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THESIS

DURABILITY OF FLY ASH BASED GEOPOLYMER MORTAR

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A Thesis Submitted in Partial Fulfillment of
the Requirements for the Degree of
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The purpose of this study is to assess the durability of fly ash based geopolymer mortar in adverse environments. The attacking conditions were sulfuric acid, acetic acid, sodium and magnesium sulfate solutions, chloride solution and carbonation atmosphere. Mechanical properties were weight change and compressive strength. The effects of exposure to attacking agents on the microstructures were studied by using scanning electron microscopy. The variable parameters were 6M, 10M and 14M sodium hydroxide used in producing geopolymer, exposed to 1%, 3% and 5% sulfuric acid, 1%, 3% and 5%acetic acid, saturated sodium sulfate, saturated magnesium sulfate and 5% chloride solution, 7% carbon dioxide atmosphere.

From the experiment results, 14 M sodium hydroxide yielded geopolymer mortar was the most resistant to acids and to sulfate attacks. As for rapid chloride test, carbonation permeation test and chloride penetration test, they showed that OPC mortar was more resistant than geopolymer mortar group.

Student's signature	Thesis Advisor's signature	___ / ___ / ___

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Chutchavan Visitanupong
August 2009

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LIST OF SYMBOLS AND ABBREVIATIONS

Al = Aluminum
ASR = Alkali silica reactions
Ave. = Average
ASTM = American Society of Testing and Materials
Ca = Calcium
CaO = Calcium Oxide
cm. = Centimeter
cm./s. = Centimeter per second
CO_2 = Carbon dioxide
CSH = Calcium silicate hydrate
EDS = Energy Dispersive Spectrometer
GEO = Geopolymer
h. = Hours
Kg. = Kilogram
ksc. = Kilogram per square centimeter
min. = Minute
mm. = Millimeter
M = Molarity
M.W. = Molecular
MPa = Mega Pascal or Newton per square millimeter
NaCl = Sodium Chloride
NaOH = Sodium hydroxide
Na_2SiO_3 = Sodium silicate
O = Oxygen
OPC = Ordinary Portland cement
RCPT = Rapid chloride penetration test
SEM = Scanning Electron Microscope
Si = Silicon

LIST OF SYMBOLS AND ABBREVIATIONS (Continued)

SiO_2 = Silica

V. = Voltages

XRF = X-ray Fluorescence

^{o} C = Celsius degree temperature

pH = Power of Hydrogen ion

w/b = Water to binder ratio

w/c = Water to cement ratio

Ø = Diameter of cylinder

DURABILITY OF FLY ASH BASED GEOPOLYMER MORTAR

INTRODUCTION

The production of cement generates large amount of carbon dioxide. Carbon dioxide could be reduced if the production of cement could be reduced as well. Scientists have been doing research and development for more than 20 years on a new material called “geopolymer” to replace the use of cement. This material is made basically of a mixture of sodium hydroxide and sodium silicate solution which when combined with certain powder material such as fly ash or calcined kaolin forms a material with cementitious properties similar to and in the same range as Portland cement paste. Although the three components can vary a great deal, from the concentration of sodium hydroxide and sodium silicate to the ratio of the two solutions to the composition of the fly ash, there is a general consensus that the reaction producing the geopolymer is in the form of polymerization.

The long term requirements of structure dictates that durability of material be given a serious consideration. Although geopolymer is an entirely different type of material from Portland cement concrete, it is worth finding how well geopolymer performs compared with concrete under the same conditions. In concrete, three adverse conditions are widely used to test its durability, namely, carbonation permeability, sulfate attack and chloride ingress resistance. The objectives of this study were to assess the performances of geopolymer under the three adverse conditions and to compare them with those of cement mortar.

Humans have overused the resources in the environment bringing about negative changes, such as acid rain, that affect structures. Acid resistance is a desirable property for structural materials used in the aggressive environment of chemical, mining, mineral processing and other industries.

This research presented experimental work undertaken to develop class C fly ash based geopolymers and attempted to answer how to improve resistance in the adverse condition comparing experiment models with Ordinary Portland cement.

OBJECTIVES

The main objectives of this present research study were to determine:

1. The development of compressive strength of geopolymer mortar with OPC mortar at the same age

2. The effect of concentrated alkaline activators in durability of geopolymer mortar

3. The effect of acid attack on the strength of geopolymer mortar

4. The effect of sulfate attack on the strength of geopolymer mortar

5. The effect of carbonation of geopolymer mortar

6. The effect of rapid chloride of geopolymer mortar

7. The effect of chloride penetration of geopolymer mortar

Scope of Research

1. Acid and sulfate resistant: mainly to determine the durability of fly ash-based geopolymer mortar from various proportional and different Morality of sodium hydroxide.

2. Scanning electron microscopy (SEM) and energy dispersive spectrometer (EDS) analyses were performed on the fly ash-based geopolymer.

3. Chloride ingress into geopolymer mortar: mainly to determine quantity of electric charge by comparison flow pass and depth of chloride penetration of specimens.

4. Carbon dioxide ingress into geopolymer mortar: mainly to determine carbonation depth of specimens.

5. Fly ash used in this study is class C fly ash.

6. Concentration of sodium hydroxide (NaOH) liquid measured in terms of Molarity (M) is 6M, 10M and 14M.

7. Curing temperature in an oven at a specified 60 ^{0}C for 48 hours

LITERATURE REVIEW

1. Geopolymer binder

1.1 Introduction to geopolymer

In the past, geopolymer which was known as mineral polymer or inorganic polymer glass, received attention as a promising new form of inorganic polymer material that could replace OPC, plastics and many mineral-based products.

Davidovits created the term “Geopolymer’ in 1979 (Davidovits 1979) to describe a new family of mineral binder whose matrix was based on a poly (sialate) Si-O-Al- O framework structure with alternating SiO_4 and AlO_4 Tetrahedral joined together in three directions by sharing all the oxygen atoms. The replacement of Al^{3+} (four-fold coordination) for Si^{4+} caused a negative charge, which needed alkalis or alkali-earths to balance, like Na^+ , K^+ , Ca^{2+} or Mg^{2+}.

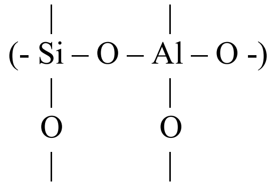
The empirical formula (Davidovits 1991) was:

$$M_n\,[-(SiO_2)_z-AlO_2]_n\,.wH_2O$$

Wherein M was a cation such as potassium, sodium or calcium,
‘n’ was a degree of polycondensation;
‘z’ was 1, 2 or 3.

The Si-O-Al linkages were further defined as follows:

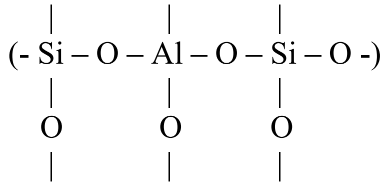
PS
Poly(sialate)



$$(-\mathrm{Si}-\mathrm{O}-\mathrm{Al}-\mathrm{O}-)$$

$SiO_2:Al_2O_3 = 2$

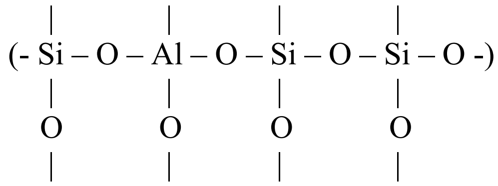
PSS
Poly(sialate-siloxo)



$$(-\mathrm{Si}-\mathrm{O}-\mathrm{Al}-\mathrm{O}-\mathrm{Si}-\mathrm{O}-)$$

$SiO_2:Al_2O_3 = 4$

PSDS
Poly(sialate-disiloxo)



$$(-\mathrm{Si}-\mathrm{O}-\mathrm{Al}-\mathrm{O}-\mathrm{Si}-\mathrm{O}-\mathrm{Si}-\mathrm{O}-)$$

$SiO_2:Al_2O_3 = 6$

Polysilicates were sodium or potassium silicate supplied by chemical industry or manufactured fine silica powder as a by-product of ferro-silicon metal industry. Unlike ordinary Portland pozzolanic cements, geopolymers do not form calcium-silicate-hydrates (CSHs) for matrix formation and strength, but utilize polycondensation of silica and alumina precursors and a high alkali content to attain structural strength. (Davidovits 1988).

1.2 Synthesis and Mechanism

First of all it is necessary to briefly discuss the formation of zeolites as they follow very much the same line. This view is supported by Davidovits (1982, 1994, 1988, 1999) who stated that aluminosilicate geopolymers have a three dimensional structure and belong to the category of zeolites and feldspathoids. The chemical compositions of geopolymer materials are similar to zeolite but they reveal an amorphous microstructure.

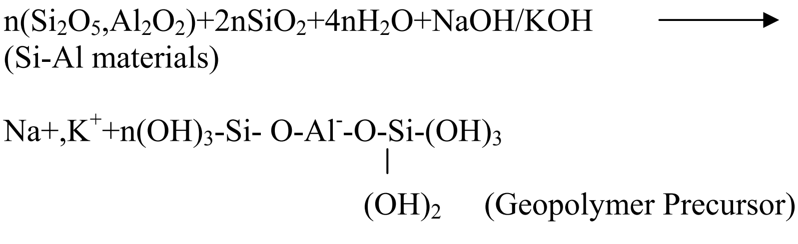
Zeolites are based on a crystalline aluminosilicate framework and are three dimensional network inorganic polymers built up of $(Si,Al)O_4$ tetrahedra linked by sharing oxygen atoms into ring and cages. The stoichiometry of zeolites can be represented by the general formula (Bell 1999):

$$M^{n+}\,[(AlO_2)(SiO_2)_x]\,.zH_2O$$

Where x represents the atomic ratio of Si: Al. The extra lattice cation M^{n+} such as H^+, Na^+, K^+, Cu^+ and $[Fe(OH)_2]^+$ is required for charge compensation. Zeolites are found naturally but can also be synthesized hydrothermally from a caustic mixture of sodium silicate, aluminium hydroxide and an organic templating agent. The framework of zeolites is formed by corner sharing of SiO_4 and AlO_4 tetrahedra.

Zeolite synthesis depends on the use of highly reactive starting materials, a relatively high pH, a high degree of saturation resulting in large numbers of nuclei, and a relatively low temperature. Zeolites are commonly synthesised by sol-gel techniques. In a typical procedure, a soluble source of Al is dissolved in a highly alkaline solution of sodium silicate resulting in an amorphous aluminosilicate gel. Crystallisation is normally carried out in the temperature range of 100 – 180 °C for a few hours to a few days. During this period the amorphous gel undergoes continual dissolution and reconstruction, and the crystalline zeolite phase grows (Ray, 1978; Bell, 1999).

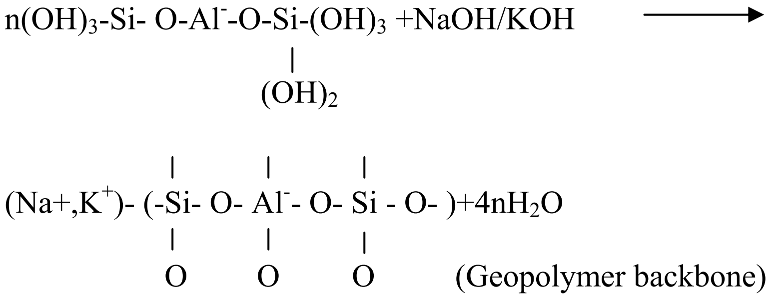
Geopolymerisation involved a chemical reaction between various alumino-silicate oxides (in Al^{3+} four-fold coordination) with silicates under highly alkaline conditions, yielding polymeric Si–O–Al–O bonds, which can be presented schematically as follows:



$$\underset{\text{(Si-Al materials)}}{n(Si_2O_5,Al_2O_2)+2nSiO_2+4nH_2O+NaOH/KOH} \longrightarrow$$

$$Na+,K^+ + n(OH)_3\text{-Si- O-Al}^-\text{-O-}\underset{\underset{(OH)_2}{|}}{\text{Si}}\text{-}(OH)_3 \qquad (1)$$

(Geopolymer Precursor)



$$n(OH)_3\text{-Si-O-Al}^{-}\text{-O-Si-}(OH)_3 + NaOH/KOH \longrightarrow \quad (\text{with } (OH)_2 \text{ on Al})$$

$$(Na^+,K^+)\text{-}(\text{-}\underset{O}{\overset{|}{\underset{|}{Si}}}\text{-O-}\underset{O}{\overset{|}{\underset{|}{Al^{-}}}}\text{-O-}\underset{O}{\overset{|}{\underset{|}{Si}}}\text{-O-}) + 4nH_2O \qquad (2)$$

(Geopolymer backbone)

The above two reaction paths indicate that any Si-Al materials might become sources of geopolymerisation (Van Jaarsveld *et al.*, 1997). The structure of geopolymers could be either amorphous or crystalline, depending on the condensation temperature. Amorphous polymers are obtained at temperatures ranging from 20 to 90 °C, while crystalline polymers are obtained at 150–200 °C. The structure of crystalline geopolymers resembles that of zeolite (Davidovits, 1991).

In reactions (3) and (4), the amount of Al–Si materials used depends on the particle size, the extent of dissolution of Al–Si materials and the concentration of the alkaline solution. With finer particle sizes (<0.5 μm) and hence higher extent of dissolution, comparatively lower ratios of alumino-silicate powder alkaline solution could be used, as most alumino-silicate particles could then be dissolved as a gel. In most cases, however, alumino-silicate particles couldn't be converted totally from the solid phase to the gel phase. Undissolved alumino-silicate solids contained in a geopolymer could behave as reinforcement of the matrix (Palomo *et al.*, 1992).

$$\text{Al-Si materials(s)} + MOH(aq) + Na_2SiO_3(\text{s or aq}) \qquad (3)$$

$$\downarrow$$

$$\text{Al-Si materials(s)} + [M_z(AlO_2)_x(SiO_2)_y.nMOH.mH_2O] \text{ gel} \qquad (4)$$

$$\downarrow$$

$$\text{Al-Si materials(s)} + [M_a((AlO_2)_a(SiO_2)_b.nMOH.mH_2O] \qquad (5)$$

Geopolymers with amorphous structure

A series of chemical reaction formulae have been proposed but have not yet been adequately proven. The overall process was described in four steps (Xu *et al*., 2001).

1) The dissolution of aluminosilicate in alkaline environment occurs first. When aluminosilicate minerals were subjected to a high pH environment the bonds between interlinked silicate and aluminate tetrahedral are broken.

2) The dissolved aluminum and silicon complexes diffuse from the solid aluminosilicate surface to the interparticle space.

3) A gel phase was formed, resulting from polymerization between an added silicate solution and aluminum and silicon complexes.

4) The gel phase hardens due to the exclusion of spare water to form a geopolymer product.

1.3 Geopolymer cement

Davidovits (1982) studied the production of alkali-activated cement by using dexydroxylated kaolinite. The resulting cement which was known as geopolymer cement or (K-Ca) poly (sialate-siloxo) cement was claimed to have unique properties such as high early strength and low shrinkage. The most significant impact of geopolymer cements was its potential to contribute to environmental protection.

A(K-Ca)Poly(silate-siloxo) ((K-CA)-PSS cement, Si:Al = 2) comprises three major compounds, namely :

- Specific aluminosilicate of kaolinite clay species, calcined at 750°C
- Alkali-disilicates (Na_2 or K_2) $(H_2SiO_4)_2$
- Calcium disilicates $Ca(H_3SiO_4)_2$

Geopolymer was also known by other names, such as low temperature aluminosilicate glass (Rahier *et al*., 1996a), alkali-activated material (Malek and Roy 1997; Palomo *et al*., 1999b) and geocement (Krivenko 1997).

The production of geopolymer had two main constituents which are solid materials and alkaline solutions. Solid materials for geopolymers should be rich in Si and Al. These can be natural minerals such as kaolinite, clays, micas, and alousite, spinel whose empirical formula contains Si, Al, and oxygen. Early on metakaolinite was the traditional raw material to use to make geopolymers. Later on solid materials for geopolymers were fly ash, silica fume, slag and rice-husk and alkaline solution sodium or potassium based. The most common alkaline liquids used in geopolymerisation were combination of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate or potassium silicate.

1.4 Strength of geopolymer

Most of the past research on the behavior of geopolymeric material was based on the binder paste or mortar using small size specimens. The laboratory tests on fly ash-based geopolymer binder, consisted of three variables to effect strength and hardening. The first variable was concentration of NaOH Solution (M). When increasing concentration of NaOH Solution, compressive strength was higher than the specimens which were activated by lower concentration of NaOH Solution.

Table 1 Effects of activator composition on strength development

Mixture	NaOH solution(M)	Na_2SiO_3:NaOHby mass	Strength(MPa) 60 °C 24 h.
A-1	8	0.4	17.3
A-2	8	2.5	56.8
A-3	14	0.4	47.9
A-4	14	2.5	67.6

Source: Hardijo *et al*. (2004a)

The second variable was ratio of Na_2SiO_3: NaOH; Hardijo *et al.* (2004a) proved that this ratio was suitable 2.5, compressive strength was 67.7 MPa at the same curing condition from Table 1 and the third variable was curing condition that in the past had many researchers make conclusions such as;

Davidovits, (1994a) concluded that structural integrity and reasonable strength of the resulting material were attained in a very short time. In most cases, 20% to 30% of the final compressive strength was developed in the first few hours of setting. The high early strength of geopolymer cement designed particularly for waste containment could be enhanced with the adjunction of microwave preheating devices in order to raise the temperature of the waste up 30-35°C.

Palomo *et al.* (1992) showed that the curing temperature, the curing time, and the type of activator affected the compressive strength, while the solution-to-fly ash ratio was not a relevant parameter. Increase in the curing temperature increased the compressive strength. The type of alkaline activator that contained soluble silicates resulted in a higher reaction rate than when hydroxides were used as the only activator. While van Jaarsveld *et al.*, confirmed the importance of curing at elevated temperature for fly ash-based geopolymeric material, they found that curing for a longer period of time at elevated temperature weakened the microstructure.

Swanepoe and Strydom (2002) showed that the optimum condition was found to be at 60°C for 48 hours and compressive strength measurements showed a maximum strength of almost 8MPa after 28days. The infrared spectra indicated that the geopolymerisation reaction occurred to some extent in the sample heated at 60 ° C for 48 hours.

While van Jaarsveld *et al.* (2002) confirmed the importance of curing at elevated temperature for fly ash-based geopolymeric material, they found that curing for a longer period of time at elevated temperature weakened the microstructure.

1.5 Advantages of Geopolymers

Geopolymer was a new binder. Its manufacture consumes less energy and releases much lower CO_2 compared to Portland cement. Geopolymer mortar or concrete is superior to normal concrete in terms of durability (Davidovits 1994b). The manufacture of Portland cement is always accompanied by the emission of CO_2. The production of one ton of Portland cement directly generates 0.55 ton of CO_2 and yields an additional 0.40 ton due to the combustion of carbon-fuel. Geopolymer has been targeted as one type of potential low- CO_2 cementing system (Gartner 2004).

When an industrial by-product, like fly ash, was used, then no supplementary CO_2 will be released. Moreover, although the manufacture of the activator itself (i.e. alkali silicate) would have CO_2 emission similar to the making of ordinary "bottle" glass, the activator addition in a geopolymer concrete mix was very low. So in terms of CO_2 emission per unit volume of concrete, the total CO_2 emission level in geopolymer concrete was theoretically 10 times more than pure Portland cement concrete (Gartner 2004). Given the relatively low greenhouse intensity of geopolymer in producing cementitious materials, it was a potential environmentally friendly binder for building materials (Spannagle 2002).

The technology of geopolymerisation has been applied to produce some cement related products that can be bought commercially (Davidovits 1991, Davidovits 1994a). Due to some of their superior properties over Portland cement, geopolymer cements were suggested for their applications in many areas such as:

- Massive concrete panels, grouts, and fiber reinforced sheets.
- Building component such as bricks and ceramics tiles.
- Structural surfaces such as floor and storage areas as well as runways.

2. Durability of concrete

The environment has deteriorated due to acid, sulfate, chloride and carbon dioxide. These are the most important problems concerning the durability of concrete structures. Concrete durability has become a critical issue for the future (Mehta 2001) because many concrete structures in urban and coastal environments start to deteriorate after 20 to 30 years, though their design life was at least 50 years.

Acid resistance is a desirable property for structural materials used in the aggressive environment of chemical, mining, mineral processing and other industries. Basic in nature, concretes made with Portland cement and alkaliactivated slag deteriorate in the acid environment (Harrison, 1987). In the case of acid attack on OPC concrete, calcium salts of the attacking acid rapidly form and decreased strength of concrete and deteriorated quickly (Bakharev, 2003).

Sulfate attack is one of the most serious problems concerning the durability of concrete structures. Under the sulfate environment, cement paste undergoes deterioration resulting from expansion, spalling and softening. It is generally recognized that addition of pozzolan reduces the calcium hydroxide in cement paste and improves the permeability of concrete. This helped to increase the resistance of concrete to the attack of sulfate (Malhotra, 1987). In 1997 Khatri *et al.* found that sulfate attack has been demonstrated for both laboratory and field concretes. The common ways to improve resistance to sulfate attack were to reduce the permeability by restricting the water to cementitious materials ratio.

RCPT has been used to evaluate the chloride permeability of hardened cement mortars and concretes made with special cements or supplementary cementing materials (Ozyildirm and Halstead, 1988). It is obvious that the use of RCPT in some of those studies has resulted in some invalid or misleading conclusions. In one study (Roy *et al.*, 1987) it was found that the inclusion of sands or Class F fly ash decreased chloride permeability significantly, while their effects on water permeability were much smaller.

Khunthongkeaw *et al*. (2004) concluded that under natural exposure environments, the carbonation rate was the highest when cement mortar specimens were exposed in the city. The decreased ratio of water to binder and fly ash content led to a better carbonation resistance. For the same fly ash content, specimens of high-CaO fly ash showed a better carbonation resistance than those of low CaO fly ash. However, the test results on mortar were worse by the use of fly ash than those of concrete.

V'eleva *et al*. (1998) showed that the basic factor influencing carbonation was the diffusivity of the hardened cement paste. Carbonation rate was controlled by the ingress of CO_2 into concrete pore system by diffusion with a concentration gradient of CO_2 acting as the driving force. Factors affecting diffusion rate include the type and amount of cement, porosity of the material, time of curing, type and quantity of pozzolanic additions.

3. Durability of Geopolymer

The Pyramids in Egypt remain unaffected displaying extreme durability. It was found that the long-term durability in those ancient structures was due to the silicon-aluminosilicate structure (Davidovits 1987). Therefore, previously scientists tried to find the results of durability from many harsh conditions, to answer the questions of durability. From the past, research was related to synthesize geopolymer with higher compressive strength. A mixed alkaline activator of sodium hydroxide and sodium silicate was suggested (Xu and van Deventer 2000) because the addition of extra silicate can supply sufficient silicon in the alkaline solution to start the geopolymerisation. However, it was found that geopolymer with potassium hydroxide as the alkaline activator was disadvantageous for sulfuric acid resistance (Bakharev, 2005c).

The deterioration of geopolymer materials in acidic media was connected to depolymerisation of aluminosilicate polymers and liberation of silicic acid, replacement of Na and K cations by hydrogen or hydronium ion and dealumination of the geopolymer structure. It was also connected to condensation of siliceous of the geopolymer and zeolites, which in some cases leads to significant loss of strength. In acidic environment, high-performance geopolymer materials deteriorate with the formation of fissures in amorphous polymer matrix, while low-performance geopolymers deteriorate through crystallization of zeolites and formation of fragile grainy structures. The materials tested had a significant difference in the degrees of intrinsic ordering within the polymer gel. More crystalline geopolymer material prepared with sodium hydroxide was more stable in the aggressive environment of sulfuric and acetic acid solutions than amorphous geopolymers prepared with the sodium silicate activator (Bakharev, 2005c).

