



Author: Leong, Hsiao Yun; Leong Ong, Dominic Ek; Sanjayan, Jay G.; Nazari, Ali
Title: Suitability of Sarawak and Gladstone fly ash to produce geopolymers: a physical, chemical, mechanical, mineralogical and microstructural analysis
Year: 2016
Journal: Ceramics International
URL: <http://hdl.handle.net/1959.3/414969>

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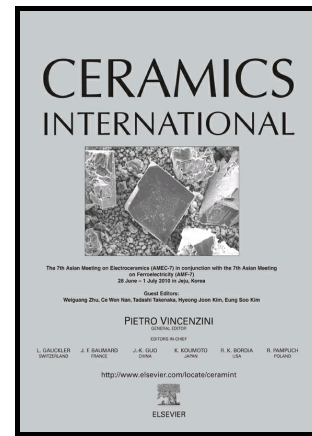
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www.elsevier.com/locate/ceri

PII: S0272-8842(16)30177-8
DOI: <http://dx.doi.org/10.1016/j.ceramint.2016.03.046>
Reference: CERI12417

To appear in: *Ceramics International*

Received date: 31 January 2016
Revised date: 18 February 2016
Accepted date: 6 March 2016

Cite this article as: Hsiao Yun Leong, Dominic Ek Leong Ong, Jay G. Sanjayan and Ali Nazari, Suitability of Sarawak and Gladstone fly ash to produce geopolymers: A physical, chemical, mechanical, mineralogical and microstructural analysis, *Ceramics International*, <http://dx.doi.org/10.1016/j.ceramint.2016.03.046>

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Suitability of Sarawak and Gladstone fly ash to produce geopolymers: A physical, chemical, mechanical, mineralogical and microstructural analysis

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Abstract

Two types of fly ash sourced from Sarawak, Malaysia and Gladstone, Australia reflect differences in chemical compositions, mineral phase and particle size distributions. In this paper, the Sarawak fly ash was used to produce geopolymer in comparison to the well-developed Gladstone fly ash-based geopolymer. Characteristics of fly ash and mixtures proportions affecting compressive strength of the geopolymers were investigated. It is found that the variations of both fly ash types on particle size distributions, chemical compositions, morphology properties and amorphous phase correspond to the compressive strength. The results obtained show that after 7 days, geopolymer using Sarawak fly ash has lower compressive strength of about 55 MPa than geopolymer using Gladstone fly ash with strength of about 62 MPa. In comparison with Gladstone fly ash-based geopolymer, it showed that Sarawak fly ash-based geopolymer can be a potential construction material. Moreover, the production of Sarawak fly ash-based geopolymer aids to widen the application of Sarawak fly ash from being treated as industrial waste consequently discharging into the ash pond.

Keywords: Sarawak fly ash; Gladstone fly ash; Geopolymer; Compressive strength; Morphology

1. Introduction

Use of fly ash has been widely researched for making geopolymer concrete, a possible alternative to ordinary Portland cement (OPC) concrete. The term 'geopolymer' was introduced by Davidovits in 1979 [1]. Geopolymer has been known to exhibit ceramic-like properties as it comprises alumino-silicate materials such as fly ash in alkaline environment.

High emission levels of CO₂ during the manufacturing of OPC have become an issue since this level of emissions is considered a threat to the existing global climate. The low carbon footprint of geopolymer, which is approximately 80% lower than OPC [2], has shown that geopolymer can be an attractive alternative construction material to OPC. The superior properties of geopolymer such as better acid resistance and long durability have been reported [3]. Geopolymer also shows better performance at elevated temperature as compared to OPC concrete [4].

Properties of fly ash can be varied due to its origin, resources or coal type [5]. Fly ash sourced from different places may have different chemical compositions, mineralogy, morphology, particle size distributions or unburned carbon content [6]. Both chemical and physical properties of fly ash can effectively influence the performance of geopolymer.

The particle size distribution of fly ash plays an important role on the strength development of geopolymer [7]. Fly ash with higher amount of small particle size has been found to exhibit excellent compressive strength [8]. In the alkali activation, small particles are more active than larger particles [9]. The reactivity of fly ash is proportionally to the particle size smaller than 10 μ m rather than the particle size greater than 45 μ m [10]. The former particle size increases the compressive strength while the latter particle size decreases the compressive strength. It is known that the morphology is affected by fly ash particle size [11].

