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BIOMASS AGGREGATE GEOPOLYMER CONCRETE – MALAYSIA EXPERIENCE

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ABSTRACT

This study explores the exciting journey of innovative biomass aggregate utilization in geopolymer concrete to address the global issue of climate change. Self-compacting concrete (SCC) with and without cement have been experimented. The highest compressive strength was around 80 MPa with slump flow of 530 mm. The treated expanded polystyrene (EPS) and biomass aggregate reduced the specimens density by about 4%. Geopolymer concrete prism specimen containing glass fibre achieved flexural strength of 6 MPa. Geopolymer concrete specimens achieved lower water penetration compared to Portland cement concrete. In sulphuric acid test, geopolymer concrete has less localized crack. The weight loss and compressive strength reduction of geopolymer concrete was less than Portland cement concrete. The rapid portable water penetration test system has potential to be used as an innovative non destructive tests for concrete cube specimens. The experience could lead to some viable business opportunities in the biomass industries (www.biomass.org.my) on renewable energy and sustainable construction (www.1.net.my) for improving the quality of life and generate high investment returns

I. INTRODUCTION

Cement production is a highly energy intensive production process. The energy consumption by the cement industry is estimated around 2% of the global primary energy consumption or almost 5% of the total global industrial energy consumption [1]. Cement industry produces carbon dioxide (CO_2) which causes global issue of climate change. With every tonne of cement produced, almost a tonne of CO_2 is emitted [2]. All of these contribute about 7% of the total CO_2 generated worldwide [3]. Attempt is made to produce concrete with less natural resources and less energy to minimize carbon dioxide emissions [4].

Biomass aggregate and fly ash are used in this study. It was estimated in 1998 that more than 390 million tonnes of fly ash was produced annually but its use was less than 15% [5]. Production of fly ash will increase especially in countries such as China and India. It is now estimated that about 780 million tonnes of fly ash was produced in 2010 [6]. The volume of fly ash increases as the demand for power increases. Fly ash created by a typical 500 megawatt coal-fired power plant is more than 125,000 tonnes. More than 75% of this waste material is disposed off in unmonitored onsite landfills and surface impoundments [7]. Hence, proper disposal and utilization of these ashes are needed to preserve the ecosystem.

To address the issue of global climate change, several materials were proposed to replace cement during production concrete. In 1978, Davidovits has introduced an alternative binder to cement. This alternative material was known as geopolymer as it reacts with alkaline liquid and geological materials [8].

Geopolymer concrete (GPC) is produced from fly ash, sodium silicate and sodium hydroxide. It does not require high temperature. Naturally occurring kaolin or fly ash are suitable geopolymeric raw materials. Innovative utilization of geopolymeric material will lead to reduction of the energy consumption and reduced CO_2 emission. As reported by Davidovits, 3/5 energy was required and 90% less CO_2 is generated for the production of geopolymer than Portland cement [9]. Geopolymer concrete has features such as greater corrosion resistance, substantially higher fire resistance, high compressive and tensile strength, a rapid strength gain and lower shrinkage in comparison with ordinary Portland cement [10].

This study explores possibilities with grade 35 concrete mix design of OPC and GPC with workability of 500mm slump flow. The effect of glass fiber, biomass aggregate, treated expanded polystyrene (EPS), waterproofing admixture and superplasticizer were experimented. The mechanical and physical properties were determined by laboratory tests.

II. GEOPOLYMER CONCRETE

Geopolymer was developed by the French polymer chemist, Joseph Davidovits in 1980. At early stage, geopolymer material was alumino-silicates based on reactions of alkali with de-hydroxylated kaolinite [11]. Davidovits discovered that Egyptians have used geological based source material in their monumental buildings [12].

Chemical compositions of geopolymer concrete materials are similar to zeolite. Geopolymerisation process consists of chemical reaction of Si-Al mineral in alkaline condition that involves the dissolution of Si-O-Al-O bond. The alkaline chemicals used in geopolymerisation are $Ca(OH)_2$, NaOH, Na_2SiO_3, a combination of NaOH and sodium silicate, and a combination of KOH and NaOH, potassium silicate and its combination and sodium carbonate. A combination of alkaline solution determines the final product and geopolymer strength. As reported by Fernandez [13], combination of sodium hydroxide and sodium silicate produced a solid material without pore and has strong bond between aggregate and geopolymer matrix. However, several researchers reported a meso-porous character of geopolymer concrete. This is due to fusion of fly ash highly in Si and Al elements with alkaline solution [14]. Types of activator solution play an important role to convert fly ash into meso-porous product [15]. Fly ash based geopolymer gel is porous because evaporation of the aqueous pore solution leaving the empty voids, insufficient geopolymer gel to fill the gaps in between an unreacted fly ash and porosity of partially reacted fly ash particles. It was found that the total volume of concrete increases as the curing temperature is elevated [16].