All visual physical deterioration could be described by visual observation, including colour change, softening, spalling of the edges and corner expansion. Geopolymer specimens retained their shapes after sulfuric acid attack but the cylinder surface appeared pitted and eroded after exposed in 2% sulfuric acid for one year (Wallah *et al.*, 2005)

When geopolymer was studied, the change in mechanical strength was used to identify change in the structure (Wastiels *et al.* 1993; Wallah *et al.*, 2005). It found that geopolymers using sodium hydroxide and sodium silicate as alkaline lost their strength significantly as shown in Table 2.

Table 2 Compressive strength of geopolymers after sulfuric acid attack

Immersion in sulfuric acid	Strength (MPa.)		Strength change (%)	Reference
	Before	After		
14 weeks in 20% acid	52.7	37.4	29	Wastiels *et al.*1993
One year in 5% acid	~55	~20	~65	Wallah *et al.*2005

Source: Wastiels *et al.* (1993); Wallah *et al.* (2005)

Finally there are two methods to determine the extent of corrosion after acid and sulfate exposure. The first is based on physical change that was compressive strength change and weight change and the second was alkalinity change and microstructure change by SEM –EDS. SEM could give the images while the EDS could detect the chemical composition of the solid geopolymers.

The SEM can give the images while the EDS can detect the chemical composition of solid geopolymers. It was noted (Janhanian and Rostami, 2001) that when curing at an ambient temperature or at 80°C for three hours, FA particles have been found with etched surface by the alkali but without any intersection between them. When curing time and temperature were 80°C for 18 hours, the FA particles penetrated into each other and a solid mass was produced. The synthesized geopolymer matrix consisted of the gel and the undissolved FA spheres as seen in Figure 2(a). This geopolymer paste was initially cured at 95°C for 24 hours (Bakharev *et al.,* 2005c).

After being exposed in a 5% sulfuric acid for two months, the geopolymer paste became porous and fragile as shown in Figure 2(b)

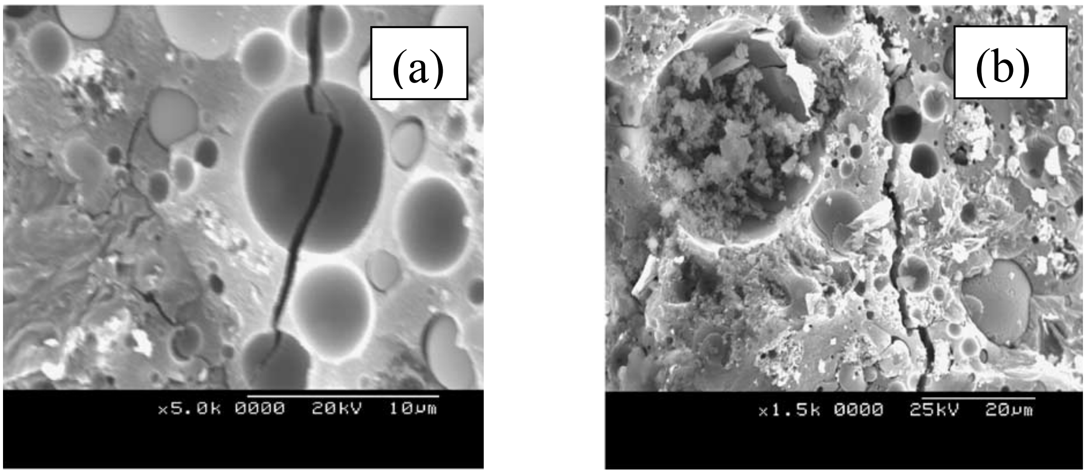


Figure 1 SEM of geopolymer paste (a) before immersion in sulfuric acid, (b) after immersion in 5% sulfuric acid for two months.

MATERIALS AND METHODS

Materials

1. Fly ash: Fly ash was collected from Mae-Moh lignite power plant in Lampang province. The chemical composition of the fly ash, as determined by XRF analysis is as shown in Appendix Table A1.
2. Sodium silicate solution, grade B (Na_2O=14.7%, SiO_2=29.4% and water=55.9% by mass.).
3. Sodium Hydroxide (NaOH) in flake form (98% purity).
4. Water: Distilled water
5. Fine aggregate : Fine sand
6. 1,3,5 % Acetic acid solution
7. 1,3,5 % Sulfuric acid solution
8. 5%Sodium chloride solution
9. Saturated sodium sulphate solution
10. Saturated magnesium sulphate solution
11. Carbon dioxide CO_2 concentrates 7%
12. Ordinary Portland cement
13. Plastic Bowl
14. Thermometer couple
15. Molds cubic50*50*50 mm
16. Molds cylinder Ø50*100 mm
17. Molds cylinder Ø102*204 mm
18. Compressive strength testing machine
19. Scanning Electron Microscope

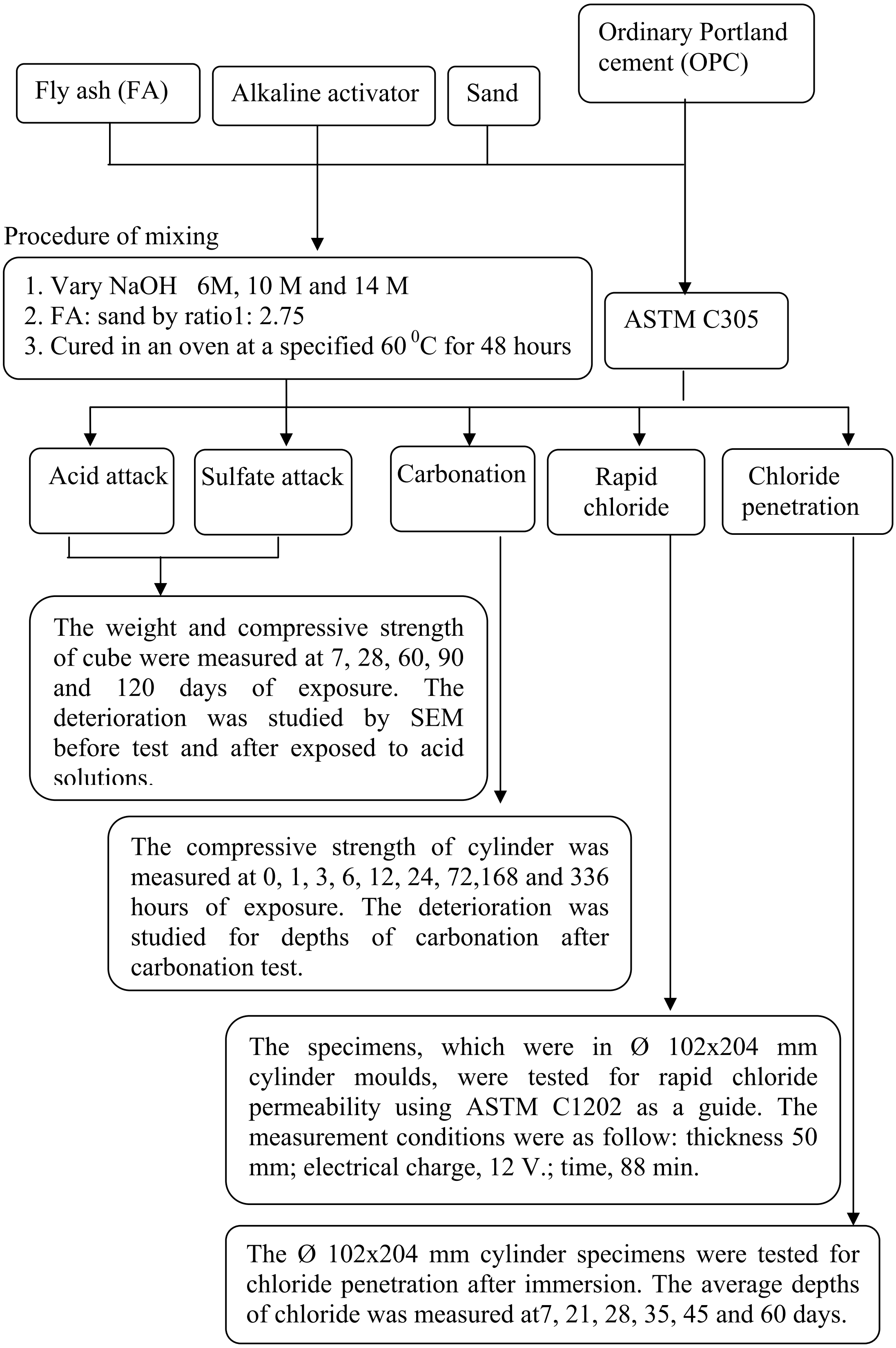
Methods

1. Procedure of mixing

Analytical grade sodium hydroxide in flake form NaOH with 98% purity and sodium silicate solutions (Na_2O=14.7%, SiO_2=29.4% and water=55.9% by mass**)** were used as the alkali activator. Sodium hydroxide flakes were dissolved in distilled water.

The materials and methods can be seen in Figure 2. The activator solution was prepared at least one day prior to its use. The sand and the fly ash were mixed dry in a bowl mixer for 3-5 minutes by ratio 2.75:1. Sodium hydroxide solution was prepared in terms of molarity (M), in the range of 6M, 10M and 14 M, then added to the sand-fly ash mix and mixed for another 3-5 minutes. Then the activator (sodium silicate), providing 9% Na in the mixtures and water/binder (w/b) ratio of 0.4 were mixed together as shown in Table 2. The mixture was divided into three parts. The first part was cast in 50x50x50 mm cubic moulds to test acid attack and sulphate attack. The second part was cast in Ø 50x100 mm cylinder moulds for carbonation test and the third part was cast in Ø 102x204 mm cylinder moulds for rapid chloride test and chloride penetration test. Immediately after casting, the specimens were covered by a plastic sheet to avoid the loss of water due to evaporation during curing. Ordinary Portland cement mortar (OPC) from ASTM C 305 with w/b ratio of 0.4 was used for comparison of durability.

For geopolymer after being left in room temperature for 60 minutes, specimens were cured in a steam oven at 60^0C temperature for 48 hours. Ordinary Portland cement mortar curing was for 24 hours at room temperature followed by 7days in water.



1. Vary NaOH 6M, 10 M and 14 M
2. FA: sand by ratio1: 2.75
3. Cured in an oven at a specified 60 ^{0}C for 48 hours

The weight and compressive strength of cube were measured at 7, 28, 60, 90 and 120 days of exposure. The deterioration was studied by SEM before test and after exposed to acid solutions.

The compressive strength of cylinder was measured at 0, 1, 3, 6, 12, 24, 72,168 and 336 hours of exposure. The deterioration was studied for depths of carbonation after carbonation test.

The specimens, which were in Ø 102x204 mm cylinder moulds, were tested for rapid chloride permeability using ASTM C1202 as a guide. The measurement conditions were as follow: thickness 50 mm; electrical charge, 12 V.; time, 88 min.

The Ø 102x204 mm cylinder specimens were tested for chloride penetration after immersion. The average depths of chloride was measured at7, 21, 28, 35, 45 and 60 days.

Figure 2 General programs for experiment of this thesis

Table 3 Mix design of fly ash-based geopolymer by Na_2SiO_3/ NaOH = 2.0

Mix specimens	Concentration of NaOH	NaOH (gram)	Na_2SiO_3 (gram)	Fly ash (gram)	Sand (gram)	H_2O (gram)
GEO 6M	6 M.	12	24	63	173	5
GEO 10M	10M.	12	24	63	173	5
GEO 14M	14M.	12	24	63	173	5

Table 4 Oxide -Mole Ratios of the Reactant Mixture

Mix specimens	Concentration of NaOH	SiO_2 (Mole)	Al_2O_3 (Mole)	Na_2O (Mole)	H_2O (Mole)
GEO 6M	6 M.	0.65	0.1	0.09	1.05
GEO 10M	10M.	0.65	0.1	0.10	1.07
GEO 14M	14M.	0.65	0.1	0.12	1.09

2. Experimental step

To test acid attack and sulphate attack, initial compressive strengths of 50x50x50 mm. specimens were determined. The resistance of materials to acid attack was studied by immersion of cube specimens in 1%, 3%and5% solutions of acetic acid, sulphuric acid, saturated sodium and saturated magnesium sulphate. The strength of acid solutions used in the test was not equal. The testing media were replaced monthly with fresh solutions. The compressive strength of the cubes was measured at7, 28, 60, 90 and 120 days of exposure.

Deterioration was studied by scanning electron microscopy (SEM). For the analysis, the specimens were taken from the surface (1–2 mm. depth) exposed to solutions before test and after 3 months exposure to the solutions.

The carbonation tests were carried out in accelerated carbonation apparatus. Eighteen geopolymer mortar specimens and eighteen of OPC mortar specimens were used. The specimens were kept in mould for 1 day, and cured in chamber for 28 days. These specimens were placed inside the tank and the lid of the tank was tightly closed. In each experiment, the temperature and relative humidity in the carbonation chamber was controlled at 40 ^{0}C and 55%, respectively. The CO_2 concentration was 7%. The depths of carbonation were determined by spraying on a freshly broken surface of the specimens with 1% of phenolphthalein in the solution of 70% ethyl alcohol. The phenolphthalein solution was colorless and used as an acid–base indicator.

The color of the solution changes into purple when pH was higher than the range of approximately nine. Therefore, when the solution is sprayed on a broken specimen’s surface, the carbonated portion was uncolored and non-carbonated portion was purple. The average depths of carbonation were measured. Specimens were stored at the laboratory for period of 0, 1, 3, 6, 12, 24, 72,168 and 336 hours. The specimens were taken from the chamber and their compressive strength was measured.

The specimens, which were in Ø 50x200 mm cylinder moulds, were tested for rapid chloride permeability according to ASTM C1202. Sodium hydroxide solution (0.3N NaOH) and sodium chloride solution (3% NaCl by mass) were placed in the chambers on two sides of the specimens, and 12 V. direct current voltage were applied. The measurement conditions were as follow: thickness 50 mm; time, 82 min.

The specimens, which were in Ø 102x204 mm cylinder moulds, were tested for chloride penetration after immersion. The average depths of chloride were measured at7, 21, 28, 35, 45 and 60 days using 0.141 N silver nitrate spray.

RESULTS AND DISCUSSION

1. The development of compressive strength

As shown in Figure 8, the compressive strengths of geopolymer mortar specimens group were higher than OPC mortar specimens group, except the geopolymer mortar 6M specimens which were lower than OPC mortar specimens. The strength of the tested geopolymeric specimens depended on the concentration of activator used in specimen preparation. The specimens prepared with high concentration sodium hydroxide had more compressive strength than specimens prepared with low concentration sodium hydroxide activator. The age increase did not significantly increase compressive strength of geopolymer mortar group. On the contrary, compressive strength of OPC mortar group was stead until it reached the age of 28 days.

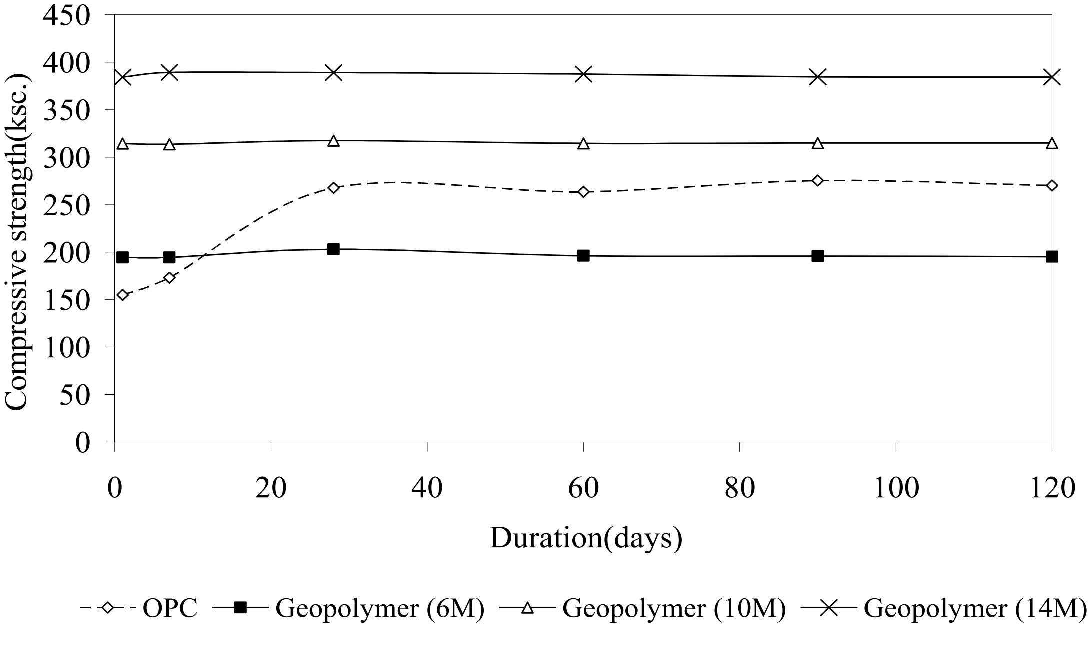


Figure 3 Developed compressive strength of geopolymer mortar and OPC mortar

2. Resistance to acid solutions

2.1 Strength and weight change

For the experiment of sulfuric acid and acetic acid resistance, the result showed that the compressive strength and percentage weight of the specimens, which were immersed in sulfuric acid, decreased more than the specimens immersed in acetic acid. Geopolymer mortar 14 M was the most resistant to those acids when compared with OPC mortar.

As seen in Figure 4 and Figure 5, all specimens of geopolymer mortar remained intact even after 120 days in the same acidic environment, though some very fine cracks had developed. This comparison demonstrated that the geopolymer mortar was superior to OPC mortar in resisting sulfuric and acetic acid attack. Geopolymer specimens showed very small change in appearance after 120 days of immersion in the acidic solutions. In the sulfuric acid, there was small change in appearance of geopolymer specimens group and fine cracks were observed on the specimen surfaces as shown in geopolymer specimens group. This cracking phenomenon was overlooked at first. However, after 120 days, some white reaction products were observed on specimen surfaces in 5% sulfuric acid. The whitish reaction products as seen in Figure 12 and Figure13 were examined under SEM analyzed with EDS. These were mainly crystal sections as shown in Figure 12 and Figure13, which is a type of gypsum as reported by Rendell and Jauberthie (1999). The EDS data showed the domain elements of calcium and sulfur, hence the white products were determined to be gypsum.

The examination of specimens exposed to the sulfuric acid solution showed severe deterioration of the OPC mortar specimens that were consistent with high content of calcium in these specimens. Within 120 days, OPC mortar specimens had a thick layer of white paste formed on the surface of OPC specimens deteriorated to a depth of 5 mm after 30 days and 12 mm after 120 days. In acetic solution, there was no significant loss of cement paste material from the surface in OPC specimens but the colour of the surface layer in OPC specimens had been changed.

As for the experiment of sulfuric acid and acetic acid resistance, it was found that geopolymer mortar 14 M was the most resistance to those acids when compared with OPC mortar. Percentage of Compressive strength change of geopolymer mortar at 14 M and OPC mortar at 120 days was -24.35 and -37.89 respectively after immersed in5% sulfuric acid. The percentage of compressive strength change of geopolymer mortar at 14 M and OPC mortar after 120 days immersed in5% acetic acid was -20.11 and -30.65 respectively, So the compressive strength of geopolymer mortar decreased but not as much as OPC. However, geopolymer mortar 6 M had a percentage compressive strength change after 120 days immersed in5% sulfuric and 5% acetic acid is -43.09 and -41.95 which are lower than OPC mortar. Therefore, geopolymer mortar at 6 M was less resistant than OPC mortar.

Decreased strength and rapid deterioration of OPC mortar, explains that sulfuric acid was a very aggressive acid which reacted with the free lime $Ca(OH)_2$, in cement paste forming gypsum ($CaSO_4 \cdot 2H_2O$). The destructive action was the reaction between calcium aluminate present in cement mortar and gypsum crystals. Both products formed the less soluble reaction product, ettringite ($3CaO \cdot Al_2O_3 \cdot 3\ CaSO_4 \cdot 32H_2O$). These were the expansive compounds causing internal pressure in the OPC mortar specimens, which led to the formation of cracks and spalling and caused mass and strength loss (Attiogbe and Rizkalla, 1988). In the same way Bakharev (2005c) concluded that acid attack on OPC concrete, calcium salts of the attacking acid rapidly form and deceased strength of concrete and deteriorated quickly.

From Figures 6 to 8, it was found that the proportionate decrease in percentage of compressive strength of the geopolymer specimens from 14M, 10M and 6M were the same. The concentration of sodium hydroxide did significantly affect the performance of the material. When concentration of sodium hydroxide increased, the percentage compressive strength of the geopolymer specimens immersed in acid solutions decreased.

By comparing these with the specimens from OPC mortar, it was found that the concentration of sodium hydroxide significantly affected the performance of the material. There was not a significant difference between the geopolymer mortar group and OPC mortar group because the trend was the same direction.

The comparison of the percentage weight change is shown in Figure 9 to 11. The OPC mortar underwent more percentage weight loss loss than the geopolymer mortar specimens. The highest weight loss was 45.03 % in OPC mortar fewer than 5% sulfuric acid immersions, followed by OPC under 5% acetic acid immersion which was 28.64%. The percentage of weight loss was 4.9% in geopolymer mortar14M, 8.03 %in geopolymer mortar 10M and 12.6 % in geopolymer mortar 10M under 5% sulfuric acid immersion respectively. In 5% acetic acid immersion it was 2.89 %in geopolymer mortar14M, 6.56% in geopolymer mortar 10M and 7.47 % in geopolymer mortar 10M respectively.

Therefore sulfuric acid was stronger than other acids, which was expected to be more harmful, and the results substantiated such expectation. For 3% and 1% concentration, the types of acids showed the significant differences on the percentage weight losses of geopolymer mortar14M which was 4.9% under 5% sulfuric acid immersion, 2.91% under 3% sulfuric acid immersion and 1.58% under 1% sulfuric acid immersion respectively. On the other hand, the percentage losses of geopolymer mortar 6M was 8.03%under 5% sulfuric acid immersion, 6.6% under 3% sulfuric acid immersion and 6.43% under 1% sulfuric acid immersion respectively. The increment of acid concentration also led to the increment of percentage weight change loss of geopolymer mortar. Both OPC mortar and geopolymer specimens did not show trend of the different percentage weight changes.

Breck (1974) found the acid attack would cause breakage of the Si–O–Al bonds, increased number of Si–OH and Al– OH groups in geopolymers and an increased amount of silicic acid ions and dimers in solution, and this process led to weight loss of the geopolymer materials. Polymer structures with a Si/Al ratio were subject to the attack by the acid more than the siliceous polymer which is explained in microstructure of next part. This caused geopolymer mortar to decrease strength and decrease weight but it decreased less than OPC mortar.