Small particle appears to have smoother surface than large particle [12]. The reduction of particle size improves the workability of the mixture [8]. The formation of irregular grains in fly ash could be due to the incomplete combustion process [11]. Fly ash consists of crystalline phase and amorphous phase has been reported [13, 14]. The amorphous phase of fly ash may be useful for the industry characterisation [14]. The most common phases in fly ash such as quartz and mullite are important to the strength development. However, high content of mullite and quartz decrease the reactivity of fly ash [1].

In Sarawak, few coal fired power stations are planned to be constructed within the development masterplan of Sarawak Corridor of Renewable Energy (SCORE). The production of Sarawak fly ash will increase in tandem with the development. Despite being use on the construction of major dams in Sarawak such as Bengoh Dam, Murum Dam and Bakun Dam, most of the Sarawak fly ash is still being treated as industrial waste and dumped into the ash pond nearby. From the environmental point of view, the widening of Sarawak fly ash application can effectively reduce the land for disposal, moreover, lowering the risk of ground contamination due to improper management of discharged fly ash. From the construction material point of view, the development of Sarawak fly ash-based geopolymer provides an alternative to the ordinary Portland cement-based concrete. The world's first building using geopolymer for structural purpose in Australia has proven the potential use of geopolymer [15]. Therefore, it shows the significance of benchmarking of Sarawak fly ash against the well-developed Gladstone fly ash-based for producing geopolymer.

In this paper, two different types of fly ash, namely Sarawak fly ash (SFA) from Malaysia and Gladstone fly ash (GFA) from Australia have been used to fabricate geopolymer. Study of geopolymer using GFA has been well reported by other researchers [16-20]. As the research around SFA is very limited, the study of geopolymer made of SFA in comparison to GFA can effectively identify the factors influencing the difference of their compressive

strength for future in-depth studies on geopolymer using SFA. It is postulated that the geopolymers produced by GFA and SFA may behave very differently in their respective strength capabilities.

2. Background of the Fly Ashes

2.1. Sarawak fly ash (Malaysia)

In Sarawak, Sejingkat Power Station and Mukah Power Station are the two main coal-fired power stations that are used to generate electricity. Sejingkat Power Station is located in the Sarawak State capital of Kuching in Malaysia. The coal is mainly supplied from the hinterland. Approximately 1 million tons of coal is utilized for the combustion and the daily production of coal ashes is estimated about 1,400 tons. The combustion of coal is carried out in 2 boilers operating independently. The first or older boiler has a capacity to generate 2 units x 50 MW of electricity, while the second or newer boiler has a capacity to generate slightly more electricity at 2 units x 55 MW. The combustion temperature of coal is set at 540 °C. The cooling system utilized water pumped from river and the flow rate of the cooling system is about 10,275 m³/hr. The by-product of the power plant, fly ash, is efficiently captured by the electrostatic precipitator (approximately 99 %) and only 1 % of the fly ash is discharged to the environment through the 120 m chimney. The captured fly ash is disposed into two ash ponds nearby. The coal used for the combustion is classified as sub-bituminous. The geological age of the coal ranges from Miocene to Miocene-Pliocene. In this research, the Sarawak fly ash is sourced from Sejingkat Power Station.

2.2. Gladstone fly ash (Australia)

Another fly ash used in this research is the Gladstone fly ash. GFA is sourced from Gladstone Power Station. This power station is situated at Gladstone, Queensland, Australia. It is the largest power station in Queensland, which generates electricity of 1,680 MW by 6

boilers. The combustion temperature of coal is 540 °C. The cooling water is pumped from Auckland inlet and the flow rate of the cooling system is about 51,840 m³/hr [21]. It is estimated that 4 million tons of coal is used for the combustion annually [22]. The coal is supplied from the mining field at Central Queensland. In this region, the coal is classified as bituminous coal with the coal age ranged from Permian, Triassic, Jurassic and Cretaceous [23]. This fly ash is chosen for comparison because there are already a relatively large number of publications associated to GFA and hence, it would be easier to develop benchmarks against GFA [24].

3. Experimental works

3.1. Materials

The chemical composition of both fly ash types was studied using WD-X-ray Fluorescence Spectrometer (WD-XRF) and the results are shown in Table 1. Both SFA and GFA are classified as Class F in accordance to the ASTM C618 standard [25].

