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NAME: Mr. Jirabute Kuntreerattanarom

THIS THESIS HAS BEEN ACCEPTED BY

THESIS ADVISOR

(Associate Professor Prasert Suwanvitaya, Ph.D.)

THESIS CO-ADVISOR

(Associate Professor Trakool Armraks, Ph.D.)

DEPARTMENT HEAD

(Associate Professor Korchoke Chantawarangul, Ph.D.)

APPROVED BY THE GRADUATE SCHOOL ON

DEAN

(Associate Professor Gunjana Theeragool, D.Agr.)

THESIS

THE INFLUENCE OF SODIUM HYDROXIDE MOLARITY AND LEACHING TIME ON THE PROPERTIES OF FLY ASH-BASED GEOPOLYMER

JIRABUTE KUNTREERATTANAROM

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The purpose of this study was to determine the influence of sodium hydroxide molarity and leaching time on the properties of fly ash-based geopolymer. In this experiment, class C and class F fly ash in accordance with ASTM C618 were used. Fly ash samples were dissolved in sodium hydroxide solution. The mix was left standing for a pre-specified period, after which a sample was taken from the solution to determine the amount of silica, alumina and calcium ions leached out. Sodium silicate was then added and the solution thoroughly mixed together. Samples from the mixtures were then taken for determination of setting times and compressive strength. Broken pieces were collected for X-ray diffraction and Mercury Intrusion Porosimetry examination.

From the experimental results, the amounts of dissolved silica, alumina and calcium from fly ash depended on leaching time and molarity of NaOH. Maximum leachates were obtained at 20 minutes. Higher concentration of NaOH extracted more silica and alumina but less calcium. The concentrations of dissolved calcium ions from class C fly ash were higher than class F fly ash at all leaching times. Examination of Si/Al ratio showed the increase in the ratio increased the compressive strength of the matrix. The pore size and porosity of both classes of fly ash increased as the leaching time increased, resulting in the decrease in strength. From XRD analysis, the relative intensity of peaks in class C fly ash were higher than class F fly ash, suggesting that more dissolution from class C fly ash than class F had a significant effect to the peak of relative intensity which was compatible with compressive strength results.

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Jirabute Kuntreerattanarom

September 2011

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LIST OF ABBREVIATIONS

Al	=	Aluminium
ASTM	=	American Standard Testing Method
Ca	=	Calcium
FA	=	Fly ash
KOH	=	Potassium hydroxide
ksc	=	Kilogram per square centimeter
MIP	=	Mercury Intrusion Porosimetry
NaOH	=	Sodium hydroxide
ppm	=	Part per million
SEM	=	American Standard Testing Method
Si	=	Silicon
Sol	=	Solution
XRD	=	X-Ray Diffractometer
XRF	=	X-Ray Fluorescence

THE INFLUENCE OF SODIUM HYDROXIDE MOLARITY AND LEACHING TIME ON THE PROPERTIES OF FLY ASH-BASED GEOPOLYMER

INTRODUCTION

Ordinary Portland cement is still the most commonly used binder for construction materials. Unfortunately, the production of Portland cement releases large amounts of the green house CO_2 into the atmosphere causing global warming. Portland cement production is estimated to contribute around 7% of global CO_2 emissions. To reduce greenhouse gas emissions, efforts have been made to promote the use of pozzolans to partially replace Portland cement. Recently, another class of cementitous material, produced from an alumino-silicate precursor activated in a high alkali solution, has been developed. This cementitious material is termed as geopolymer. To synthesize this material, waste products such as fly ash, metakaolin and blast furnace slag were also used.

Polymerization process of fly ash–based geopolymer involves a chemical reaction of alumino-silicate oxides (Si_2O_5, Al_2O_2) with alkali polysilicates and yields polymeric Si – O – Al bonds. Polysilicates are generally 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. Therefore, geopolymers are sometimes referred to as alkali activated alumino silicate binders. Chemical composition of geopolymers material is similar to natural zeolites materials, but its microstructure is amorphous.

Two main constituents of geopolymers are powder materials and alkaline liquids. Powder materials for geopolymers based on alumino-silicate should be rich in silicon (Si) and aluminium (Al). These could be natural minerals such as kaolinite, clays, micas, andalousite which contains Si, Al, and oxygen. Alternatively, by product materials such as fly ash, silica fume, slag, rice-husk ash, red mud could be used as source materials. The choice of powder materials for making geopolymers depends on factors such as availability, cost, and type of application and specific demand of end users. Alkaline liquids are from soluble alkali metals that are usually sodium or potassium based. The most common alkaline liquids used in geopolymerisation are combination of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate or potassium silicate.

Particle size, calcium content, alkali metal content, amorphous content, morphology and origin of fly ash affect the properties of geopolymers. Calcium content in fly ash plays a significant role in strength development. Its content in fly ash in significant quantities could interfere with polymerization setting rate and alter the microstructure. It appears that the use of low calcium (ASTM Class F) fly ash is preferable to high calcium (ASTM Class C) fly ash as a source material to make geopolymer.

OBJECTIVES

The main objectives of this research were, through experimental studies, to establish the following.

1. To study the effect of leaching time on the dissolution of ions from fly ash.

2. To study the effect of proportions and molarities of sodium hydroxide on dissolution ions.

3. To study the effect of dissolution ions on mechanical and microstructural properties of geopolymer.

Scope of Research

The study consists of laboratory tests on fly ash-based geopolymer which using class C and class F fly ash as starting material;

1. Dissolved ions: to determine the concentrations of dissolved silica alumina and calcium ions from fly ash by using sodium hydroxide as alkali activator at different leaching times.

2. Engineering properties: to determine the compressive strength and setting time of geopolymer paste using sodium hydroxide solution, sodium silicate solution and fly ash with various proportions, molarities and different classes of fly ash.

3. Microstructure: X-Ray diffraction (XRD) and Mercury Intrusion Porosimetry (MIP) analyses were performed on the fly ash-based geopolymer.

LITERATURE REVIEW

1. Concrete and Environment

The trading of carbon dioxide (CO_2) emissions is a critical factor for the industries including the cement industries, as the greenhouse effect created by the emissions is considered to produce an increase in the global temperature that may result in climate change.

Climate change is attributed to global warming, but also to the paradoxical global dimming due to the pollution in the atmosphere. Global dimming is associated with the reduction of the amount of sunlight reaching the earth due to pollution, particles in the air blocking the sunlight. With an effort to reduce air pollution that has been implemented, the effect of global dimming may be reduced, however it will increase the effect of global warming (Fortune, 2005). In this view, the global warming phenomenon should be considered more seriously, and any action to reduce the effect should be given more attention and effort.

The production of cement is increasing about 3% annually (McCaffrey, 2002). The production of one ton of cement liberates about one ton of CO_2 to the atmosphere, as the result of de-carbonation of the limestone in the kiln during manufacturing of cement and the combustion of fossil fuels (Roy, 1999)

The contribution of Portland cement production worldwide to the green house gas emission is estimated to be about 1.35 billion tons annually or about 7% of the total greenhouse gas emissions to the earth’s atmosphere. Cement is also among the most energy-intensive construction materials, after aluminium and steel. Furthermore, it has been reported that the durability of ordinary Portland cement (OPC) concrete is under examination, as many concrete structures, especially those built in corrosive environments, start to deteriorate after 20 to 30 years, even though they have been designed for more than 50 years of service life.

The concrete industry has recognized these issues. For example, the U.S. Concrete Industry has developed plans to address these issues in “Vision 2030: A Vision for the U.S. Concrete Industry”. The document states that concrete technologists are faced with the challenge of leading future development in a way that protects environmental quality while projecting concrete as a construction material of choice. Public concern will be responsibly addressed regarding climate change resulting from the increased concentration of global warming gases. In this document, strategies to retain concrete as a construction material of choice for infrastructure development, and at the same time to make it an environmentally friendly material for the future have been outlined.

In order to produce environmentally friendly concrete, many authors suggested the use of fewer natural resources, less energy, and minimizing carbon dioxide emissions. They categorized these short-term efforts as “industrial ecology”. The long term goal of reducing the impact of unwanted by-products of industry can be attained by lowering the rate of material consumption. Likewise, McCaffrey (2002) suggested three alternatives to reduce the amount of carbon dioxide (CO_2) emission by the cement industries, i.e. to decrease the amount of calcined material in cement, to decrease the amount of cement in concrete, and to decrease the number of buildings using cement.

2. Fly Ash

According to the American Concrete Institute (ACI) Committee 116R, fly ash is defined as “the finely divided residue that results from the combustion of ground or powered coal and that is transported by flue gases from the combustion zone to the particle removal system” (ACI Committee 232, 2004). Fly ash is removed from the combustion gases by the dust collection system, either mechanically or by using electrostatic precipitators, before they are discharged to the atmosphere. Fly ash particles are typically spherical, finer than Portland cement and lime, ranging in diameter from less than 1μm to no more than 150 μm.

The type and relative amounts of incombustible matter in the coal determine the chemical composition of fly ash. The chemical composition is mainly composed of the oxides of silicon (SiO_2), aluminium (Al_2O_3), iron (Fe_2O_3), and calcium (CaO), whereas magnesium, potassium, sodium, titanium, and sulphur are also present in a lesser amount. The combustion of sub-bituminous coal contains more calcium and less iron than fly ash from bituminous coal. The physical and chemical characteristics depend on the combustion methods, coal source and particle shape. The chemical compositions of various fly ashes show a wide range, indicating that there is a wide variations in the coal used in power plants all over the world (Malhotra and Ramezanianpour, 1994).

Fly ash that results from burning sub-bituminous coals is referred as ASTM Class C fly ash or high calcium fly ash, as it typically contains more than 20 percent of CaO. On the other hand, fly ash from the bituminous and anthracite coals is referred as ASTM Class F fly ash or low calcium fly ash. It consists of mainly an alumino-silicate glass, and has less than 10 percent of CaO. The colour of fly ash can be tan to dark grey, depending upon the chemical and mineral constituents (Malhotra and Ramezanianpour, 1994; America Coal Ash Association, 2003). The majority of Thailand fly ash falls in the category of ASTM Class C fly ash.

Aside from the chemical composition, the other characteristics of fly ash that are generally considered are loss on ignition (LOI), fineness and uniformity. LOI is a measurement of unburnt carbon remaining in the ash. Fineness of fly ash mostly depends on the operating conditions of coal crushers and the grinding process of the coal itself. Finer gradation generally results in a more reactive ash and contains less carbon.

In 2001, the annual production of fly ash in the USA was about 68 million tons. Only 32 percent of this was used in various applications, such as in concrete, structural fills, waste stabilization/solidification etc. (ACAA, 2003). Worldwide, the estimated annual production of coal ash in 1998 was more than 390 million tons. The main contributors for this amount were China and India. Only about 14 percent of this fly ash was utilized while the rest was disposed in landfills (Malhotra, 1999). By the year 2012, the amount of fly ash produced worldwide is estimated to be about 780 million tons annually (Malhotra, 2002b). The utilization of fly ash, especially in concrete production, has significant environmental benefits, viz, improved concrete durability, reduced use of energy, diminished greenhouse gas production, reduced amount of fly ash that must be disposed in landfills, and saving of the other natural resources and materials (ACAA, 2003).

3. Geopolymers

3.1 The structure of geopolymers

In 1979, Davidovits used the term "Geopolymer" for the first time to describe the inorganic polymer binders resulting from geochemical processes (Davidovits, 1999a). Geopolymerisation involves a chemical reaction in which Si-O-Al-O bonds are formed as a result of the reaction between an alkaline and a source of Alumina-Silicate oxides. Geopolymer compositions are similar to natural Zeolite; however, their structures are amorphous to semi-crystalline. This is due to the faster reaction time of geopolymers compared with Zeolites that yield crystalline structures.

The geopolymers like other polymers, undergo transformation and polycondensation and tale shape at low temperatures; but they are also "geopolymers"; thus they are mineral materials which are hard, weather resistant and can stand high temperature (Davidovits, 1988).

The polymerization process can be indicated by the following formula (Davidovits, 1999a):

$$M_n(-(SiO_2)z\text{-}AlO_2,wH_2O$$

Where, "z" is 1, 2 or 3; M is a cation such as potassium or sodium and "n" is a degree of polycondensation.

