

Strength Characteristic of Geopolymer Made using Sarawak Fly Ash

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ABSTRACT: The Sarawak coal used for the combustion at Sejingkat Power Station is classified as sub-bituminous. Sarawak fly ash which is produced from the power plant falls under Class F type, where its total percentage of $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ is greater than 70%. The coal forms under the Balingian Formation of late Miocene to Early Pliocene age is mined nearer to the ground surface. The particle size distribution of Sarawak fly ash is $d_{10}=1.8\mu\text{m}$, $d_{30}=5\mu\text{m}$ and $d_{60}=17\mu\text{m}$. The Coefficient of Uniformity and the Coefficient of Curvature are 9.4 and 0.8, respectively. In this research, geopolymer made with different ratios of $\text{Na}_2\text{SiO}_3/\text{NaOH}$ and alkali activator/fly ash are presented. The results obtained from the experiments show that the compressive strength of geopolymer increases when the ratios of $\text{Na}_2\text{SiO}_3/\text{NaOH}$ and alkali activator/fly ash are increased. However, further increment of these ratios result in reduction of the compressive strength. The workability is found to increase when alkali activator/fly ash is increased. Inversely, the workability decreases when $\text{Na}_2\text{SiO}_3/\text{NaOH}$ is increased. Having high compressive strength and adequate workability, geopolymer can be a potential environmental friendly and sustainable construction material for various applications in geotechnical field.

KEYWORDS: Geopolymer, Fly ash, Mixture proportions, Compressive Strength

1. INTRODUCTION

Geopolymer is an inorganic polymer which comprises aluminosilicate materials such as fly ash in alkaline environment (Davidovits 2008; Ozer and SezenSoyer-Uzun 2015). The use of fly ash in making geopolymer has gained much interest and popularity worldwide. It is the by-product from coal-fired power station. For making geopolymer, fly ash is commonly activated by alkali activator such as sodium hydroxide (NaOH) (Criado et al. 2007; Heah et al. 2012; Lizcano et al. 2012; Nematollahi and Sanjayan 2014; Palomo et al. 1999; Ryu et al. 2013), potassium hydroxide (KOH) (Lizcano et al. 2012; Palomo et al. 1999), sodium silicate (Na_2SiO_3) (Criado et al. 2007; Heah et al. 2012; Lizcano et al. 2012; Nematollahi and Sanjayan 2014; Palomo et al. 1999; Ryu et al. 2013), potassium silicate (K_2SiO_3) (Lizcano et al. 2012; Palomo et al. 1999) etc. The combined use of NaOH and Na_2SiO_3 is the most common practice in term of cost effectiveness and compressive strength performance.

The utilisation of fly ash in making geopolymer can greatly reduce the annual disposal of fly ash, consequently reducing land space for landfill, the risk of air pollution and groundwater contamination. The reduction of carbon emission of fly ash-based geopolymer in comparison to conventional Ordinary Portland Cement (OPC) concrete provides the benefits of geopolymer being more environmental friendly and as a greener material (Duxson et al. 2007). Geopolymer has been used as a sustainable construction material in structural elements of buildings such as beams, columns and piles (Power Pile 2013; Sarker 2008; Shrest 2013; Uretok 2014), besides also being viable as a ground treatment method when mixed with weaker clayey soils (Cristelo et al. 2013; Cristelo et al. 2012; Zhang et al. 2013).

In Sarawak, there are two coal-fired power stations. Sejingkat Power Station is located in Kuching whereas Mukah Power Station is located in Mukah. In this research, the Sarawak fly ash which is sourced from the former power station is studied. The combustion of coal at Sejingkat Power Station is carried out in 2 boilers (i.e. 2 units x 50 MW and 2 units x 55 MW). The annual coal combustion is approximately 1 million tons whereas the production of fly ash is approximately 7 to 10% out of the annual coal combustion. This fly ash is captured by the electrostatic precipitator. However, most of the captured fly ash is discharged into two ash ponds nearby. As the disposal of fly ash has triggered environmental

issue, it is crucial to widen the application of this industrial by-product.

In this research, geopolymer made from different ratios of $\text{Na}_2\text{SiO}_3/\text{NaOH}$ and alkali activator/fly ash are studied. It is aimed to develop a better understanding and overview of the compressive strength of geopolymer made using Sarawak fly ash. It also aids to enhance the development of fly ash-based geopolymer in Malaysia particular in Sarawak; moreover, to reduce the land for disposing the ash.