Table 1 Chemical Composition of Fly Ash

| Elements (%) | Gladstone Fly Ash (GFA) | Sarawak Fly Ash (SFA) | Manganese Slag[26] | Ordinary Portland cement (OPC)[27] |
|--------------------------------|-------------------------|-----------------------|--------------------|------------------------------------|
| SiO ₂ | 51.1 | 43.8 | 28.3 | 21.8 |
| Al ₂ O ₃ | 25.7 | 18.1 | 10.5 | 5.8 |
| Fe ₂ O ₃ | 12.5 | 7.7 | 0.3 | 3.3 |
| CaO | 4.3 | 3.9 | 11.0 | 63.0 |
| MgO | 1.5 | 0.5 | 14.9 | 2.0 |
| MnO | 0.2 | 22.8 | 26.0 | - |
| K ₂ O | 0.7 | 2.0 | 5.1 | 0.3 |
| Na ₂ O | 0.8 | 0.3 | 2.7 | 0.5 |
| SO ₃ | 0.2 | 0.1 | - | 2.4 |
| TiO ₂ | 1.3 | 0.6 | - | - |
| P ₂ O ₅ | 0.9 | 0.1 | - | - |

| | | | | |
|-----|-----|-----|---|-----|
| LOI | 0.6 | 0.5 | - | 1.0 |
|-----|-----|-----|---|-----|

From the vision observation, SFA is darker in shade (i.e. grey color) when compared to GFA (i.e. brownish) as shown in Fig. 1. It has been observed that fly ash with lighter in shade may consists of finer particle size [7] and produced from anthracite or bituminous coal. It may be an indicator for better quality of the fly ash.



Fig. 1. Physical appearance of (a) GFA-brownish and (b) SFA-grey colour

From the geological point of view, the coal used to produce SFA (i.e. sub-bituminous) is geologically younger (Balingian Formation of late Miocene age – Begrih Formation of Early Pliocene age) and it is mined nearer to the ground surface compared to the coal used to produce GFA (i.e. bituminous) (Permian age – Cretaceous age). The quality of coal is in the increasing order from subbituminous to bituminous.

The basicity index and hydration modulus of both SFA and GFA are evaluated using the equations as given in Equation (1) and (2):

$$K_b = \frac{\text{CaO} + \text{MgO}}{\text{SiO}_2 + \text{Al}_2\text{O}_3} \quad (1)$$

$$\text{HM} = \frac{\text{CaO} + \text{MgO} + \text{Al}_2\text{O}_3}{\text{SiO}_2} \quad (2)$$

The basicity index of GFA and SFA is 0.08 and 0.07, respectively. Both are considered acidic (≤ 1). The acidic character of the fly ashes shows some pozzolanic activity due to the

high presence of SiO_2 [28]. The hydraulicity of acidic fly ash in the presence of alkaline solution is weaker in comparison to basic fly ash.

From the hydration moduli obtained, it implies the hydraulicity of both fly ashes is very low. The self-cementing properties are very poor due to the lack of CaO content. Being different from Portland cement and Class C type fly ash, it does not harden in the presence of water. Consequently, alkaline activator is essentially needed to activate both fly ashes.

3.2. Sample Preparation

In this paper, the alkaline solution used for the experiment was 8M sodium hydroxide (NaOH) solution, which was prepared from the NaOH pellet with 97% purity, and sodium silicate (Na_2SiO_3) with $\text{Na}_2\text{O}=14.7\%$ and $\text{SiO}_2=29.4\%$. Washed sand was selected as aggregate in the experiments. Two kinds of sand conditions were prepared: (a) without saturated surface dry (SSD) condition and (b) with SSD condition in accordance to the Australian standard AS1141.5 [29].

The original moisture of sand at room temperature was 9%. However, the water absorption of the sand was only 1% and it is thought that this amount of water would be absorbed into the sand particles, namely absorbed water. Therefore, sample with and without SSD condition would be differed by moisture of 8%. This moisture level is believed to have contributed to the free moisture on the surfaces of the sand particles. From vision observation, the free moisture is therefore making the appearances of the sand particles shiny. As the absorbed water is not considered when the liquid/ash ratio is evaluated, the sample with and without SSD condition would be differed by the free moisture. The effect of SSD on compressive strength is being investigated here-in-after.

The materials were mixed according to proportions shown in Table 2. The ratio of fly ash to sand used for these series of experiments was 1: 2 by mass ratio, whereas the ratio of $\text{Na}_2\text{SiO}_3/\text{NaOH}$ was 2.5 by mass ratio. Different ratios of liquid to ash were used on GFA

and SFA in order to achieve similar workability. It is found that the mixture becomes very viscous and difficult to flow when the ratio of liquid to ash on SFA is similar as for GFA.

