moulds of 100 x 200 mm size were prepared and water cured before tested at 7, 28 and 90 days. The specimens after being split into two parts were sprayed with 0.2N silver nitrate solution.

The acid resistance of concrete produced of various POFA fineness and plain concrete were investigated by immersing the specimens in hydrochloric acid solution for 1800 hours. Three sets of mixes known as Control Po, POFA45 and POFA10 mix were produced in the form of cubes (100 x 100 x 100 mm) and then subjected to water curing for 28 days before immersed in acid solution. The durability performances of the specimens were determined by measuring the loss of weights of the samples at every 100 hour. The pH of the solution was controlled to about 2 throughout the immersion period (Abdul Awal, 1998).

Finally, durability of concrete produced various mixes towards sulphate attack were also studied by testing cubes and mortar bars following the procedures stated in ASTM C1012-89 (1994). The variations in the mass of the specimens and evaluation on its strength are measured using cubes (100 x 100 x 100 mm) and the length changes are calculated on the mortar bars (25 x 25 x 250 mm). Each set of specimens either for cubes or mortar bars consist of three types of mixes, that is Po, POFA45 and POFA10 whereby all of it were water cured for 28 days before being placed into 10% sodium sulfate solution. X-ray diffraction analysis was also performed on the specimens at the later part of the study in order to further verify and strengthen the result obtained.

4.0 Results and Discussion

4.1 Workability and Strength Performance

Table 4 presents results of the test carried out during the initial stage involving the studies on the effect of POFA fineness towards workability and compressive strength of concrete. It was observed that during the VeBe test, POFA45 and POFA10 concretes has close VeBe characteristics while Po shown lower value of VeBe. Furthermore, POFA specimens show no significant bleeding. The compacting factor test also provide result supporting the Vebe test result clearly indicating that integration of POFA reduces the workability of high strength concrete compared to control concrete. Similarly, Abdul Awal (1998) has also stated that POFA reduces concrete workability owing to its bigger surface area resulting from the grinding process.

Looking at compressive strength, the value obtained shows that both POFA45 and POFA10 concrete exhibit higher strength than control mix. Only slight difference can be observed in the strength of POFA45 concrete compared to control. Probably POFA45 developed their early strength at a slower rate due to two factors that is the dependency of pozzolanic reaction on the existence of free lime from hydration process that occurs initially and the use of coarser particles that reduce the reactivity of particles in the mixture in comparison to POFA10. The influence of ash fineness towards concrete strength development has been discussed by Ranganath *et al*. (1998) who highlighted that the use of coarser particles would lower the strength of concrete. On overall, POFA10 exhibit the highest strength of all because of its higher fineness. The effectiveness of POFA 10 µm having higher fineness than POFA 45µm in increasing strength of concrete has been verified by Swamy (1997) who reported that very fine pozzolan to be naturally highly reactive.

Table 4: Results of Vebe, Compacting Factor and Compressive Strength Test

Concrete Code	Vebe Time (sec)	Compaction Index	28-day Compressive Strength (MPa)
Po	7.42	0.913	54.40
POFA 45	9.37	0.918	54.80
POFA 10	9.81	0.893	58.65

4.2 Resistance to Chloride Diffusion

Chloride penetration of control mix, and concrete with pozzolanic materials exposed to 5% sodium chloride solution for 7, 28 and 90 days are presented in Figure 1.

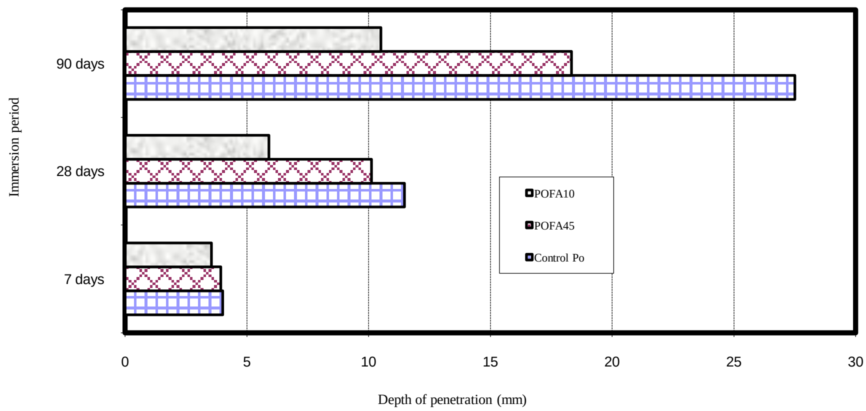

Figure 1: Chloride penetration for specimens with various mixes at 7, 28 and 90 days

Evidently, the depth of chloride penetration is the highest for control specimen compared to POFA specimens clearly indicating that integration of POFA enhance the high strength concrete durability towards chloride attack. Comparing the performance of POFA45 and POFA10, the chloride penetration depth is lesser for POFA10 that is formed using POFA with higher fineness. Inclusion of POFA having higher fineness speeds up the pozzolanic reaction resulting towards formation of more extra C-S-H gel making the concrete denser and enabling it to exhibit better resistance to chloride attack.