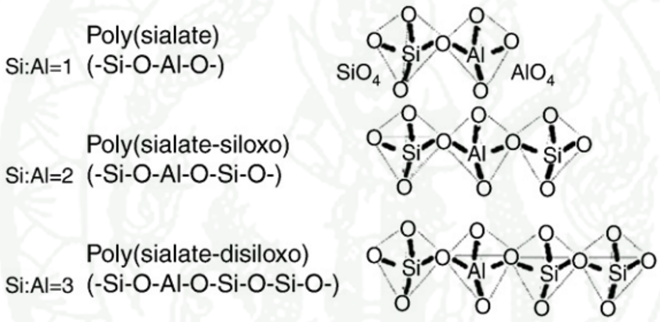
Regarding the Si:Al ratio, geopolymers structures may consist of three of the following forms:

[-Si-O-Al-O-] bonds or Poly (sialate)

[-Si-O-Al-O-Si-O-] bonds or Poly (sialate-siloxo)

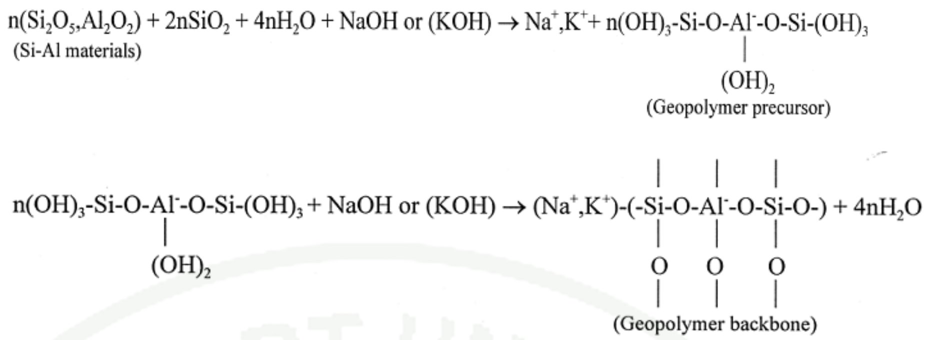
[-Si-O-Al-O-Si-O-Si-O-] bonds or Poly (sialate-disiloxo)

Or schematically,



Sialate is an abbreviation for silicon-oxo-aluminate. The sialate networks consist of SiO_4 and AlO_4 linked alternately by sharing oxygen. Positive ions such as Na^+ or K^+ must be present in the framework to balance the negative charge of Al^{3+} in IV-fold coordination,

The main steps involved in the formation of geopolymers include the following two equations (Davidovits, 1999a; Van Jaarsveld *et al*., 1997):



Although the exact process of geopolymerisation is not completely understood, it was proposed that the process includes dissolution, transportation or orientation, as well as a re-precipitation (polycondensation) (Davidovits, 1988).

3.2 Dissolution process

An alkali metal or hydroxide is required for the dissolution of various components. Alumina and silica dissolved in high amount because they were the main components in source materials. With increased dissolution, a part of the material will be destroyed at the surface and produce surface pores that facilitate easy reaction of the liquid. The type and concentration of alkali solution affect the dissolution of fly ash. Leaching of silica and alumina ions are generally high with sodium hydroxide solution compared to potassium hydroxide solution (Van Jaarsveld and Van Deventer, 1999; Xu and Van Deventer, 1999). Therefore, alkali concentration is a significant factor in controlling the leaching of silica and alumina from fly ash particles, subsequent geopolymerisation and mechanical properties of hardened geopolymer. The coordination of alumina in the source material has an effect on the bonding strength of the matrix.

Researchers studied the leaching time which is a mixing period between alkali solution and source material for dissolving ions of silica and alumina by mixing fly ash with NaOH solution for different time intervals. The amount of leaching was dependent on NaOH concentration and leaching time (Rattanasak and Chindaprasirt, 2009). The leaching time has different effect on compressive strength and setting time, depending on type of fly ash (Nawittayanan and Suwanvitaya, 2009).

3.3 Source material

Researchers have used different source material for developing geopolymer binders. These include natural minerals such as kaolinite, albite, feldspar and stibnite; treated minerals such as metakaolin; and by-products such as blast furnace slag and fly ash. Theoretically, any source of amorphous silica and aluminum could be used to manufacture geopolymer binders (Hardjito and Rangan, 2005). Davidovits (1999a) used metakaolin as a source of silica and aluminum to produce geopolymer pastes. Metakaolin is obtained by calcining kaolin clay at 750°C for 6 hours. Other researchers have also used Metakaolin (Barbosa and MacKenzie 2003; Duxson *et al.*, 2007a; Fernandez-Jimenez *et al.,* 2008). Xu and Van Deventer (2000) examined 15 natural Si-Al minerals to study the effect of mineral properties on the compressive strength of the synthesized geopolymer.

The use of a combination of two source material was also reported such as ground granulated blast-furnace slag and fly ash (Sofi *et al*., 2007), kaolonite and stilbite (Xu & Van Deventer, 2002b), Class C fly ash and granulated blast furnace slag (Goretta *et al*., 2004), Metakaolin and class F fly ash (Fernandez-Jimenez *et al.,* 2008) and metakaolin and calcium hydroxide (Alonso and Palomo, 2001).

The use of fly ash in geopolymer concrete has been looked at as a promising development in recent years and has been studied by numerous researchers as the sole source of silica-aluminum. Fly ash is as by-product which is generated by the combustion of coal and needs no more process in a laboratory, whereas, for the production of metakaolin, the kaolin clay must be heated up to 700-800 °C, a highly energy consuming process. According to Duxon *et al.* (2007b):

The use of metakaolin in geopolymers would also increase the CO_2 emissions per tonne of product; however, the high cost of metakaolin and the high water demand of metakaolin geopolymers mean that this is not considered a workable possibility for large-scale geopolymer production in construction applications.

Thus, the utilization of fly ash, as a raw material in the synthesis of geopolymeric materials, has been the subject of numerous studies. Van Jaasvaeld *et al*. (2003) used six types of fly ashes from different sources to investigate the characterization of source materials in fly ash-based geopolymers. Alvarez-Ayuso *et al.* (n.d.) utilized four types of fly ash, derived from structural characteristics of geopolymer matrice. Fernandez-Jimenez *et al*. (2008) used metakaolin and fly ash to examine the variation in mineralogical and microstructural characteristics of the alkaline inorganic polymers obtained by alkaline activation, Using three source materials, Xu and Van Deventer (2002a) concluded that substantial reduction in reaction time may be achieved along with a significant improvement in compressive strength when a calcined source material, such as fly ash, is added to the geopolymerisation of non-calcined materials such as kaolinite and albite.

3.4 Alkaline Liquids

It has been shown that alkali materials must be present to react with alumina and silica in source materials to form geopolymeric gel. Different alkali liquids have been used by researchers to investigate the effect of alkali material on formation, strength and durability of geopolymers. Davidovits (1999a) used sodium hydroxide solution to react with kaolinite. Duxson *et al*. (2007a) studied the effect of alkali type on the development of mechanical properties of geopolymer. In their work, they used sodium and potassium hydroxide, and sodium silicate to activate metakaolin. The use of sodium hydroxide and potassium hydroxide has been reported by many researchers. Barbosa and MacKenzie (2003) reported the use of potassium hydroxide and metakaolin as the starting material to study the thermal stability of geopolymers. Testing 16 natural Si-Al minerals, Xu and Van Deventer (2000) concluded that the rate of dissolution of minerals is higher in NaOH than KOH. Other researchers used a mixture of sodium silicate and sodium hydroxide to activate a combination of fly ash with metakaolin (Fernandez-Jimenez *et al.*, 2008) or kaolinite (Swanepoel and Strydom, 2002).

3.5 Properties of geopolymer

3.5.1 Acid resistance

Compared to Portland cement binders, geopolymers are much more resistant when exposed to acid environments. Portland cement binders rely on lime and thus, are susceptible to deterioration caused by acid environments (Davidovits, 2002).

3.5.2 Compressive strength

It has been shown that geopolymer concrete can be made employing the similar methods used for making conventional concrete (Hardjito and Rangan 2005a).

3.5.3 Alkali-aggregate reaction

Under specific circumstances, alkalis present in ordinary Portland cement can react with certain forms of reactive silica in aggregates and cause deleterious alkali-aggregate reaction. Alkali-aggregate reaction results in expansion which can damage the concrete structures. As a consequence, the tendency has been to avoid using susceptible aggregate or high alkali cements in concrete. It is now known that using fly ash as a partial replacement for ordinary Portland cement can control the expansion caused by alkali-aggregate reaction. The effect of fly ash in preventing the expansion can be attributed to a number of factors, like the reduced alkalinity in pore solution of concrete or the lower calcium content in the system.

Although reaction can also take place in geopolymer matrix, the proneness of geopolymer concrete to deterioration caused by alkali-aggregate reaction is notably less (Garcia-Lodeiro *et al.,* 2007). Other researchers have also studied the alkali-aggregate reaction in alkali-activated granulated slag and reported the slower rate of expansion in comparison with Ordinary Portland Cement (OPC) mortars (Fernandez-Jimenez and Puertas, 2002).

3.5.4 Toxic waste management

The contaminant migration derived from toxic waste materials can be inhibited by physical and geochemical barriers. The durability of the matrix is a key feature in determining the suitability of the barrier. Geopolymers have been shown to possess great potential to immobilize toxic wastes as well as to convert the semi-solid wastes to adhesive solid materials (Davidovits, 1988). Furthermore, geopolymers, as durable compounds, encapsulate solidified waste and prevent the leaching of hazardous material into the environment.

3.5.5 Geopolymeric cements and concretes

Aside from the promising environmental benefits that geopolymer binders present, the good mechanical and durability features of gropolymer cements and concretes make them interesting construction materials. Geopolymer concrete mixtures with 7^{th} day compressive strength over 70 MPA can be made employing the conventional method used for the production of ordinary concrete. Regarding durability features, geopolymer concrete exhibits low drying shrinkage and shows good resistance to acid and sulfate environments (Hardjito and Rangan 2005).

3.5.6 Fire-proof geopolymeric cements

The resistance of concrete members to high temperature has been investigated for decades. It is always desirable to have fire-proof structural members that can withstand heat for a long time hence allowing residents the chance to escape.

While conventional concrete may explode above 300 °C, geopolymer cements can be fire-resistant up to 1200 °C (Davidovits, 1999b).

MATERIALS AND METHODS

Materials

1. Fly ash
   - Class C fly ash from Mae Moh power station in Lampang province
   - Class F fly ash from BLCP power station in Rayong province
2. Laboratory grade Sodium Hydroxide in pellet form (98 percent purity)
3. Sodium Silicate solution (14.5% Na_2O, 30% SiO_2 and 55.5% water)
4. Sulfuric Acid
5. Distilled water
6. X-ray fluorescence spectrometer (XRF)
7. Atomic Absorption Spectrophotometer (AAS)
8. Compressive strength testing machine
9. X-ray diffractometer (XRD)
10. Mercury Intrusion Poremaster (MIP)
11. Vicat apparatus
12. Vacuum filtration set (including vacuum pump and filter holder)
13. Membrane filter size 0.45µm
14. PH indicator
15. Digital scale
16. Vernier caliper
17. Mold cylinders 1.5x3.0 inches
18. Computer

Figure 1 Mold cylinders 1.5x3.0 inches.

Figure 2 Filter holder and vacuum pump.

Methods

1. Chemical preparation for testing

1.1 The X-Ray fluorescence (XRF) revealed the composition of fly ash used during the study. The data are presented in table 1.

1.2 A sodium hydroxide solution was prepared by dissolving sodium hydroxide pellets in water. The degree of purity of the pellets was 98% and was taken into account to modify the quantities. Distilled water was used to dissolve the pellets to avoid affecting the solution by tap water contamination. Four molar and 8 molar solutions were prepared as shown in table 2.

1.3 A sodium silicate solution was used with the following composition: 14.5% Na_2O, 30.0% SiO_2 and 55.5% water. Sodium silicate was kept as solution in drums and pumped when needed during the study.

Table 1 Results of the chemical analysis of fly ash by X-Ray Florescence spectrometer.

Chemical compositions of fly ash	Class C fly ash %	Class F fly ash %
SiO_2	25.64	59.83
Al_2O_3	11.30	18.09
Fe_2O_3	17.22	7.55
CaO	33.46	4.49
MgO	1.98	1.17
Na_2O	1.09	0.56
K_2O	2.62	1.57

Table 2 Proportional of NaOH solution.

NaOH molarity (M)	98% purity (g/L)	100% purity (g/L)
4	160	163.20
8	320	326.40

2. Dissolution procedure

2.1 All samples were prepared for dissolution process using NaOH : FA ratio of 0.50 and 0.33 by weight.

2.2 NaOH solution and fly ash were placed into the mixer and mixed, using the leaching times of 5, 20, 40, 60 and 90 minutes.

2.3 At the expiry of the leaching time, the prepared mix was vacuum filtered through a 45 µm membrane.

2.4 The filtrate samples were neutralized for quantitative analyses by adding sulfuric acid until the pH was below 5.

2.5 The acid samples were analyzed to determine quantities of dissolved ions by Atomic Absorption Spectrophotometer (AAS).

Figure 3 Filter holder containing paste specimen.