2. EXPERIMENTAL PROCEDURES

2.1 Materials

Sarawak fly ash was obtained from Sejingkat Power Station. The chemical compositions of the fly ash are obtained using WD-X-Ray Fluorescence Spectrometer (WD-XRF) as shown in Table 1. According to ASTM-C618 (2005), Sarawak fly ash is classified as Class F type, where its total percentage of $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ is greater than 70%.

Washed sand with saturated surface dry condition was prepared prior to sample casting. The combined used of 8M NaOH and Na_2SiO_3 (8.8%–9.5% Na_2O and 28%–30.6% SiO_2 by weight) was selected in this research.

Table 1. Chemical Composition of Sarawak Fly Ash

Elements (%)	Sarawak Fly Ash (SFA)
SiO_2	43.8
Al_2O_3	18.1
Fe_2O_3	7.7
CaO	3.9
MgO	0.5
MnO	22.8
K_2O	2.0
Na_2O	0.3
SO_3	0.1
TiO_2	0.6
P_2O_5	0.1
LOI	0.5

2.2 Sample Preparation and Tests

The geopolymer samples made with different ratios of $\text{Na}_2\text{SiO}_3/\text{NaOH}$ and alkali activator/ash are tabulated in Table 2. Fly ash was initially mixed with sand using the Mortar mixer. It was further mixed with alkali activators. The mixture was casted into the cubic moulds with dimensions of 50 mm × 50 mm × 50 mm. The samples were placed on the vibrating table until the air bubbles within the sample were removed. The samples were then sealed with plastic sheet to prevent the loss of moisture when it was subjected to heat curing in oven at 60°C. After 24 hours, the samples were removed from the oven and demoulded for cube test or further curing at room temperature until the date test.

The workability of the mixture was conducted using the flow table in accordance to ASTM-C1437 (2013). The compressive strength of the samples were obtained using the compression test machine in accordance to ASTM-C109/C109M (2005).

Table 2. Mix ratios use for casting of geopolymer samples

Ash/sand ratio	Alkali activator type	$\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio	Alkali activator/ash ratio	Curing age
1:2	Combined use of NaOH and Na_2SiO_3	0.5, 1, 1.5, 2, 2.5, 3	0.3, 0.4, 0.5, 0.6	1 day, 7 days

3. RESULTS AND DISCUSSION

3.1 Characterisation of Sarawak fly ash

Sarawak fly ash is produced from burning sub-bituminous coal. From the geological point of view, this coal is formed as part of the Balingian Formation of late Miocene age – Begrih Formation of Early Pliocene age. It is mined nearer to the ground surface.

Sarawak fly ash is darker in shade (i.e. grey in colour). The particle size distribution of this fly ash is $d_{10} = 1.8 \mu\text{m}$, $d_{30} = 5 \mu\text{m}$ and $d_{60} = 17 \mu\text{m}$. It comprises 90% of the total fly ash particle (d_{90}) smaller than 40 μm . As reported by Chatterjee (2011) that geopolymer made of fly ash with smaller particle size exhibits excellent compressive strength. It also enhances the geopolymerisation as smaller particles are more active in the alkali activation process than larger particles (Komljenovi et al. 2010). It is postulated that Sarawak fly ash which consists of high amount of fine particles could significantly increase the compressive strength of geopolymer.

The Coefficient of Uniformity (C_u) and the Coefficient of Curvature (C_c) are 9.4 and 0.8, respectively. It is classified as well graded. The C_u and C_c values imply that Sarawak fly ash is potential being a raw material for making high strength geopolymer. As it contains wider ranges of particle sizes, the structure formed tends to be very rigid due to the closely packed of particles and lesser voids within the sample. Fine particles could fill up the voids between larger particles; moreover, it increases the density of sample thus enhancing the strength capability.

3.2 Workability

The workability of the sample increases when the alkali activator/ash ratio is increased as shown in Figure 1. The results show similar pattern to the research findings as reported by Wee et al. (2010). From alkali activator/ash of 0.4 to 0.5, the workability intensively increases. The mixture tends to become more fluid when the alkali activator/ash ratio is increased. It is because that higher amount of liquid content presents in the mixture than the solid content at higher ratio. However, the increment of workability decreases from alkali activator/ash of 0.5 to 0.6. The highest

workability is observed to be approximately 230 mm when alkali activator/ash ratio is 0.6. When alkali activator/ash ratio is 0.3, the mixture collapses and becomes unmeasurable when it is subjected to flow table test. It is supposed that the alkali activators are insufficient to dissolve the fly ash particles in the mixture. The mixture tends to be very dry when higher solid content than liquid content is presented in the mixture thus making it difficult to flow.