Figure 4 Geopolymer mortar and OPC mortar immersed in sulfuric acid 5% after 120 days

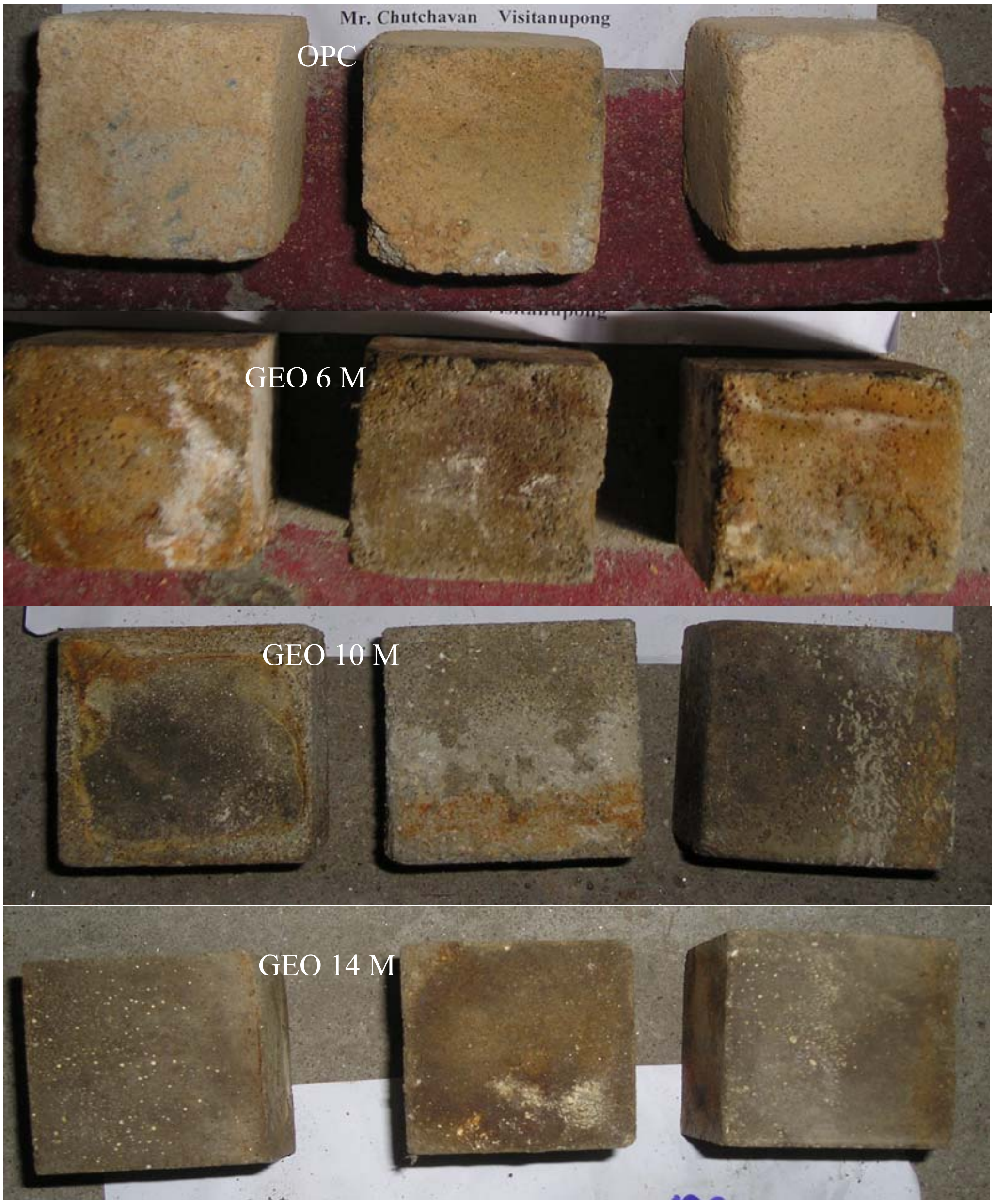


Figure 5 Geopolymer mortar and OPC mortar immerse in acetic acid 5% after 120 days

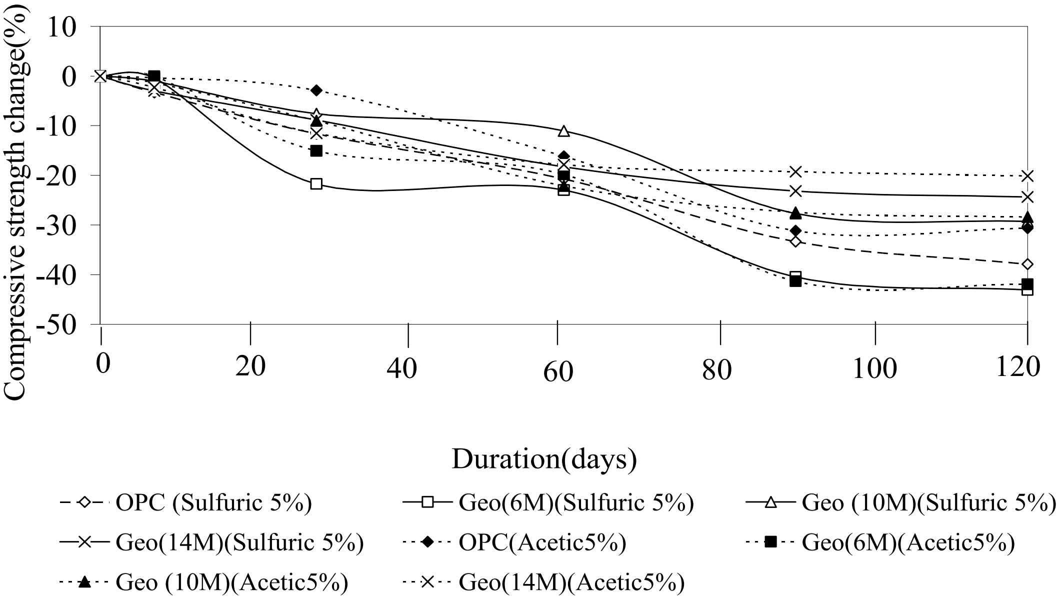


Figure 6 Percentage compressive strength of the geopolymer mortar and OPC mortar immersed in sulfuric acid and acetic acid 5%

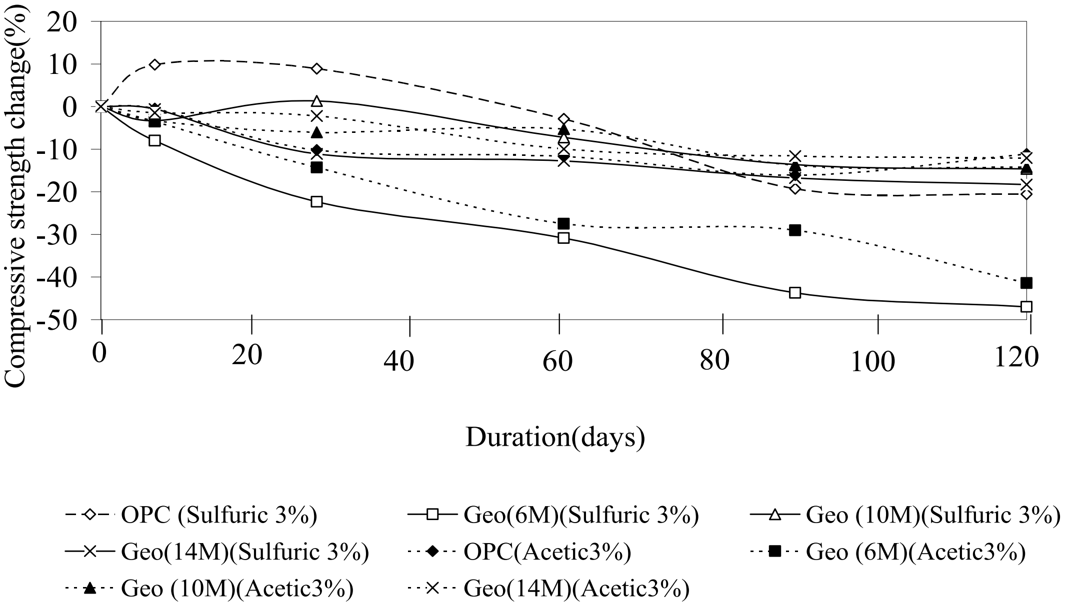


Figure 7 Percentage compressive strength of the geopolymer mortar and OPC mortar immersed in sulfuric acid and acetic acid 3%

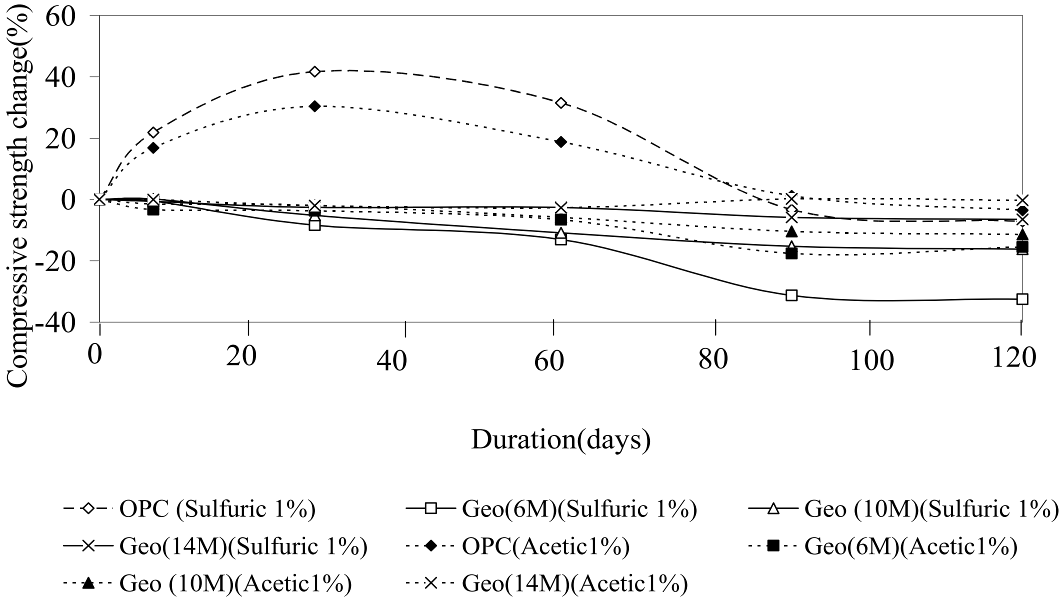


Figure 8 Percentage compressive strength of the geopolymer mortar and OPC mortar immersed in sulfuric acid and acetic acid 1%

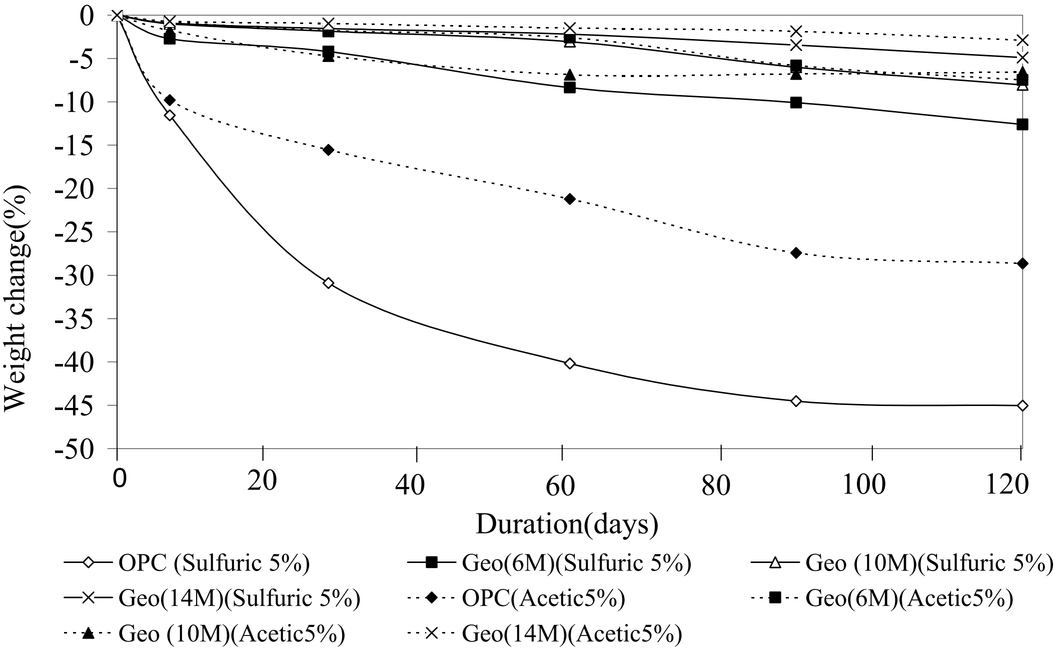


Figure 9 Percentage weight change comparison between the geopolymer mortar and OPC mortar immersed in sulfuric acid and acetic acid 5%

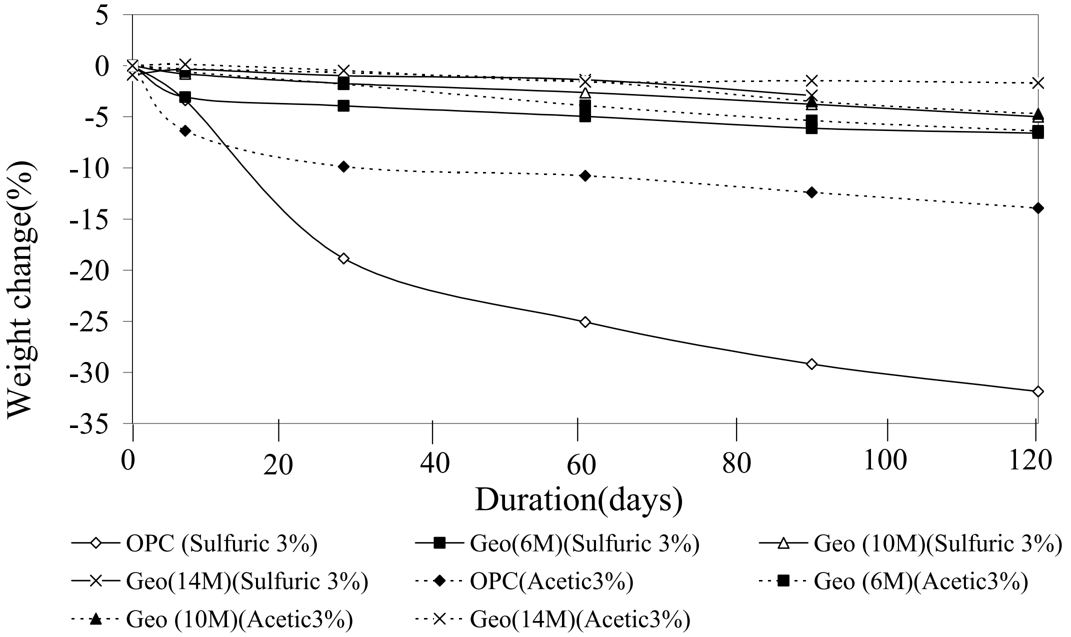


Figure 10 Percentage weight change comparison between the geopolymer mortar and OPC mortar immersed in sulfuric acid and acetic acid 3%

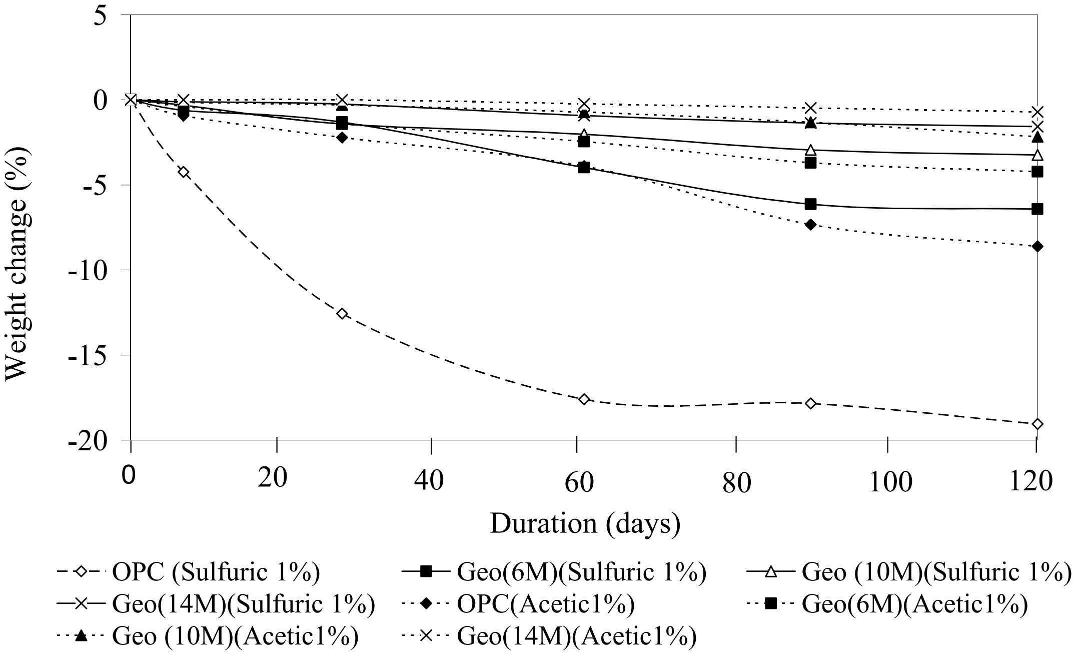


Figure 11 Percentage weight change comparison between the geopolymer mortar and OPC mortar immersed in sulfuric acid and acetic acid 1%

2.2 Microstructure scanning electron microscopy

By comparing Figure 12(b) and (c) showing the SEM images of the geopolymer mortar 6M with Figure 12 (a) showing SEM images of the Geopolymer mortar 6M before immersion test, it was observed that gel decreased and became porous after exposure to acid. Crystal materials appeared after immersion in sulfuric acid test Figure 12 (b) and (c) respectively. No porous structure was observed in the geopolymer mortar 14M. The crystal materials appeared after the immersion sulphuric acid test. As Figure 13 (c), SEM was used to record micrographs and EDS was used as an additional tool for the semi-quantitative chemical analysis. According to EDS analysis, the result was the atomic percentage of each element.

Only the major elements over the whole area in Figure 12and Figure 13 were determined via the EDS analysis and their atomic percentage has been shown. The Si/Al ratios had been calculated. They are also found in Figure 11and Figure 12. The replacement of each aluminum atom for silicon in the SiO_4tetrahedra needed one sodium atom to balance the change. The Si/Al ratios were 3.21, 3.47 increased after geopolymer 6M specimens immersed in acetic acid 5% and sulfuric acid 5% solution respectively because Al bonding was broken.

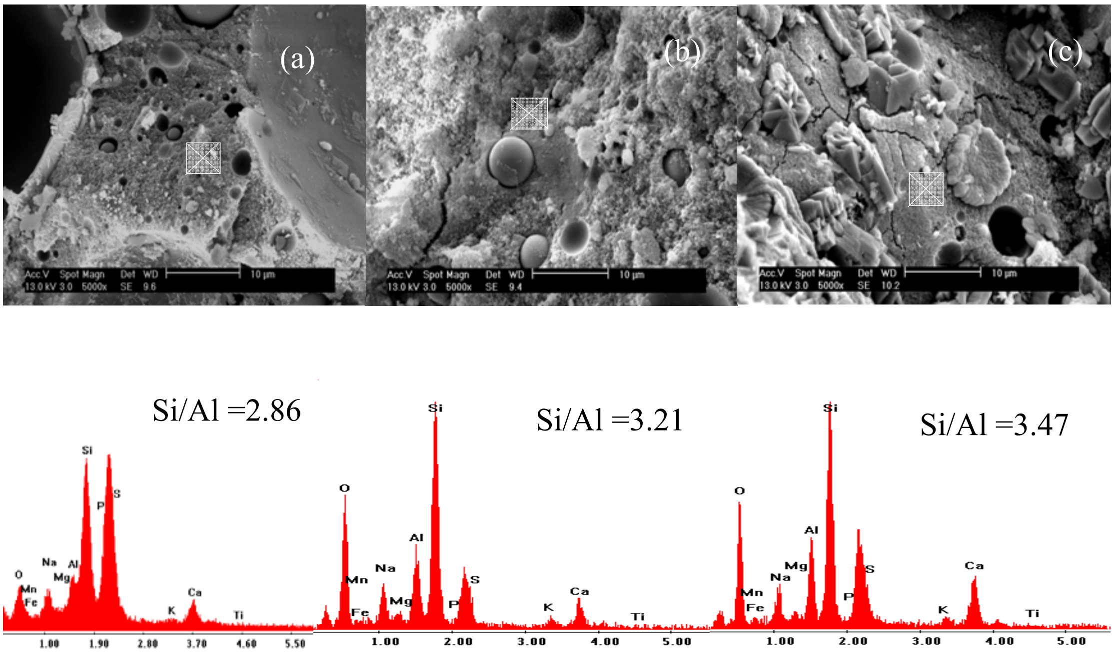


Figure 12 SEM-EDS Geo 6M (a) before immersion in acid, (b) after immersion in acetic acid 5%, (c) after immersion sulphuric in acid 5%,

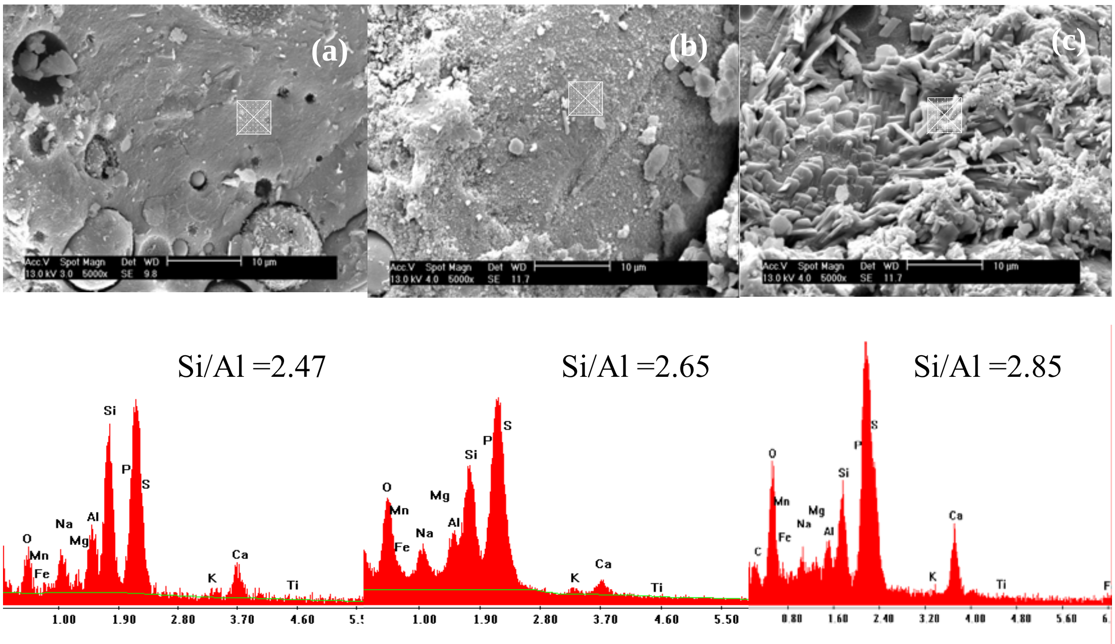


Figure 13 SEM-EDS Geo 14M (a) before immersion in acid, (b) after immersion in acetic acid 5%, (c) after immersion in sulphuric acid 5%,

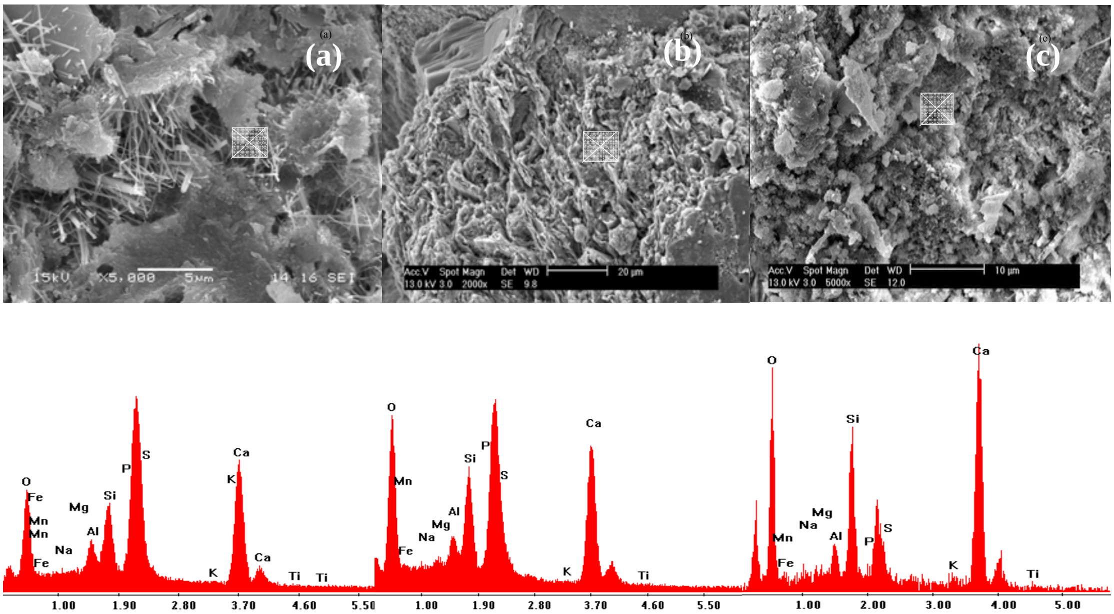


Figure 14 SEM-EDS OPC (a) before immersion in acid, (b) after immersion in acetic acid 5%, (c) after immersion sulphuric in acid 5%,

As in Figure 14 (a), SEM –EDS images of the OPC mortar specimens had a very high CSH before immersion acetic acid 5% and sulphuric acid 5% solution test. As shown in Figure14(b) and (c), OPC mortar specimens had less CSH but Ca had increased after immersion in acetic acid 5% and in sulphuric in acid 5% solution test.