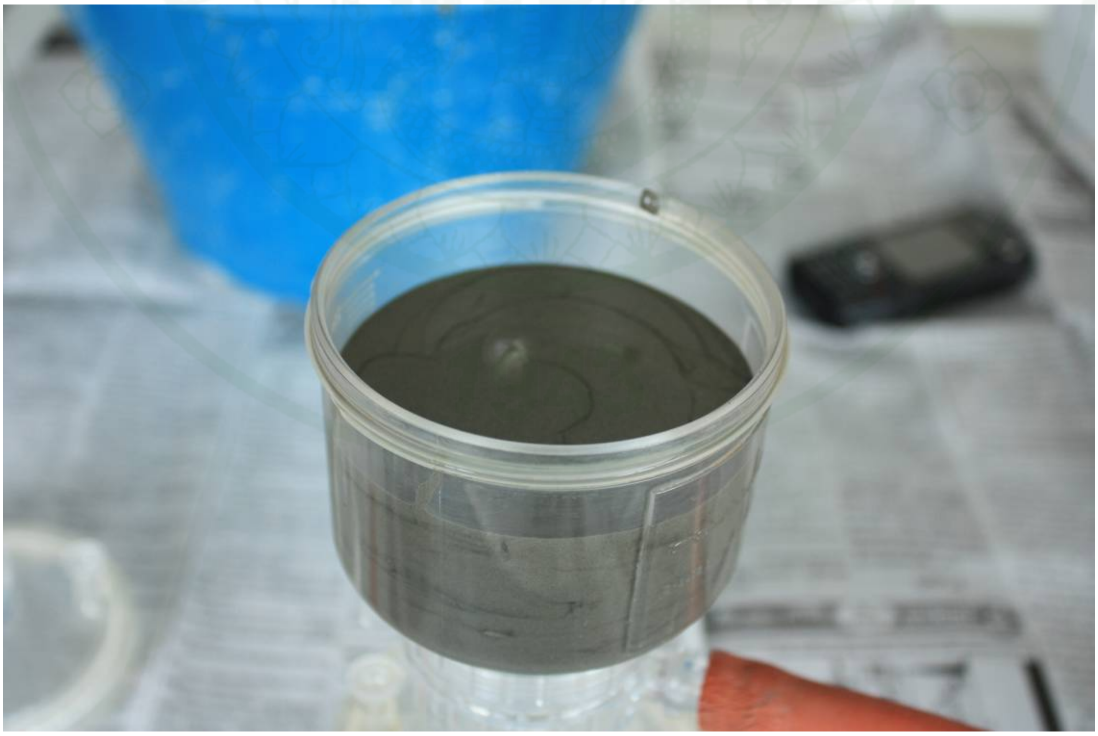


Figure 4 Paste specimen before vacuum.

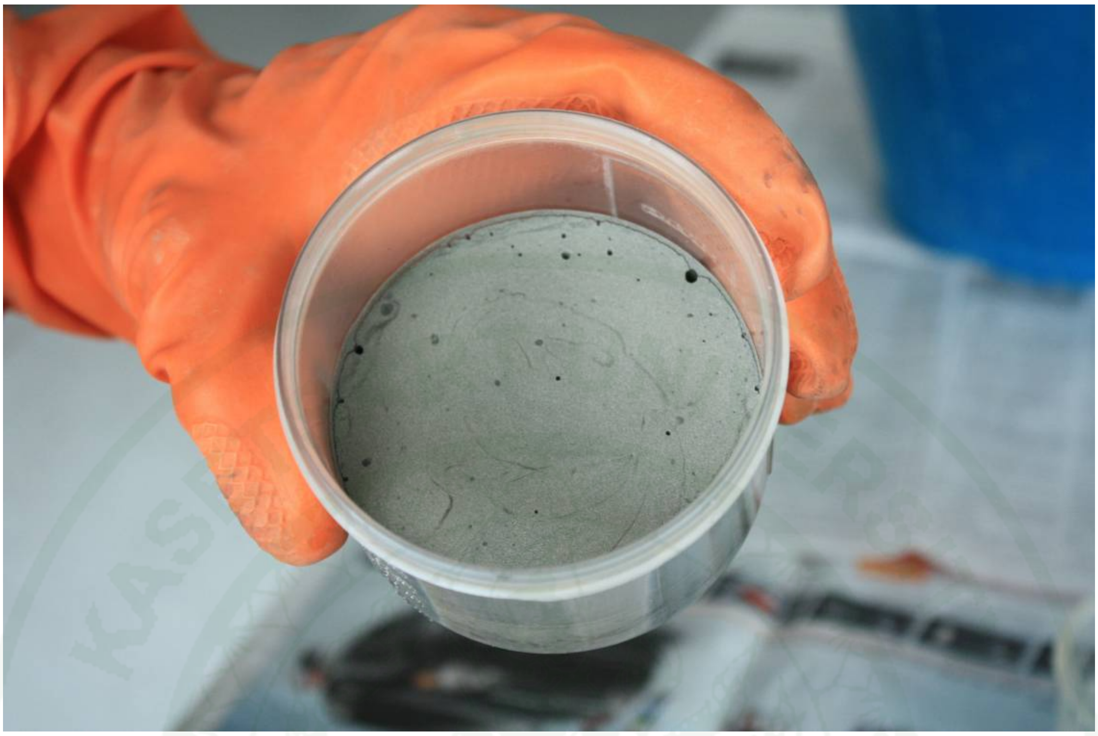


Figure 5 Paste specimen after vacuum.

Figure 6 Filtrate sample**.**

3. Geopolymer mixing procedure

3.1 The solution of sodium hydroxide and fly ash was mixed by varying the NaOH : FA ratios and leaching times as in 2.1 to 2.2.

3.2 The sodium silicate solution was added as a weight percent of sodium hydroxide solution into the paste from 3.1 for 5 minutes to produce a geopolymer paste.

3.3 Paste specimens were cast into 3x1.5 inches cylinder molds and cured at room temperature in zipped lock bag to prevent the moisture loss.

4. Engineering properties test

4.1 Setting time of geopolymer paste was tested in accordance with ASTM C 191.

4.2 Compressive strength tests were determined using a Versa Tester machine. The specimens were tested at various ages (3, 7, 14 and 28 days). Specimens were cylindrical, 1.5 inches in diameter and 3 inches high to maintain a 2:1 aspect ratio, which fulfils the standard requirement for compression test ASTM C773. Sample surfaces were polished flat and parallel to avoid the requirement for capping. All values presented in the current work were an average of three samples.

5. Microstructural characterization

A mineralogical analysis was conducted by X-ray diffraction (Shimadzu model XRD 6000). The setting conditions for the XRD were as follows: Cu Kα radiation, 40 kV accelerating voltage, 30 mA current, 2-80° 2θ scanning range, 0.02° step and holding time of 0.6 sec for each step. Pore structure (total porosity and average pore diameter) was studied with a Mercury Porosimetry Analyzer model: PoreMaster at a contact angle of 140° and surface tension of 480 erg/cm^2.

RESULTS AND DISCUSSION

1. Dissolved ions

The concentrations of the dissolved ions of class C fly ash activated with NaOH solution at various leaching times are shown in figure 7. The silica contents rapidly increased from 5 minutes and reached maximum at 20 minutes. Alumina and calcium ions followed the same trend. After 20 minutes all three ions rapidly decreased until each attained a constant concentration.

Figure 8 presented the dissolution trends of silica, alumina and calcium prepared by class F fly ash.in much the same fashion that was observed in the case of class C fly ash. The highest concentrations of the dissolved ions occurred at 20 minutes and rapidly decreased later to their respective constant concentrations.

It was also found that the dissolved silica were higher than alumina and calcium at each leaching time. This could be caused partly by the higher percentage of silica composition than others in the fly ash (see table 1). Therefore the dissolution of alumina ion is always lower than the dissolution of silica ion. The equilibrium concentrations of silica, alumina and calcium are not proportional to their oxide percentage in the starting material. For example, the highest percentage of composition oxide was calcium (33.46% CaO) for class C fly ash, but the amount of dissolved calcium was lower than silica (25.64% SiO_2) as shown in table 3.

Table 3 The chemical composition and leaching results of fly ash dissolved by 4M NaOH at leaching time of 5, 20 and 90 minutes.

Fly ash class	Leaching time	Chemical composition of fly ash			Dissolved ions		
	(min.)	SiO_2 %	Al_2O_3 %	CaO %	Silica (ppm)	Alumina (ppm)	Calcium (ppm)
C	5	25.64	11.30	33.46	390.00	14.59	120.97
	20				465.00	17.76	207.90
	90				196.13	11.12	79.60
F	5	59.83	18.09	4.49	273.60	91.04	19.90
	20				496.80	133.39	17.56
	90				1150.80	472.18	11.59

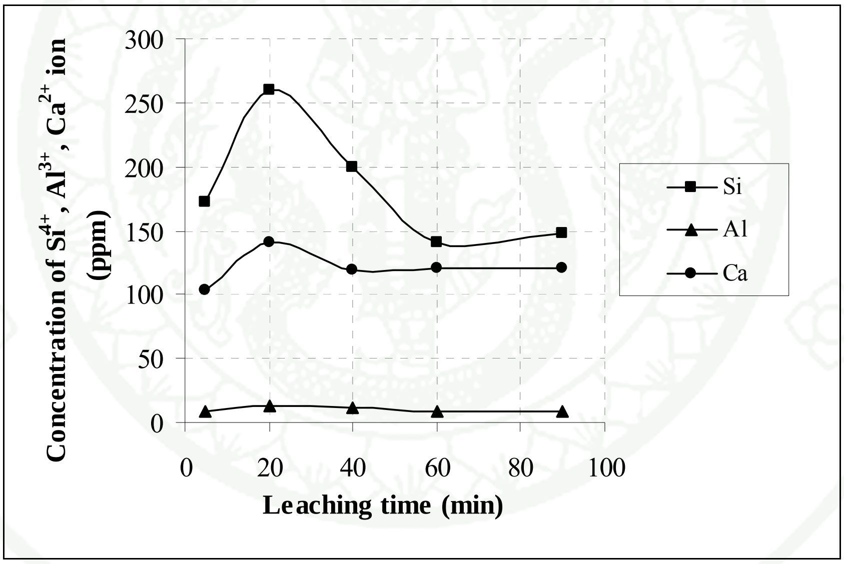


Figure 7 Concentrations of dissolved Si, Al and Ca from class C fly ash at different leaching times.

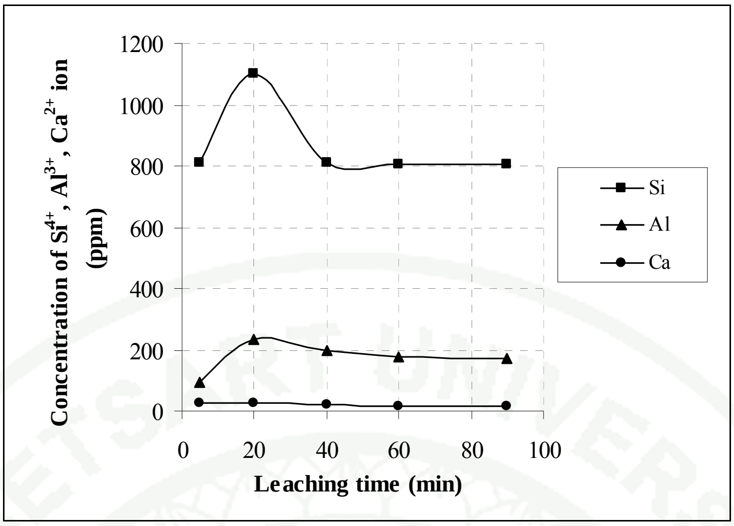


Figure 8 Concentrations of dissolved Si, Al and Ca from class F fly ash at different leaching times.

Figure 9 shows the Si/Al ratio at different leaching times. The highest Si/Al ratio of class C fly ash and class F fly ash peaked to 21.6 and 9.0 at leaching time of 5 minutes, respectively. As leaching time increased, the ratio decreased steadily until no change was observed at 60 and 90 minutes. The result of class C fly ash showed higher Si/Al ratio compared with class F fly ash at all leaching times.

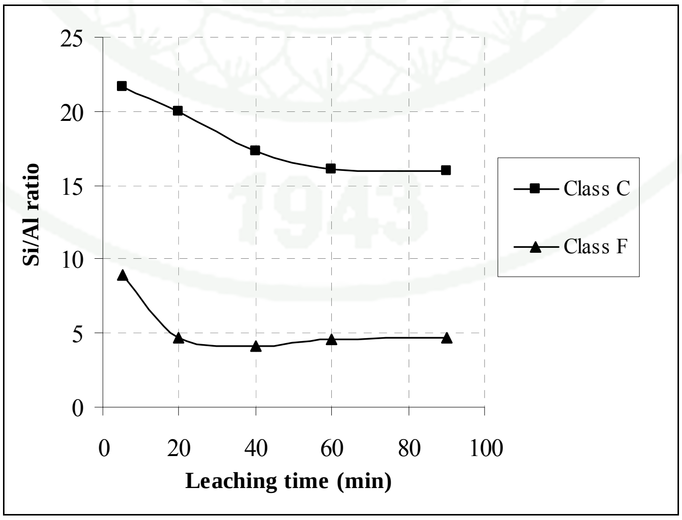


Figure 9 Si/Al ratio from class C fly ash and class F fly ash at different leaching times.