As shown in Figure 2, the increase of $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio decreases the workability of the sample. It is most likely due to the high amount of Na_2SiO_3 presents in the mixture at higher ratio. Na_2SiO_3 are highly viscous whereas NaOH is fluid-like nature. Therefore, the increase of Na_2SiO_3 increases the viscosity thus reducing the workability. When alkali activator/ash ratio is 0.6, the workability is consistent regardless of the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratios. It seems that alkali activator/ash of 0.6 is the optimum workability for geopolymer made using NaOH and Na_2SiO_3 . Further increment of alkali activator/ash could not lead to higher workability. In this research, the highest workability is obtained when $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio is 0.5.

From the ground improvement point of view, geopolymer with high workability implies good and faster flow ability. The geopolymer slurry can easily flow further from the original injection point. Besides that, it acts as binder which can easily fill up the voids between the soft soils particles in order to improve the soil strength and stiffness. However, high workability has negative effect on compressive strength. The effect of workability on compressive strength can be observed hereinafter.

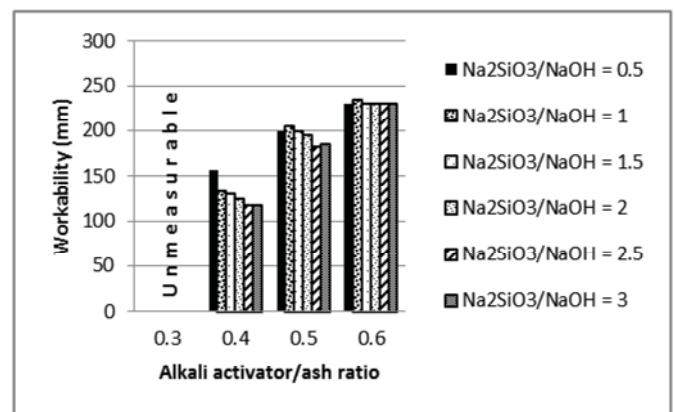


Figure 1 Effect of alkali activator/ash on workability of geopolymer

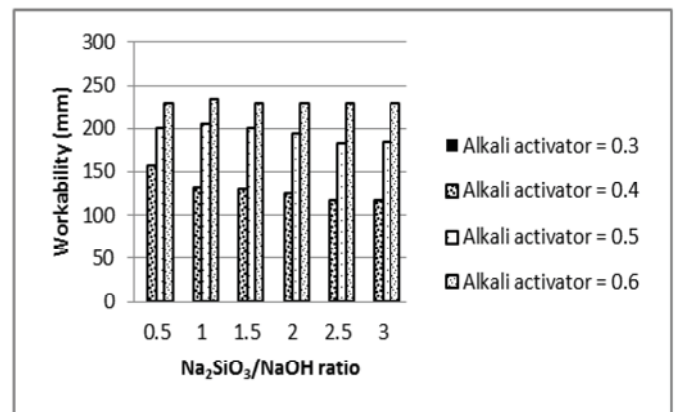


Figure 2 Effect of $\text{Na}_2\text{SiO}_3/\text{NaOH}$ on workability of geopolymer

3.3 Compressive Strength

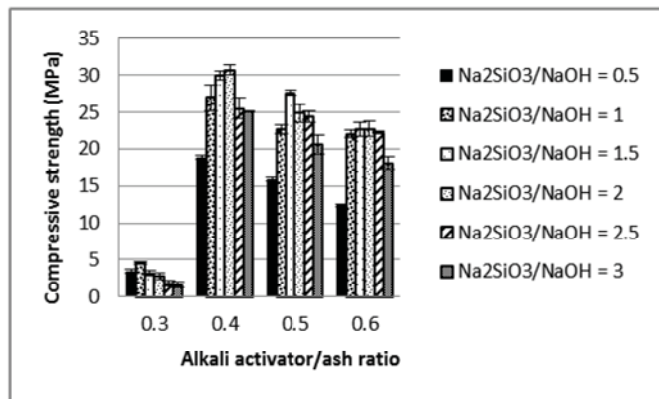
3.3.1 Effect of alkali activator/ash ratio on compressive strength

The effect of alkali activator/ash ratio on compressive strength is shown in Figure 3. The compressive strength is initially very low when alkali activator/ash ratio is 0.3. It intensively increases when alkali activator/ash ratio is 0.4. However, the compressive strength decreases with the further increment of alkali activator/ash. Alkali activator/ash of 0.4 is the optimum ratio to obtain the highest compressive strength regardless of the ratio of $\text{Na}_2\text{SiO}_3/\text{NaOH}$.