Fly ash and sand was premixed using a mortar mixer. Then, Na_2SiO_3 and NaOH solutions were added into the mixture and further mixing took place for another 5 minutes. The mixture was casted into cube moulds measuring $50 \text{ mm} \times 50 \text{ mm} \times 50 \text{ mm}$. The moulds were vibrated on the vibrating table to dissipate air bubbles from within samples. The moulds were then sealed with plastic sheet and placed into the curing box to be heat-cured in the oven at 60°C for 24 hours. After 24 hours of curing, the samples were taken out from the oven and demoulded. The samples were then tested for compressive strength (i.e. strength after 1 day). The remaining samples were cured at room temperature until the date of strength test (i.e. strength after 7 days).

3.3. Tests

X-Ray Diffraction (XRD) test was carried out using (Bruker AXS D8 Advance XRD) to determine the phase component of the tested ashes. The test was operated with CuK_α radiation at a scanning rate of 0.02 time per step over a 2θ range scanned from 10 to 90 steps. The results obtained from this test were qualitative in nature.

The particle size distributions (PSD) of the fly ashes were obtained using Laser Particle Size Analyser (CILAS 1190). The morphology of the fly ashes was studied using the Scanning Electron Microscopy (SEM) (ZEISS SUPRA 40 VP SEM).

Loss on Ignition (LOI) test was conducted using the Muffle Furnace. The fly ash was heated in the furnace at 1100°C with temperature increase rate of $3.33^\circ\text{C}/\text{min}$. Subsequently, the temperature was decreased to 110°C and samples were cooled in the furnace for 2 hours. The weight of the sample was measured before placing into the furnace and after the test finished.

Table 2 Details of geopolymer samples

| Group | Sample | Ash/ sand ratio | Na ₂ SiO ₃ /NaOH ratio | Liquid/ash ratio |
|--------------|--------|-----------------|--|------------------|
| Sand without | GFA | 1:2 | 2.5 | 0.51 |
| SSD | SFA | 1:2 | 2.5 | 0.61 |
| Sand with | GFA | 1:2 | 2.5 | 0.35 |
| SSD | SFA | 1:2 | 2.5 | 0.45 |

Note: Sample of sand with and without SSD condition differs by free moisture of 8%.

The workability of the sample was measured using the flow table in accordance to the ASTM-C1537 standard [30]. The compressive strength test was carried out in accordance to the ASTM-C109/C109M standard [31]. Three samples from each mix were tested for the strength and the average value was reported as the compressive strength of the corresponding mixture.

4. Results and Discussions

4.1. Compressive Strength

The compressive strengths of geopolymer using GFA and SFA were determined after 1 day and 7 days of curing as shown in Fig. 2. The test results show that the compressive strength of GFA geopolymer was generally higher than SFA geopolymer. The highest compressive strength was obtained on GFA samples after 7 days (i.e. 62 MPa) and SFA samples after 7 days (i.e. 55 MPa). Factors affecting the strength of SFA and GFA geopolymers are discussed in the following section.