Preparation of geopolymer raw material is an important aspect especially is selecting the activator solution that could impact the strength development. Sodium hydroxide (NaOH) is generally used for its greater efficiency in liberating aluminates and silicates from the source material. Concentration of sodium hydroxide results in greater solubility of the source material [17]. However, excessive of alkali concentration tends to retard strength development of geopolymer concrete. Sodium silicate (Na_2SiO_3) is preferred as activator solution due to its soluble silicate content which helps to accelerate the polymerization reaction. However, activator solution containing more NaOH to fly ash ratios greater than 0.16 are difficult for geopolymer concrete to harden. Concrete made with these excessive ratio activators solution tend to exhibit poor workability and slower set. Geopolymer concrete was reported to have good mechanic properties, durable in acidic environment, and does not generate any deleterious alkali aggregate reaction with presence of high alkalinity [18].

Geopolymer concrete tends to increase its strength following a period of curing at elevated temperature. Curing period of geopolymer concrete is from 24 hours to 48 hours. Several studies have shown the effect of increased temperature which accelerated hardening [19]. Other studies have achieved compressive strength required for structural application through room temperature curing [20].

Most of the past research was based on mortar or small scale specimens. Some laboratory tests [21] have shown that the curing temperature, curing time, mixing time, rest period, water to geopolymer solid ratio, alkaline ratio, and concentration of sodium hydroxide are factors affecting strength development of geopolymer concrete. Longer curing period of geopolymer concrete at elevated temperature will weaken the microstructure [22] due to loss of water. Water is required for mixing geopolymer paste. Water content plays an important role on the properties of geopolymer binder [23]. Excessive water content will cause geopolymer concrete strength to decease and higher shrinkage due to water evaporated at elevated temperature.

Strength and deflection of reinforced concrete members is dependent on the stress-strain relationship of concrete. Mechanism strength development of geopolymer concrete is different than Portland cement concrete. It needs to obtain a suitable expression for the constitutive model of geopolymer concrete. Past research [24-27] reported the experimental work of geopolymer concrete elasticity modulus. Based on experimental work, stress-strain behaviour of geopolymer concrete was reported by Hardjito et al. [28]. Modulus of elasticity of geopolymer concrete was developed by Hardjito et al [29]. Expression for geopolymer concrete is similar to that given by the ACI 363 [30] with different values of the constants. These equations are expressed as function of concrete compressive strength.

$$Ec = 3.38\rho^{2.5}(\sqrt{f'c})^{0.65} \times 10^{-5} \quad (1)$$

Where: *Ec* is modulus of elasticity, *fc'* is compressive strength

The production of geopolymer concrete is estimated about 10 to 30 percent lower than Portland cement concrete. Besides that, one tonne of fly ash can be utilized to manufacture approximately 2.5 cubic meters of fly ash based geopolymer concrete and earn monetary benefits through carbon credit trade [31]. Geopolymer concrete has little drying shrinkage, low creep, and good resistance to sulfate attack as well as sulphuric acid attack. Geopolymer concrete are suitable for precast concrete such as railway sleepers, electric power poles, precast box culvert, precast wall [32]. Besides that, it can also be used in various applications such as fire and heat resistant fibre composites, sealants, and ceramics as waste encapsulation to immobilize toxic metals [33].

III. EXPERIMENTAL

The raw materials for geopolymer concrete mixes are coarse aggregate, fine aggregate, biomass aggregate, treated expanded polystyrene, fly ash, sodium silicate, and sodium hydroxides as well as water. Fly ash was collected from the Sejingkat power plant in Kuching Sarawak. The chemical composition of fly ash was determined with X-ray fluorescence (XRF) shown in Table 1. Biomass aggregate is produced from the burning process of palm oil biomass. It consists of palm oil fibre and palm oil kernel incinerated in the furnace with temperature around 500^{o}C to generate the heat required for the processing of biomass. 50% of biomass aggregate was used to replace the fine aggregate in this study. Expanded polystyrene (EPS) was treated at elevated temperature of 150^{0}C. The treated EPS particle was finer and harder.

TABLE I: CHEMICAL COMPOSITION OF FLY ASH

Chemical composition	Percentage (%)
CO_2	0.10
SiO_2	55.80
Al_2O_3	24.20
Fe_2O_3	9.10
K_2O	4.41
CaO	2.46
MgO	1.37
TiO_2	1.34
P_2O_5	0.27
BaO	0.25
Na_2O	0.21
MnO	0.18

Two series of concrete mix were prepared for the experimental work. Series 1 mix consists of OPC and GPC concrete as control. Series 2 mix consists of glass fibre, biomass aggregate and treated expanded polystyrene (EPS) in GPC mixtures. Total aggregate content normally occupies of 70% to 80% of the mass of the concrete. The sodium silicate to sodium hydroxides ratio was fixed as 2.5 and concentration of NaOH was taken as 12 M and 16 M. Alkaline liquid to fly ash ratio was fixed as 0.42. Water to cement ratio of used for entire OPC concrete batches is 0.45. Meanwhile, water to geopolymer solid ratio for entire GPC concrete batches is 0.22.The mix proportions for the present study are tabulated in Table 2 and 3.