Ca which appeared was gypsum ($CaSO_4 \cdot 2H_2O$) of which there was less before immersion acetic acid 5% and sulphuric acid 5% solution test than after test. So it was found that the bonding in the strength of OPC mortar decreased as seen from Figure 12, Figure 13 and the conclusion of Attiogbe and Rizkalla (1988).

3. Resistance to sulfate solution

3.1 Strength and weight change

As shown in Figure 15 and Figure 16, The specimens exposed to the sodium sulfate and magnesium sulfate solutions showed that there were no visual signs of deterioration of the OPC mortar specimens and geopolymer mortar specimens. The surface of the samples had no deposits. It was as smooth as before the test. This comparison shows that the geopolymer mortar 14M was far superior to OPC mortar in resisting sulfate attack. Geopolymer mortar specimens had a very small change in appearance after 120 days of immersion in the sulfate solutions.

From Figure 17, the percentage compressive strength change of geopolymer mortar 14 M and OPC mortar were -6.74 and -31.53 respectively after immersed in saturated magnesium sulfate solution after 120 days**.** Percentage compressive strength changes of geopolymer mortar 10 M at 120 days after immersed in saturated magnesium sulfate solution and saturated sodium sulfate solution were -11.84 and -7.87 respectively. In the experimental of saturated sodium and magnesium sulfate resistance, it was shown that geopolymer mortar 14 M was the most resistant to the sulfate solutions when compared with OPC mortar. Geopolymer mortar 14 M is a sulfate material. So the deterioration by sulfate solution was small occurrence. As shown in Figure 21, the inside structure was changed a little.

However geopolymer mortar 6 M had a percentage compressive strength change at 120 days after immersed in saturated sodium sulfate and saturated magnesium sulfate solutions of -55.23 and -28.38 which were lower than OPC mortar. Therefore, geopolymer mortar 6 M had less sulfate resistance than OPC mortar. The reason of this result was that the inside crystal structure of geopolymer mortar 6 M might be different from mortar 14 M. As seen in Figure 19 and Figure 20, it was found that the gel of geopolymer mortar 14 M had no pore and less Fly ash. The reaction might be more perfect than geopolymer mortar 6M. This made more sulfate resistance. OPC mortar had calcium hydroxide which rapidly reacted to sulfate. The result was gypsum which makes expansion, spalling and softening (Malhotra, 1987).

By considering percentage of weight change from Figure 18and Figure 19, it was found that the percentage weight change of OPC mortar increased less than the geopolymer mortar 6M. The highest increase of weight change was 6.52% in geopolymer mortar 6M under saturated sodium sulfate immersions followed by those under saturated magnesium sulfate immersion which was 5.95%. Percentage of weight change increase was 2.25% in geopolymer mortar 14M under saturated sodium sulfate immersions followed by those under saturated magnesium sulfate immersion which was 2.08%.

From Figure 18 and Figure 19, percentage of weight change increased 3.97% in OPC mortar under saturated sodium sulfate immersions, followed by those under saturated magnesium sulfate immersion which was 5.67%. Therefore, percentage of weight change in geopolymer mortar 14M specimens increased less than the OPC mortar specimens for the same reasons as the said percentage compressive strength change.

As shown in Figure 18 and Figure 19, percentage of weight change of all specimens in both types of sulfate solution was not significant on deterioration of all specimens. Neither did they show the different trend in percentage weight changes between OPC mortar group and geopolymer mortar group.

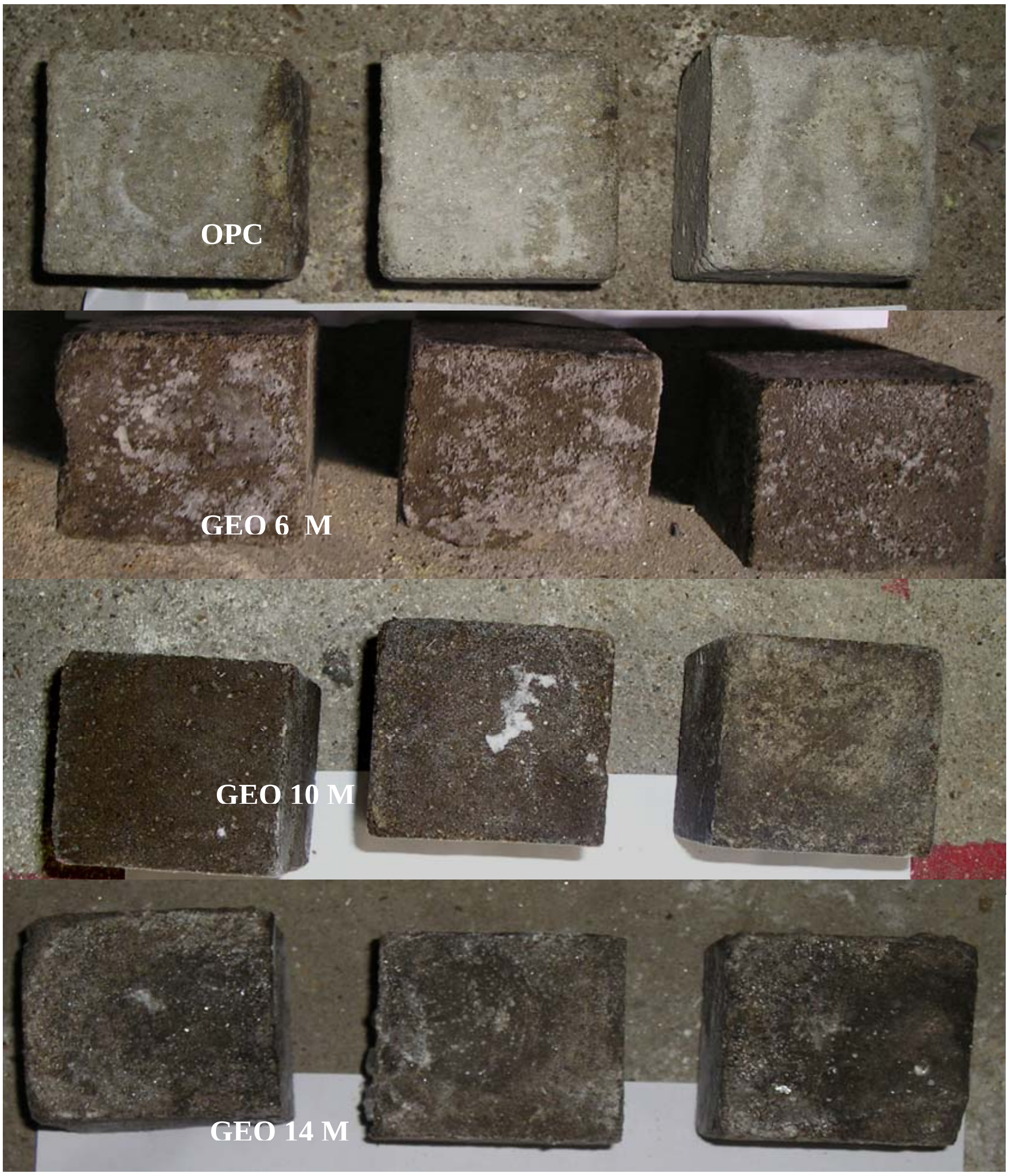


Figure 15 Geopolymer mortar and OPC mortar immersed in saturated sodium sulfate solution after 120 days

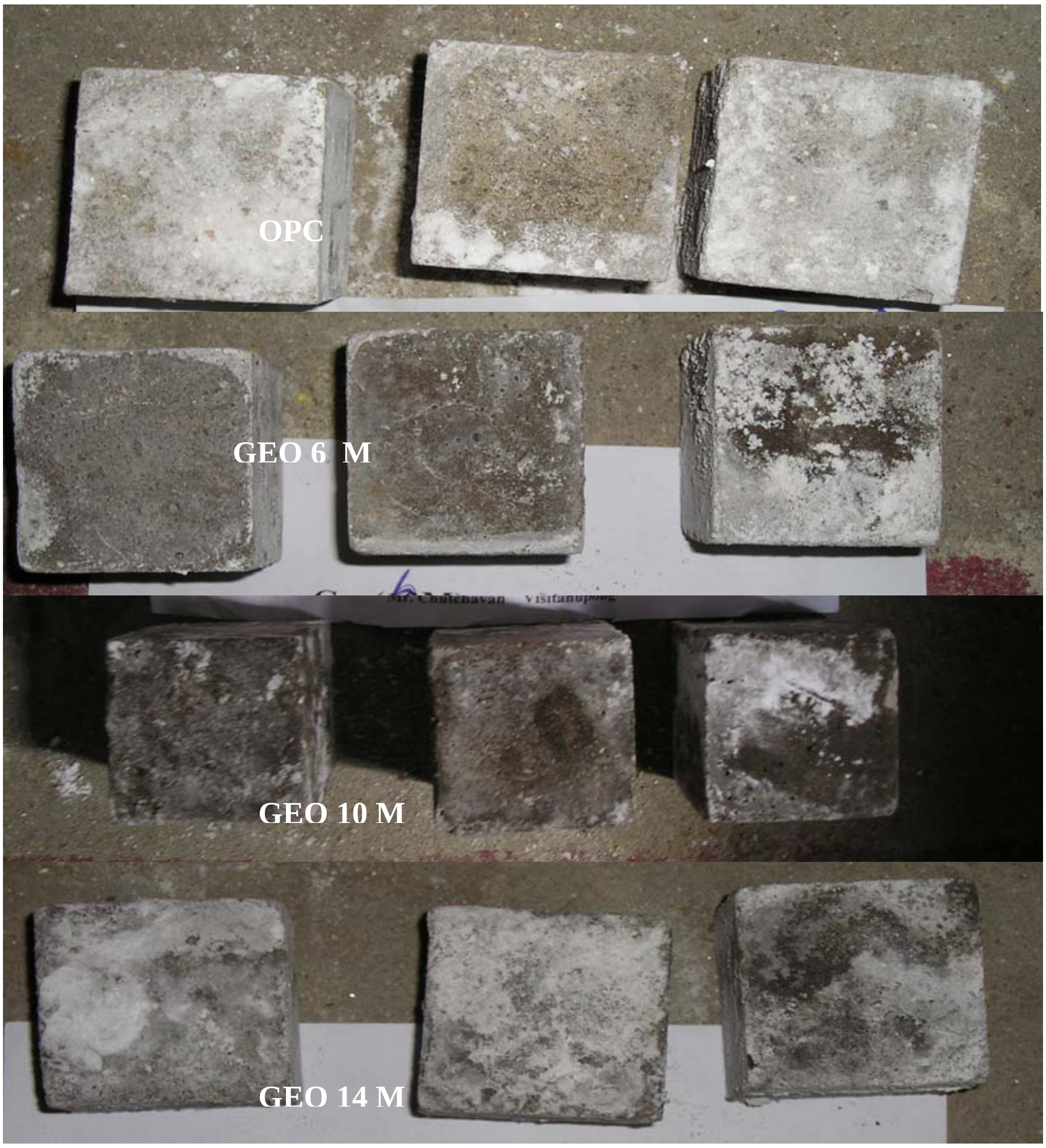


Figure 16 Geopolymer mortar and OPC mortar immersed in saturated magnesium sulfate solution after 120 days

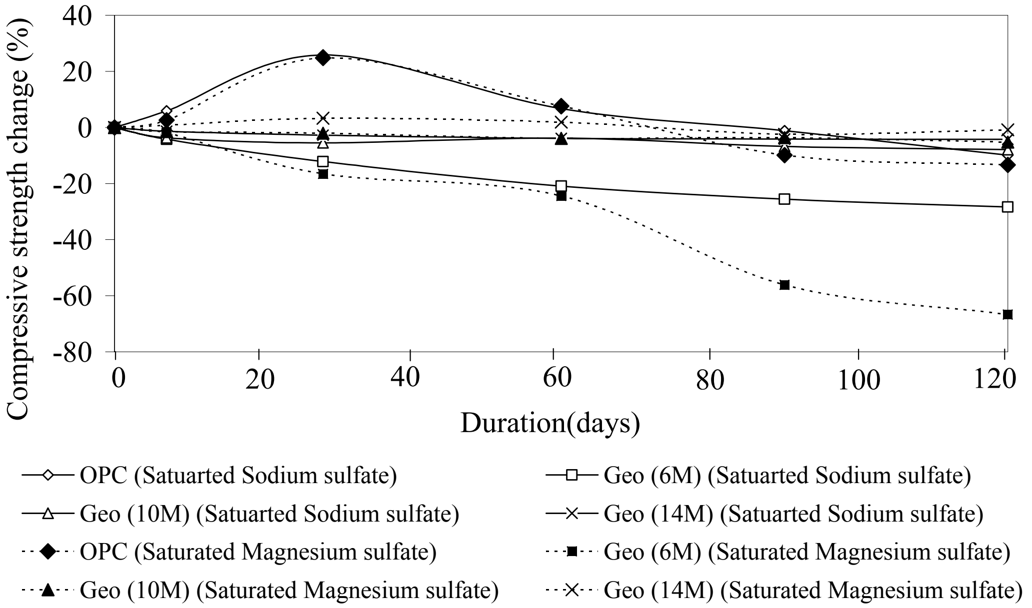


Figure 17 Percentage compressive strength evolutions of the geopolymer mortar and OPC mortar immersed in saturated sodium Sulfate and saturated magnesium sulfate solution

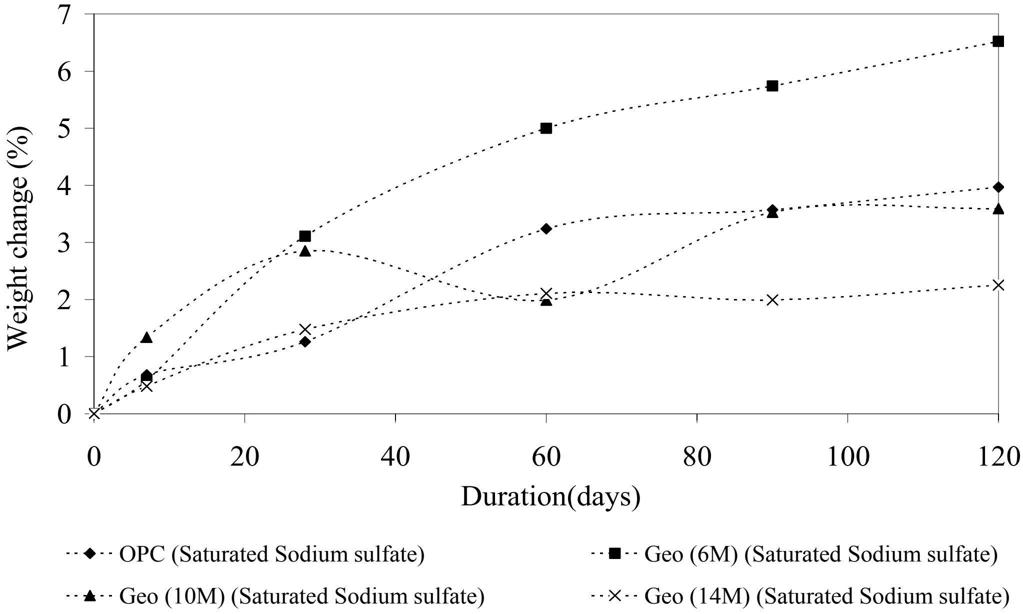


Figure 18 Percentage weight change comparison between geopolymer mortar and OPC mortar immersed in saturated Sodium Sulfate solution

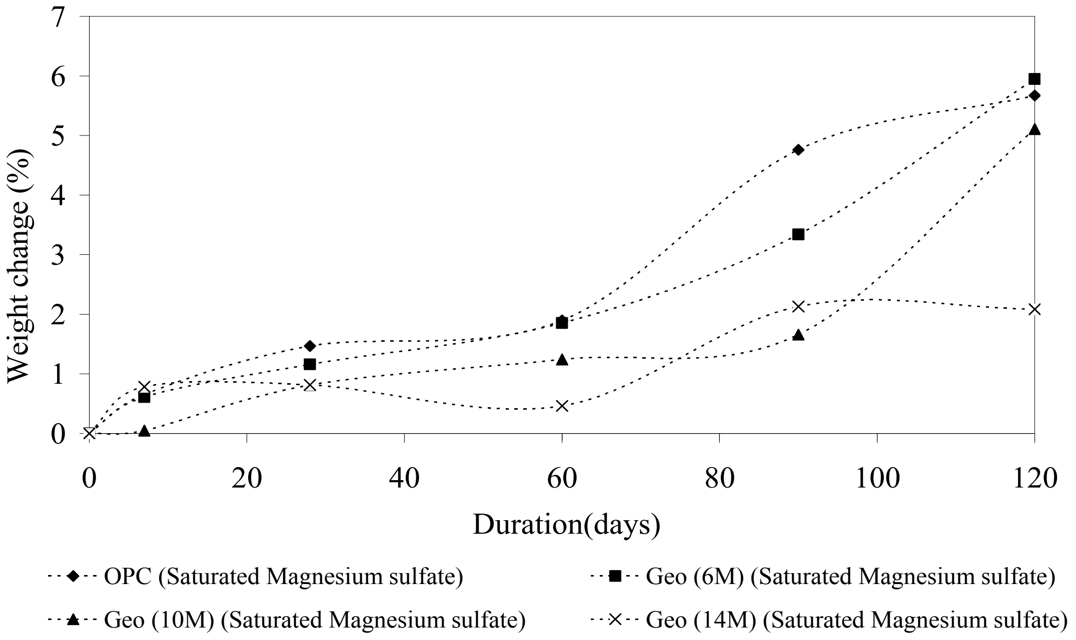


Figure 19 Percentage weight change comparison between geopolymer mortar and OPC mortar immersed in saturated Magnesium Sulfate solution

3.2 Microstructure scanning electron microscopy

From Figure 20(a) and Figure 21(a), SEM–EDS images of the Geopolymer mortar 6M before immersion test, the surface was smooth. In Figure 20(b) and Figure 21(b), it was observed that the gel decreased and some crystals appeared after having been exposed in saturated magnesium sulfate. There was a small cracking after immersion saturated magnesium sulfate test from Figure 20 (b) and Figure 21(b) respectively. Figure 22 (b) and Figure 22 (c) represent SEM images of the OPC mortar which had crystal appearance and a little CSH after immersion in sulfate solutions. SEM was used to record micrographs while EDS was used as an additional tool for the semi-quantitative chemical analysis. The results which were obtained from the EDS analysis were the atomic percentage of each element.

In the solution of saturated magnesium sulfate, SEM examination revealed the formation of vertical cracks in geopolymer mortar 6M and geopolymer mortar 14M specimens. Cohen and Mather (1991) presented that Bulk chemical variation across the specimens showed an increase of Ca, Mg and S concentrations in the surface area, a slight decrease of Al content, while Si content stayed without change. Therefore, the migration of Ca from inside of the specimen to the surface area, S and Mg from the solution into aluminosilicate matrix could be suggested. As seen from Figure 20 and Figure 21, the immigration of these ions into aluminosilicate gel did not significantly affect the strength of geopolymer 14M, but the strength of geopolymer 6 M decreased.