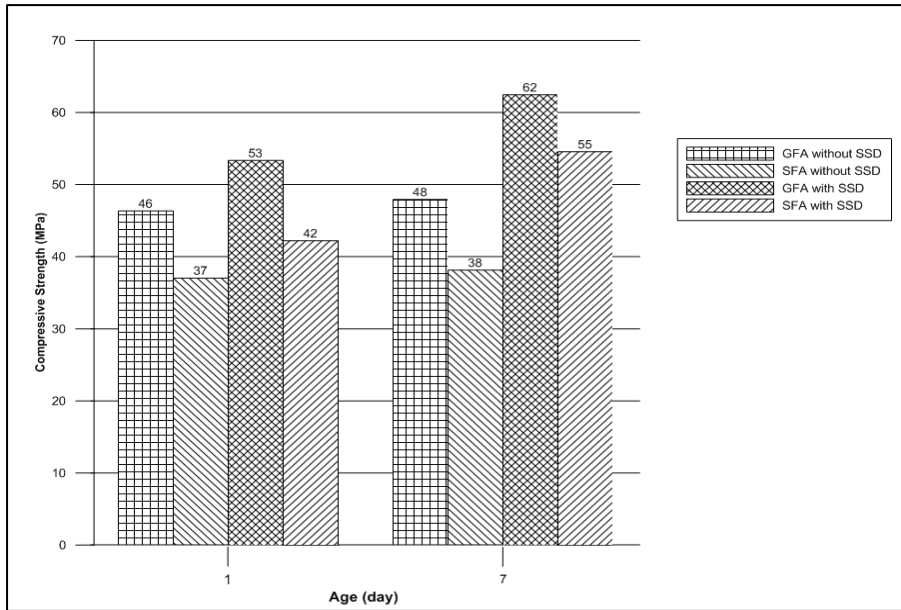


Fig. 2. Compressive strength of geopolymer using GFA and SFA

4.2. Chemical Composition

As presented in Table 1, the chemical compositions of GFA and SFA are rather similar but different in proportions. The major components of both GFA and SFA are SiO_2 , Al_2O_3 and Fe_2O_3 , followed by CaO , MgO and K_2O . Other components present in small quantities. Basically, all the elements on GFA are higher than SFA with the exception of K_2O and MnO .

It is important to note that SFA contains relatively large quantities of MnO . As compared to the other fly ashes or OPC, MnO content in SFA is similar to manganese slag as presented in Table 1. The influence of MnO content on the quality of fly ash is assessed with regard to the quality index as given in Equation (1):

$$I_a = \frac{\text{CaO} + 0.5\text{MgO} + \text{Al}_2\text{O}_3 + \text{CaS}}{\text{SiO}_2 + \text{MnO}} \quad (1)$$

The large quantities of MnO content in SFA significantly reduce the quality of fly ash by 2 times as compared to GFA, i.e. 0.6 for GFA and 0.3 for SFA. High amount of MnO content reduces the geopolymer strength as it has poorer hydraulicity and high porous structure. It also inhibits the early strength development [32]. The reason of high MnO content can be most likely attributed to the existence of pyrite and illite minerals bound to the original coal

and should be removed during pre-combustion coal cleaning [33]. The Mn compound is predominantly deposited in larger fly ash particle size and the amount increases with the particle size. The particle size distribution of SFA as discussed in the following section is shown to agree well to this statement.

High amount of unburned carbon content hinder the geopolymerisation reaction. Besides, it may affect the workability and strength capability [5]. However, the LOI values of GFA and SFA in this research were found to be 0.57% and 0.49%, respectively. The results indicate that both fly ash types have very low unburnt carbon content and hence, the effect of LOI on geopolymer strength can be neglected.

4.3. Mineralogy

The mineralogy of GFA and SFA was studied based on the XRD test results. The peaks represent the presence of the crystalline phases. The XRD result of GFA is similar to the corresponding XRD result of SFA as shown in Fig. 3. The dominant minerals observed in both GFA and SFA are mullite and quartz. The highest peak for both GFA and SFA was observed at approximately 26.5° at 2θ . This broad hump indicated that the presence of greater amount of amorphous material. However, the identification of crystalline peaks on amorphous materials can be difficult due to overlapping some of the peaks [28]. The MnO content in SFA is believed to be amorphous-like instead of crystalline-like thus making it difficult to be identified from the XRD result.

The XRD pattern of GFA shows wider band from 20° to 40° . This shows that the amorphous nature on GFA is more prominent than SFA. It can be attributed to the instant cooling after the high temperature of coal combustion which causes the conversion of material phase from crystalline to amorphous [34]. As provided in the background of both coal fired power plant, the combustion temperature at both power plant is 540°C ; however, the flow rate of the cooling system at Gladstone Power Plant is 5 times faster than at

Sejngkat Power Plant. The mineral matter is quenched into the particle after the combustion of coal and therefore, the particle tends to behave more spherical to rounded shape with glassy exterior surface [35]. The greater flow rate ensures the combustion is cooled at a faster rate thus the temperature gradient is greater. This quenching associates with the instant cooling, controls the growth and the agglomeration of particles. More amorphous content can be quenched into the fly ash particles and thus, as a result of better amorphous nature of fly ash. Consequently, GFA shows richer amorphous phase than SFA and enhances the strength development. More amorphous silica and alumina can be dissolved from GFA and contribute to the geopolymerisation and therefore, form stronger geopolymer structure.