TABLE II: MIX PROPORTIOS OF SERIES 1 MIX

Material	Mass (kg/ m^3)			
	OPC1	GPC1	GPC2	GPC3
Cement	433	-	-	-
Coarse aggregate	1063	1123	1123	1123
Fine aggregate	708.8	749	749	374
Biomass aggregate	-	-	-	375
Fly ash	-	372	372	372
Sodium silicate	-	111	111	111
Sodium hydroxide	-	45(12M)	45(16M)	45(12M)

TABLE III: MIX PROPORTIOS OF SERIES 2 MIX

Material	Mass (kg/ m^3)			
	OPCF1	GPCF1	GPCF2	GPCF3
Cement	433	-	-	-
Coarse aggregate	1063	1123	1123	1123
Fine aggregate	708.8	749	749	274
Biomass aggregate	-	-	-	375
Fly ash	-	372	372	372
Sodium silicate	-	111	111	111
Sodium hydroxide	-	45(12M)	45(16M)	45(12M)
Treated EPS	-	-	-	100
Glass fiber	2.5	2.5	2.5	-

For series 1 concrete mixes, sodium hydroxide (NaOH with 98% purity) flakes were dissolved in water and sodium silicate solutions were then added. The solid of sodium hydroxide must dissolve in water to make a solution with required concentration. For instance, NaOH solution with a concentration of 12 Molar consists of 12 x 40 = 480 grams of NaOH solids per liter of solution, where 40 is molecular weight of NaOH. Both the liquid were mixed together and alkaline liquid was prepared at least two hours before use. Superplasticizer was used to improve workability of fresh concrete. Coarse aggregate and fine aggregate in saturated surface dry condition was prepared. The aggregate and fly ash were mixed dry in drum mixer for about 5 minutes.. At the end of this dry mixing, the alkaline liquid, superplasticizer and water were mixed together for ten minutes. The Series 2 concrete mixes were added glass fibre, biomass aggregate and treated expanded polystyrene in the mixtures.

After mixing, slump of fresh geopolymer concrete and diameter flow were determined. Concrete cubes and prisms of sizes (100x100x100mm) and (100x100x500mm) were cast. There were 36 prisms of GPC as control and 36 prisms with added glass fiber for flexural strength test at 7 days, 14 days, and 28 days. 108 cube size 100mm were cast to determine compressive strength at 7 days, 14 days, 28 days, and 56 days. There were 54 cubes of size 100mm for water penetration and sulphuric acid tests conducted at 7 days, 14 days, and 28 days. Each cube and prism specimens were compacted two layers with 25 strokes. The specimens were wrapped with thin vinyl sheet to avoid loss of water due to evaporation. GPC specimens were cured at ambient temperature around 33^0C and heat cured at 60^0C for 24 hours. Flexural strength test is conducted by using three point bending test to determine modulus of rupture of geopolymer concrete prisms. According to BS 1881-118:1983[34].

Water penetration test was carried out by using Rapid Portable Water Penetration (RPWP) equipment [17]. RPWP is an innovation method could consider as non destructive test which can quickly predict the water penetrates into specimen cube. Geopolymer concrete specimen subjected to water pressure at least five bars pressure within half hour and then observed. Ensure that no water leakage from steel plate with covered gasket. Depth of water penetrates in cube specimen was measure.

Concentrated sulphuric acid (98% purity) was used to prepare the diluted sulphuric acid of 10% concentration, 300 ml of sulphuric acid was mixed with 2700 ml of distilled water to get 3 liter of acid solution. To study the effects of exposure to acidic environment, specimens were immersed in 10% sulphuric acid solution at 7days, 14days and 28days. The effects of acid on the specimens were monitored through visual inspection, weight change measurement and compressive strength tests

IV. RESULTS AND DISCUSSION

Workability

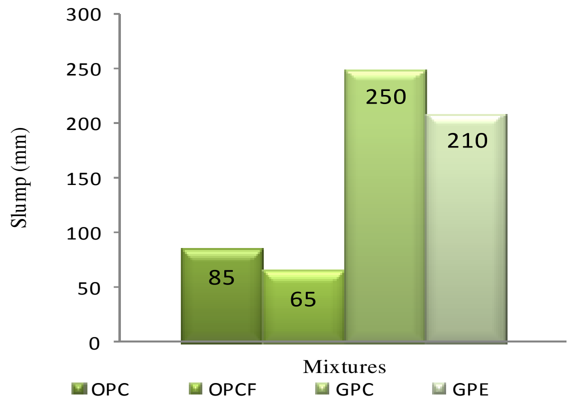

Fig. 1: Workability of OPC and GPC

Workability of GPC was measured by conventional slump measurement. The test results were shown in fig. 1. From the test results show that workability of OPC concrete is much lower than GPC concrete. Workability of GPC concrete has achieved 250 mm slump compared to OPC that is recorded 85 mm slump. In this research, water to geopolymer mass ratio for entire GPC concrete batches are 0.22 which classified is high slump as reported by other researchers. Workability of GPC concrete increases as water to geopolymer mass ratio increases. As the water to geopolymer mass ratio increase, the compressive strength of geopolymer concrete will decrease or achieve moderate strength at the end of curing period. This test trend is analogous to the well known effect of water to cement ratio on the compressive strength of Portland cement concrete. By referring fig. 1, workability of OPC concrete and GPC concrete was affected by glass fibre and treated expanded polystyrene (EPS). Their slump values were recorded are 65 mm and 210 mm. It may be due to the effect of glass fibre used and its uneven distribution in the matrix. The treated expanded polystyrene affects workability of geopolymer concrete. The GPC achieved flow diameter of 530 mm and 250 mm slump.