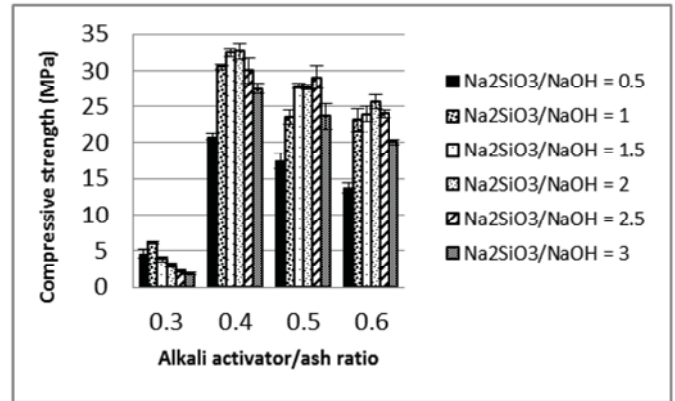
It shows that alkali activator plays an important role for the strength development of sample. When the alkali activator is insufficient to react with the fly ash particles, the sample tends to be very weak. When it is subjected to low test load, the sample fails easily. It explains why geopolymer at alkali activator/ash of 0.3 exhibits nearly null compressive strength. Contrariwise, most of the fly ash particles are activated by the alkali activator at high alkali activator/ash. Therefore, the formation of rigid structure increases the strength capability. However, excessive amount of alkali activators in the sample may hinder the geopolymerisation process. Additionally, it may further push apart the fly ash particles thus reducing the strength capability (Heah et al. 2012).

For the curing conditions, the results show that the strength gained over the age is minimal. It demonstrates that most of the strength is developed within first 24 hours. The effect of curing temperature on the compressive strength is significant. As shown in Figures 3b-c, geopolymer cured at 60°C shows significant higher compressive strength than those cured at room temperature. This phenomenon shows that curing temperature plays an important role on the strength development. Based on the study that conducted by Hardjito (2005), compressive strength of geopolymer increases when curing temperature is increased. However, strength gain after curing temperature of 60°C is not significant. It may not lead to higher compressive strength when it is cured at higher curing temperature. As the geopolymer cured at 60°C demonstrates high early strength, it shows the potential of being used as alternative construction material for precast purposes.

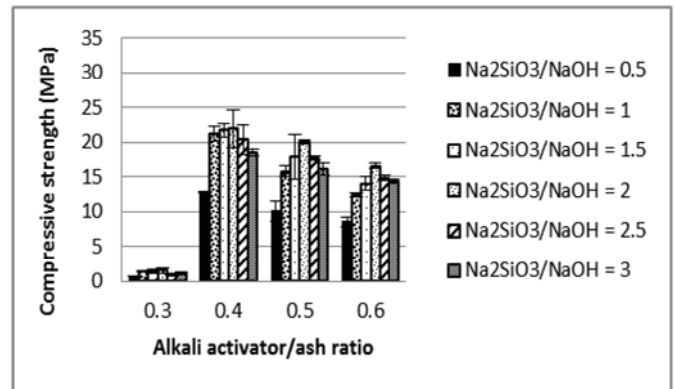
Although the compressive strength of geopolymer sample cured at room temperature is lower, it exhibits possible alternative of geopolymer being used for ground improvement. Having evidently showed that geopolymer can be formed at room temperature, the geopolymer slurry can be directly injected into soft ground to improve the soil strength. It is more practical and reasonable to bind the soft soil with the geopolymer slurry in-situ at room temperature rather than other curing temperatures.