4.3 Resistance to Acid Attack

4.3.1 Mass Change

The details of the mass change of concrete cube specimens at each period of exposure in acid solution has been plotted in Figure 2. It can be seen that the overall loss in mass of the control concrete Po was much higher as compared to the losses in the POFA concrete specimens which is in line with discovery made by (Abdul Awal, 1998; Budiea *et al*., 2008b). Not only that, visually there is difference on the specimens condition before and after exposure to acidic environment as illustrated in Figures 3 and 4. The damage done by acid to OPC specimens can be seen through the occurrence of changes in color and corner losses on the specimen. However, not much change was detected on POFA specimen. In terms of POFA specimens' performance, the concrete prepared with POFA10 showed a relatively smaller mass change than the specimen produced using POFA45. Simply phrased, utilization of POFA with higher fineness speeds up the conversion of free lime towards additional C-S-H gel thus contribute to densification of concrete faster than specimen produced using coarser ash.

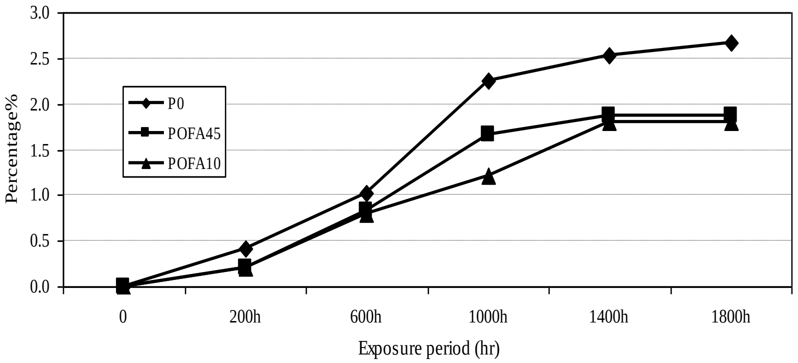

Figure 2: Mass change of concrete cube specimens

Figure 3: Specimens before exposure to acid solution

Figure 4: Specimens after exposure to acid solution

4.3.2 *Relative Compressive Strength*

At the end of the testing period of specimens in acid solution, specimens were tested for compression to determine its residual strength. Companion specimens comprising of six OPC, six POFA45 and six POFA10 concrete cubes, that have been continuously cured in water were also tested at the same time for comparison purposes. The difference in the reduction of compressive strength value of specimens exposed to hydrochloric acid and water cured specimen can be observed in Figure 5. It is evident all specimens exposed to acidic environment exhibit lower ability to resist load in contrast to water cured specimens. However, the performance of specimen exposed to acidic environment is justifiable since Somayaji (2001) has highlighted that the crystalline calcium hydroxide produced during hydration process does not contribute as a binder and this material has confirmed by Mehta (1985) in his study that it is highly vulnerable to acid attack.

Looking at the performance of specimens after exposure to acidic solution, the control specimen exhibit highest strength reduction ratio compared to both cubes formed of using POFA blended cement. Actually, the abundant free lime of the hydrated cement paste makes plain control specimen very susceptible to acid attack. The better resistance of POFA specimen towards acid attack is expected since presence of POFA has lead towards pozzolanic reaction which manages to reduce amount of calcium hydroxide that is susceptible to acid attack besides creating secondary C-S-H gel that makes the concrete denser. The effectiveness of POFA with higher fineness towards increasing the particles reactivity that fastens the pozzolanic reaction