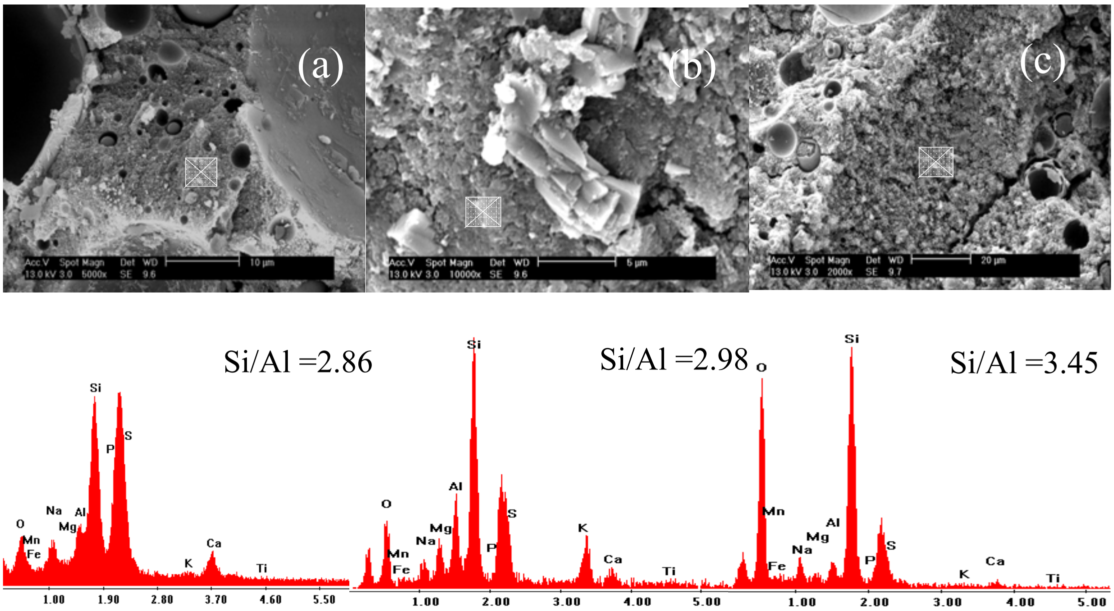


Figure 20 SEM-EDS Geo 6M (a) before immersion in sulfate solution,
(b) after immersion in saturated Magnesium sulfate solution,
(c) after immersion in saturated Sodium Sulfate solution

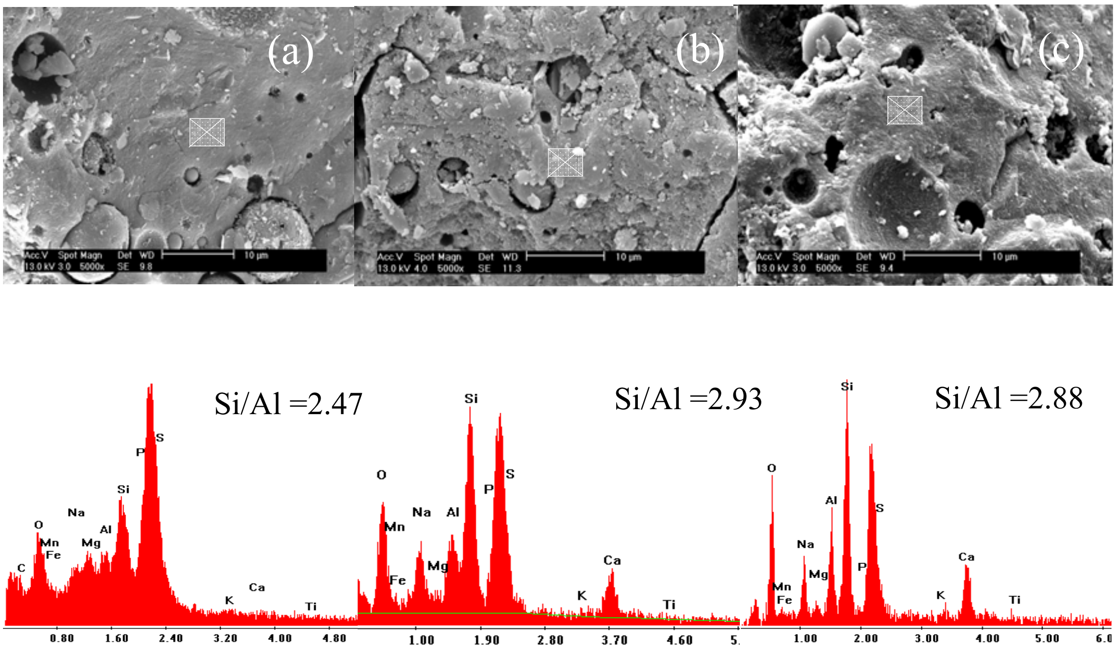


Figure 21 SEM-EDS Geo 14M (a) before immersion in sulfate solution,

(b) after immersion in magnesium sulfate solution,

(c) after immersion in saturated sodium sulfate solution

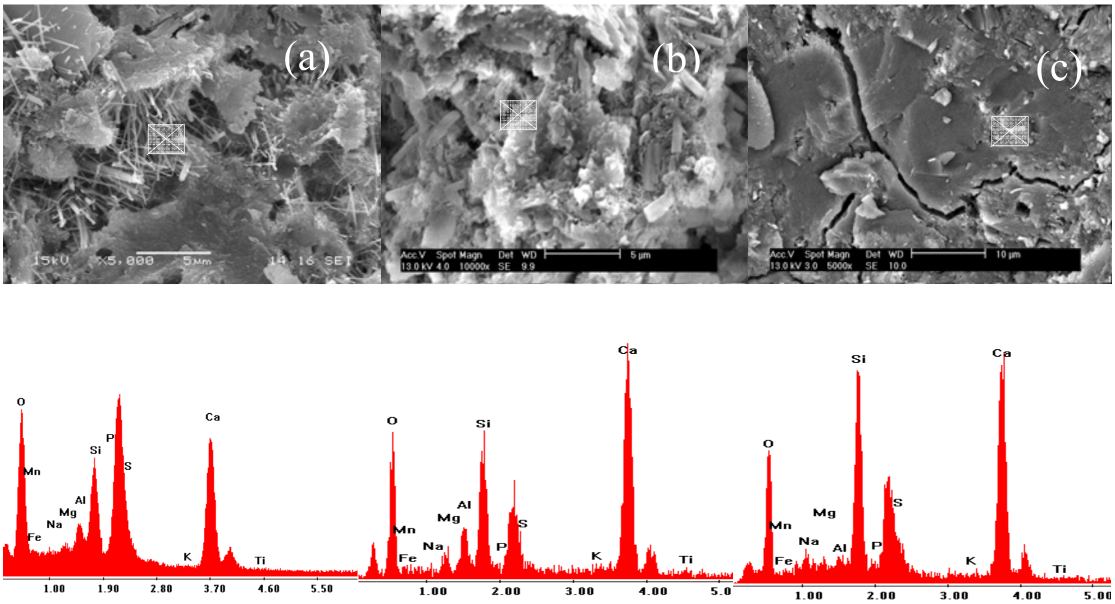


Figure 22 SEM-EDS OPC (a) before immersion in sulphate solution,

(b) after immersion in Magnesium sulfate solution,

(c) after immersion saturated in Sodium Sulfate solution

4. Carbonation Test

From Figure 23, the visual examination, specimens was split and cleaned. The depths of carbonation were determined by spraying on a freshly broken surface with 1% of phenolphthalein in the solution of 70% ethyl alcohol. The phenolphthalein solution is colorless. It was used as an acid–base indicator. The color of the solution was changed to purple when pH was higher than the range of approximately nine. When the solution was sprayed on a broken specimen surface, the carbonated portion was colorless and non-carbonated portion was purple. The average depths of carbonation geopolymer mortar 6M specimens were higher than geopolymer mortar 14M and OPC mortar. This comparison demonstrated that OPC mortar group was far superior to geopolymer mortar group in resisting carbonation test.

The carbonation depths are shown in Figure 24 and Figure25 by age of all samples measured at 0,3,6,12,24,72,168, and 336 hours according to the phenolphthalein indicator method. It can be observed that the carbonation depth of geopolymer mortar 6M was larger than geopolymer mortar 14M. Therefore can be explained that for specimens having three different concentrated sodium hydroxide solutions, when the sodium hydroxide was more concentrated, the carbonation depth decreased but in OPC it appeared the carbonation depth was less because the structure of geopolymer mortar has more free CaO ,which is seen in the reaction:

$$CaO + CO_2 \longrightarrow CaCO_3 .$$

Roper and Baweja (1991) concluded that the basic factor influencing carbonation is the diffusivity of the hardened cement paste. Carbonation rate is controlled by the ingress of CO_2 into concrete pore system by diffusion with a concentration gradient of CO_2 acting as the driving force. Factors affecting diffusion rate include the type and amount of cement, porosity of the material, time of curing, type and quantity of pozzolanic additions.

From the experiment, it was found that carbonation depth in the geopolymer mortar group was deeper than in the OPC mortar group. This showed relationship between the connectivity of the pore system and conductivity of pore fluid**.** The increment of pore structures made low permeability values. So OPC mortar has less permeability. Geopolymer mortar 6M showed the highest permeability.

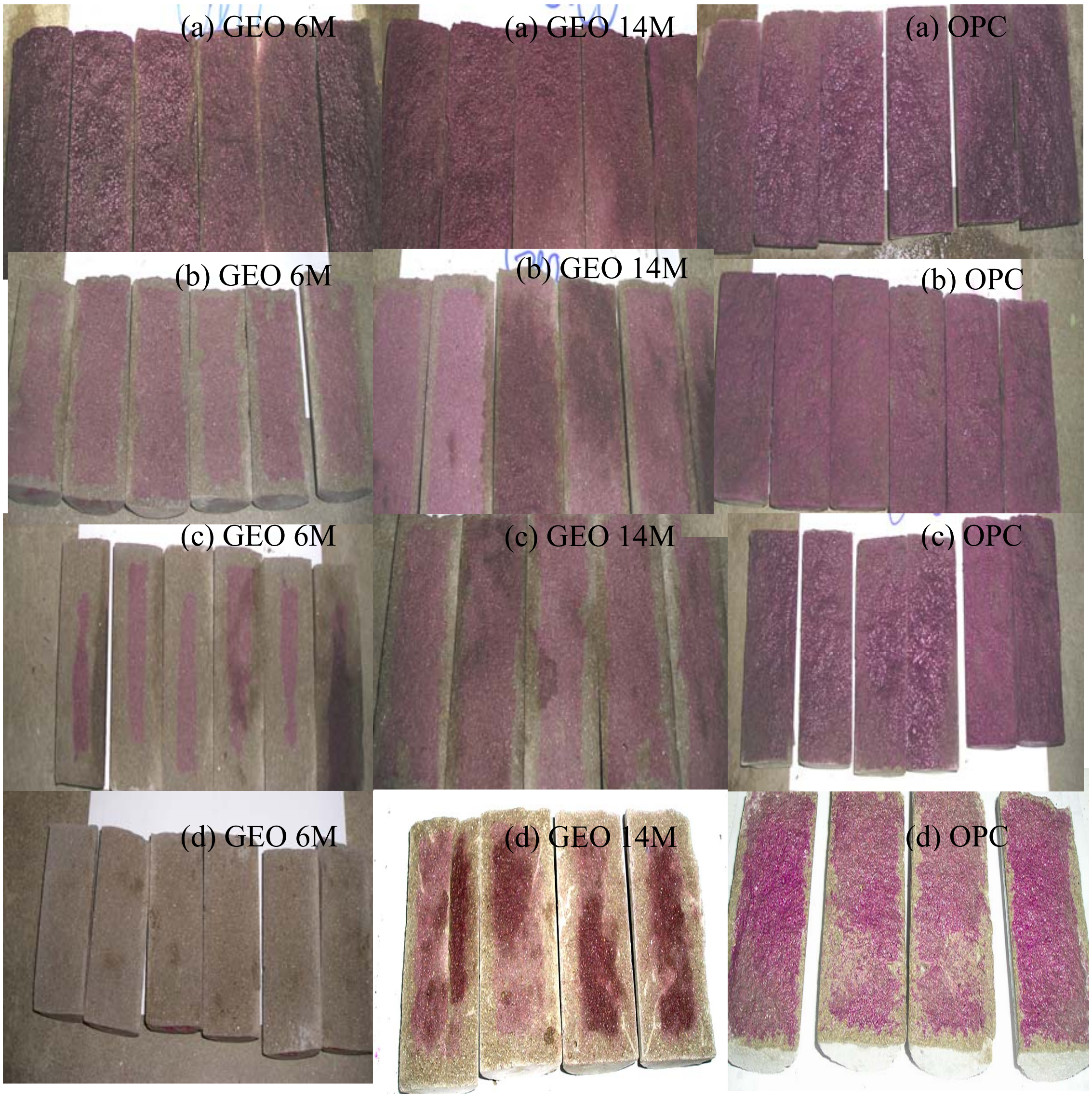


Figure 23 Carbonation of depths of geopolymer and OPC mortar
(a) before carbonation test, (b) after carbonation test at 24 hours,
(c) after carbonation test at 72 hours, (d) after carbonation test at
168 hours

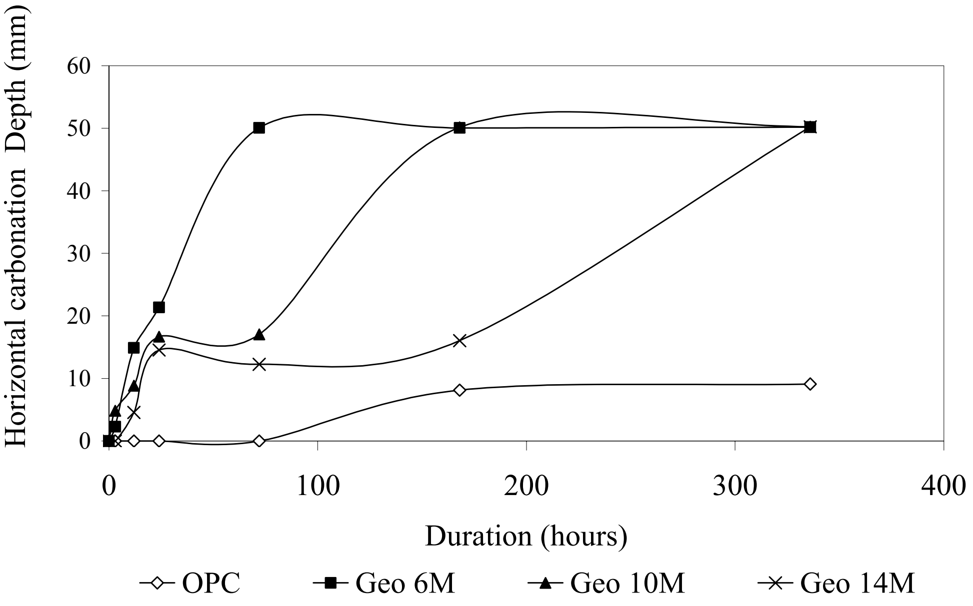


Figure 24 Horizontal depth (mm.) after carbonation tests of all specimens

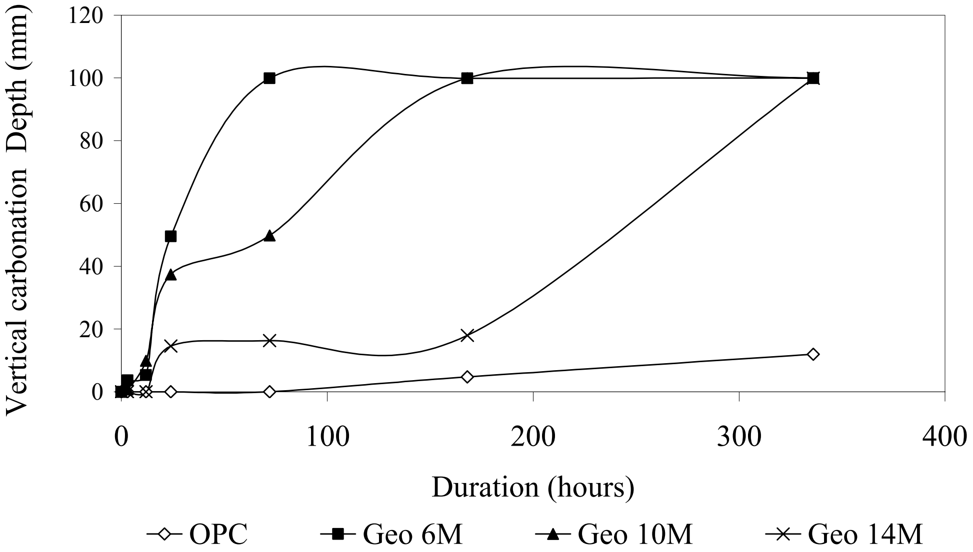


Figure 25 Vertical depth (mm.) after carbonation tests of all specimens

Figures 26 showed the proportionate decrease in percentage compressive strength of the geopolymer specimens from 14M, 10M and 6M. The concentration of sodium hydroxide did significantly affect the performance of the material. When the concentration of sodium hydroxide increased, the percentage compressive strength of geopolymer specimens was ingressed by CO_2 decreased. By comparing with OPC mortar specimens, it was also found that percentages loss of compressive strength of 14M and 10M geopolymer specimens were less than OPC mortar specimens. The obtained result from the evaluation of carbonation depths was opposite to the result from the percentage compressive strength of 14M and 10M geopolymer specimens.

It is also clear that there was no significant difference between the geopolymer mortar group and OPC mortar group because the trend was in the same direction. This result from experiment was in line with conclusion of Davidovits (1994a) that a permeability value (cm./s.) of geopolymer was 10^{-7} the other OPC was 10^{-10}.

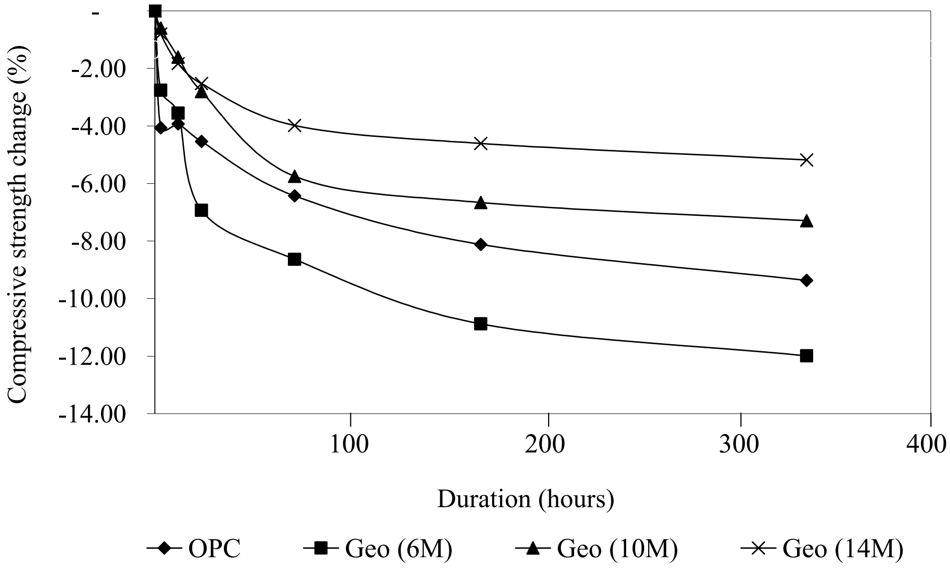


Figure 26 Percentage compressive strength change of all specimens after carbonation test

5. Rapid Chloride Penetration Test

Figure 27 showed the rate of electrical charge passing through specimens. The values of electrical charge which passed through specimens of geopolymer mortar 6M was higher than geopolymer mortar 14M. The values of electrical charge passing through decreased when NaOH was more concentrated. The value of electrical charge passing through cement mortar was the less.

Caijun Shi (2000) presented that the permeability of concrete depends on the pore structure of concrete. The electrical conductivity of concrete was determined by pore structure and the chemistry of the pore solution. This explains that the increment of values of electrical charge passing through specimens' pore structure was great. The experiments showed that the increment of pore structure represented the low permeability values. So OPC mortar had less permeability and geopolymer mortar 6M had the most permeability.

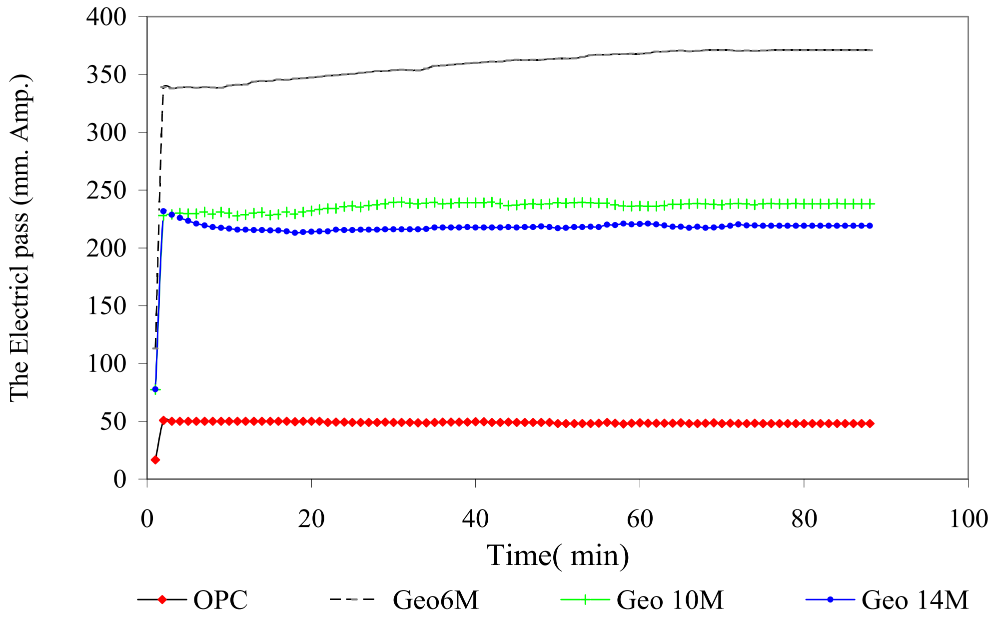


Figure 27 Illustrates the Rapid Chloride Permeability test for OPC mortar and geopolymer mortar

6. Chloride penetration Test

Visual examination of specimens exposed to the 5% sodium chloride solution found no deterioration of the OPC mortar specimens group and geopolymer mortar specimens group. But the deterioration was detected when the specimens were split and cleaned. The depths of chloride were determined by spraying on a freshly broken surface with 0.0141 normality solution of silver nitrate. The silver nitrate solution was colorless. The color of the solution was changed to gray when there was a reaction with sodium chloride. Figure 29, Figure 30 and Figure 31 showed the depth of chloride. Geopolymer mortar specimens group was 100 mm from edge side after 45 days. OPC mortar specimens group was 12mm after 45 days.

From Figure 28 and Figure 29, it can be observed that geopolymer mortar 6M had more chloride penetration depth than geopolymer mortar 14M which showed a relation between the connectivity of the pore system and conductivity of pore fluid**.** The increment of pore structures meant resulting in low permeability values. So OPC mortar had less permeability and geopolymer mortar 6M had the most permeability. The obtained result was the same as the experiment of Davidovits (1994a) because permeability value (cm./s.) of geopolymer was 10^{-7} and OPC was 10^{-10}

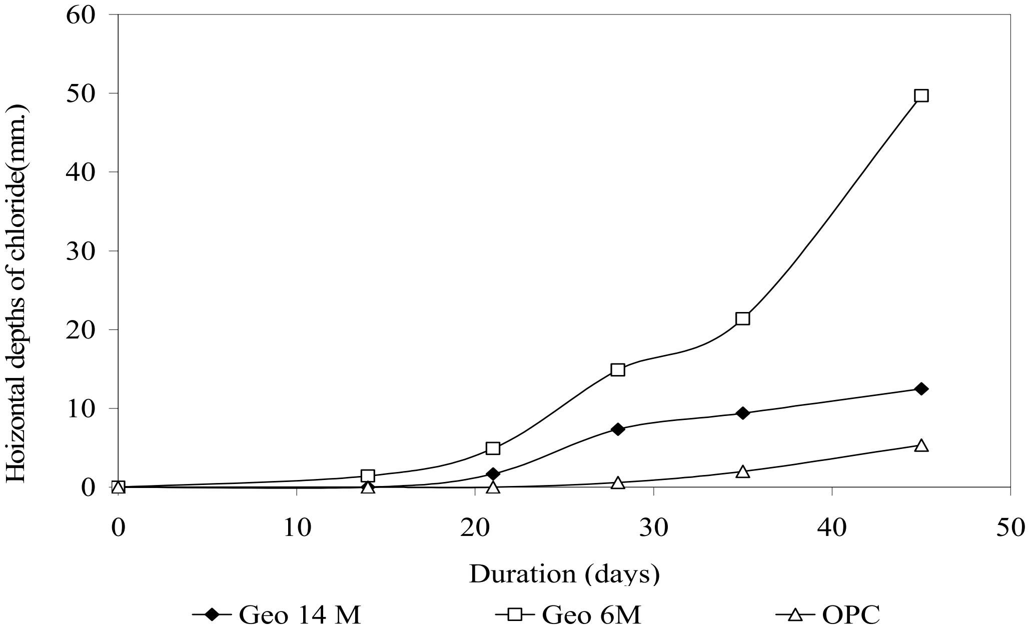


Figure 28 Horizontal depth (mm.) after chloride penetration tests all specimens

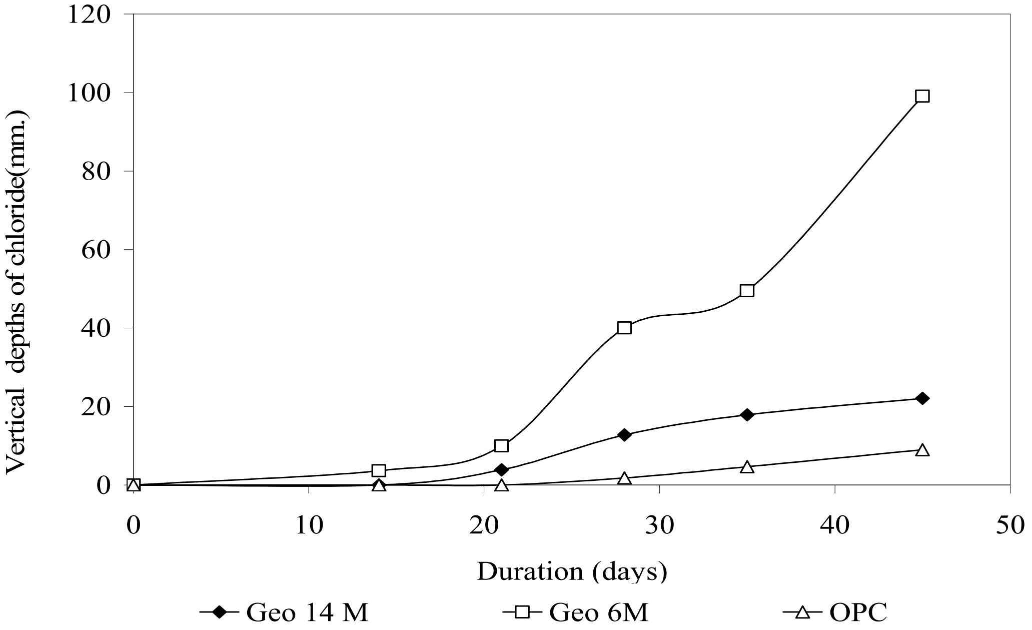


Figure 29 Vertical depths (mm.) after chloride penetration tests all specimens

Figure 30 Chloride penetration depths of geopolymer mortar 6M

Figure 31 Chloride penetration depths of geopolymer mortar 14M

Figure 32 Chloride penetration depths of OPC mortar

CONCLUSION

1. The specimens prepared with high concentration sodium hydroxide had more compressive strength than specimens prepared with low concentration sodium hydroxide activator.