Figure 10, 11 and 12 show the effect of NaOH:FA ratios on the dissolution of silica, alumina and calcium at different dissolution periods. As expected, 0.50 NaOH:FA ratio showed higher dissolution capacity than 0.33 NaOH:FA ratio. The more leachant, the greater the leachate.

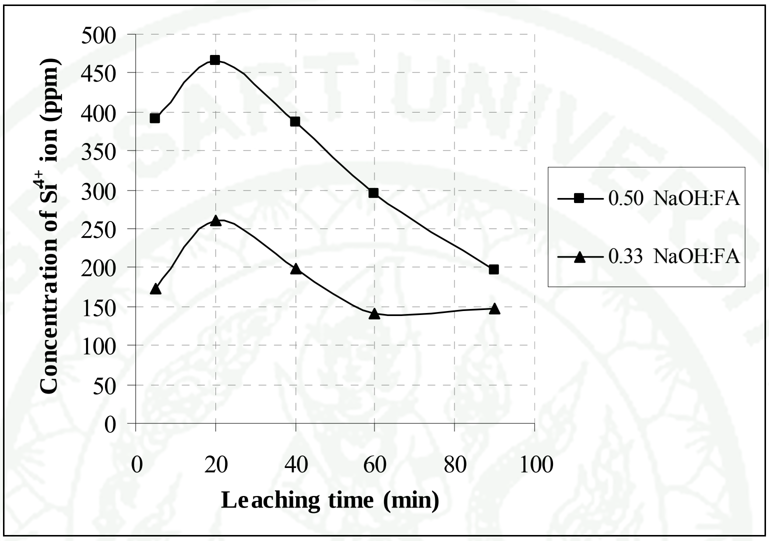


Figure 10 Concentrations of dissolved Si from class C fly ash at different leaching times.

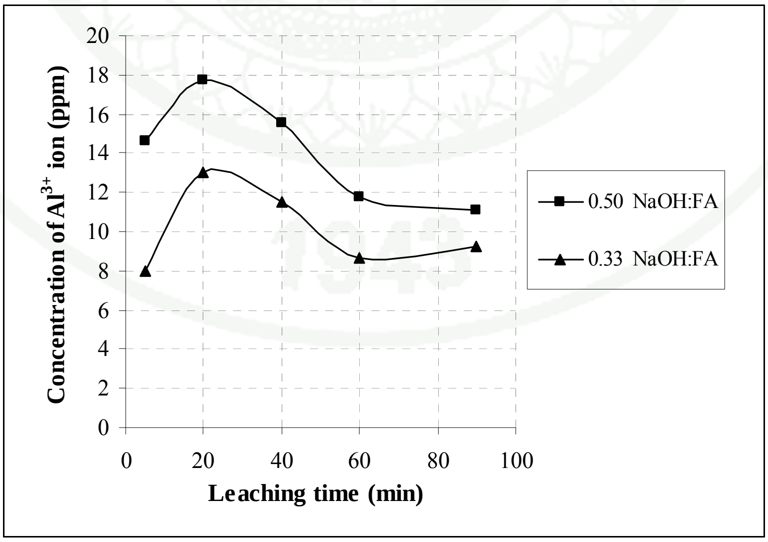


Figure 11 Concentrations of dissolved Al from class C fly ash at different leaching times.

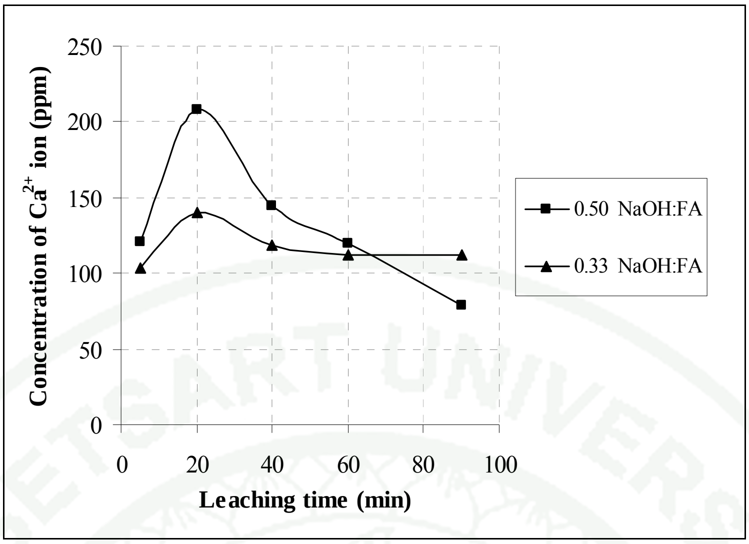


Figure 12 Concentrations of dissolved Ca from class C fly ash at different leaching times.

The effects of NaOH molarity on the dissolutions of ions are shown in figures 13, 14 and 15. It can be seen that the solution with higher molarity extracted more silica and alumina but less calcium from fly ash. This result conformed to previous research of Rattanasak and Chindaprasirt (2009).

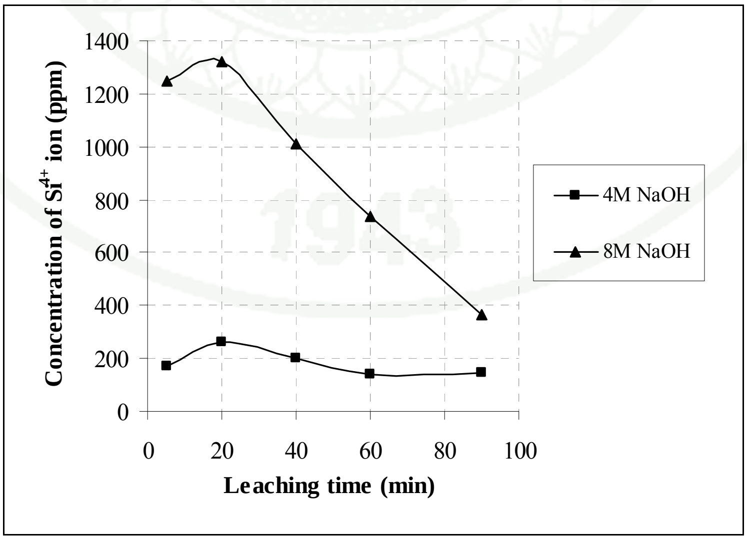


Figure 13 Concentrations of dissolved Si from class C fly ash at different leaching times.

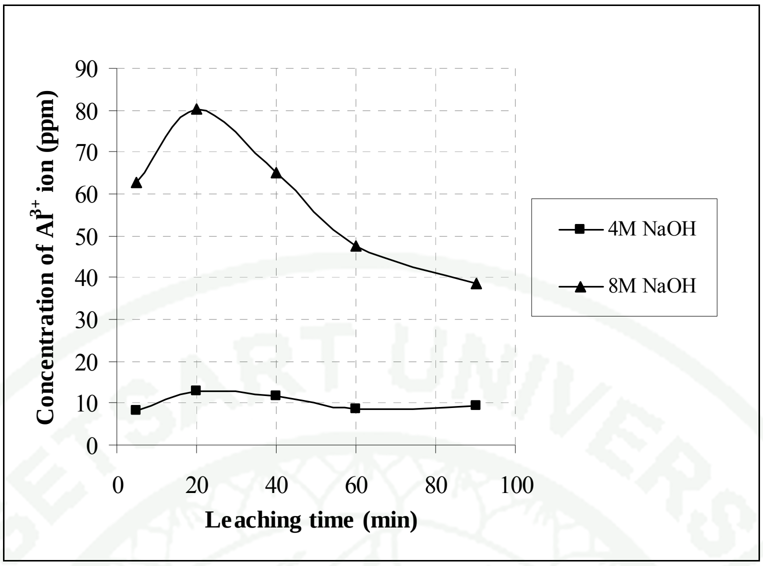


Figure 14 Concentrations of dissolved Al from class C fly ash at different leaching times.

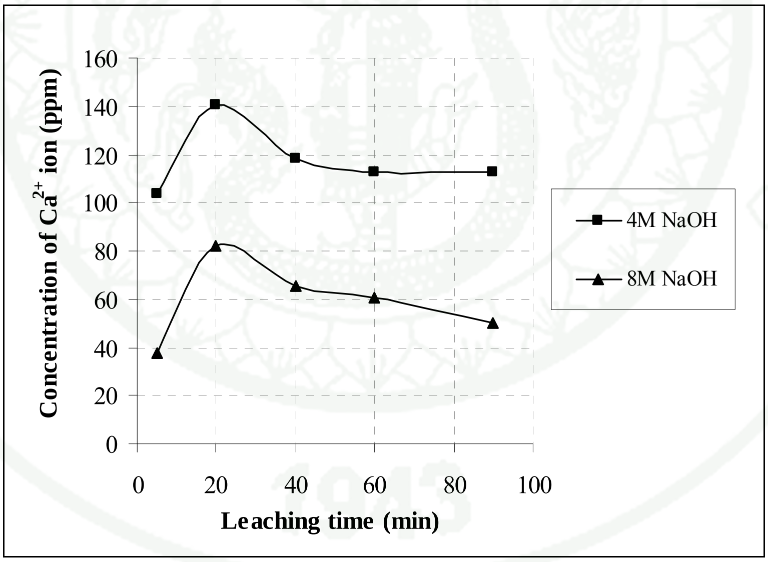


Figure 15 Concentrations of dissolved Ca from class C fly ash at different leaching times.

2. Setting time

A Vicat needle was used to be measure the geopolymer setting time. The time of needle penetration 25 mm into the paste specimen was taken as the initial setting time. The final setting time was when the needle did not sink visibly into the paste. Figures 16 and 17 show the effect of leaching time on the setting time. It can be seen that increasing the leaching time resulted in increasing the setting time of both class C fly ash and class F fly ash geopolymer. The results of geopolymer setting time is consistent with the research of Nawittayanan and Suwanvitaya (2009) that the more leaching time applied, the more setting time will be required.

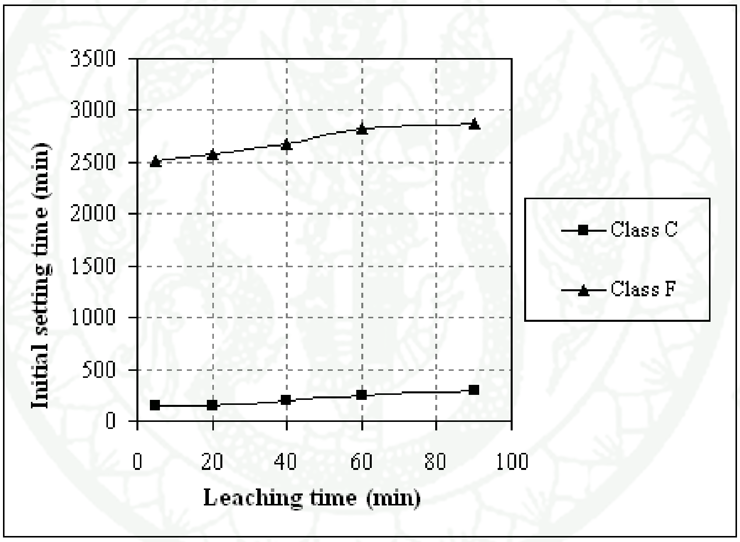


Figure 16 Initial setting times of geopolymers at different leaching times.

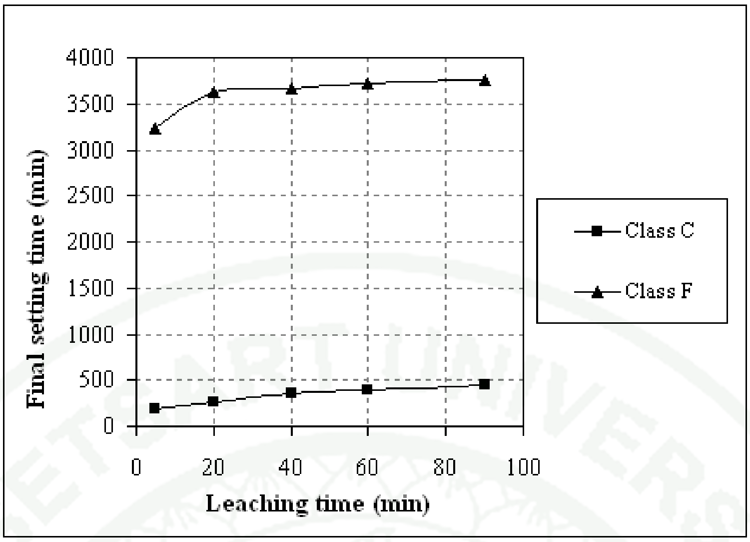


Figure 17 Final setting times of geopolymers at different leaching times.