Density

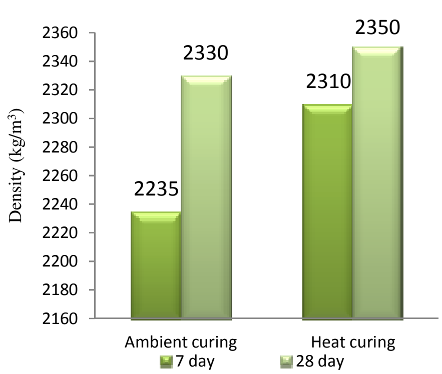

Fig. 2: Variety Density of GPC

Fig.2 shows that density of GPC specimens increased from 7 days and gradually increases at age of 28 days. Two types of curing methods were adopted ambient curing and heat curing. The test results show that GPC subjected to ambient curing achieved lower density compared to heat curing that is 2235 kg/m^3 and 2330 kg/m^3 at 7 days and 28 days. Geopolymer concrete subjected to heat curing achieved densitier of 2310 kg/m^3 and 2350 kg/m^3. Although the GPC specimens are subjected to ambient curing and heat curing the tests result show that density of geopolymer concrete was approximately equal to conventional concrete density ranging from 2235 kg/m^3 to 2350 kg/m^3. By referring to fig.18, density of GPC specimens under heat curing regime significantly results in higher density compared to specimens ambient curing in regime. Typically, as the age of concrete increases slight increase in the density of concrete is observed.

Compressive strength

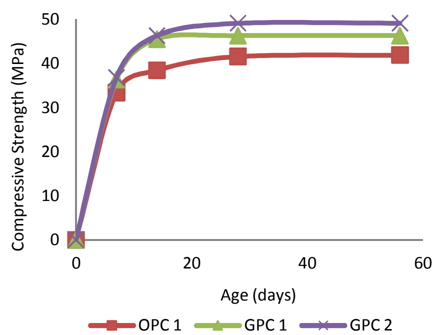

Fig. 3 (a): Ambient curing of concrete specimens (series I)

It can seen in Fig. 3(a) that GPC 2 mix achieved a higher compressive strength when exposed to ambient curing. The compressive strength of GPC 2 mix achieved 49.06 MPa at the age of 56 days. Compressive strength of GPC is influenced by several factors. GPC 2 which contains higher concentration (16 Molar) of sodium hydroxide liquid (Fig. 3 (a)), achieved higher compressive strength compared to GPC 1 (12 Molar). Curing age and curing temperature also influence the compressive strength of GPC specimens. Longer duration of curing and higher temperature for GPC will increase the polymerization process and hence increase the compressive strength.

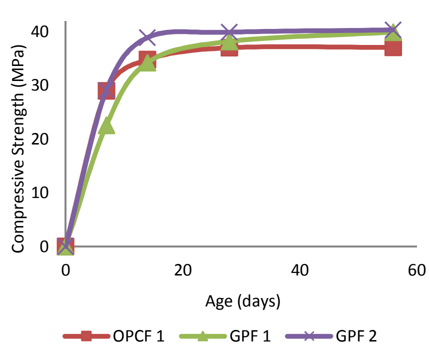

Fig. 3(b): Ambient curing of concrete specimens (series II)

Fig. 3 (b) shows that addition of glass fibres slightly reduces the GPC specimen compressive strength. The compressive strength of OPCF 1 achieved 37.11 MPa at the age of 56 days. GPF 1 and GPF 2 achieved 39.92 MPa and 40.35 MPa respectively at age of 56 days. The test results show that glass fibre does not increase the concrete compressive strength of GPC compared to control. Although both concrete specimens with glass fibre show lower compressive strength but fibers are useful to increase flexural strength of beams or slabs.