2. Increase in sodium hydroxide molarity increased the acid resistance of geopolymer. Acid resistance of OPC mortar was between the highest and lowest value of geopolymer mortar.

3. Increase in sodium hydroxide molarity increased the sulfate resistance of geopolymer. Sulfate resistance of OPC mortar was between the highest and lowest value of geopolymer mortar.

4. Increase in sodium hydroxide molarity decreased the carbonation depth of geopolymer. OPC mortar was more resistant to carbonation than geopolymer mortar.

5. Increase in sodium hydroxide molarity decreased the permeability of geopolymer. OPC mortar was less permeable than geopolymer mortar.

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APPENDICES

Appendix A

Test Results

Appendix Table A1 Chemical analysis of fly ash

Component	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	Na_2O	K_2O
Composition (mass %)	35.3	21.5	18.7	14.2	3.0	2.5	2.0

Appendix Table A2 Weight of specimens before and after immersion in 5% sulfuric solution

Specimens	Weight (gram)					
	before immersion	after immersion(days)				
		7	28	60	90	120
OPC	279.10	274.20	234.20	204.50	203.30	193.40
OPC	281.80	262.10	212.10	211.70	207.50	180.50
OPC	279.10	275.30	235.30	213.20	184.10	198.40
Average	**280.00**	**270.53**	**227.20**	**209.80**	**198.30**	**190.77**
GEO 6M	269.60	261.50	256.40	261.20	259.20	249.40
GEO 6M	284.70	265.30	260.10	257.90	258.50	265.90
GEO 6M	271.10	273.20	276.50	265.40	257.20	255.60
Average	**275.13**	**266.67**	**264.33**	**261.50**	**258.30**	**256.97**
GEO 10M	270.50	283.40	270.30	269.20	265.30	259.30
GEO 10M	278.20	266.40	279.50	263.80	261.90	260.80
GEO 10M	280.20	272.50	264.70	274.10	270.50	267.40
Average	**276.30**	**274.10**	**271.50**	**269.03**	**265.90**	**262.50**
GEO 14M	272.90	273.50	270.20	271.30	278.50	262.40
GEO 14M	277.40	273.80	275.40	268.40	264.30	266.90
GEO 14M	273.50	275.50	275.10	276.10	269.80	270.50
Average	**274.60**	**274.27**	**273.57**	**271.93**	**270.87**	**266.60**

Appendix Table A3 Compressive strength of specimens before and after immersion in 5% sulfuric solution

Specimens	Strength (ksc.)					
	before immersion	after immersion(days)				
		7	28	60	90	120
OPC	158.10	226.83	141.39	126.07	100.40	130.23
OPC	207.52	185.90	209.72	146.67	150.11	125.23
OPC	229.54	162.74	174.77	198.87	146.13	114.18
Average	**198.38**	**191.82**	**175.29**	**157.20**	**132.21**	**123.21**
GEO 6M	181.74	214.41	153.84	180.36	107.61	120.90
GEO 6M	202.16	162.11	154.95	124.46	121.00	102.73
GEO 6M	197.23	202.18	145.95	142.86	117.40	107.09
Average	**193.71**	**192.90**	**151.58**	**149.23**	**115.34**	**110.24**
GEO 10M	311.88	301.21	318.10	266.36	297.11	215.21
GEO 10M	302.11	313.14	281.44	304.88	215.13	201.13
GEO 10M	320.96	310.90	264.35	260.31	163.92	244.45
Average	**311.65**	**308.42**	**287.96**	**277.18**	**225.39**	**220.26**
GEO 14M	371.78	405.13	367.83	300.60	274.37	334.00
GEO 14M	422.38	370.74	393.44	326.50	341.52	274.94
GEO 14M	401.98	384.62	328.69	350.01	303.21	295.89
Average	**398.71**	**386.83**	**363.32**	**325.70**	**306.37**	**301.61**

Appendix Table A4 Weight of specimens before and after immersion in 3% sulfuric solution

Specimens	Weight (gram)					
	before immersion	after immersion(days)				
		7	28	60	90	120
OPC	279.10	274.20	234.20	204.50	203.30	193.40
OPC	281.80	262.10	212.10	211.70	207.50	180.50
OPC	279.10	275.30	235.30	213.20	184.10	198.40
Average	**280.00**	**270.53**	**227.20**	**209.80**	**198.30**	**190.77**
GEO 6M	269.60	261.50	256.40	261.20	259.20	249.40
GEO 6M	284.70	265.30	260.10	257.90	258.50	265.90
GEO 6M	271.10	273.20	276.50	265.40	257.20	255.60
Average	**275.13**	**266.67**	**264.33**	**261.50**	**258.30**	**256.97**
GEO 10M	270.50	283.40	270.30	269.20	265.30	259.30
GEO 10M	278.20	266.40	279.50	263.80	261.90	260.80
GEO 10M	280.20	272.50	264.70	274.10	270.50	267.40
Average	**276.30**	**274.10**	**271.50**	**269.03**	**265.90**	**262.50**
GEO 14M	272.90	273.50	270.20	271.30	278.50	262.40
GEO 14M	277.40	273.80	275.40	268.40	264.30	266.90
GEO 14M	273.50	275.50	275.10	276.10	269.80	270.50
Average	**274.60**	**274.27**	**273.57**	**271.93**	**270.87**	**266.60**

Appendix Table A5 Compressive strength of specimens before and after immersion in 3 % sulfuric solution

Specimens	Strength (ksc.)					
	before immersion	after immersion(days)				
		7	28	60	90	120
OPC	227.27	202.18	187.83	185.01	143.81	150.60
OPC	187.75	194.54	208.68	194.10	189.42	175.79
OPC	179.64	256.44	251.00	198.26	146.86	146.01
Average	**198.22**	**217.72**	**215.84**	**192.46**	**160.03**	**157.47**
GEO 6M	247.52	253.39	189.63	200.80	135.92	136.20
GEO 6M	308.16	266.30	238.60	192.60	170.05	162.44
GEO 6M	255.93	226.83	202.02	167.67	151.02	131.58
Average	**270.53**	**248.84**	**210.08**	**187.02**	**152.33**	**143.41**
GEO 10M	297.62	277.77	305.71	346.53	279.44	272.73
GEO 10M	345.01	344.48	328.69	296.44	299.40	283.97
GEO 10M	320.54	308.77	341.33	250.50	253.03	265.29
Average	**321.06**	**310.34**	**325.24**	**297.82**	**277.29**	**273.99**
GEO 14M	395.24	391.35	339.32	360.01	311.87	289.42
GEO 14M	382.32	403.52	390.12	350.82	350.01	340.68
GEO 14M	405.28	380.82	322.23	321.16	322.58	336.35
Average	**394.28**	**391.90**	**350.56**	**343.99**	**328.15**	**322.15**

Appendix Table A6 Weight of specimens before and after immersion in 1% sulfuric solution

Specimens	Weight (gram)					
	before immersion	after immersion(days)				
		7	28	60	90	120
OPC	297.00	292.00	247.60	267.60	246.40	247.50
OPC	296.60	287.50	262.50	240.50	258.10	250.20
OPC	299.50	275.80	270.80	227.80	229.20	225.30
Average	**297.70**	**285.10**	**260.30**	**245.30**	**244.57**	**241.00**
GEO 6M	270.90	268.50	275.00	262.60	260.50	260.50
GEO 6M	280.30	269.30	270.00	269.30	256.10	258.30
GEO 6M	273.50	281.80	268.90	260.00	257.50	252.90
Average	**274.90**	**273.20**	**271.30**	**263.97**	**258.03**	**257.23**
GEO 10M	281.50	280.00	274.90	267.90	260.50	271.70
GEO 10M	274.80	274.20	268.30	271.90	270.10	257.90
GEO 10M	270.50	270.00	271.90	270.30	271.90	270.40
Average	**275.60**	**274.73**	**271.70**	**270.03**	**267.50**	**266.67**
GEO 14M	270.80	270.50	270.80	279.10	266.00	262.20
GEO 14M	280.30	278.30	278.60	274.30	278.50	280.10
GEO 14M	279.80	281.20	279.40	269.80	275.10	275.50
Average	**276.97**	**276.67**	**276.27**	**274.40**	**273.20**	**272.60**

Appendix Table A7 Compressive strength of specimens before and after immersion in 1% sulfuric solution

Specimens	Strength (ksc.)					
	before immersion	after immersion(days)				
		7	28	60	90	120
OPC	189.24	243.54	270.01	284.06	190.55	211.43
OPC	231.30	288.85	326.31	271.28	180.31	200.71
OPC	178.57	197.62	252.52	232.79	208.67	144.36
Average	**199.70**	**243.34**	**282.95**	**262.71**	**193.18**	**185.50**
GEO 6M	248.51	253.39	249.50	220.88	150.60	215.57
GEO 6M	257.43	335.35	254.98	227.72	190.66	143.71
GEO 6M	284.30	197.24	219.56	238.48	201.62	173.80
Average	**263.41**	**261.99**	**241.35**	**229.03**	**180.96**	**177.70**
GEO 10M	357.16	296.45	350.78	309.39	231.39	294.10
GEO 10M	257.93	378.51	297.06	258.47	324.35	271.09
GEO 10M	346.57	288.27	263.94	289.42	259.49	240.96
Average	**320.55**	**321.08**	**303.93**	**285.76**	**271.74**	**268.72**
GEO 14M	357.87	386.15	380.01	366.47	390.00	375.75
GEO 14M	401.79	388.47	407.56	367.79	53.59	342.05
GEO 14M	420.85	398.41	362.17	415.83	367.82	385.79
Average	**393.50**	**391.01**	**383.25**	**383.36**	**370.47**	**367.87**

Appendix Table A8 Weight of specimens before and after immersion in 5% acetic solution

Specimens	Weight (gram)					
	before immersion	after immersion(days)				
		7	28	60	90	120
OPC	298.60	275.80	250.50	242.10	209.50	212.50
OPC	299.70	258.40	255.70	229.50	212.90	202.40
OPC	288.50	265.70	242.80	227.20	221.20	217.90
Average	**295.60**	**266.63**	**249.67**	**232.93**	**214.53**	**210.93**
GEO 6M	275.30	278.30	258.00	268.30	257.40	247.40
GEO 6M	274.80	267.50	273.20	267.50	266.20	250.20
GEO 6M	271.70	269.60	276.00	264.60	250.30	262.80
Average	**273.93**	**271.80**	**269.07**	**266.80**	**257.97**	**253.47**
GEO 10M	277.60	269.50	260.90	253.50	255.80	257.80
GEO 10M	272.50	273.20	256.80	260.70	260.20	260.00
GEO 10M	272.90	265.60	266.50	252.20	251.10	251.20
Average	**274.33**	**269.43**	**261.40**	**255.47**	**255.70**	**256.33**
GEO 14M	278.20	273.30	267.10	267.10	268.70	270.30
GEO 14M	275.40	276.20	278.60	274.20	278.40	267.80
GEO 14M	272.70	270.90	272.70	272.70	263.80	264.30
Average	**275.43**	**273.47**	**272.80**	**271.33**	**270.30**	**267.47**

Appendix Table A9 Compressive strength of specimens after immersion in 5% acetic solution

Specimens	Strength (ksc.)					
	before immersion	after immersion(days)				
		7	28	60	90	120
OPC	228.63	248.01	221.77	146.11	123.24	144.36
OPC	212.17	229.09	183.66	214.37	163.10	131.61
OPC	198.81	160.16	215.57	175.58	153.83	167.62
Average	**213.20**	**212.42**	**207.00**	**178.69**	**146.73**	**147.86**
GEO 6M	205.41	206.28	201.21	125.73	118.79	108.52
GEO 6M	207.92	226.85	188.87	227.69	150.87	139.93
GEO 6M	237.15	216.97	162.27	167.97	111.85	129.13
Average	**216.83**	**216.70**	**184.11**	**173.80**	**127.17**	**125.86**
GEO 10M	334.63	346.46	318.74	270.00	265.82	245.87
GEO 10M	347.22	321.14	288.84	289.43	246.98	222.22
GEO 10M	317.47	318.09	301.81	218.69	212.12	247.47
Average	**333.10**	**328.56**	**303.13**	**259.37**	**241.64**	**238.52**
GEO 14M	376.23	376.24	337.99	358.57	350.00	290.59
GEO 14M	419.16	402.58	386.90	347.92	269.47	350.01
GEO 14M	397.62	386.90	330.66	273.36	343.43	312.50
Average	**397.67**	**388.57**	**351.85**	**326.61**	**320.97**	**317.70**

Appendix Table A10 Weight of specimens before and after immersion in 3% acetic solution

Specimens	Weight (gram)					
	before immersion	after immersion(days)				
		7	28	60	90	120
OPC	290.00	267.40	267.00	252.10	251.20	230.40
OPC	288.30	272.10	262.60	261.80	249.60	251.90
OPC	286.80	270.50	250.20	258.20	257.10	262.30
Average	**288.37**	**270.00**	**259.93**	**257.37**	**252.63**	**248.20**
GEO 6M	273.20	275.10	274.50	268.80	252.40	254.10
GEO 6M	274.30	271.00	267.30	256.80	257.50	248.40
GEO 6M	270.80	267.30	261.70	260.90	264.40	263.50
Average	**272.77**	**271.13**	**267.83**	**262.17**	**258.10**	**255.33**
GEO 10M	278.30	279.60	268.40	279.60	252.40	272.30
GEO 10M	275.10	263.40	273.70	263.40	263.70	260.50
GEO 10M	269.50	277.50	275.10	267.50	278.10	251.40
Average	**274.30**	**273.50**	**272.40**	**270.17**	**264.73**	**261.40**
GEO 14M	280.50	273.30	277.30	257.50	280.10	258.10
GEO 14M	273.10	260.20	271.20	262.60	265.20	268.50
GEO 14M	260.90	282.10	262.10	281.50	257.20	274.20
Average	**271.50**	**271.87**	**270.20**	**267.20**	**267.50**	**266.93**

Appendix Table A11 Compressive strength of specimens after immersion in 3% acetic solution

Specimens	Strength (ksc.)					
	before immersion	after immersion(days)				
		7	28	60	90	120
OPC	239.04	236.69	190.38	183.70	179.04	203.21
OPC	218.69	222.96	211.69	228.35	203.28	219.31
OPC	249.50	244.18	232.79	212.49	211.23	205.90
Average	**235.75**	**234.61**	**211.62**	**208.18**	**197.85**	**209.47**
GEO 6M	298.21	194.92	199.61	151.51	178.47	136.81
GEO 6M	245.98	284.91	210.00	211.27	197.04	141.66
GEO 6M	219.13	256.42	244.51	190.77	166.29	168.89
Average	**254.44**	**245.42**	**218.04**	**184.52**	**180.60**	**149.12**
GEO 10M	258.45	363.44	268.39	318.10	247.89	298.91
GEO 10M	380.43	320.91	330.01	290.00	232.32	247.37
GEO 10M	323.07	245.56	305.39	302.97	349.02	278.86
Average	**320.65**	**309.97**	**301.26**	**303.69**	**276.41**	**275.04**
GEO 14M	408.38	397.61	365.01	357.15	351.49	337.97
GEO 14M	392.91	364.88	399.20	348.61	339.33	349.40
GEO 14M	378.49	400.18	389.22	356.43	351.91	350.00
Average	**393.26**	**387.56**	**384.48**	**354.06**	**347.58**	**345.79**

Appendix Table A12 Weight of specimens after immersion of specimens after immersion in 1% acetic solution

Specimens	Weight (gram)					
	before immersion	after immersion(days)				
		7	28	60	90	120
OPC	283.70	280.70	277.20	257.20	267.30	269.10
OPC	272.00	268.00	259.80	278.50	248.50	239.40
OPC	280.30	279.50	280.50	267.80	258.90	255.50
Average	**278.67**	**276.07**	**272.50**	**267.83**	**258.23**	**254.67**
GEO 6M	276.40	278.00	268.50	274.20	255.00	250.10
GEO 6M	274.20	272.10	269.20	259.30	264.80	265.40
GEO 6M	270.50	267.80	271.80	267.50	270.90	270.90
Average	**273.70**	**272.63**	**269.83**	**267.00**	**263.57**	**262.13**
GEO 10M	272.30	277.10	273.80	274.30	265.20	269.30
GEO 10M	276.80	272.50	264.50	263.10	268.80	260.80
GEO 10M	270.40	268.70	278.70	276.20	274.70	271.70
Average	**273.17**	**272.77**	**272.33**	**271.20**	**269.57**	**267.27**
GEO 14M	271.30	256.30	278.30	272.00	259.30	265.00
GEO 14M	280.60	274.20	263.40	280.50	281.60	282.10
GEO 14M	261.70	283.10	271.90	259.20	268.80	260.70
Average	**271.20**	**271.20**	**271.20**	**270.57**	**269.90**	**269.27**

Appendix Table A13 Compressive strength of specimens after immersion in 1% acetic solution

Specimens	Strength (ksc.)					
	Before immersion	after immersion(days)				
		7	28	60	90	120
OPC	243.06	266.28	265.73	259.49	266.90	262.45
OPC	217.40	255.00	321.78	299.40	183.29	198.67
OPC	201.76	252.38	276.15	227.72	220.01	177.74
Average	**220.74**	**257.89**	**287.89**	**262.20**	**223.40**	**212.96**
GEO 6M	223.21	293.52	220.00	247.52	270.42	216.01
GEO 6M	286.56	197.62	248.51	240.00	205.82	181.09
GEO 6M	263.42	256.42	276.10	234.54	160.64	256.11
Average	**257.73**	**249.19**	**248.20**	**240.69**	**212.30**	**217.74**
GEO 10M	308.30	326.31	318.73	277.23	240.98	288.46
GEO 10M	325.43	303.79	323.07	288.85	331.99	251.51
GEO 10M	314.95	304.50	288.85	327.38	277.21	300.60
Average	**316.23**	**311.53**	**310.22**	**297.82**	**283.39**	**280.19**
GEO 14M	390.58	362.82	425.77	357.86	364.27	441.77
GEO 14M	397.84	369.59	378.49	370.00	393.43	390.78
GEO 14M	387.67	443.23	348.61	416.66	420.85	340.01
Average	**392.03**	**391.88**	**384.29**	**381.51**	**392.85**	**390.85**

Appendix Table A14 Weight of specimens after immersion of specimens after immersion in saturated magnesium sulfate solution

Specimens	Weight (gram)					
	Before immersion	after immersion(days)				
		7	28	60	90	120
OPC	292.10	290.90	298.30	300.50	300.10	304.10
OPC	285.90	298.30	287.90	283.30	301.20	300.10
OPC	281.10	275.50	285.50	291.60	298.70	303.60
Average	**286.37**	**288.23**	**290.57**	**291.80**	**300.00**	**302.60**
GEO 6M	284.30	280.40	283.20	285.30	294.30	299.40
GEO 6M	280.90	283.10	281.50	282.70	280.90	293.80
GEO 6M	270.50	277.30	280.70	283.20	288.40	292.20
Average	**278.57**	**280.27**	**281.80**	**283.73**	**287.87**	**295.13**
GEO 10M	274.90	283.50	272.10	277.00	292.10	286.50
GEO 10M	279.70	278.10	287.30	291.10	286.90	295.80
GEO 10M	283.40	276.80	285.40	280.30	272.90	298.50
Average	**279.33**	**279.47**	**281.60**	**282.80**	**283.97**	**293.60**
GEO 14M	279.00	288.60	277.40	283.80	287.00	288.60
GEO 14M	286.60	282.60	291.80	286.20	286.60	282.60
GEO 14M	278.90	279.90	282.20	278.40	288.90	290.90
Average	**281.50**	**283.70**	**283.80**	**282.80**	**287.50**	**287.37**

Appendix Table A15 Compressive strength of specimens after immersion in saturated magnesium sulfate solution

Specimens	Strength (ksc.)					
	before immersion	after immersion(days)				
		7	28	60	90	120
OPC	207.11	189.62	189.24	204.18	149.28	136.71
OPC	178.21	225.48	209.17	167.65	164.70	135.90
OPC	230.00	216.09	199.60	186.27	162.72	148.69
Average	**205.11**	**210.40**	**199.34**	**186.03**	**158.90**	**140.43**
GEO 6M	258.45	179.65	139.72	157.78	168.32	147.35
GEO 6M	198.41	233.13	207.50	194.61	157.78	127.19
GEO 6M	207.52	239.05	222.78	181.72	139.16	153.46
Average	**221.46**	**217.28**	**190.00**	**178.04**	**155.09**	**142.67**
GEO 10M	308.29	288.84	288.85	307.54	299.40	287.13
GEO 10M	324.12	327.39	314.37	308.15	281.61	278.88
GEO 10M	339.32	341.37	348.61	288.27	286.00	290.63
Average	**323.91**	**319.20**	**317.28**	**301.32**	**289.00**	**285.55**
GEO 14M	407.55	361.41	448.21	389.23	353.61	372.53
GEO 14M	379.24	428.29	374.75	405.93	394.21	364.16
GEO 14M	385.37	391.08	387.68	399.20	366.34	356.43
Average	**390.72**	**393.59**	**403.55**	**398.12**	**371.39**	**364.37**