Besides, it was obvious that the setting times of class C fly ash geopolymer were much faster than class F fly ash at all leaching times. It is interesting that the large differences of setting time between class C fly ash and class F fly ash geopolymer is expected as the results from the difference of CaO in starting materials and dissolved calcium ions in dissolution stage. As shown in table 4, the concentrations of dissolved calcium from class C fly ash were higher than class F fly ash approximately 6-10 times. From the above results, it can be concluded that the effect of calcium content related to setting time of fly ash-based geopolymer. More calcium contents has an affect to less setting time.

Table 4 The initial and final setting times of fly ash geopolymer by using 4M NaOH.

Fly ash class	NaOH/FA ratio	Leaching time (min.)	Dissolved calcium (ppm)	Setting time	
				Initial (min.)	Final (min.)
C	0.50	5	120.97	155	205
	0.50	90	79.60	550	600
	0.33	5	103.97	145	185
	0.33	90	112.45	290	445
F	0.50	5	19.90	NA	NA
	0.50	90	11.59	NA	NA
	0.33	5	17.93	2520	3240
	0.33	90	10.68	2880	3750

Remark: NA = Paste specimen cannot be hard as geopolymer.

As shown in figures 18 and 19, the setting times of class C fly ash geopolymer activated with 4M NaOH were faster than that of 8M NaOH. This suggested that the increase of NaOH morality increased the initial and final setting times.

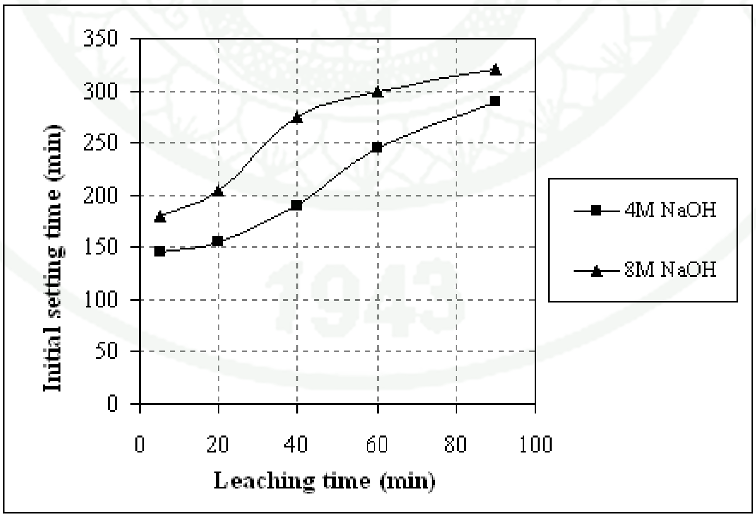


Figure 18 Initial setting time of class C fly ash geopolymer at different leaching times.

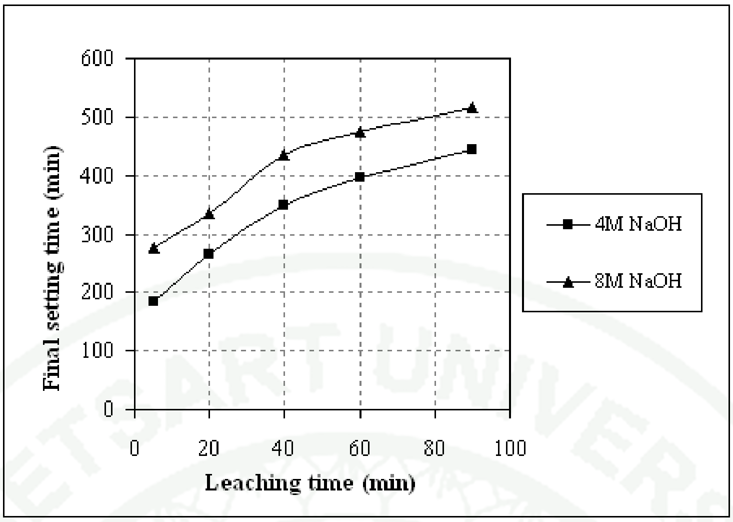


Figure 19 Final setting time of Class C fly ash geopolymer at different leaching times.

3. Compressive strength

Figure 20 shows the compressive strength of class C fly ash geopolymer. It can be seen that the compressive strength rapidly increased at 3 to 14 days period and then slowed down at 14 to 28 days. The compressive strength achieved maximum value of 241 ksc at leaching time of 5 minutes at the age of 28 days.

Figure 21 presents the compressive strength of class F fly ash geopolymer from various leaching times. The 3 days compressive strength specimens of class F fly ash geopolymer were not hard enough to be tested. The compressive strength was found to increase rapidly during the first 14 days and peaked at 194 ksc at leaching time of 5 minutes at the age of 28 days.

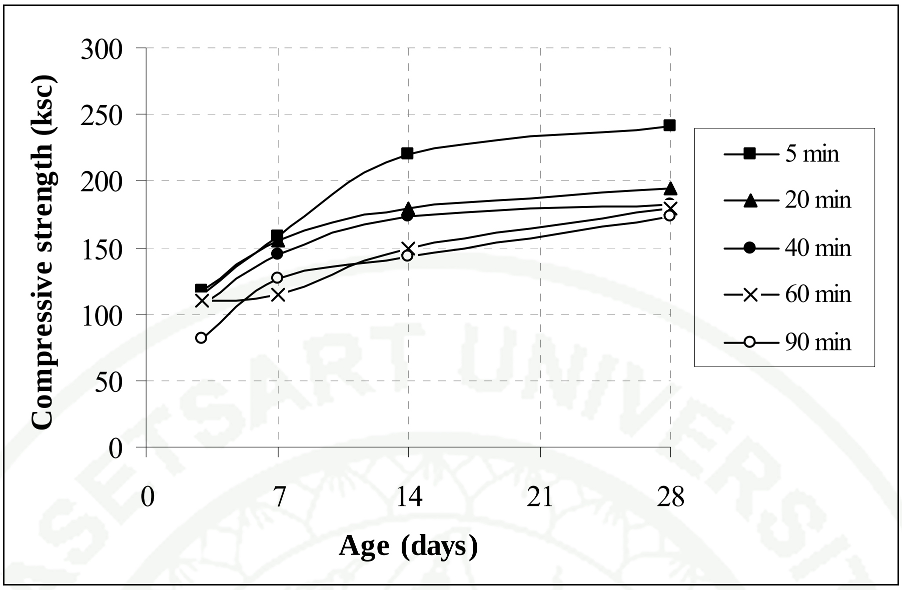


Figure 20 Compressive strength of class C fly ash geopolymer at different leaching times.

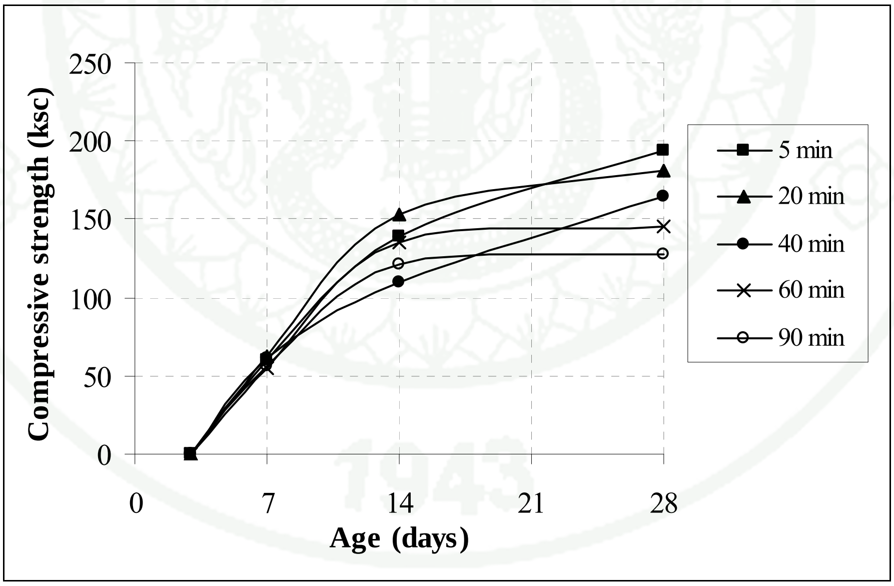


Figure 21 Compressive strength of class F fly ash geopolymer at different leaching times.

From the above results, it was found that although the highest dissolution amounts of silica, alumina and calcium were detected at 20 minutes of leaching time, the compressive strength did not seem to show the highest value. This phenomenon also noticed that the compressive strength which developed after geopolymerisation was not dependent only on the amounts of dissolved ions but also strongly dependent on the proportion of dissolved silica and alumina. As shown in table 5, it can be seen that the specimens which indicated higher Si/Al ratio seem to show greater compressive strength than lower Si/Al ratio. These results might explain that the effect of Si/Al ratio relates significantly to compressive strength.

Table 5 The compressive strength of class C and class F fly ash geopolymer at 28 days age.

Fly ash class	NaOH/FA ratio	Leaching time (min.)	Si/Al ratio	Compressive strength (ksc)
C	0.33	5	21.60	241
	0.33	40	17.25	182
	0.33	90	15.98	173
F	0.33	5	8.91	194
	0.33	40	4.15	165
	0.33	90	4.69	127

The compressive strength at 28 days age was compared between 4M NaOH and 8M NaOH against leaching time as shown in figure 22. The result of 8M NaOH gave compressive strength higher than 4M NaOH at all leaching times because higher concentration of NaOH dissolved more silica and alumina. The increasing concentration of alkaline activator led to the compressive strength increase. This was compatible with the findings by Dimitrios *et al.* (2006).

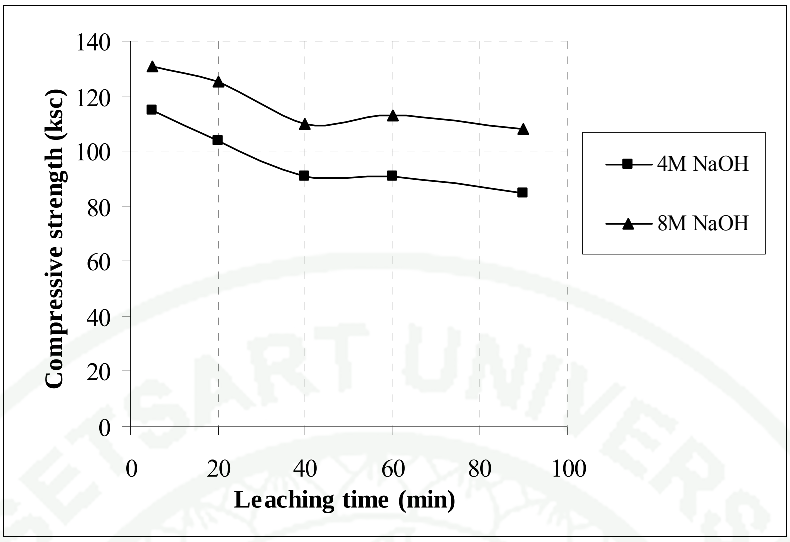


Figure 22 Compressive strength at 28 days of class C fly ash geopolymer by using 4M and 8M NaOH at different leaching times.

4. X-ray diffraction (XRD)

Mineralogical characterization was carried out by X-ray diffraction (XRD). Scans were performed from 2-80° 2θ scanning range at 0.02° step. The XRD patterns expressed for samples of both class C and class F fly ash at age of 28 days that the quartz (SiO_2) and calcite ($CaCO_3$) peaks were observed.

Figures 23 and 24 show the X-ray diffractograms for class C and class F fly ash geopolymer activated with 8M NaOH, respectively. The relative intensity of maximum peaks in class C fly ash geopolymer were 700 (calcite) and 625 (quartz) compared with 600 (calcite) and 550 (quartz) for class F fly ash geopolymer, suggesting that more dissolution from class C fly ash than class F indicated a significant effect to the peaks of relative intensity which related in the crystalline pattern. The result of different relative intensity peaks was compatible with the compressive strength results, which indicated higher compressive strength in class C fly ash than class F fly ash.