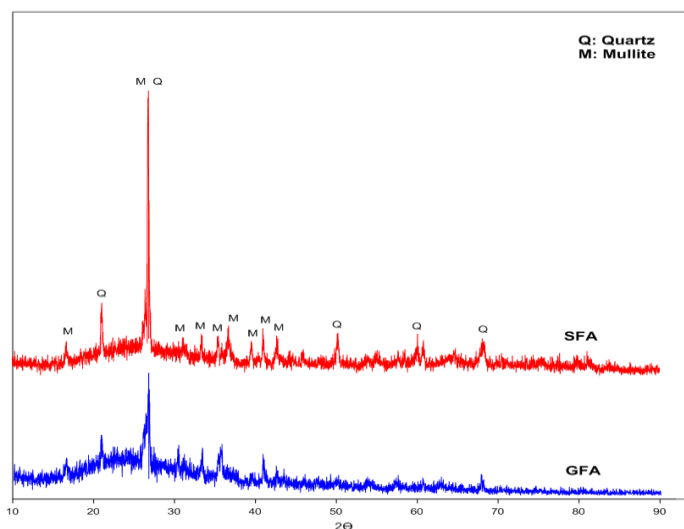
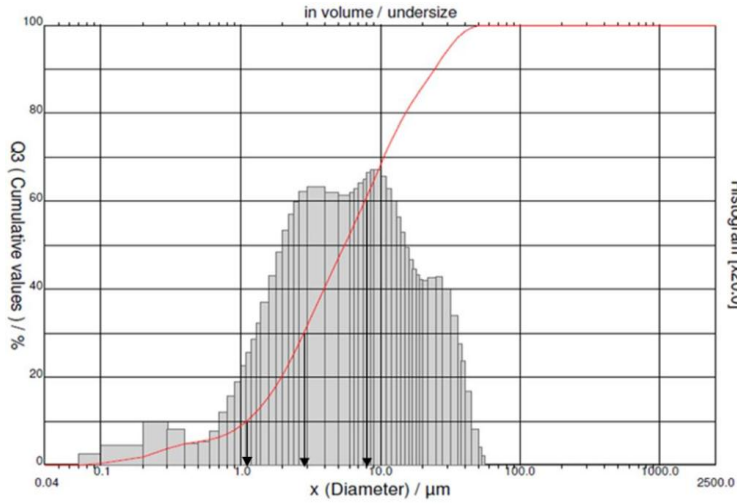


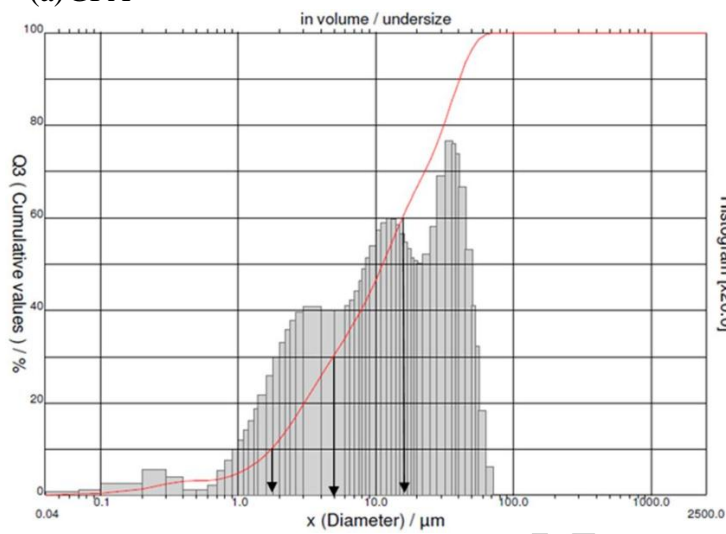
Fig. 3. Result of X-ray diffraction (XRD) on GFA and SFA

4.4. Particle Size Distribution

The results of the particle size distribution on GFA and SFA are presented in Fig. 4. Table 3 shows the test results of particle diameter at 10% (d_{10}), 50% (d_{50}) and 90% (d_{90}), and the mean diameter. Both GFA and SFA show broad distribution pattern in their respective particle size distribution plots. However, GFA particles are observed to be approximately two times smaller than SFA. For GFA, it is predominantly smaller than 24 μm whereas SFA is predominantly smaller than 40 μm , both comprising 90% of the total fly ashes. The mean particle diameter of GFA is 9.3 μm whereas SFA is 16 μm .



(a)GFA



(b)SFA

Fig. 4. Particle size distribution of (a) GFA and (b) SFA

Table 3 Diameter of GFA and SFA particles at 10%, 50% and 90% of the total fly ash content; mean diameter and specific surface

| Sample | GFA | SFA |
|---|-------------------|-------------------|
| Diameter at 10% (d_{10}) | 1.1 μm | 1.8 μm |
| Diameter at 50% (d_{50}) | 5.5 μm | 11 μm |
| Diameter at 90% (d_{90}) | 24 μm | 40 μm |
| Mean diameter | 9.3 μm | 16 μm |
| Specific surface (cm^2/g) | 31382 | 24920 |

The particle size distribution of both GFA and SFA is categorized into 4 groups as presented in Table 4 to ease the comparison, namely (a) ultrafine: $< 0.6 \mu\text{m}$ (b) fine: 0.6 to $6 \mu\text{m}$ (c) coarse: 6 to $20 \mu\text{m}$ and (d) coarser: $> 20 \mu\text{m}$.