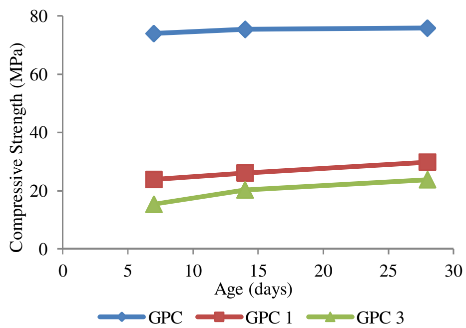

Fig. 3 (c): Heat curing of concrete specimens

As shown in fig. 3 (c), GPC specimen heat cured at 60 ^{0}C for 24 hours enhanced chemical reaction within geopolymer paste. The test results show that GPC 3 containing of biomass aggregate and treated expanded polystyrene (EPS) achieved lower compressive strength that is 23.78 MPa compared to GPC that achieved 75.81 MPa at 28 days. In this study, 50 % of natural fine aggregate was replaced by biomass aggregate. Which is derived from controlled incineration of nature fibre and shell from oil palm industrial waste. This types of aggregate is used for lightweight concrete because aggregate itself is lightweight. The density of lightweight concrete is ranging from 300 kg/m^3 to 1800 kg/m^3 compared to conventional concrete density of about 2400 kg/m^3.Therefore, although biomass aggregate used in geopolymer concrete does not increase compressive strength it is still able achieve the minimum strength according to BS 8110-1:1997. EPS foam was treated in 150^{0}C became a small fine solid particle helps to reduce 4 % density of GPC specimens based on the experimental. The treated EPS is a lightweight material with density of 38 kg/m^3. Treated EPS is useful in lightweight structure especially in the construction of embankments in soft soil.

Flexural strength

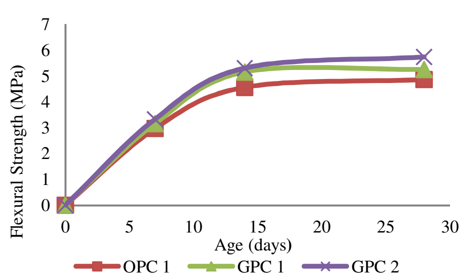

Fig. 4(a): Flexural strength development (series I)

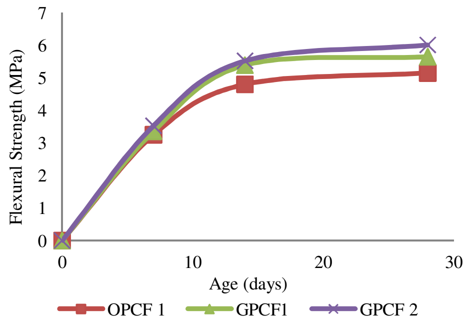

Fig. 4 (b): Flexural strength development (series II)

All concrete specimens achieved more or less the same flexural strength at age of 28 days. This has been shown in fig. 4 (a) and fig. 4 (b). The flexural strength of geopolymer concrete has increased at higher rate from 7 days to 14 days of concrete age, but increase gradually from 14 days to 28 days. It is predicted that the flexural strength of geopolymer concrete will remain fairly constant after 28 days of concrete age. In fig. 4 (a), it was found that GPC 2 concrete specimen achieved higher flexural strength of 5.72 MPa compared to OPC 1 concrete which 4.85MPa at the age of 28 days. However, geopolymer concrete specimens with were added glass fiber achieved higher flexural strength compared to series I (control set) as shown in fig. 4 (b). The highest flexural strength achieved by GPCF 2 was recorded that is 6.01 MPa at age of 28 days. By referring to fig. 4 (b), it can be seen that OPCF 1 with added glass fibre has recorded a high flexural strength of 5.15 MPa compared to OPC 1 without presence of glass fibre.

Typically, fibre was added into mixtures to increase the concrete structural integrity. Glass fibres are types of short discrete fibre that uniform distribution will increase the flexural strength and ductility of concrete. Fibres are good to reduce shrinkage cracking. It will stop the spread of micro-crack of composite and increase tensile strength of concrete. Presence of glass fibre into mixtures, OPC concrete and GPC concrete specimen does not break immediately in middle of span after initiation of the first crack. Glass fibres are types of short fibres which significantly to avoid large strain localization and very effective mix controlling micro-crack of composites.

Correlation between the flexural strength and compressive strength

American Concrete Institute (ACI) had suggested many equations to estimate correlation between flexural strength and compressive strength. The suggested correlation between flexural strength and compressive strength that given by ACI 325[35], ACI 330 [36] and ACI 318 [37] are used to determine relationship of flexural strength concrete based on its compressive strength. The expressions were shown in (2), (3) and (4)

$$fr = 0.75\sqrt{fc'} \quad (2)$$

$$fr = 0.44fc'^{2/3} \quad (3)$$

$$fr = 0.7\sqrt{fc'} \quad (4)$$

Where:

f r is flexural strength value
fc' is compressive value

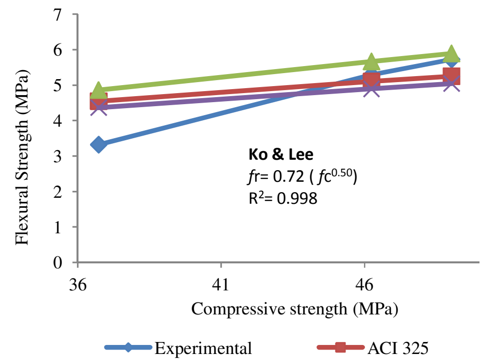

Fig. 5 (a): Correlation between flexural strength and compressive strength for GPC concrete series 1

Fig. 5 (a) shows a plot of flexural strength and compressive strength of geopolymer concrete series 1. The experimental results show a linear relationship between flexural strength and compressive strength of geopolymer concrete series 1. The coefficient of determination (R^2) value for the relationship is 0.998 which is close to 1. By referring fig. 5 (a), it was found that the equation was established by ACI 325 that is 0.75 √ *f*c' is not suitable to predict the flexural strength of geopolymer based on its compressive strength. Hence, a new correlation based on experimental result was established that is 0.72 √ *f*c' (denoted as Ko & Lee) for this geopolymer concrete.