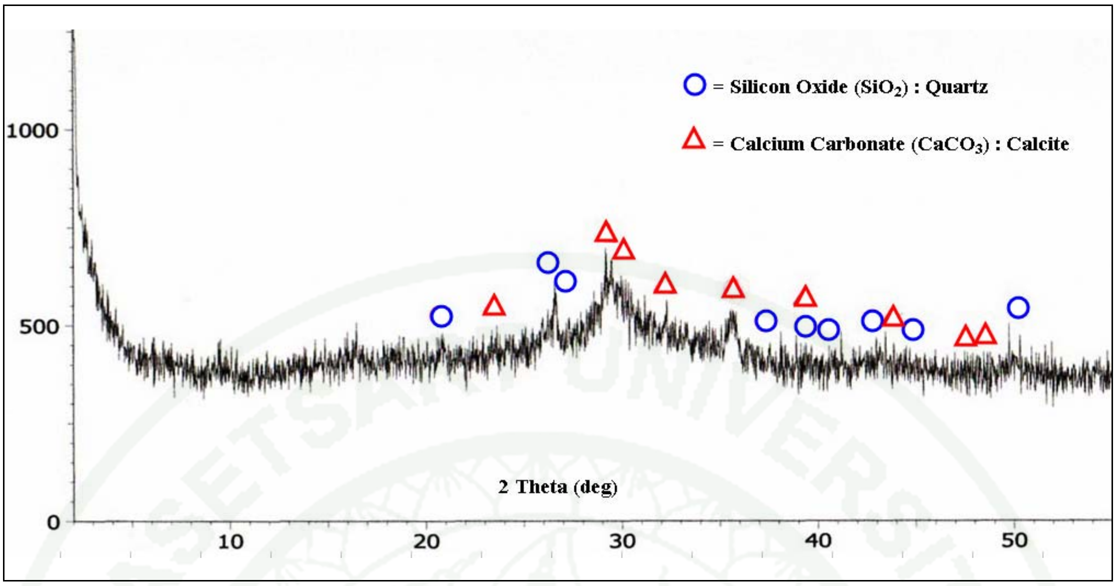


Figure 23 XRD patterns at 28 days of class C fly ash geopolymer paste.

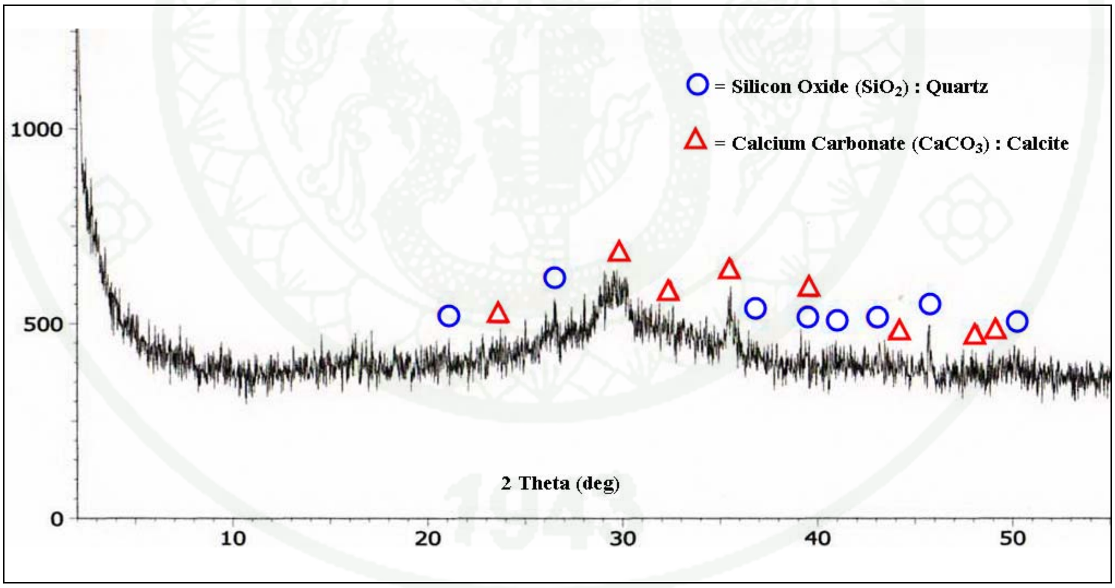


Figure 24 XRD patterns at 28 days of class F fly ash geopolymer paste.

5. Mercury Intrusion Porosimetry

Mercury Intrusion Porosimetry (MIP) was applied to determine the difference in porosity and pore size distribution of the hardened geopolymer paste of class C fly ash and class F fly ash. Table 6 shows the results of the MIP measurements on the hardened geopolymer paste specimens at 28 days age with 5 and 90 minutes leaching time of class C fly ash and class F fly ash. It can be seen that class C fly ash yielded larger average pore size but lower total porosity than those of class F. This was compatible with the compressive strength results, which showed highest strength in class C fly ash. The relative result between porosity and compressive strength aligns with previous study by Thokchom *et al*. (2009) who pointed out that specimen of geopolymer with higher porosity lost more strength than that with lesser corresponding value.

The results showed that the pore size and pore volumes increased with leaching time, for both classes of fly ash. Again, this was compatible with the strength results which showed that increasing leaching time decreased the compressive strength.

Table 6 The results of pore size and porosity.

Specimen type	Pore size (micron)		Total porosity (%)	
	Leaching time 5 minutes	Leaching time 90 minutes	Leaching time 5 minutes	Leaching time 90 minutes
Class C fly ash				
- 4M-0.33	6.50	10.75	23.39	25.61
- 8M-0.33	10.39	20.28	23.15	30.92
Class F fly ash				
- 4M-0.33	0.0122	0.0126	35.21	41.13
- 8M-0.33	0.0189	0.0217	34.29	45.20

CONCLUSION AND RECOMMENDATIONS

Conclusion

1. The concentrations of dissolved silica, alumina and calcium ions from fly ash depended on leaching period and NaOH molarity. The results indicated that leaching time of 20 minutes was sufficient for dissolving ions. More leaching time did not show the increasing dissolved ions. The higher molarity of NaOH extracted more silica and alumina but less calcium from fly ash.

2. The quantity of NaOH solution related to the dissolution ability of fly ash. The higher NaOH quantity resulted in increase of the dissolved ions of silica, alumina and calcium. The more the leachant, the more the leachate.

3. The setting times of fly ash geopolymer also depended on leaching time and NaOH molarity. Increasing the leaching time resulted in increasing the setting times of both class C fly ash and class F fly ash geopolymer. The more leaching time applied, the more setting time will be required. And the greater NaOH morality increased the initial and final setting times of fly ash geopolymer.

4. For compressive strength of fly ash geopolymer, the amounts of dissolved ions was not the only factor but also strongly dependent on the proportion of dissolved silica and alumina ions. The specimens which indicated higher Si/Al ratio showed greater compressive strength than those of lower Si/Al ratio.

5. From XRD analysis, it can be proved that more dissolution from class C fly ash compared with class F indicated a significant effect to the peaks of relative intensity which related to crystalline pattern of geopolymer. The result of different relative intensity peaks was compatible with the compressive strength results, which indicated higher compressive strength in class C fly ash than class F fly ash.

6. The investigation of microstructure from MIP analysis found that class C fly ash yielded larger average pore size but lower total porosity that those of class F. This was compatible with the compressive strength results, which showed highest strength in class C fly ash.

Recommendations

The influence of sodium hydroxide molarity and leaching time on the properties of fly ash-based geopolymer needs further investigation. A similar approach which can be applied to the recommendation for future research works are;

1. Study the effect of other types of starting material with different chemical compositions.

2. There should be more study on the different types of alkali activator.

3. Study the effect of various mix proportions of starting material to alkali activator.

4. Study the effect of dissolution ions on other engineering properties of geopolymer. For example, tensile strength, flexural strength and flow should be considered.

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APPENDIX

Appendix Table 1 Detail of mix proportions for class C fly ash-based-geopolymer.

Mix No.	Designation	Fly Ash	NaOH		Na2SiO3	Leaching Time
			4M	8M		
		(gram)	(gram)	(gram)	(gram)	(minute)
1	C-0.5-4M-5	1200	600	0	600	5
2	C-0.5-4M-20					20
3	C-0.5-4M-40					40
4	C-0.5-4M-60					60
5	C-0.5-4M-90					90
6	C-0.33-4M-5	2000	666	0	666	5
7	C-0.33-4M-20					20
8	C-0.33-4M-40					40
9	C-0.33-4M-60					60
10	C-0.33-4M-90					90
11	C-0.5-4M-5	1200	0	600	600	5
12	C-0.5-4M-20					20
13	C-0.5-4M-40					40
14	C-0.5-4M-60					60
15	C-0.5-4M-90					90
16	C-0.33-8M-5	2000	0	666	666	5
17	C-0.33-8M-20					20
18	C-0.33-8M-40					40
19	C-0.33-8M-60					60
20	C-0.33-8M-90					90

Appendix Table 2 Detail of mix proportions for class F fly ash-based-geopolymer.

Mix No.	Designation	Fly Ash	NaOH		Na2SiO3	Leaching Time
			4M	8M		
		(gram)	(gram)	(gram)	(gram)	(minute)
1	F-0.5-4M-5	1200	600	0	600	5
2	F-0.5-4M-20					20
3	F-0.5-4M-40					40
4	F-0.5-4M-60					60
5	F-0.5-4M-90					90
6	F-0.33-4M-5	2000	666	0	666	5
7	F-0.33-4M-20					20
8	F-0.33-4M-40					40
9	F-0.33-4M-60					60
10	F-0.33-4M-90					90
11	F-0.5-4M-5	1200	0	600	600	5
12	F-0.5-4M-20					20
13	F-0.5-4M-40					40
14	F-0.5-4M-60					60
15	F-0.5-4M-90					90
16	F-0.33-8M-5	2000	0	666	666	5
17	F-0.33-8M-20					20
18	F-0.33-8M-40					40
19	F-0.33-8M-60					60
20	F-0.33-8M-90					90

Appendix Table 3 Result of dissolution ions test.

Mix No.	Designation	Dissolution Silica (mg/L)	Dissolution Alumina (mg/L)	Dissolution Calcium (mg/L)
1	C-0.5-4M-5	390.00	14.59	120.97
2	C-0.5-4M-20	465.00	17.76	207.90
3	C-0.5-4M-40	386.40	15.54	144.21
4	C-0.5-4M-60	295.30	11.78	120.11
5	C-0.5-4M-90	196.13	11.12	79.60
6	C-0.33-4M-5	172.80	8.10	103.97
7	C-0.33-4M-20	260.40	13.29	140.22
8	C-0.33-4M-40	199.20	11.55	118.58
9	C-0.33-4M-60	140.12	8.69	112.45
10	C-0.33-4M-90	147.60	9.23	112.45
11	C-0.5-8M-5	1500.75	70.00	59.90
12	C-0.5-8M-20	2345.85	105.62	96.84
13	C-0.5-8M-40	1715.40	82.48	67.46
14	C-0.5-8M-60	1686.99	84.21	54.06
15	C-0.5-8M-90	1750.94	100.23	68.52
16	C-0.33-8M-5	1249.20	62.55	37.90
17	C-0.33-8M-20	1321.20	80.21	82.33
18	C-0.33-8M-40	1008.44	65.55	65.23
19	C-0.33-8M-60	734.40	47.52	60.57
20	C-0.33-8M-90	364.20	38.59	50.32

Appendix Table 3 (Continued)

Mix No.	Designation	Dissolution Silica (mg/L)	Dissolution Alumina (mg/L)	Dissolution Calcium (mg/L)
21	F-0.5-4M-5	273.60	91.04	19.90
22	F-0.5-4M-20	496.80	133.39	17.56
23	F-0.5-4M-40	810.00	239.21	13.38
24	F-0.5-4M-60	943.20	321.50	10.89
25	F-0.5-4M-90	1150.80	472.18	11.59
26	F-0.5-8M-5	670.00	419.18	12.80
27	F-0.5-8M-20	975.60	478.08	11.82
28	F-0.5-8M-40	1454.40	660.86	9.94
29	F-0.5-8M-60	2145.60	930.40	8.62
30	F-0.5-8M-90	2977.20	1260.07	7.62
31	F-0.33-4M-5	811.11	91.04	26.05
32	F-0.33-4M-20	1100.79	232.40	27.23
33	F-0.33-4M-40	810.88	195.30	18.74
34	F-0.33-4M-60	804.24	175.22	15.25
35	F-0.33-4M-90	806.65	172.23	14.34
36	F-0.33-8M-5	2111.24	180.64	17.93
37	F-0.33-8M-20	3100.52	555.32	16.55
38	F-0.33-8M-40	2200.05	400.11	13.91
39	F-0.33-8M-60	2045.15	320.10	12.07
40	F-0.33-8M-90	2190.85	390.50	10.68

Appendix Table 4 Result of compressive strength testing for geopolymer mixed with class C fly ash and 4M NaOH : FA ratio of 0.50 at leaching time of 5 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	9.12	4.30	0.227	14.51	525	36	
3	2	9.04	4.34	0.221	14.79	500	34	39
	3	8.97	4.35	0.221	14.85	675	46	
	1	8.98	4.33	0.226	14.72	1200	82	
7	2	8.80	4.33	0.221	14.72	1400	95	86
	3	9.16	4.33	0.230	14.72	1200	82	
	1	9.06	4.33	0.226	14.72	1625	110	
14	2	9.25	4.33	0.230	14.72	1500	102	109
	3	9.04	4.33	0.227	14.72	1700	116	
	1	8.90	4.33	0.217	14.72	1550	105	
28	2	9.00	4.33	0.225	14.72	1850	126	115
	3	9.20	4.33	0.230	14.72	1675	114	

Appendix Table 5 Result of compressive strength testing for geopolymer mixed with class C fly ash and 4M NaOH : FA ratio of 0.50 at leaching time of 20 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	9.11	4.31	0.227	14.58	800	54	
3	2	9.04	4.33	0.226	14.72	925	63	59
	3	9.00	4.35	0.230	14.85	880	60	
	1	9.12	4.33	0.230	14.72	1200	82	
7	2	9.13	4.33	0.231	14.72	1750	119	94
	3	9.00	4.33	0.225	14.72	1200	82	
	1	9.12	4.33	0.229	14.72	1250	85	
14	2	9.26	4.33	0.230	14.72	1600	109	100
	3	9.03	4.33	0.230	14.72	1550	105	
	1	9.00	4.33	0.225	14.72	1700	116	
28	2	9.20	4.33	0.228	14.72	1500	102	104
	3	9.24	4.33	0.232	14.72	1400	95	

Appendix Table 6 Result of compressive strength testing for geopolymer mixed with class C fly ash and 4M NaOH : FA ratio of 0.50 at leaching time of 40minutes.