Table 4 Particle size distribution

| Mode | Particle Size Group (μm) | GFA (%) | SFA (%) |
|---------------|---------------------------------------|---------|---------|
| Ultrafine | < 0.6 | 6 | 4 |
| Fine | $0.6 - 6$ | 47 | 30 |
| Coarse | $6 - 20$ | 32 | 31 |
| Larger Coarse | > 20 | 15 | 35 |
| | < 10 | 68 | 46 |
| | > 45 | 2 | 7 |

Most of GFA has distributed in the range of fine portion but it gradually decreases from fine portion (47%), coarse portion (32%) to coarser portion (15%). For SFA, the particle size has evenly distributed among fine portion (30%), coarse portion (31%) and coarser portion (35%). The highest percentage of particle size distribution is found in the coarser portion. For both GFA and SFA, lesser amount of particle sizes is observed in the ultrafine portion at 6% and 4% respectively. This could be due to the difficulty of capturing such fine particle sizes and mostly escape to the environment through the chimney. Nevertheless, the amount of this particle size in the overall fly ash particle is insignificant.

As the fine portion is found to be highest on GFA, this fine portion of particles plays an important role on the strength development and the rate of geopolymerisation. Smaller particles are more active in the alkali activation process thus leading to higher compressive strength [9]. As most of GFA particles are distributed in fine portion, higher specific surface enhances the reactivity of the particle and hence, provides larger active surface area for the reaction. The higher fine portion on GFA also explains why lesser liquid content is required for GFA to achieve similar workability as SFA because smaller particle size improves the flow of the mixture.

The Coefficient of Uniformity (C_u) and Coefficient of Curvature (C_c) were also used to compare the uniformity of particle sizes and the gradation of the particle size distribution curve for GFA and SFA as given in Equations (4) and (5).

$$C_u = \frac{d_{60}}{d_{10}} \quad (4)$$

$$C_c = \frac{d_{30}^2}{d_{60} \times d_{10}} \quad (5)$$

It was found that the C_u for GFA is 7.3, which is lower than SFA with a value of 9.4. Higher C_u value represents the particle size distribution being more non-uniform and contains wider ranges of particle sizes. However, the higher amount of fine particles in GFA enhances the filler effect. This in turn suggests that GFA has capability of more closely packed particles than SFA and therefore, lesser voids and higher strength potential. The structure formed tends to be more compact and rigid.

C_c value indicates the degree of curvature of the particle size distribution plot. Both GFA and SFA have a C_c value of approximately 1, which is within the range of 1 to 3. Therefore, both fly ash particle size distributions are classified as well-graded.

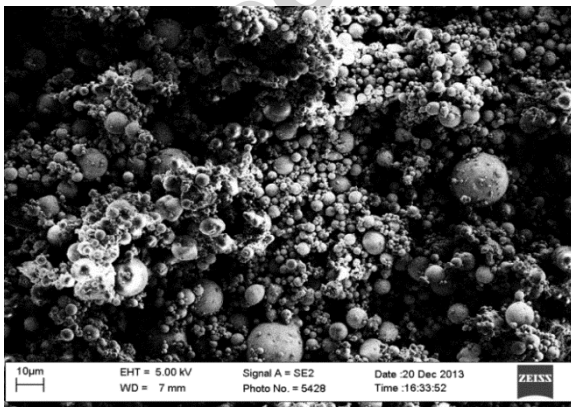
4.5. Scanning Electron Microscopy

As shown in the SEM micrographs, the fly ash particles of GFA are observed to be predominantly smaller than SFA (see Fig. 5a and b). The distribution of both types of fly ash are generally heterogenous and non-uniform as observed under the microscope. Distinct distribution of particle size between large particles and small particles are obvious on GFA. For SFA, the particle sizes are evenly distributed. This observation is consistent to the results of the PSD.