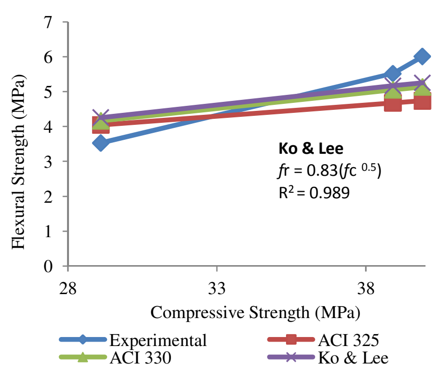

Fig. 5 (b): Correlation between flexural strength and compressive strength for GPC concrete series 2

The flexural strength and compressive strength of GPC concrete series 2 is plotted as shown in fig. 5 (b). Glass fibre was added into mixtures of geopolymer concrete series 2. It clearly shows that both linear relationship between geopolymer concrete series 1 and series 2 is slightly differences. By referring fig. 5 (b), the value of determination (R^2) of geopolymer concrete series 2 is 0.989. The results indicate a linear relationship between flexural strength and compressive strength of geopolymer concrete series 2. Equation was established by ACI 325 that is 0.75 √ *fc*' is not suitable to predict flexural strength based on its compressive strength. Experimental results show that equation was established (denoted Ko & Lee) that is 0.83 $fc'^{0.5}$ suitable to predict flexural strength of geopolymer based on its compressive strength. Typically, additive of glass fibre significantly increase the correlation between the flexural strength and compressive strength.

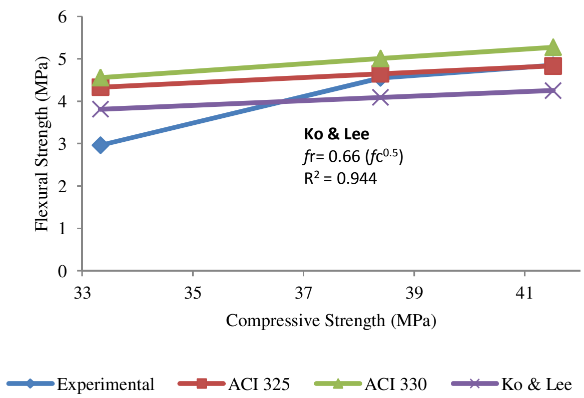

Fig. 5 (c): Correlation between flexural strength and compressive strength for OPC concrete series 1

As shown in fig. 5 (c), it was found that relationship between the flexural strength and compressive strength of Portland cement concrete series 1 is slightly linear. The value of determination (R^2) is 0.944. Based on figure above, it shows that equation established by ACI 325 that is 0.75 $\sqrt{fc'}$ tend to overestimate the flexural strength of Portland cement concrete based on its compressive strength. Therefore, a new correlation based on the experimental result was established (denoted as Ko & Lee) that is 0.66 $\sqrt{fc'}$ for this Portland cement concrete.

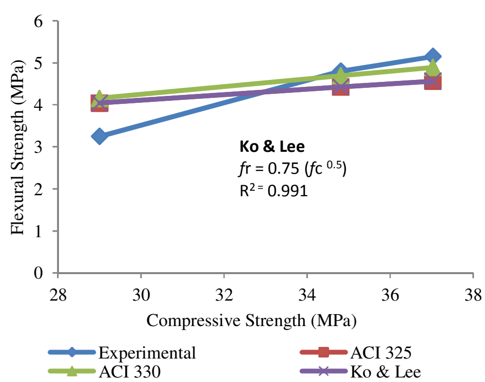

Fig. 5 (d): Correlation between flexural strength and compressive strength for OPC concrete series 2

By referring to fig. 5 (d), it was found that the relationship between flexural strength and compressive strength is linear. The value of determination (R^2) is 0.991. Compared to fig. 5 (c), it shows that linearity of Portland cement concrete series 2 is higher than Portland cement concrete series 1 due to presence of glass fibre into mixtures. Based on figure above, it shows that equation was established by ACI 325 that is 0.75 $\sqrt{fc'}$ is appropriate to predict the flexural strength of OPC concrete based on its compressive strength. The equation established by ACI 325 that is 0.75 $\sqrt{fc'}$ is similar to experimental equation (denoted as Ko & Lee) for this Portland cement concrete.

Water penetration

In this research, 100 mm geopolymer concrete cube specimens were tested by using Rapid Portable Water Penetration equipment (RPWP) to determine water penetrates into cube specimens. Rapid Portable Water Penetration is considered an alternative non destructive testing method which could quickly predict depth of water penetrates in cube specimens. The water penetration tests result was shown in fig. 6 (a) and fig. 6 (b).

Compared to conventional water permeability tests, RPWP test is more convenient and reliable method for assessing concrete durability. It due to conventional water permeability test method would take few weeks to obtain results. Besides that, procedures to conduct the water permeability test is required some precaution during setting up the apparatus. It is to prevent any seepage of water from the concrete cover in contact with the pressure chamber. Additional, the apparatus needs calibrated with mature concrete cube test of known value of water permeability and conditioned for the calibration.