Appendix Table A16 Weight of specimens after immersion of specimens after immersion in saturated sodium sulfate solution

Specimens	Weight (gram)					
	before immersion	after immersion(days)				
		7	28	60	90	120
OPC	290.00	280.90	290.30	290.20	299.40	290.70
OPC	278.80	286.30	289.80	297.90	289.50	300.80
OPC	280.10	287.50	279.50	288.30	290.30	291.10
Average	**282.97**	**284.90**	**286.53**	**292.13**	**293.07**	**294.20**
GEO 6M	280.50	275.40	287.30	288.50	300.00	292.00
GEO 6M	268.40	280.30	273.40	287.40	288.10	302.50
GEO 6M	271.60	269.60	285.30	285.60	279.50	279.50
Average	**273.50**	**275.10**	**282.00**	**287.17**	**289.20**	**291.33**
GEO 10M	275.70	275.30	268.40	282.10	270.00	280.10
GEO 10M	267.50	280.50	277.30	277.40	280.50	277.40
GEO 10M	270.10	268.40	290.80	270.00	291.50	285.00
Average	**271.10**	**274.73**	**278.83**	**276.50**	**280.67**	**280.83**
GEO 14M	281.00	263.50	282.60	290.00	274.40	287.30
GEO 14M	260.80	280.50	269.50	265.40	285.20	264.80
GEO 14M	270.40	272.10	272.10	273.90	268.80	278.40
Average	**270.73**	**272.03**	**274.73**	**276.43**	**276.13**	**276.83**

Appendix Table A17 Compressive strength of specimens after immersion in saturated sodium sulfate solution

Specimens	Strength (ksc.)					
	before immersion	after immersion(days)				
		7	28	60	90	120
OPC	205.41	218.69	229.55	206.28	165.99	141.96
OPC	217.82	207.51	209.16	213.97	154.39	164.05
OPC	193.07	187.00	197.63	188.12	202.24	154.39
Average	**205.43**	**204.40**	**212.12**	**202.79**	**174.21**	**153.47**
GEO 6M	177.86	239.05	208.76	205.46	166.98	205.46
GEO 6M	299.40	220.00	216.54	158.42	196.07	168.31
GEO 6M	209.17	198.41	177.86	178.93	147.93	117.88
Average	**228.81**	**219.16**	**201.05**	**180.93**	**170.33**	**163.88**
GEO 10M	308.15	318.73	290.00	298.80	314.96	287.70
GEO 10M	337.97	328.70	329.35	341.78	333.32	325.65
GEO 10M	347.91	310.02	320.00	315.58	278.33	302.41
Average	**331.34**	**319.15**	**313.12**	**318.72**	**308.87**	**305.25**
GEO 14M	424.06	386.90	359.28	388.45	352.22	402.58
GEO 14M	392.65	390.30	377.73	395.01	403.39	374.75
GEO 14M	372.53	396.04	419.16	359.28	384.60	362.10
Average	**396.41**	**391.08**	**385.39**	**380.91**	**380.07**	**379.81**

Appendix Table A18 Result of carbonation depth before test

Specimens			Depth horizontal(mm.)				Depth Vertical(mm.)		
			Top	Middle	Tip	Ave	Top	Bottom	Ave.2
Geopolymer 14 M	1	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	2	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	3	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
					Ave.	0			0
Geopolymer 10 M	1	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	2	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	3	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
					Ave.	0			0
Geopolymer 6 M	1	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	2	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	3	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
					Ave.	0			0
OPC	1	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	2	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	3	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
					Ave.	0			0

Appendix Table A19 Result of carbonation depth after 3 hours

Specimens			Depth horizontal(mm.)				Depth Vertical(mm.)		
			Top	Mid	Tip	Ave.1	Top	Bot.	Ave.2
Geopolymer 14 M	1	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	2	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	3	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
					Ave.	0			0
Geopolymer 10 M	1	Right	2.50	3.80	5.30	3.87	1.00	0.90	0.95
		Left	3.00	3.70	5.20	3.97	0.90	0.80	0.85
	2	Right	3.30	5.90	6.40	5.20	0.70	0.70	0.70
		Left	4.30	5.60	6.30	5.40	0.50	0.80	0.65
	3	Right	4.60	5.00	5.80	5.13	0.40	0.80	0.60
		Left	5.70	4.90	5.80	5.47	0.50	0.90	0.70
					Ave.	4.84			0.74
Geopolymer 6 M	1	Right	1.30	1.70	2.00	1.67	3.80	4.80	4.30
		Left	1.90	1.60	2.10	1.87	3.70	4.60	4.15
	2	Right	0.90	1.60	1.30	1.27	2.20	1.50	1.85
		Left	1.40	1.70	1.50	1.53	2.00	1.40	1.70
	3	Right	3.30	3.60	4.00	3.63	4.50	5.60	5.05
		Left	3.50	3.70	4.20	3.80	4.40	5.50	4.95
					Ave.	2.29			3.67
OPC	1	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	2	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	3	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
					Ave.	0.00			0.00

Appendix Table A20 Result of carbonation depth after 12 hours

Specimens			Depth horizontal(mm.)				Depth Vertical(mm.)		
			Top	Mid	Tip	Ave.1	Top	Bot.	Ave.2
Geopolymer 14 M	1	Right	6.50	4.80	4.50	5.27	4.30	5.80	5.05
		Left	6.40	4.60	4.40	5.13	4.10	5.50	4.80
	2	Right	5.20	4.50	3.10	4.27	5.40	5.20	5.30
		Left	5.00	4.60	3.00	4.20	5.30	5.40	5.35
	3	Right	5.30	4.30	3.00	4.20	4.80	7.90	6.35
		Left	5.40	4.40	3.20	4.33	5.00	5.40	5.20
					Ave.	4.57			5.34
Geopolymer 10 M	1	Right	7.80	8.80	9.30	8.63	10.80	12.80	11.80
		Left	7.90	8.90	9.10	8.63	10.70	13.00	11.85
	2	Right	7.50	8.60	9.40	8.50	7.10	14.20	10.65
		Left	7.40	8.50	9.30	8.40	7.00	14.00	10.50
	3	Right	8.80	9.20	10.50	9.50	4.50	10.10	7.30
		Left	8.70	9.00	10.40	9.37	4.60	10.00	7.30
					Ave.	8.84			9.90
Geopolymer 6 M	1	Right	16.0	15.5	12.20	14.57	25.40	40.10	32.75
		Left	16.2	15.4	12.30	14.63	25.50	40.00	32.75
	2	Right	14.0	14.5	13.00	13.83	30.50	49.00	39.75
		Left	14.2	14.5	13.10	13.93	30.60	48.90	39.75
	3	Right	15.3	16.0	17.00	16.10	45.10	50.30	47.70
		Left	15.5	16.2	17.10	16.27	45.20	50.20	47.70
					Ave.	14.89			40.07
OPC	1	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	2	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	3	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
					Ave.	0.00			0.00

Appendix Table A21 Result of carbonation depth after 24 hours

Specimens			Depth horizontal(mm.)				Depth Vertical(mm.)		
			Top	Mid	Tip	Ave.1	Top	Bot.	Ave.2
Geopolymer 14 M	1	Right	10.5	12.4	14.8	12.57	12.8	17.4	15.10
		Left	11.9	13.2	15.3	13.47	12.4	18.1	15.25
	2	Right	9.0	10.9	14.0	11.30	12.6	17.7	15.15
		Left	9.5	11.7	14.8	12.00	12.8	15.2	14.00
	3	Right	8.8	10.0	15.5	11.43	13.2	14.5	13.85
		Left	8.1	10.5	15.0	11.20	12.9	14.9	13.90
					Ave.	11.99			14.54
Geopolymer 10 M	1	Right	13.2	17.5	18.3	16.33	22.2	57.7	39.95
		Left	11.2	16.7	17.1	15.00	21.5	55.8	38.65
	2	Right	15.8	18.5	19.8	18.03	25.5	40.3	32.90
		Left	14.2	17.3	19.2	16.90	26.8	40.1	33.45
	3	Right	14.3	18.8	17.5	16.87	24.8	53.2	39.00
		Left	15.8	17.2	17.7	16.90	25.3	55.1	40.20
					Ave.	16.67			37.36
Geopolymer 6 M	1	Right	20.0	19.3	21.4	20.23	50.5	48.7	49.35
		Left	20.1	19.2	21.5	20.27	50.1	48.6	49.35
	2	Right	22.1	23.3	23.5	22.97	48.9	50.0	49.45
		Left	22.3	23.4	23.5	23.07	49.1	49.8	49.45
	3	Right	21.0	20.4	21.2	20.87	49.8	49.8	49.80
		Left	21.0	20.3	21.1	20.80	49.7	49.6	49.65
					Ave.	21.37			49.51
OPC	1	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	2	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	3	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
					Ave.	0.00			0.00

Appendix Table A22 Result of carbonation depth after 72 hours

Specimens			Depth horizontal(mm.)				Depth Vertical(mm.)		
			Top	Mid.	Tip	Ave.1	Top	Bot.	Ave.2
Geopolymer 14 M	1	Right	13.2	15.0	11.4	13.20	16.00	30.40	23.20
		Left	13.0	15.0	11.3	13.10	15.70	31.00	23.35
	2	Right	10.5	12.8	13.3	12.20	14.00	10.20	12.10
		Left	10.4	12.6	13.5	12.17	13.80	10.00	11.90
	3	Right	10.3	11.5	12.2	11.33	12.50	14.50	13.50
		Left	10.2	11.7	12.5	11.47	12.40	14.70	13.55
					Ave.	12.24			16.27
Geopolymer 10 M	1	Right	13.2	15.0	17.4	15.20	43.30	33.40	38.35
		Left	13.0	15.0	17.3	15.10	43.70	33.00	38.35
	2	Right	15.5	16.8	18.3	16.87	64.20	52.40	58.30
		Left	15.4	17.2	18.5	17.03	64.10	52.60	58.35
	3	Right	19.3	18.5	19.2	19.00	33.00	72.50	52.75
		Left	19.2	18.7	19.5	19.13	33.10	72.60	52.85
					Ave.	17.06			49.83
Geopolymer 6 M	1	Right	50.1	50.0	50.3	50.13	99.80	100.00	99.90
		Left	50.0	50.1	50.5	50.20	99.70	100.00	99.85
	2	Right	50.3	50.2	49.8	50.10	99.50	100.20	99.85
		Left	50.4	50.3	49.7	50.13	99.70	100.10	99.90
	3	Right	50.2	49.6	50.0	49.93	99.80	100.00	99.90
		Left	50.1	49.7	50.0	49.93	99.60	100.00	99.80
					Ave.	50.07			99.87
OPC	1	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	2	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	3	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
					Ave.	0.00			0.00

Appendix Table A23 Result of carbonation depth after 168 hours

Specimens			Depth horizontal(mm.)				Depth Vertical(mm.)		
			Top	Mid.	Tip	Ave.1	Top	Bot.	Ave.2
Geopolymer 14 M	1	Right	15.1	14.5	14.4	14.53	15.7	18.0	16.85
		Left	15.3	14.6	13.8	14.57	15.9	18.3	17.10
	2	Right	17.0	15.5	16.3	16.27	17.6	19.7	18.65
		Left	17.2	15.3	16.1	16.20	17.5	19.8	18.65
	3	Right	16.4	17.3	18.6	17.43	19.2	17.4	18.30
		Left	16.3	17.2	18.4	17.30	19.0	17.3	18.15
					Ave.	16.05			17.95
Geopolymer 10 M	1	Right	49.9	49.8	50.9	50.20	100.0	99.8	99.90
		Left	49.8	50.0	51.0	50.27	100.2	99.5	99.85
	2	Right	50.2	50.1	50.0	50.10	100.1	99.7	99.90
		Left	50.0	50.0	50.0	50.00	100.0	100.2	100.10
	3	Right	50.0	50.1	50.2	50.10	99.90	100.0	99.95
		Left	50.1	50.3	50.3	50.23	99.80	100.2	100.00
					Ave.	50.15			99.95
Geopolymer 6 M	1	Right	50.1	50.0	50.3	50.13	100.1	99.80	99.95
		Left	50.0	50.1	50.4	50.17	100.0	99.70	99.85
	2	Right	49.9	49.8	50.3	50.00	100.2	99.50	99.85
		Left	49.8	49.7	50.1	49.87	100.2	99.60	99.90
	3	Right	50.1	49.8	50.2	50.03	99.7	100.0	99.85
		Left	50.0	49.9	50.3	50.07	99.6	100.1	99.85
					Ave.	50.04			99.88
OPC	1	Right	9.10	9.80	4.00	7.63	4.80	4.20	4.50
		Left	9.00	9.90	4.30	7.73	4.70	4.10	4.40
	2	Right	8.50	9.70	7.50	8.57	5.80	4.50	5.15
		Left	8.40	9.60	7.70	8.57	5.60	4.40	5.00
	3	Right	-	-	-	-	-	-	-
		Left	-	-	-	-	-	-	-
					Ave.	8.13			4.76

Appendix Table A24 Result of carbonation depth after 336 hours

Specimens			Depth horizontal(mm.)				Depth Vertical(mm.)		
			Top	Mid.	Tip	Ave.1	Top	Bot.	Ave.2
Geopolymer 14 M	1	Right	50.0	50.2	50.3	50.17	99.7	100.0	99.85
		Left	50.0	50.1	50.2	50.10	99.6	100.0	99.80
	2	Right	50.3	50.2	50.4	50.30	99.8	100.1	99.95
		Left	50.2	50.2	50.3	50.23	99.7	100.0	99.85
	3	Right	50.2	50.4	50.5	50.37	99.7	100.2	99.95
		Left	50.1	50.3	50.4	50.27	99.6	100.1	99.85
					Ave.	50.24			99.88
Geopolymer 10 M	1	Right	50.1	50.3	50.2	50.20	100.4	99.7	100.05
		Left	50.0	50.2	50.1	50.10	100.3	99.8	100.05
	2	Right	50.3	50.2	50.1	50.20	100.2	99.8	100.00
		Left	50.2	50.1	50.1	50.13	100.0	99.6	99.80
	3	Right	50.4	50.5	50.6	50.50	99.8	100.0	99.90
		Left	50.3	50.4	50.5	50.40	99.9	100.0	99.95
					Ave.	50.26			99.96
Geopolymer 6 M	1	Right	50.3	50.2	50.0	50.17	99.8	100.3	100.05
		Left	50.2	50.1	50.0	50.10	99.7	100.2	99.95
	2	Right	50.2	50.1	50.0	50.10	99.8	100.2	100.00
		Left	50.0	50.1	50.1	50.07	99.7	100.1	99.90
	3	Right	50.2	50.4	50.3	50.30	99.7	100.0	99.95
		Left	50.3	50.3	50.2	50.27	99.8	100.0	100.00
					Ave.	50.17			99.98
OPC	1	Right	14.5	13.4	11.0	12.97	12.5	13.2	12.85
		Left	14.4	13.3	11.1	12.93	12.4	13.1	12.75
	2	Right	10.5	10.1	9.3	9.63	13.4	14.5	13.95
		Left	10.4	10.0	8.2	9.53	13.3	14.4	13.85
	3	Right	5.0	4.7	4.5	4.73	10.0	8.3	9.15
		Left	5.0	4.8	4.5	4.77	10.0	8.3	9.15
					Ave.	9.10			11.95

Appendix Table A25 Compressive strength of specimens before and after carbonation test

Specimens	Strength (ksc.)						
	before	after test carbonation (hours)					
		3	12	24	72	168	336
OPC	216.93	201.73	201.74	203.35	210.55	202.94	201.73
OPC	227.40	189.88	215.63	197.00	202.94	179.37	186.89
OPC	200.93	227.41	202.54	215.63	190.27	210.56	196.21
Average	**215.09**	**206.34**	**206.64**	**205.33**	**201.25**	**197.63**	**194.94**
GEO 6M	189.88	176.52	164.24	151.30	164.56	143.57	142.72
GEO 6M	151.90	151.30	171.58	161.07	151.30	150.40	164.24
GEO 6M	164.24	164.25	152.21	158.55	146.45	156.99	138.42
Average	**168.68**	**164.02**	**162.68**	**156.98**	**154.11**	**150.32**	**148.46**
GEO 10M	264.25	252.67	239.08	215.20	237.67	215.64	198.95
GEO 10M	240.05	246.35	214.77	254.14	227.41	226.96	251.17
GEO 10M	226.05	226.96	264.78	240.52	223.31	239.09	226.98
Average	**243.45**	**242.00**	**239.55**	**236.62**	**229.46**	**227.23**	**225.70**
GEO 14M	277.94	276.84	311.45	278.51	268.50	260.19	288.84
GEO 14M	291.73	288.27	265.84	310.14	266.37	311.39	266.37
GEO 14M	303.82	301.40	280.17	262.79	303.81	261.65	273.02
Average	**291.16**	**288.84**	**285.82**	**283.81**	**279.56**	**277.74**	**276.08**

Appendix Table A26 Result of Electrical charge passing OPC mortar

Time (min.)		Electrical Charge (.mm Amp.)			Ave.	Remark
		20 Sec.	40 Sec.	60 Sec.		
00:01:00	1	0	0	50	16.667	
00:02:00	2	51	51	50	50.667	
00:03:00	3	50	50	50	50.000	
00:04:00	4	50	50	50	50.000	
00:05:00	5	50	50	50	50.000	
00:06:00	6	50	50	50	50.000	
00:07:00	7	50	50	50	50.000	
00:08:00	8	50	50	50	50.000	
00:09:00	9	50	50	50	50.000	
00:10:00	10	50	50	50	50.000	
00:11:00	11	50	50	50	50.000	
00:12:00	12	50	50	50	50.000	
00:13:00	13	50	50	50	50.000	
00:14:00	14	50	50	50	50.000	
00:15:00	15	50	50	50	50.000	
00:16:00	16	50	50	50	50.000	
00:17:00	17	50	50	50	50.000	
00:18:00	18	50	50	49	49.667	
00:19:00	19	50	50	50	50.000	
00:20:00	20	50	50	50	50.000	
00:21:00	21	50	50	50	50.000	
00:22:00	22	49	49	49	49.000	
00:23:00	23	49	49	50	49.333	
00:24:00	24	50	49	49	49.333	
00:25:00	25	49	49	49	49.000	
00:26:00	26	49	49	49	49.000	
00:27:00	27	49	49	49	49.000	
00:28:00	28	49	49	49	49.000	
00:29:00	29	49	49	50	49.333	
00:30:00	30	49	49	49	49.000	
00:31:00	31	49	49	49	49.000	
00:32:00	32	49	49	49	49.000	
00:33:00	33	49	49	48	48.667	
00:34:00	34	48	49	49	48.667	
00:35:00	35	49	49	49	49.000	
00:36:00	36	49	50	49	49.333	
00:37:00	37	49	50	49	49.333	
00:38:00	38	49	49	50	49.333	
00:39:00	39	49	50	49	49.333	
00:40:00	40	50	50	49	49.667	
00:41:00	41	50	50	49	49.667	

Appendix Table A26 (Continued)

Time (min.)		Electrical Charge (.mm Amp.)			Ave.	Remark
		20 Sec.	40 Sec.	60 Sec.		
00:42:00	42	49	49	49	49.000	
00:43:00	43	49	49	49	49.000	
00:44:00	44	50	49	49	49.333	
00:45:00	45	49	49	49	49.000	
00:46:00	46	49	49	49	49.000	
00:47:00	47	49	49	49	49.000	
00:48:00	48	49	49	49	49.000	
00:49:00	49	49	49	49	49.000	
00:50:00	50	48	48	48	48.000	
00:51:00	51	48	48	48	48.000	
00:52:00	52	48	48	48	48.000	
00:53:00	53	48	48	48	48.000	
00:54:00	54	48	48	48	48.000	
00:55:00	55	48	48	49	48.333	
00:56:00	56	49	49	49	49.000	
00:57:00	57	48	49	48	48.333	
00:58:00	58	48	48	47	47.667	
00:59:00	59	48	48	49	48.333	
01:00:00	60	48	49	49	48.667	
01:01:00	61	48	49	48	48.333	
01:02:00	62	48	49	48	48.333	
01:03:00	63	49	48	48	48.333	
01:04:00	64	49	48	48	48.333	
01:05:00	65	49	48	49	48.667	
01:06:00	66	48	48	48	48.000	
01:07:00	67	48	48	48	48.000	
01:08:00	68	49	48	48	48.333	
01:09:00	69	49	48	49	48.667	
01:10:00	70	48	48	48	48.000	
01:11:00	71	48	49	48	48.333	
01:12:00	72	48	48	48	48.000	
01:13:00	73	48	48	48	48.000	
01:14:00	74	48	48	49	48.333	
01:15:00	75	48	48	48	48.000	
01:16:00	76	48	48	48	48.000	
01:17:00	77	48	48	48	48.000	
01:18:00	78	48	48	48	48.000	
01:19:00	79	48	48	48	48.000	
01:20:00	80	48	48	48	48.000	
01:21:00	81	48	48	48	48.000	
01:22:00	82	48	48	48	48.000	

Appendix Table A27 Result of Electrical charge passing geopolymer 14M mortar

Time (min.)		Electrical Charge (.mm Amp.)			Ave.	Remark
		20 Sec.	40 Sec.	60 Sec.		
00:01:00	1	0	0	339	113.000	
00:02:00	2	339	339	339	339.000	
00:03:00	3	338	338	338	338.000	
00:04:00	4	339	339	338	338.667	
00:05:00	5	338	339	340	339.000	
00:06:00	6	338	339	338	338.333	
00:07:00	7	339	339	339	339.000	
00:08:00	8	339	339	338	338.667	
00:09:00	9	338	338	339	338.333	
00:10:00	10	340	340	341	340.333	
00:11:00	11	341	341	341	341.000	
00:12:00	12	341	341	342	341.333	
00:13:00	13	343	344	344	343.667	
00:14:00	14	344	345	344	344.333	
00:15:00	15	345	344	344	344.333	
00:16:00	16	345	346	346	345.667	
00:17:00	17	345	346	345	345.333	
00:18:00	18	346	346	347	346.333	
00:19:00	19	346	347	347	346.667	
00:20:00	20	347	347	348	347.333	
00:21:00	21	348	348	348	348.000	
00:22:00	22	348	350	349	349.000	
00:23:00	23	349	349	350	349.333	
00:24:00	24	350	350	350	350.000	
00:25:00	25	350	350	351	350.333	
00:26:00	26	351	351	352	351.333	
00:27:00	27	352	352	352	352.000	
00:28:00	28	352	354	353	353.000	
00:29:00	29	353	353	353	353.000	
00:30:00	30	354	354	353	353.667	
00:31:00	31	354	354	354	354.000	
00:32:00	32	354	353	354	353.667	
00:33:00	33	354	353	353	353.333	
00:34:00	34	354	355	356	355.000	
00:35:00	35	357	357	358	357.333	
00:36:00	36	357	358	358	357.667	
00:37:00	37	358	358	359	358.333	
00:38:00	38	359	359	359	359.000	
00:39:00	39	359	360	360	359.667	
00:40:00	40	360	360	360	360.000	
00:41:00	41	361	361	360	360.667	

Appendix Table A27 (Continued)