Age (days)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	9.00	4.33	0.226	14.72	800	54	
3	2	9.02	4.33	0.226	14.72	750	51	54
	3	9.00	4.33	0.228	14.72	825	56	
	1	9.06	4.33	0.227	14.72	1225	83	
7	2	9.05	4.33	0.228	14.72	1150	78	81
	3	9.14	4.33	0.231	14.72	1200	82	
	1	8.98	4.33	0.229	14.72	1250	85	
14	2	8.80	4.33	0.224	14.72	1350	92	85
	3	8.90	4.33	0.228	14.72	1150	78	
	1	9.10	4.33	0.228	14.72	1400	95	
28	2	8.90	4.33	0.222	14.72	1300	88	91
	3	8.94	4.33	0.224	14.72	1300	88	

Appendix Table 7 Result of compressive strength testing for geopolymer mixed with class C fly ash and 4M NaOH : FA ratio of 0.50 at leaching time of 60 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	9.04	4.35	0.232	14.85	650	44	
3	2	9.05	4.34	0.230	14.79	500	34	37
	3	9.08	4.30	0.226	14.51	500	34	
	1	9.06	4.34	0.229	14.79	950	64	
7	2	9.06	4.34	0.229	114.79	1110	75	68
	3	9.05	4.33	0.228	14.72	950	65	
	1	8.80	4.33	0.224	14.72	1325	90	
14	2	8.96	4.33	0.229	14.72	1175	80	84
	3	8.94	4.33	0.226	14.72	1200	82	
	1	9.20	4.33	0.232	14.72	1375	93	
28	2	8.50	4.33	0.213	14.72	1375	93	91
	3	9.14	4.33	0.233	14.72	1300	88	

Appendix Table 8 Result of compressive strength testing for geopolymer mixed with class C fly ash and 4M NaOH : FA ratio of 0.50 at leaching time of 90 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	9.13	4.33	0.230	14.72	700	47	
3	2	8.98	4.33	0.225	14.72	600	40	44
	3	9.06	4.40	0.232	15.20	675	45	
	1	8.90	4.33	0.223	14.72	1300	89	
7	2	9.00	4.30	0.226	14.72	1000	68	74
	3	8.80	4.33	0.220	14.51	950	65	
	1	9.03	4.33	0.229	14.72	1050	71	
14	2	9.03	4.33	0.227	14.72	1025	70	76
	3	8.92	4.33	0.227	14.72	1300	88	
	1	9.02	4.33	0.227	14.72	1275	87	
28	2	9.04	4.33	0.229	14.72	1250	85	85
	3	8.90	4.33	0.224	14.72	1225	83	

Appendix Table 9 Result of compressive strength testing for geopolymer mixed with class C fly ash and 4M NaOH : FA ratio of 0.33 at leaching time of 5 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	9.03	4.35	0.240	14.85	1750	118	
3	2	9.13	4.33	0.240	14.72	1760	118	117
	3	9.12	4.36	0.238	14.92	1700	114	
	1	8.92	4.36	0.236	14.92	2300	154	
7	2	9.00	4.36	0.240	14.92	2525	170	158
	3	9.08	4.37	0.238	14.99	2250	152	
	1	9.15	4.33	0.245	14.72	3300	224	
14	2	9.36	4.33	0.248	14.72	3250	221	220
	3	8.98	4.33	0.239	14.72	3200	217	
	1	9.00	4.33	0.237	14.72	3375	229	
28	2	9.01	4.33	0.238	14.72	3500	238	241
	3	9.00	4.33	0.237	14.72	3750	255	

Appendix Table 10 Result of compressive strength testing for geopolymer mixed with class C fly ash and 4M NaOH : FA ratio of 0.33 at leaching time of 20 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	8.96	4.34	0.239	14.79	1825	123	
3	2	9.12	4.35	0.239	14.85	1700	114	115
	3	9.00	4.35	0.240	14.85	1600	108	
	1	8.81	4.35	0.233	14.85	2500	168	
7	2	9.04	4.36	0.242	14.85	2000	135	155
	3	9.00	4.33	0.242	14.92	2375	161	
	1	8.90	4.33	0.235	14.72	2700	183	
14	2	8.99	4.33	0.241	14.72	2700	183	179
	3	9.06	4.33	0.239	14.72	2500	170	
	1	9.02	4.33	0.239	14.72	3000	204	
28	2	8.85	4.33	0.232	14.72	2675	182	195
	3	8.90	4.33	0.235	14.72	2925	199	

Appendix Table 11 Result of compressive strength testing for geopolymer mixed with class C fly ash and 4M NaOH : FA ratio of 0.33 at leaching time of 40 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	8.75	4.33	0.229	14.72	1500	102	
3	2	8.92	4.34	0.237	14.79	1775	120	108
	3	8.92	4.31	0.233	14.58	1475	100	
	1	9.00	4.36	0.238	14.92	2100	142	
7	2	8.85	4.33	0.232	14.72	2325	158	145
	3	9.08	4.34	0.239	14.79	2000	136	
	1	9.00	4.33	0.235	14.72	2575	175	
14	2	8.90	4.33	0.237	14.72	2625	178	173
	3	8.96	4.33	0.237	14.72	2425	165	
	1	8.98	4.33	0.236	14.72	2800	190	
28	2	8.90	4.33	0.235	14.72	2600	177	182
	3	8.80	4.33	0.230	14.72	2650	180	

Appendix Table 12 Result of compressive strength testing for geopolymer mixed with class C fly ash and 4M NaOH : FA ratio of 0.33 at leaching time of 60 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	8.90	4.33	0.239	14.72	1600	109	
3	2	8.92	4.32	0.239	14.65	1775	121	111
	3	8.92	4.32	0.239	14.65	1500	102	
	1	8.83	4.33	0.232	14.72	1950	133	
7	2	8.70	4.33	0.229	14.65	1500	102	115
	3	8.70	4.32	0.223	14.72	1600	109	
	1	8.96	4.33	0.238	14.72	2475	168	
14	2	8.80	4.33	0.233	14.72	2050	139	149
	3	8.80	4.33	0.233	14.72	2050	139	
	1	8.78	4.33	0.229	14.72	2675	182	
28	2	8.90	4.33	0.235	14.72	2600	177	179
	3	9.02	4.33	0.241	14.72	2625	178	

Appendix Table 13 Result of compressive strength testing for geopolymer mixed with class C fly ash and 4M NaOH : FA ratio of 0.33 at leaching time of 90 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	9.00	4.34	0.243	14.79	1300	88	
3	2	9.13	4.31	0.241	14.58	1225	83	82
	3	8.93	4.33	0.238	14.72	1100	75	
	1	9.12	4.33	0.243	14.72	1925	130	
7	2	9.14	4.33	0.246	14.72	1800	121	127
	3	8.70	4.38	0.231	15.06	1875	126	
	1	8.76	4.33	0.234	14.72	2250	153	
14	2	8.50	4.33	0.233	14.72	2025	138	143
	3	8.50	4.33	0.233	14.72	2025	138	
	1	8.80	4.33	0.237	14.72	2625	178	
28	2	8.82	4.33	0.238	14.72	2500	170	173
	3	8.82	4.33	0.238	14.72	2500	170	

Appendix Table 14 Result of compressive strength testing for geopolymer mixed with class C fly ash and 8M NaOH : FA ratio of 0.50 at leaching time of 5 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	8.90	4.33	0.230	14.72	810	54	
3	2	9.03	4.40	0.235	15.20	700	47	49
	3	9.03	4.40	0.235	15.20	700	47	
	1	9.05	4.33	0.233	14.72	1125	76	
7	2	8.94	4.35	0.235	14.85	1225	83	81
	3	9.23	4.33	0.240	14.72	1225	83	
	1	8.80	4.33	0.230	14.72	1975	134	
14	2	8.50	4.33	0.217	14.72	1750	119	127
	3	7.40	4.33	0.183	14.72	1875	127	
	1	9.00	4.33	0.229	14.72	2025	138	
28	2	9.20	4.33	0.237	14.72	1950	132	131
	3	8.20	4.33	0.201	14.72	1800	122	

Appendix Table 15 Result of compressive strength testing for geopolymer mixed with class C fly ash and 8M NaOH : FA ratio of 0.50 at leaching time of 20 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	9.00	4.34	0.233	14.79	590	40	
3	2	9.03	4.32	0.231	14.65	500	34	40
	3	9.02	4.30	0.234	14.51	675	46	
	1	9.06	4.33	0.233	14.72	1000	68	
7	2	9.06	4.33	0.235	14.72	800	54	68
	3	9.08	4.33	0.236	14.72	1200	82	
	1	8.80	4.33	0.228	14.72	1650	112	
14	2	8.80	4.33	0.231	14.72	1500	102	105
	3	8.80	4.33	0.232	14.72	1475	100	
	1	9.20	4.33	0.236	14.72	1975	134	
28	2	8.90	4.33	0.230	14.72	1700	116	125
	3	9.16	4.33	0.234	14.72	1850	126	

Appendix Table 16 Result of compressive strength testing for geopolymer mixed with class C fly ash and 8M NaOH : FA ratio of 0.50 at leaching time of 40 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	9.00	4.32	0.231	14.65	450	31	
3	2	9.00	4.33	0.231	14.72	675	46	38
	3	9.00	4.33	0.231	14.72	550	37	
	1	8.80	4.34	0.241	14.79	2200	148	
7	2	8.80	4.40	0.242	15.20	2350	158	68
	3	8.80	4.33	0.240	14.72	2200	149	
	1	8.55	4.33	0.214	14.72	1300	88	
14	2	8.50	4.33	0.212	14.72	1225	83	80
	3	8.50	4.33	0.216	14.72	1000	68	
	1	8.46	4.33	0.204	14.72	1750	119	
28	2	8.46	4.33	0.204	14.72	1650	112	110
	3	8.46	4.33	0.204	14.72	1450	99	

Appendix Table 17 Result of compressive strength testing for geopolymer mixed with class C fly ash and 8M NaOH : FA ratio of 0.50 at leaching time of 60 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	8.92	4.36	0.235	14.92	675	45	
3	2	8.90	4.40	0.233	15.20	600	41	43
	3	9.00	4.36	0.237	14.92	650	45	
	1	8.75	4.23	0.230	14.05	825	58	
7	2	8.80	4.23	0.235	14.05	1325	91	76
	3	8.75	4.36	0.230	14.92	1125	76	
	1	8.90	4.33	0.234	14.72	1350	92	
14	2	8.78	4.33	0.228	14.72	1225	83	90
	3	8.80	4.33	0.231	14.72	1400	95	
	1	8.84	4.33	0.233	14.72	1550	105	
28	2	8.82	4.33	0.231	14.72	1800	122	113
	3	8.82	4.33	0.231	14.72	1650	112	

Appendix Table 18 Result of compressive strength testing for geopolymer mixed with class C fly ash and 8M NaOH : FA ratio of 0.50 at leaching time of 90 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	8.76	4.36	0.229	4.36	225	15	
3	2	8.66	4.33	0.227	4.33	225	15	15
	3	8.66	4.32	0.227	4.32	220	15	
	1	8.75	4.33	0.230	4.33	1000	68	
7	2	8.75	4.36	0.233	4.36	1050	71	72
	3	8.80	4.33	0.227	4.33	1125	76	
	1	8.80	4.33	0.232	14.72	1250	85	
14	2	8.50	4.33	0.227	14.72	1000	68	78
	3	8.50	4.33	0.232	14.72	1200	82	
	1	8.80	4.33	0.228	14.72	1650	112	
28	2	8.78	4.33	0.231	14.72	1625	110	108
	3	9.22	4.33	0.239	14.72	1475	100	