Typically, water penetration of conventional concrete is higher at early state of fresh concrete at age of 7 days but gradually decrease as the age increase at 28 days. It i predicted that the water penetration of geopolymer concrete will remains fairly constant after 28 days of concrete age.

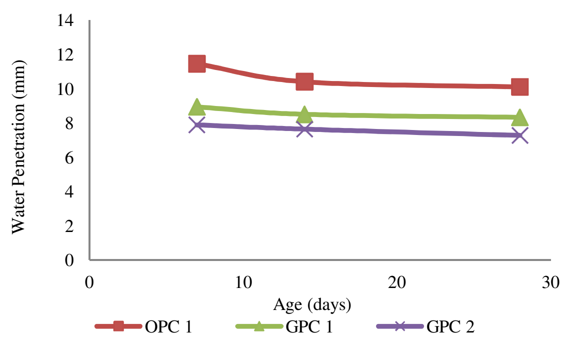

Fig. 6 (a): Water penetration development of concrete series 1

In fig. 6 (a), depth of water penetration of Portland cement concrete was 11.45 mm which is higher than geopolymer concrete. When the water cement ratio is high and degree of hydration is low, the cement pastes exhibited high capillary porosity. Therefore, depth of water penetration for Portland cement concrete would results higher than geopolymer concrete. As hydration progresses, most of the pores will be reduced in size and will lose their interconnections. Hence, the depth of water penetration in Portland cement concrete cube specimens tends to decrease and achieved 10.1 mm at the end of 28 days.

Form fig. 6 (a), it can be seen that the depth of water penetration in geopolymer cube specimens (GPC1 and GPC 2) have achieved 8.94 mm and 7.88 mm at 7 days of concrete age. However, the depth of water penetration of geopolymer concrete gradually decreased to 8.5 mm and 7.26 mm at the end of 28 days of concrete age. Compared to Portland cement concrete, geopolymer concrete has better water penetration resistance. Pozzolanic material will enhance pore refinement of geopolymer paste to prevent water penetrate into geopolymer concrete.

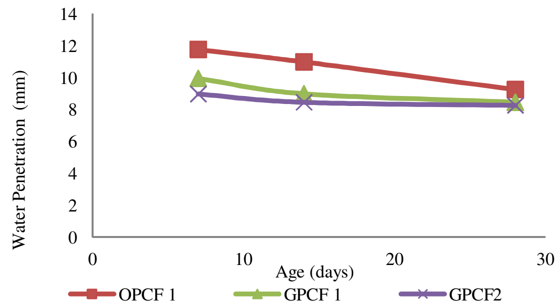

Fig. 6 (b): Water penetration development of concrete series 2

By referring fig. 6 (b), it can be seen that at early stage of water penetration of geopolymer concrete (GPCF 1 and GPCF 2) have achieved 9.95 mm and 8.97 mm at 7 days of concrete age. However, the depth of water penetration in cube specimens was gradually decreased at 14 days of concrete age with increasing in NaOH concentration from 12 Molar to 16 Molar. It was found that the depth of water penetration for geopolymer concrete (GPCF 1 and GPC F2) has decreased as the concrete age increase and higher concentration of NaOH. From fig. 6 (b), it can be seen that the geopolymer concrete (GPCF2) has water penetration of 8.25 mm at the end of 28 days. The test results show that the presence of glass fibre absorbs more water compared to control set was shown in fig. 6 (a).

Geopolymer concrete specimens remained structurally intact in the same acidic solution after 28 days of concrete age. Form the observation, geopolymer concrete exhibit very fine localized cracks and soft surface. Geopolymer concrete consists of fly ash which known as a pozzolana and low reactivity material. Pozzolana material used to improve the durability of geopolymer concrete. With adequate curing, pozzolana generally enhances pore refinement of concrete specimens. Although geopolymer concrete specimens immersed in 10% of sulphuric acid at 28 days, but it still remain intact structurally and did not show any deterioration compared to Portland cement concrete. Therefore, geopolymer concrete is suitable for construction in tough environment.

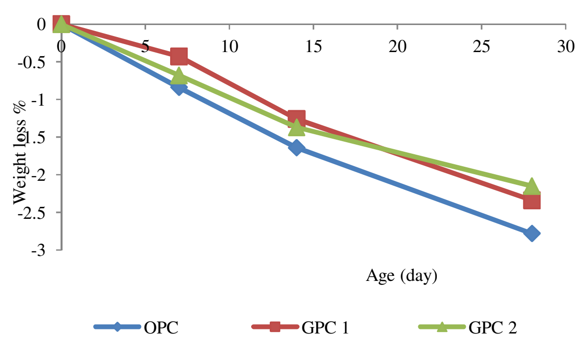

Fig. 7: Weight changes in geopolymer concrete specimens in 10% of sulphuric acid

Portland cement concrete and geopolymer concrete with different concentration of sodium hydroxide (12M and 16M) were immersed in 10% of sulphuric acid test conducted at 7 days, 14 days and 28 days. Typically, it was found that the weight of concrete specimens decrease as the concrete age increase in 10% of concentration sulphuric acid. This is shown in Fig. 7.