Time (min.)		Electrical Charge (.mm Amp.)			Ave.	Remark
		20 Sec.	40 Sec.	60 Sec.		
00:42:00	42	360	362	361	361.000	
00:43:00	43	361	361	361	361.000	
00:44:00	44	362	362	362	362.000	
00:45:00	45	362	363	363	362.667	
00:46:00	46	362	363	362	362.333	
00:47:00	47	363	362	363	362.667	
00:48:00	48	363	363	362	362.667	
00:49:00	49	363	363	364	363.333	
00:50:00	50	364	363	364	363.667	
00:51:00	51	364	363	364	363.667	
00:52:00	52	364	364	364	364.000	
00:53:00	53	364	364	367	365.000	
00:54:00	54	366	367	367	366.667	
00:55:00	55	367	367	367	367.000	
00:56:00	56	367	367	367	367.000	
00:57:00	57	368	368	367	367.667	
00:58:00	58	368	368	367	367.667	
00:59:00	59	367	368	369	368.000	
01:00:00	60	368	368	368	368.000	
01:01:00	61	368	368	369	368.333	
01:02:00	62	370	369	370	369.667	
01:03:00	63	369	370	370	369.667	
01:04:00	64	370	371	370	370.333	
01:05:00	65	370	371	371	370.667	
01:06:00	66	370	369	371	370.000	
01:07:00	67	371	369	371	370.333	
01:08:00	68	371	371	371	371.000	
01:09:00	69	371	371	371	371.000	
01:10:00	70	371	371	371	371.000	
01:11:00	71	371	371	371	371.000	
01:12:00	72	370	371	370	370.333	
01:13:00	73	370	371	371	370.667	
01:14:00	74	370	371	370	370.333	
01:15:00	75	370	371	371	370.667	
01:16:00	76	371	371	371	371.000	
01:17:00	77	371	371	371	371.000	
01:18:00	78	371	371	371	371.000	
01:19:00	79	371	371	371	371.000	
01:20:00	80	371	371	371	371.000	
01:21:00	81	371	371	371	371.000	
01:22:00	82	371	371	371	371.000	

Appendix Table A28 Result of Electrical charge passing geopolymer 10M

Time (min.)		Electrical Charge (.mm Amp.)			Ave.	Remark
		20 Sec.	40 Sec.	60 Sec.		
00:01:00	1	0	0	50	16.667	
00:02:00	2	51	51	50	50.667	
00:03:00	3	50	50	50	50.000	
00:04:00	4	50	50	50	50.000	
00:05:00	5	50	50	50	50.000	
00:06:00	6	50	50	50	50.000	
00:07:00	7	50	50	50	50.000	
00:08:00	8	50	50	50	50.000	
00:09:00	9	50	50	50	50.000	
00:10:00	10	50	50	50	50.000	
00:11:00	11	50	50	50	50.000	
00:12:00	12	50	50	50	50.000	
00:13:00	13	50	50	50	50.000	
00:14:00	14	50	50	50	50.000	
00:15:00	15	50	50	50	50.000	
00:16:00	16	50	50	50	50.000	
00:17:00	17	50	50	50	50.000	
00:18:00	18	50	50	49	49.667	
00:19:00	19	50	50	50	50.000	
00:20:00	20	50	50	50	50.000	
00:21:00	21	50	50	50	50.000	
00:22:00	22	49	49	49	49.000	
00:23:00	23	49	49	50	49.333	
00:24:00	24	50	49	49	49.333	
00:25:00	25	49	49	49	49.000	
00:26:00	26	49	49	49	49.000	
00:27:00	27	49	49	49	49.000	
00:28:00	28	49	49	49	49.000	
00:29:00	29	49	49	50	49.333	
00:30:00	30	49	49	49	49.000	
00:31:00	31	49	49	49	49.000	
00:32:00	32	49	49	49	49.000	
00:33:00	33	49	49	48	48.667	
00:34:00	34	48	49	49	48.667	
00:35:00	35	49	49	49	49.000	
00:36:00	36	49	50	49	49.333	
00:37:00	37	49	50	49	49.333	
00:38:00	38	49	49	50	49.333	
00:39:00	39	49	50	49	49.333	
00:40:00	40	50	50	49	49.667	
00:41:00	41	50	50	49	49.667	

Appendix Table A28 (Continued)

Time (min.)		Electrical Charge (.mm Amp.)			Ave.	Remark
		20 Sec.	40 Sec.	60 Sec.		
00:01:00	1	0	0	50	16.667	
00:02:00	2	51	51	50	50.667	
00:03:00	3	50	50	50	50.000	
00:04:00	4	50	50	50	50.000	
00:05:00	5	50	50	50	50.000	
00:06:00	6	50	50	50	50.000	
00:07:00	7	50	50	50	50.000	
00:08:00	8	50	50	50	50.000	
00:09:00	9	50	50	50	50.000	
00:10:00	10	50	50	50	50.000	
00:11:00	11	50	50	50	50.000	
00:12:00	12	50	50	50	50.000	
00:13:00	13	50	50	50	50.000	
00:14:00	14	50	50	50	50.000	
00:15:00	15	50	50	50	50.000	
00:16:00	16	50	50	50	50.000	
00:17:00	17	50	50	50	50.000	
00:18:00	18	50	50	49	49.667	
00:19:00	19	50	50	50	50.000	
00:20:00	20	50	50	50	50.000	
00:21:00	21	50	50	50	50.000	
00:22:00	22	49	49	49	49.000	
00:23:00	23	49	49	50	49.333	
00:24:00	24	50	49	49	49.333	
00:25:00	25	49	49	49	49.000	
00:26:00	26	49	49	49	49.000	
00:27:00	27	49	49	49	49.000	
00:28:00	28	49	49	49	49.000	
00:29:00	29	49	49	50	49.333	
00:30:00	30	49	49	49	49.000	
00:31:00	31	49	49	49	49.000	
00:32:00	32	49	49	49	49.000	
00:33:00	33	49	49	48	48.667	
00:34:00	34	48	49	49	48.667	
00:35:00	35	49	49	49	49.000	
00:36:00	36	49	50	49	49.333	
00:37:00	37	49	50	49	49.333	
00:38:00	38	49	49	50	49.333	
00:39:00	39	49	50	49	49.333	
00:40:00	40	50	50	49	49.667	
00:41:00	41	50	50	49	49.667	

Appendix Table A29 Result of Electrical charge passing geopolymer 6 M mortar

Time (min.)		Electrical Charge (.mm Amp.)			Ave.	Remark
		20 Sec.	40 Sec.	60 Sec.		
00:01:00	1	0	0	50	16.667	
00:02:00	2	51	51	50	50.667	
00:03:00	3	50	50	50	50.000	
00:04:00	4	50	50	50	50.000	
00:05:00	5	50	50	50	50.000	
00:06:00	6	50	50	50	50.000	
00:07:00	7	50	50	50	50.000	
00:08:00	8	50	50	50	50.000	
00:09:00	9	50	50	50	50.000	
00:10:00	10	50	50	50	50.000	
00:11:00	11	50	50	50	50.000	
00:12:00	12	50	50	50	50.000	
00:13:00	13	50	50	50	50.000	
00:14:00	14	50	50	50	50.000	
00:15:00	15	50	50	50	50.000	
00:16:00	16	50	50	50	50.000	
00:17:00	17	50	50	50	50.000	
00:18:00	18	50	50	49	49.667	
00:19:00	19	50	50	50	50.000	
00:20:00	20	50	50	50	50.000	
00:21:00	21	50	50	50	50.000	
00:22:00	22	49	49	49	49.000	
00:23:00	23	49	49	50	49.333	
00:24:00	24	50	49	49	49.333	
00:25:00	25	49	49	49	49.000	
00:26:00	26	49	49	49	49.000	
00:27:00	27	49	49	49	49.000	
00:28:00	28	49	49	49	49.000	
00:29:00	29	49	49	50	49.333	
00:30:00	30	49	49	49	49.000	
00:31:00	31	49	49	49	49.000	
00:32:00	32	49	49	49	49.000	
00:33:00	33	49	49	48	48.667	
00:34:00	34	48	49	49	48.667	
00:35:00	35	49	49	49	49.000	
00:36:00	36	49	50	49	49.333	
00:37:00	37	49	50	49	49.333	
00:38:00	38	49	49	50	49.333	
00:39:00	39	49	50	49	49.333	
00:40:00	40	50	50	49	49.667	
00:41:00	41	50	50	49	49.667	

Appendix Table A29 (Continued)

Time (min.)		Electrical Charge (.mm Amp.)			Ave.	Remark
		20 Sec.	40 Sec.	60 Sec.		
00:01:00	1	0	0	50	16.667	
00:02:00	2	51	51	50	50.667	
00:03:00	3	50	50	50	50.000	
00:04:00	4	50	50	50	50.000	
00:05:00	5	50	50	50	50.000	
00:06:00	6	50	50	50	50.000	
00:07:00	7	50	50	50	50.000	
00:08:00	8	50	50	50	50.000	
00:09:00	9	50	50	50	50.000	
00:10:00	10	50	50	50	50.000	
00:11:00	11	50	50	50	50.000	
00:12:00	12	50	50	50	50.000	
00:13:00	13	50	50	50	50.000	
00:14:00	14	50	50	50	50.000	
00:15:00	15	50	50	50	50.000	
00:16:00	16	50	50	50	50.000	
00:17:00	17	50	50	50	50.000	
00:18:00	18	50	50	49	49.667	
00:19:00	19	50	50	50	50.000	
00:20:00	20	50	50	50	50.000	
00:21:00	21	50	50	50	50.000	
00:22:00	22	49	49	49	49.000	
00:23:00	23	49	49	50	49.333	
00:24:00	24	50	49	49	49.333	
00:25:00	25	49	49	49	49.000	
00:26:00	26	49	49	49	49.000	
00:27:00	27	49	49	49	49.000	
00:28:00	28	49	49	49	49.000	
00:29:00	29	49	49	50	49.333	
00:30:00	30	49	49	49	49.000	
00:31:00	31	49	49	49	49.000	
00:32:00	32	49	49	49	49.000	
00:33:00	33	49	49	48	48.667	
00:34:00	34	48	49	49	48.667	
00:35:00	35	49	49	49	49.000	
00:36:00	36	49	50	49	49.333	
00:37:00	37	49	50	49	49.333	
00:38:00	38	49	49	50	49.333	
00:39:00	39	49	50	49	49.333	
00:40:00	40	50	50	49	49.667	
00:41:00	41	50	50	49	49.667	

Appendix Table A30 Result of Chloride depth after 0 days

Specimens			Depth horizontal(mm.)				Depth Vertical(mm.)		
			Top	Mid.	Tip	Ave.1	Top	Bot.	Ave.2
Geo 14 M	1	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	2	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	3	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
					Ave.	0			0
Geo 10 M	1	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	2	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	3	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
					Ave.	0			0
OPC	1	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	2	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	3	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
					Ave.	0			0

Appendix Table A31 Result of Chloride depth after 14 days

Specimens			Depth horizontal(mm.)				Depth Vertical(mm.)		
			Top	Mid.	Tip	Ave.1	Top	Bot.	Ave.2
Geo 14 M	1	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	2	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	3	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
					Ave.	0			0
Geo 10 M	1	Right	2.3	1.6	0.8	1.57	2.2	4.8	3.50
		Left	2.0	1.7	1.0	1.57	3.1	2.9	3.00
	2	Right	1.2	1.6	0.7	1.17	4.6	3.2	3.90
		Left	1.4	0.9	1.5	1.27	2.9	4.1	3.50
	3	Right	2.2	1.2	1.7	1.70	3.2	3.0	3.10
		Left	1.8	0.9	1.0	1.23	4.4	5.5	4.95
					Ave.	1.42			3.66
OPC	1	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	2	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	3	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
					Ave.	0			0

Appendix Table A32 Result of Chloride depth after 21 days

Specimens			Depth horizontal(mm.)				Depth Vertical(mm.)		
			Top	Mid.	Tip	Ave.1	Top	Bot.	Ave.2
Geo 14 M	1	Right	0.7	1.0	3.2	1.63	5.2	3.4	4.30
		Left	0.6	1.2	2.8	1.53	3.6	5.1	4.35
	2	Right	4.5	1.2	0.3	2.00	4.2	3.5	3.85
		Left	4.2	1.0	1.1	2.10	2.9	4.1	3.50
	3	Right	2.3	1.2	1.5	1.67	3.9	2.8	3.35
		Left	2.0	1.2	0.4	1.20	4.8	3.2	4.00
					Ave.	1.69			3.89
Geo 10 M	1	Right	6.3	4.0	3.8	4.70	9.3	4.5	6.90
		Left	2.5	4.1	3.9	3.50	8.2	7.3	7.75
	2	Right	4.3	5.8	3.7	4.60	10.1	9.4	9.75
		Left	7.4	5.7	5.4	6.17	12.0	14.3	13.15
	3	Right	8.2	3.8	4.8	5.60	13.6	7.8	10.70
		Left	6.3	3.8	4.3	4.80	7.9	15.1	11.50
					Ave.	4.89			9.96
OPC	1	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	2	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
	3	Right	0	0	0	0	0	0	0
		Left	0	0	0	0	0	0	0
					Ave.	0			0

Appendix Table A33 Result of Chloride depth after 28 days

Specimens			Depth horizontal(mm.)				Depth Vertical(mm.)		
			Top	Mid.	Tip	Ave.1	Top	Bot.	Ave.2
Geo 14 M	1	Right	8.2	8.5	6.5	7.73	8.5	10.3	9.40
		Left	8.0	8.3	6.7	7.67	9.6	11.5	10.55
	2	Right	10.2	7.0	6.1	7.77	8.9	15.0	11.95
		Left	10.0	7.3	6.4	7.90	12.4	17.3	14.85
	3	Right	4.8	6.5	8.6	6.63	13.2	16.4	14.80
		Left	4.6	6.3	8.4	6.43	14.5	15.8	15.15
					Ave.	7.36			12.78
Geo 10 M	1	Right	16.0	15.5	2.2	14.57	25.4	40.1	32.75
		Left	16.2	15.4	12.3	14.63	25.5	40.0	32.75
	2	Right	14.0	14.5	13.0	13.83	30.5	49.0	39.75
		Left	14.2	14.5	13.1	13.93	30.6	48.9	39.75
	3	Right	15.3	16.0	17.0	16.10	45.1	50.3	47.70
		Left	15.5	16.2	17.1	16.27	45.2	50.2	47.70
					Ave.	14.89			40.07
OPC	1	Right	1.5	0	1.2	0.90	0.7	1.2	0.95
		Left	1.3	0	1	0.77	0.8	1	0.90
	2	Right	0.8	0.7	0.5	0.67	2.3	1.3	1.80
		Left	0.7	0.5	0.3	0.50	2.5	1.1	1.80
	3	Right	0	0.4	0.7	0.37	3.1	2.3	2.70
		Left	0	0.3	0.9	0.40	2.8	2.5	2.65
					Ave.	0.60			1.80

Appendix Table A34 Result of Chloride depth after 35 days

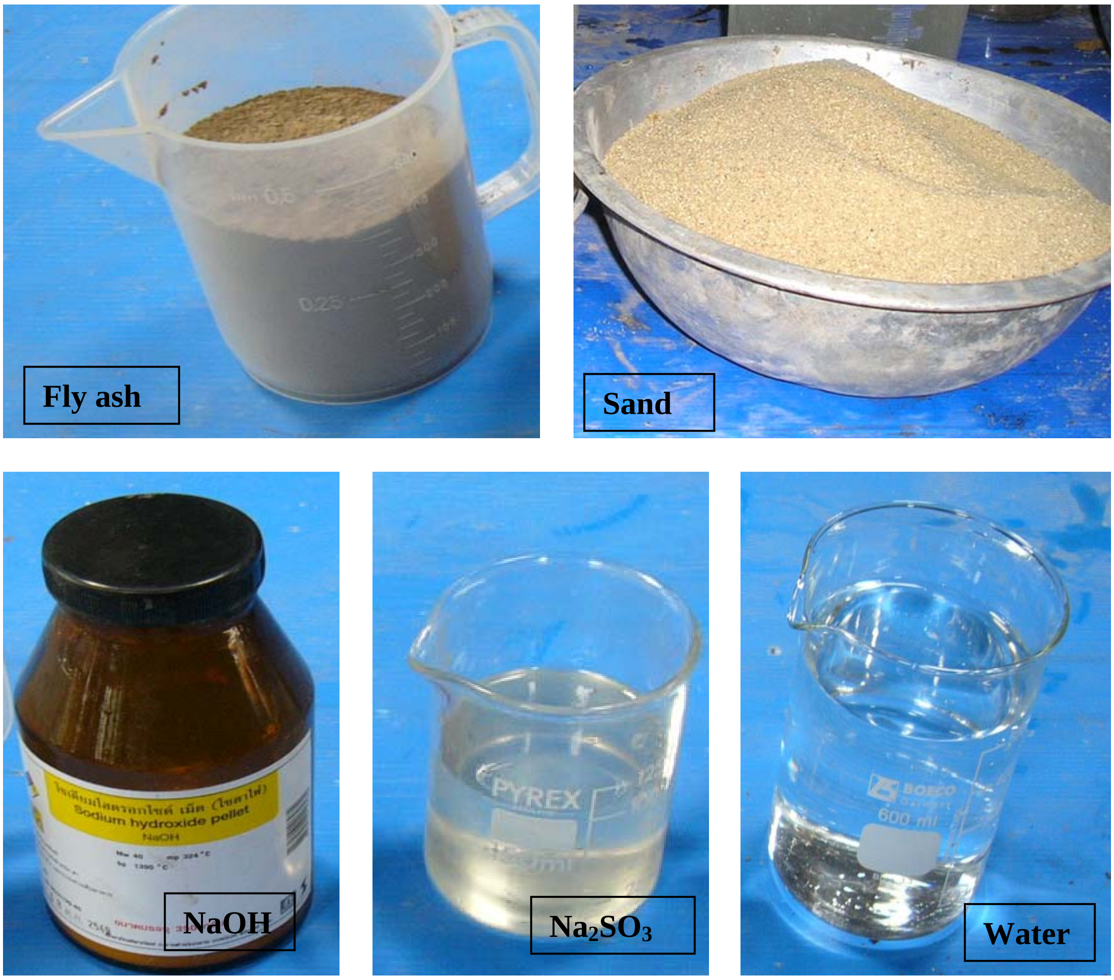
Specimens			Depth horizontal(mm.)				Depth Vertical(mm.)		
			Top	Mid.	Tip	Ave.1	Top	Bot.	Ave.2
Geo 14 M	1	Right	10.5	12.4	7.6	10.17	20.1	18.5	19.30
		Left	11.9	13.2	7.3	10.80	21.0	18.4	19.70
	2	Right	9.0	10.9	6.7	8.87	18.5	17.7	18.10
		Left	9.5	11.7	6.4	9.20	18.7	15.2	16.95
	3	Right	8.8	10.0	7.5	8.77	13.2	20.0	16.60
		Left	8.1	10.5	7.2	8.60	13.5	19.8	16.65
					Ave	9.40			17.88
Geo 10 M	1	Right	20.0	19.3	21.4	20.23	50.0	48.7	49.35
		Left	20.1	19.2	21.5	20.27	50.1	48.6	49.35
	2	Right	22.1	23.3	23.5	22.97	48.9	50.0	49.45
		Left	22.3	23.4	23.5	23.07	49.1	49.8	49.45
	3	Right	21.0	20.4	21.2	20.87	49.8	49.8	49.80
		Left	21.0	20.3	21.1	20.80	49.7	49.6	49.65
					Ave.	21.37			49.51
OPC	1	Right	1.2	2.1	1.6	1.63	3.5	5.3	4.40
		Left	0.4	2.5	2.4	1.77	3.3	4.9	4.10
	2	Right	1.2	1.4	2.2	1.60	3.6	3.7	3.65
		Left	1.8	2.5	2.1	2.13	3.7	3.8	3.75
	3	Right	2.3	1.5	1.8	1.87	4.2	7.8	6.00
		Left	3.5	2.5	3.1	3.03	5.2	6.7	5.95
					Ave.	2.01			4.64

Appendix Table A35 Result of Chloride depth after 45 days

Specimens			Depth horizontal(mm.)				Depth Vertical(mm.)		
			Top	Mid.	Tip	Ave.1	Top	Bot.	Ave.2
Geo 14 M	1	Right	13.2	15.0	11.4	13.20	16.0	30.4	23.20
		Left	13.0	15.0	11.3	13.10	5.7	31.0	23.35
	2	Right	10.5	12.8	13.3	12.20	14.0	10.2	12.10
		Left	10.4	12.6	13.5	12.17	13.8	10.0	11.90
	3	Right	10.3	13.6	12.2	12.03	12.5	14.5	13.50
		Left	10.2	13.7	12.5	12.13	12.4	14.7	13.55
					Ave.	12.47			16.27
Geo 10 M	1	Right	50.1	50.0	49.5	49.87	98.4	99.0	98.70
		Left	50.0	50.1	49.7	49.93	98.5	99.2	98.85
	2	Right	49.5	50.2	49.8	49.83	100.3	98.0	99.15
		Left	49.2	50.3	49.7	49.73	100.2	98.3	99.25
	3	Right	48.5	49.6	50.0	49.37	100.1	98.6	99.35
		Left	48.4	49.7	50.0	49.37	100.0	98.5	99.25
					Ave.	49.68			99.09
OPC	1	Right	9.10	9.80	4.0	7.63	4.8	4.2	4.50
		Left	9.00	9.90	4.3	7.73	4.7	4.1	4.40
	2	Right	8.50	9.70	7.5	8.57	5.8	4.5	5.15
		Left	8.40	9.60	7.7	8.57	5.6	4.4	5.00
	3	Right	9.40	8.00	6.0	7.80	10.1	4.2	7.15
		Left	9.00	7.30	5.3	7.20	4.7	4.1	4.40
					Ave.	11.88			7.65

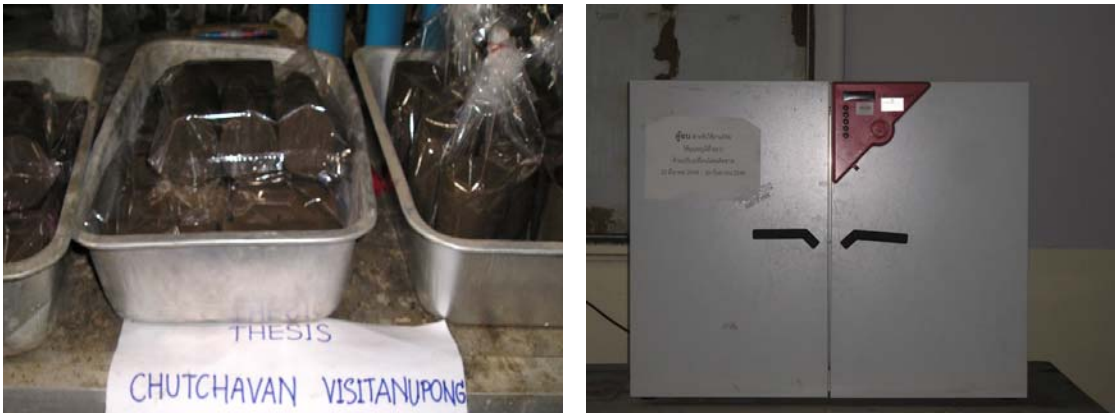
Appendix B

Materials and Equipment



Appendix Figure B1 Materials for experiment

Appendix Figure B2 Casts of mould 50x50 mm cube and Ø50x100 mm cylinder



Appendix Figure B3 Prepared specimens before curing and Curing Machine

Appendix Figure B4 Solutions for acid and sulfate attack test

Appendix Figure B5 Acid and sulfate attack test

Appendix Figure B6 Compression strength machine

Appendix Figure B7 SEM-EDS machine

Appendix Figure B8 Rapid chloride penetration test

Appendix Figure B9 Carbonation test

Appendix Figure B10 Carbonation test

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