(a) Curing age: 1 day, Curing temperature: 60 °C



(b) Curing age: 7 days, Curing temperature: 60 °C

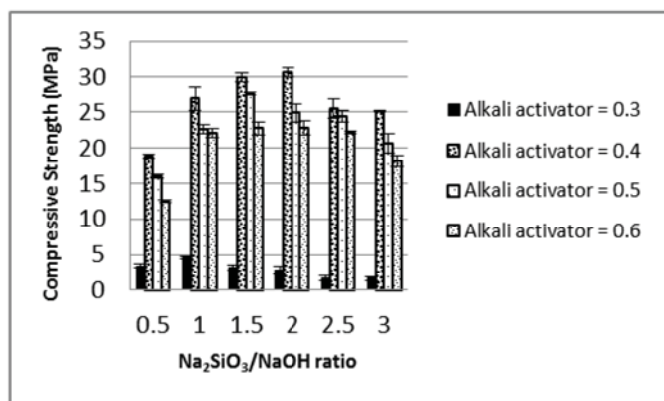


(c) Curing age: 7 days, Curing temperature: room temperature

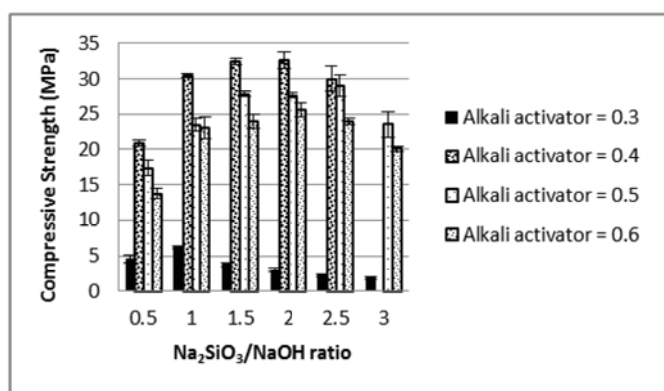
Figure 3 Effect of alkali activator/ash ratio on compressive strength of geopolymer

3.3.2 Effect of $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio on compressive strength

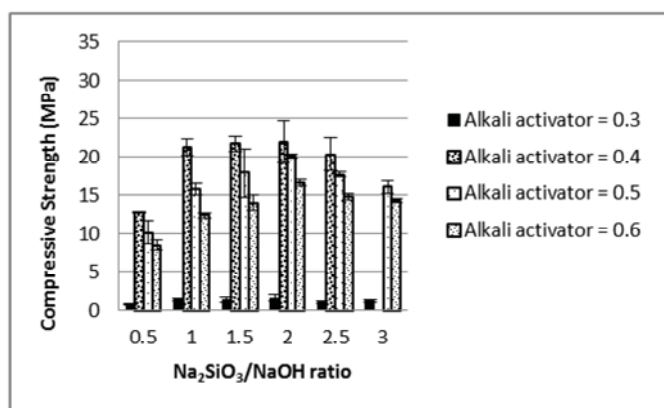
The increment of $\text{Na}_2\text{SiO}_3/\text{NaOH}$ shows positive effect on compressive strength as shown in Figure 4. The compressive strength is initially low at low $\text{Na}_2\text{SiO}_3/\text{NaOH}$. It gradually increases to a peak value then follow by a strength loss with the further increment of $\text{Na}_2\text{SiO}_3/\text{NaOH}$. The highest compressive strength is obtained when $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio is 2. The Na_2SiO_3 content increases when $\text{Na}_2\text{SiO}_3/\text{NaOH}$ is increased. It is known that Na_2SiO_3 provides Si content to the system for geopolymerisation (Xu and Deventer 2000) thus enhancing the strength development. However, excessive Na_2SiO_3 causes the formation of aluminosilicate gel precipitation moreover obstructing the alkali hydroxide to leach out Al and Si content for geopolymerisation (Lee and Deventer 2002; Villa et al. 2010). Therefore, this is supposed to be the reason causing strength loss when higher ratio is used. For samples cured at different curing conditions, the tendency of strength development shows similarity as illustrated in Figures 4a-c. Although the ratio of $\text{Na}_2\text{SiO}_3/\text{NaOH}$ is varied, the highest compressive strength is obtained when it is cured at 60 °C.



(a) Curing age: 1 day, Curing temperature: 60 °C



(b) Curing age: 7 days, Curing temperature: 60 °C



(c) Curing age: 7 days, Curing temperature: room temperature

Figure 4 Effect of Na₂SiO₃/NaOH on compressive strength of geopolymer

3.2 Potential use of geopolymer in geotechnical field

Geopolymer is a very popular alternative construction material to OPC worldwide. In Europe, USA, and Australia, geopolymer has been used for ground improvement and constructing structural elements. From the geotechnical aspect, geopolymer can be used for fabrication of concrete pile, grouting works, soil improvement as mentioned earlier.