The Initial weight losses of geopolymer concrete with concentration of sodium hydroxide (12M) dropped from 0.43 percent at 7 days and gradually dropped to 2.34 percent at the end of 28 days. In contrast, weight loss of geopolymer concrete specimen with concentration of sodium hydroxide (16M) was dropped initially from 0.68 percent at 7 days and gradually dropped to 2.15 percent at 28 days. The weight losses of geopolymer concrete specimens were influenced by different molar concentration of sodium hydroxide. Geopolymer concrete specimens with 12M has higher percentage of weight loss compared to geopolymer concrete specimens with 16M.

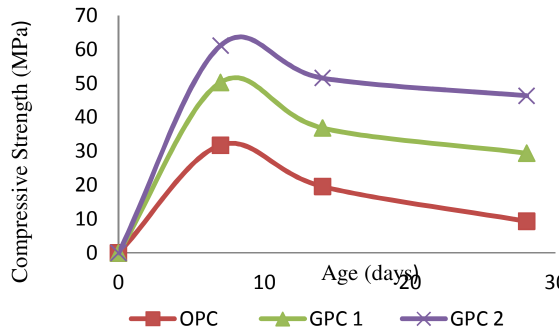

Fig. 8: Compressive strength change of concrete specimens in 10% of sulphuric acid

Compressive strength tests were carried out to determine impact of acidic attack on mechanical performance of Portland cement concrete and geopolymer concrete. This has been shown in fig. 8. Generally, compressive strength of concrete specimens increases as the concrete age increases. However, compressive strength of concrete specimens decreased as longer period immersed in 10% sulphuric acid. The initial compressive strength of Portland cement concrete has achieved 31.75 MPa at 7 days of concrete age but gradually dropped to 9.35 MPa at the end of 28 days of concrete age. The compressive strength of Portland cement concrete decreased due to hydration compound of cement was neutralized by sulphuric acid. The binder or alkali aggregate was disintegrated because the internal structure concrete loose and weak when exposure to sulphuric acid attack. Therefore, compressive strength of Portland cement concrete is weak than geopolymer concrete in sulphuric acid tests.

By referring to fig. 8, it shown that compressive strength of geopolymer concrete specimens does not change much compared to Portland cement concrete specimens. Different concentration of sodium hydroxide (12M and 16M) solution would result different value of compressive strength for geopolymer concrete. Higher concentration of sodium hydroxide (16M) in geopolymer concrete specimen results in little strength loss compared to concentration of sodium hydroxide (12M). The initial strength of geopolymer concrete with concentration of sodium hydroxide (16M) was achieved 61.2 MPa at 7 days but gradually decrease to 46.4 MPa at the end of 28 days when immersed in 10% of sulphuric acid. However, lower concentration of sodium hydroxide (12M) of geopolymer concrete exhibited large strength loss compared to higher concentration of sodium hydroxide (16M) in geopolymer concrete specimens. It may due to lower content of Na_2O in geopolymer concrete would results lower compressive strength. Geopolymer concrete specimens were observed to posses substantial residual compressive strength even when they are almost fully de-alkalized at the end of 28 days exposure in 10% of sulphuric acid solution.

V. CONCLUSION

A total of 234 concrete specimens were tested for compressive strength, flexural strength, water penetration and sulphuric acid resistance. The results were analyzed to establish a new correlation equation between flexural strength and compressive strength. The findings were compared with equations established by American Concrete Institute. The conclusions are outlined below:

(i) Geopolymer concrete specimens have achieved 250 mm slump and slump flow of 530 mm which are higher than Portland cement concrete.
(ii) Treated expanded polystyrene (EPS) and glass fibre reduces the workability of concrete.
(iii) The treated expanded polystyrene (EPS) and biomass aggregate reduced the specimens density by about 4%.
(iv) The density of geopolymer concrete was close to Portland cement concrete, ranging from 2235 kg/m^3 to 2350 kg/m^3.
(v) The geopolymer concrete cured at elevated temperature achieved higher compressive strength of 75.8 MPa.
(vi) Higher concentration of sodium hydroxide (16M) results in higher compressive strength of geopolymer concrete (GPC 2) of 49 MPa when exposed to ambient curing temperature of 33^{o}C.
(vii) Geopolymer concrete prism specimen (GPC 2) with presence of glass fibre achieved higher flexural strength of 6 MPa compared to Portland cement concrete of 5.15 MPa.
(viii) The rapid portable water penetration test system has potential to be used as an innovative non destructive tests for concrete cube specimens.
(ix) Geopolymer concrete specimens achieved lower water penetration compared to Portland cement concrete (water penetration has reduced from 10.1 mm to 7.26 mm at the end of 28 days).
(x) In sulphuric acid test, geopolymer concrete has less localized crack.
(xi) The weight loss and compressive strength reduction of geopolymer concrete was less than Portland cement concrete.

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