Appendix Table 19 Result of compressive strength testing for geopolymer mixed with class C fly ash and 8M NaOH : FA ratio of 0.33 at leaching time of 5 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	9.00	4.34	0.223	14.79	800	54	
3	2	8.82	4.34	0.218	14.79	825	55	55
	3	8.82	4.34	0.218	14.79	825	56	
	1	8.80	4.38	0.221	15.06	1000	67	
7	2	8.81	4.33	0.220	14.72	875	59	62
	3	8.81	4.33	0.220	14.72	875	59	
	1	8.82	4.33	0.220	14.72	1125	76	
14	2	8.97	4.33	0.229	14.72	1025	70	69
	3	8.97	4.33	0.229	14.72	900	61	
	1	8.92	4.33	0.213	14.72	1100	75	
28	2	8.92	4.33	0.213	14.72	1100	75	75
	3	9.10	4.33	0.213	14.72	1100	75	

Appendix Table 20 Result of compressive strength testing for geopolymer mixed with class C fly ash and 8M NaOH : FA ratio of 0.33 at leaching time of 20 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	9.02	4.33	0.249	14.72	1100	75	
3	2	9.06	4.36	0.247	14.92	1075	73	72
	3	9.03	4.32	0.244	14.65	1000	69	
	1	8.81	4.33	0.236	14.72	1200	82	
7	2	9.06	4.28	0.244	14.38	1150	78	78
	3	9.15	4.36	0.245	14.92	1100	74	
	1	8.98	4.33	0.245	14.72	1650	112	
14	2	8.90	4.33	0.236	14.72	1425	97	102
	3	8.87	4.33	0.235	14.72	1425	97	
	1	9.12	4.33	0.242	14.72	2000	136	
28	2	9.04	4.33	0.243	14.72	2025	138	133
	3	8.90	4.33	0.238	14.72	1850	126	

Appendix Table 21 Result of compressive strength testing for geopolymer mixed with class C fly ash and 8M NaOH : FA ratio of 0.33 at leaching time of 40 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	8.90	4.32	0.246	14.65	1260	85	
3	2	9.03	4.36	0.247	14.92	1260	85	84
	3	9.21	4.34	0.253	14.79	1200	81	
	1	7.90	4.33	0.197	14.72	1675	114	
7	2	8.05	4.33	0.200	14.72	1600	109	109
	3	8.02	4.33	0.201	14.72	1550	105	
	1	8.88	4.33	0.248	14.72	1800	122	
14	2	9.10	4.33	0.249	14.72	1975	134	130
	3	9.00	4.33	0.244	14.72	1975	134	
	1	9.04	4.33	0.243	14.72	2875	195	
28	2	9.12	4.33	0.238	14.72	2125	144	166
	3	9.10	4.33	0.244	14.72	2350	160	

Appendix Table 22 Result of compressive strength testing for geopolymer mixed with class C fly ash and 8M NaOH : FA ratio of 0.33 at leaching time of 60 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	9.00	4.32	0.238	14.65	1275	87	
3	2	8.85	4.36	0.243	14.92	1250	85	83
	3	8.90	4.30	0.244	14.51	1150	78	
	1	9.10	4.34	0.246	14.79	2150	145	
7	2	9.20	4.37	0.252	14.99	2025	137	104
	3	8.95	4.33	0.245	14.72	2225	151	
	1	9.10	4.33	0.247	14.72	1850	126	
14	2	8.95	4.33	0.244	14.72	1700	116	120
	3	9.00	4.33	0.251	14.72	1750	119	
	1	9.10	4.33	0.248	14.72	2700	183	
28	2	9.16	4.33	0.258	14.72	2600	177	175
	3	9.02	4.33	0.237	14.72	2425	165	

Appendix Table 23 Result of compressive strength testing for geopolymer mixed with class C fly ash and 8M NaOH : FA ratio of 0.33 at leaching time of 90 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	9.02	4.32	0.245	14.65	900	61	
3	2	9.12	4.32	0.248	14.65	930	63	63
	3	9.00	4.33	0.245	14.72	930	63	
	1	9.10	4.36	0.254	14.92	1500	101	
7	2	9.16	4.34	0.253	14.79	1575	107	103
	3	9.16	4.34	0.254	14.79	1500	102	
	1	9.00	4.33	0.253	14.72	1800	122	
14	2	8.80	4.33	0.239	14.72	1400	95	117
	3	8.80	4.33	0.240	14.72	1975	134	
	1	9.10	4.33	0.251	14.72	2625	178	
28	2	9.10	4.33	0.248	14.72	3500	238	199
	3	9.08	4.33	0.244	14.72	2650	180	

Appendix Table 24 Result of compressive strength testing for geopolymer mixed with class F fly ash and 4M NaOH : FA ratio of 0.33 at leaching time of 5 minutes.

Age (days)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	8.44	4.34	0.228	14.79	1000	68	
7	2	8.25	4.35	0.221	14.85	850	58	60
	3	8.16	4.33	0.217	14.72	800	54	
	1	8.52	4.33	0.223	14.72	2275	155	
14	2	8.22	4.33	0.229	14.72	2000	136	139
	3	8.53	4.33	0.227	14.72	1875	127	
	1	8.50	4.33	0.227	14.72	2950	200	
28	2	8.46	4.33	0.228	14.72	2750	187	194
	3	8.60	4.33	0.231	14.72	2875	195	

Appendix Table 25 Result of compressive strength testing for geopolymer mixed with class F fly ash and 4M NaOH : FA ratio of 0.33 at leaching time of 20 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	8.49	4.33	0.230	14.72	900	61	
7	2	8.20	4.33	0.218	14.72	975	66	63
	3	8.22	4.33	0.225	14.72	900	61	
	1	8.50	4.33	0.226	14.72	2650	180	
14	2	8.49	4.33	0.225	14.72	2100	143	153
	3	8.37	4.33	0.225	14.72	2025	138	
	1	8.85	4.33	0.229	14.72	2650	180	
28	2	8.40	4.33	0.226	14.72	2525	172	181
	3	8.68	4.33	0.230	14.72	2825	192	

Appendix Table 26 Result of compressive strength testing for geopolymer mixed with class F fly ash and 4M NaOH : FA ratio of 0.33 at leaching time of 40 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	8.40	4.33	0.227	14.72	925	63	
7	2	8.46	4.32	0.232	14.65	875	60	62
	3	8.60	4.33	0.231	14.72	925	63	
	1	8.55	4.33	0.229	14.72	1550	105	
14	2	8.34	4.33	0.227	14.72	1700	116	110
	3	8.55	4.33	0.230	14.72	1600	109	
	1	8.60	4.33	0.231	14.72	2500	170	
28	2	8.40	4.33	0.225	14.72	2375	161	165
	3	8.60	4.33	0.231	14.72	2375	161	

Appendix Table 27 Result of compressive strength testing for geopolymer mixed with class F fly ash and 4M NaOH : FA ratio of 0.33 at leaching time of 60 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	8.30	4.33	0.223	14.72	675	46	
7	2	8.42	4.33	0.224	14.72	875	59	55
	3	8.36	4.33	0.226	14.72	875	59	
	1	8.25	4.33	0.225	14.72	1800	122	
14	2	8.42	4.33	0.228	14.72	2025	138	135
	3	8.60	4.33	0.233	14.72	2125	144	
	1	8.58	4.33	0.230	14.72	2125	144	
28	2	8.40	4.33	0.225	14.72	2175	148	145
	3	8.40	4.33	0.224	14.72	2100	143	

Appendix Table 28 Result of compressive strength testing for geopolymer mixed with class F fly ash and 4M NaOH : FA ratio of 0.33 at leaching time of 90 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	8.43	4.33	0.228	14.72	900	61	
7	2	8.70	4.33	0.236	14.72	675	46	57
	3	8.70	4.33	0.233	14.72	925	63	
	1	8.42	4.33	0.227	14.72	2250	153	
14	2	8.53	4.33	0.228	14.72	1500	102	122
	3	8.44	4.33	0.227	14.72	1625	110	
	1	8.90	4.33	0.234	14.72	1950	132	
28	2	8.90	4.33	0.229	14.72	1775	121	127
	3	8.90	4.33	0.234	14.72	1875	127	

Appendix Table 29 Result of compressive strength testing for geopolymer mixed with class F fly ash and 8M NaOH : FA ratio of 0.33 at leaching time of 5 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	8.70	4.33	0.240	14.72	900	61	
7	2	8.50	4.34	0.236	14.79	750	51	54
	3	8.60	4.34	0.2358	14.79	750	51	
	1	8.62	4.33	0.234	14.72	2750	187	
14	2	8.74	4.33	0.240	14.72	2700	183	186
	3	8.81	4.33	0.238	14.72	2750	187	
	1	8.82	4.33	0.39	14.72	4250	289	
28	2	8.83	4.33	0.240	14.72	2700	183	248
	3	8.80	4.33	0.235	14.72	4000	272	

Appendix Table 30 Result of compressive strength testing for geopolymer mixed with class F fly ash and 8M NaOH : FA ratio of 0.33 at leaching time of 20 minutes.

Age (days)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	8.20	4.33	0.224	14.72	750	51	
7	2	8.20	4.33	0.221	14.72	850	58	50
	3	8.10	4.33	0.222	14.72	625	42	
	1	8.36	4.33	0.230	14.72	1850	126	
14	2	8.33	4.33	0.228	14.72	1850	126	136
	3	8.33	4.33	0.228	14.72	2300	156	
	1	8.60	4.33	0.233	14.72	3500	238	
28	2	8.60	4.33	0.231	14.72	3000	204	218
	3	8.40	4.33	0.225	14.72	3125	212	

Appendix Table 31 Result of compressive strength testing for geopolymer mixed with class F fly ash and 8M NaOH : FA ratio of 0.33 at leaching time of 40 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	8.45	4.33	0.231	14.72	875	59	
7	2	8.41	4.33	0.233	14.72	725	49	54
	3	8.65	4.33	0.235	14.72	800	54	
	1	8.61	4.33	0.217	14.72	2000	136	
14	2	7.98	4.33	0.232	14.72	2475	168	161
	3	8.50	4.33	0.237	14.72	2650	180	
	1	8.90	4.33	0.229	14.72	3500	238	
28	2	8.50	4.33	0.239	14.72	3250	221	238
	3	9.10	4.33	0.239	14.72	3750	255	

Appendix Table 32 Result of compressive strength testing for geopolymer mixed with class F fly ash and 8M NaOH : FA ratio of 0.33 at leaching time of 60 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	8.40	4.33	0.234	14.72	650	44	
7	2	8.65	4.33	0.236	14.72	700	48	47
	3	8.65	4.33	0.236	14.72	725	49	
	1	8.80	4.33	0.240	14.72	2000	136	
14	2	8.68	4.33	0.234	14.72	2400	163	156
	3	8.85	4.33	0.242	14.72	2500	170	
	1	9.12	4.33	0.240	14.72	3250	221	
28	2	9.22	4.33	0.243	14.72	2400	163	196
	3	8.80	4.33	0.233	14.72	3000	204	

Appendix Table 33 Result of compressive strength testing for geopolymer mixed with class F fly ash and 8M NaOH : FA ratio of 0.33 at leaching time of 90 minutes.

Age (day)	Sample No.	Height (cm.)	Dia. (cm.)	Weight (kg.)	Area (cm^2)	Load (kg.)	Compressive strength (ksc)	Average (ksc)
	1	8.85	4.33	0.229	14.72	600	41	
7	2	8.53	4.33	0.229	14.72	675	46	48
	3	8.46	4.33	0.230	14.72	825	56	
	1	8.40	4.33	0.228	14.72	1975	134	
14	2	8.25	4.33	0.225	14.72	2725	185	155
	3	8.20	4.33	0.223	14.72	2125	144	
	1	8.76	4.33	0.231	14.72	2875	195	
28	2	8.40	4.33	0.227	14.72	2650	180	184
	3	8.90	4.33	0.238	14.72	2600	177	

CIRRICULUM VITAE

NAME : Mr. Jirabute Kuntreerattanarom

BIRTH DATE : January 4, 1983

BIRTH PLACE : Bangkok, Thailand

EDUCATION :

YEAR	INSTITUTE	DEGREE/DIPLOMA
2005	Kasetsart University	B.E. (Civil Engineering)
2011	Kasetsart University	M.Eng. (Civil Engineering)

POSITION/TITLE : Civil/Structural Engineer

WORK PLACE : Technip Engineering (Thailand) LTD.