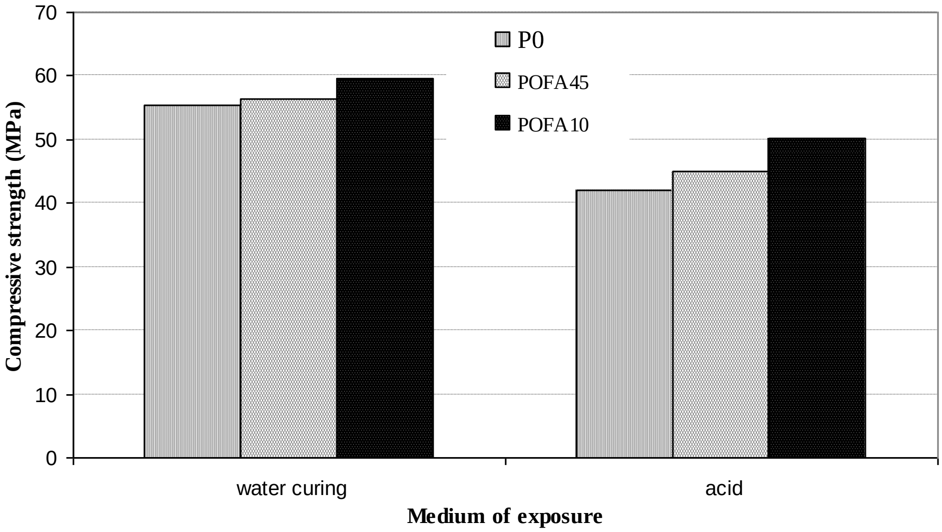

Figure 5: Relationship between the strength of the cubes after 1800 hours

thus enhancing the concrete durability to acid attack is clearly proven when POFA10 concrete produced using POFA 10µm exhibit the lowest reduction ratio compared to the one formed using POFA 45µm.

4.4 *Resistance to Sulphate Attack*

4.4.1 *Expansion of Mortar Bar*

The expansion of POFA45 and POFA10 concrete mortar bars compared to OPC specimen bars in 10% sulphate solution are graphically shown in Figure 6 below. At 3 months of exposure, Po mortar bars expand as much as 1.4% in contrast to expansion of POFA45 and POFA10 concrete bar that was insignificant. Similarly, previous researchers (Abdul Awal, 1998; Abdullah, 2008) have stated that integration of POFA as partial cement substitute enhances concrete durability towards sulphate attack. Inclusion of POFA with higher fineness, POFA 10µm has hastened the pozzolanic reaction thus forming secondary C-S-H gel in a shorter time making the concrete denser and more resistance towards sulphate attack compared to concrete produced using POFA 45µm.

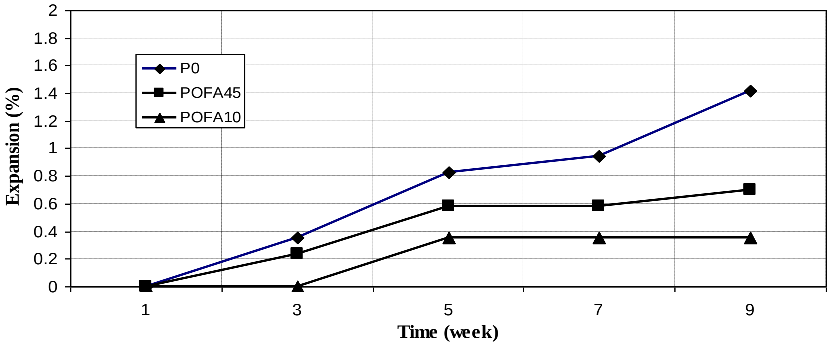

Figure 6: Expansion values of mortar bars

4.4.2 *Compressive Strength Loss*

The compressive strength of concretes immersed in 10% Na_2SO_4 solution and cured in water for 3 months is compared in Figure 7. The loss in compressive strength of Po, POFA45 and POFA10 concretes immersed in 10% Na_2SO_4 solution was approximately 7.00%, 0.77% and 0.64% respectively compared to the same mixtures cured in water. The difference between POFA45 and POFA10 concretes compared with Po concrete, agrees with the results for the expansion of mortar bars.

Being a plain concrete having large amount of free lime that is susceptible to sulphate attack, the highest loss in compressive strength occurred at Po specimens compared to POFA10 and POFA45 concretes that has lesser calcium hydroxide and more secondary C-S-H gel thus possess better resistance to sulphate attack. This result also suggests that POFA10 formed of finer POFA exhibit higher resistance to sulphate attack compared to POFA45.

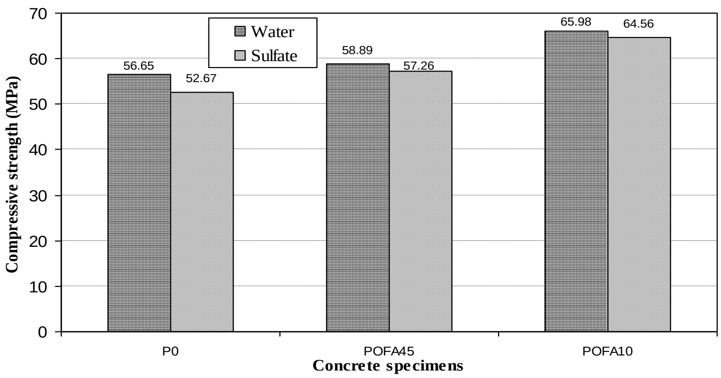

Figure 7: Compressive strength of concretes at the age of 3 months

4.4.3 *XRD Analysis*

The preliminary results of XRD analysis presented in Figure 8 below were obtained from ground samples of Po, POFA45 and POFA10 after exposed to sulphate solutions for only 3 months. It can be observed that all specimens comprised primarily of quartz, calcite and portlandite. All samples have also exhibited considerable precipitation of portlandite (P) although the amount is reduced in POFA specimens in comparison with OPC concrete. The decrease in the amount of lime available in the concrete resulting from pozzolanic reaction would be able to increase the resistance of the material towards sulphate attack. This fact has been confirmed by Rasheeduzzafar *et al.* (1990) who stated that the hardened cement pastes containing greater amount of calcium hydroxide would react more rapidly and to a greater extent with sulphates than those which contain less calcium hydroxide.