There are several types of pile fabrication such as concrete pile, timber pile, steel pile and composite pile. The most common type used for construction is concrete pile. It is known that OPC is the main material to produce concrete. The carbon emission during the manufacturing of OPC enhances the detrimental greenhouse effect and global warming. Therefore, the application of geopolymer in pile construction is not only environmental friendly but also more sustainable due to its superior properties over

traditional concrete (Gourley and Johnson 2005). Ariffin et al. (2013) reported that geopolymer show better acid resistance than OPC concrete. The latter type experiences severe deterioration upon exposure to acidic environment whereas the former type only exhibits minor effect on its sample surface, which turns softer in comparison to the original state. Kishan and Radhakrishna (2013) show that geopolymer exhibits higher water absorption than OPC concrete at early stage but the absorption ability decreases and tends to be lower than OPC concrete at the later stage. The water permeability decreases when the compressive strength increases (Wongpa et al. 2010). Having superior properties than OPC concrete, geopolymer could reduce the corrosion of the pile structure in particular the rusting of reinforcement due to the water or acid ingress through inevitable crack lines. The results obtained in this research show that geopolymer with compressive strength of approx. 32 MPa is durable and comparable to the traditional concrete for pile and foundation construction.

Another application for geopolymer in geotechnical field is for grouting purposes. For example, the injection of geopolymer into weak foundation soils to form rigid columns (Pile 2013) will underseal the voids underneath the foundation structure and to realign (i.e. lift up) sunken concrete slab with the injection of expansive geopolymer (Uretak 2014). This technique not only aids to encounter the underlying problem without disturbing the existing structure above but also reducing the duration of installation. Moreover, it increases the bearing capacity of soil under the building. Cristelo et al. (2011) studied the soil improvement methods using geopolymer grout and cement grout. In their research, it shows that cement grout obtains higher compressive strength than geopolymer grout at early age (after 28 days) but geopolymer grout exhibits higher compressive strength than cement grout after 1 year.

Other than that, geopolymer can be used to strengthen soft soils such as marine clay and peat. These two types of soils usually have low shear strength but high compressibility. In particular, the latter type consists of high organic content which is commonly found in Sarawak. Traditionally, these soft soils are stabilised using cementitious material such as cement or lime. However, the production of cement has triggered the environmental concern. It is crucial to seek for other alternatives. Zhang et al. (2013) shows that soft soils which are stabilised by geopolymer exhibits more compact microstructure, better strength capability and volume stability. The stabilisation of soft soils using geopolymer in short term although is not desirable in comparison to traditional cement or lime binder, the intensive strength gained over longer period exhibits better strength capability than using cement as stabiliser (Cristelo et al. 2012).

Although geopolymer technology is very popular and common worldwide, the application of geopolymer in Malaysia still remains at research and development stage. This research paper aims to widen the application of geopolymer in the local industry.

3. CONCLUSION

This paper presents the study of geopolymer made using Sarawak fly ash with NaOH and Na₂SiO₃ as the alkali activators. The effect of alkali activator/ash, Na₂SiO₃/NaOH and curing conditions on workability and compressive strength was reported. From the results obtained from the experiments, the workability of geopolymer increases when the alkali activator/ash ratio is increased. However, it decreases when Na₂SiO₃/NaOH is increased. When alkali activator/ash is 0.6, the workability is the optimum regardless of the ratio of Na₂SiO₃/NaOH. Having shown that geopolymer poses high workability, it ensures good and faster flow ability when it is being used for ground improvement and soil stabilisation.

The compressive strength of geopolymer increases when alkali activator/ash and Na₂SiO₃/NaOH are increased. However, it decreases by the further increment of alkali activator/ash ratio and

Na₂SiO₃/NaOH. The highest compressive strength is obtained when alkali activator/ash ratio is 0.4 and Na₂SiO₃/NaOH ratio is 2. The experimental results reveal that most of geopolymer strength builds up within first 24 hours. Curing temperature demonstrates the importance on strength development. Geopolymer cured at 60 °C exhibits higher compressive strength than geopolymer cured at room temperature. The former will be beneficial for being used as precast constructions whereas the latter can be use for in-situ casting.

The potential application of geopolymer in geotechnical field has been reported in this paper. This technology has been widely applied worldwide. However, it is still at developing stage in Malaysia. This research paper aims to widen the application of geopolymer in Malaysia, moreover developing a better understanding and overview of the compressive strength of geopolymer made using Sarawak fly ash.

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