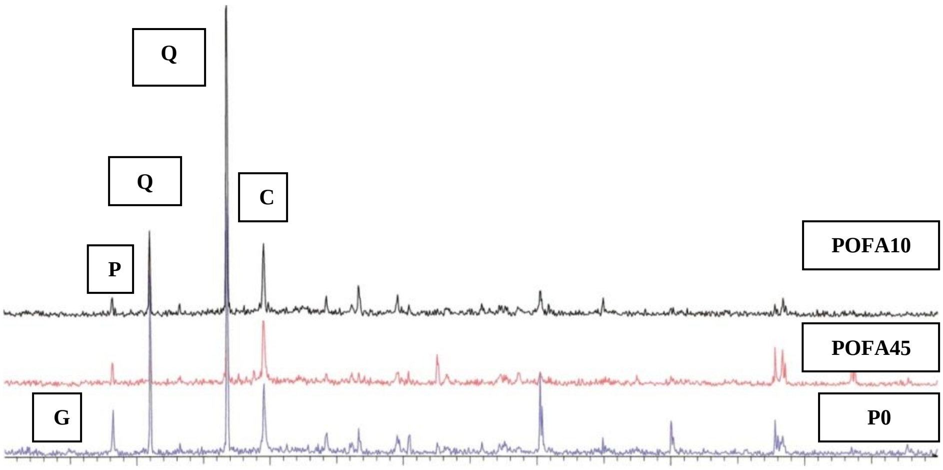

Figure 8: X-ray diffractograms of concrete cubes after 3 months in 5% sodium sulphate solution

Gypsum which is one of the products that produced after sulphate reacted with calcium hydroxide is slightly present in Po concrete. The presence of gypsum indicates that the plain concrete consisting 100% OPC has been attacked by sulphate ion. On the other hand, no gypsum or ettringite is present in POFA samples. The pozzolanic reaction that took place in POFA samples has consumed the free lime converting it to extra C-S-H gel which increases the concrete resistance towards sulphate attack. This fact has been confirmed by Irassar *et al.* (2000) who highlighted that reduction of calcium hydroxide leads to less gypsum formed and vice versa. Conclusively, this result agrees with the results of mortar bar whereby Po specimen that exhibits the largest expansion value of all indicating the susceptibility of this plain specimen towards sulphate attack as compared to POFA specimens.

5.0 Conclusions

Based on the analysis of the data obtained, the conclusions of this study can be drawn as follows:

(1) POFA was found to have pozzolanic effect on high strength concrete where concrete replaced with POFA45 and POFA10, with water to binder ratio of 0.45, were seen to develop strength exceeding the design strength of almost 60 MPa at 28-day.
(2) Even at low water to total cementitious materials ratio (W/(C + F) = 0.45), the replacement of cement by POFA45 and POFA10 at level of 20% resulted in an increase of compressive strength, and improvement of chemical resistance of concrete. It is because the pozzolanic effect further reduced the pore diameters so as to improve strength and permeation characteristics.
(3) Irrespective of degrees of fineness, POFA concrete was found to be more effective than OPC concrete in decreasing the chloride diffusion.
(4) The reduction rate of the compressive strength at 1800 hours was almost similar for both POFA concretes but more in Po concrete. Although the resistance presented by Po mixed concretes was slightly below those exhibited by POFA45 replaced concretes, concrete replaced by POFA 10 exhibit a promising performance.
(5) POFA10 formed using POFA 10µm which is finer than POFA 45µm that been used to produce POFA45 specimen exhibit better resistance to acid attack. The use of finer POFA speeds up the pozzolanic reaction in POFA10 which decreases the amount of free lime that is vulnerable to acid attack.
(6) The investigation of durability of POFA concrete in terms of examining the performance of POFA10 concrete exposed to sulfate solution shows that it performs better than POFA45 concrete and Po concrete as well.
(7) The ground POFA with high fineness of 10 µm can be used to produce high-strength durable concrete higher than that of control concrete and POFA 45 concrete.

(8) The results encourage the use of POFA, as a pozzolan for partial cement replacement in producing high durable concrete especially when its fineness has been increased.

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