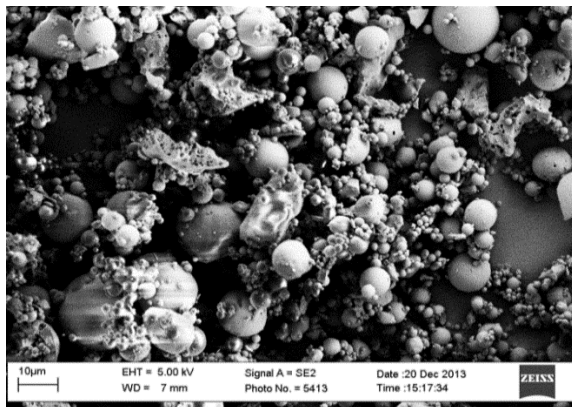
The morphology of ultrafine and fine particles are basically presented in smooth spheres and they are rounded in nature [12]. GFA has higher percentage of ultrafine and fine portion, which explains its morphology consisting of smooth spherical particles with less irregular grains (see Fig. 5c). Fly ash with smooth spherical particle shape enhances the ball bearing

and lubricant effects. Having this capability, it improves the workability and flow ability of the mixture. Therefore, less liquid content is required for GFA to achieve similar workability as SFA. Inversely, higher percentages of coarse particles exhibit particle with shape irregularities. Therefore, this explains the reason why SFA is observed to be less rounded in shape and appear with some angularities (see Fig. 5d). Moreover, SFA consists of irregular grains in which some are greater in size than those spherical particles (see Figs. 5e and f). These irregular grains could be formed by the incomplete combustion as most of the organic matters should be volatilized during the coal combustion process.[11] Additionally, agglomeration of fly ash particles is observed on SFA particles from the microstructure image.

From the workability point of view, the coarse particles of SFA with less rounded particle shape and angularity increases the internal friction. The irregular grains occupy high surface area which increases the sorption ability and the liquid demand. Therefore, higher amount of liquid solution is required to obtain the similar workability as GFA. The angularity of particle shape also affects the orientation of particles in the geopolymer matrix consequently increases the void between the particles. Therefore, it could in turn reduce the strength development on SFA. The reduction of coarse particle size on SFA is suggested and may possibly increase the geopolymer strength.

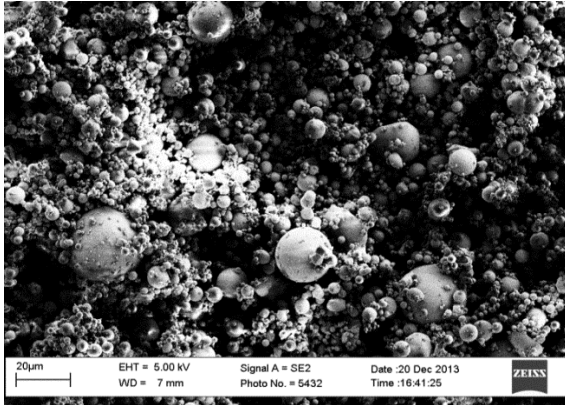


(a) GFA- distribution from fine to coarser portions is in decreasing order

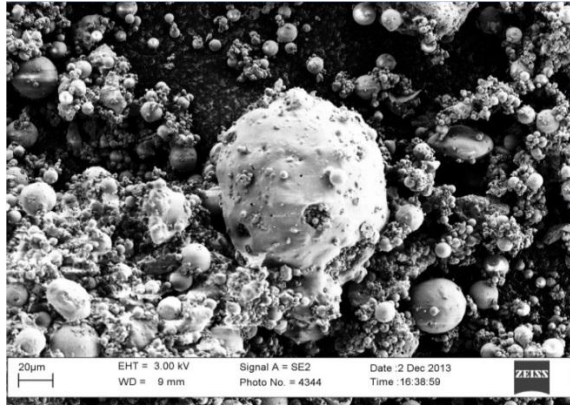


(b) SFA- distribution from fine to coarser portions is evenly (magnification to 10µm)

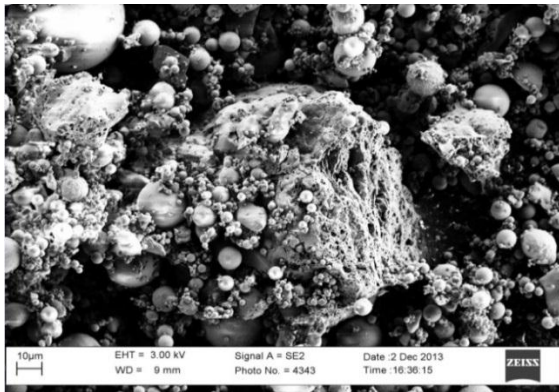
(magnification to 10 μ m)



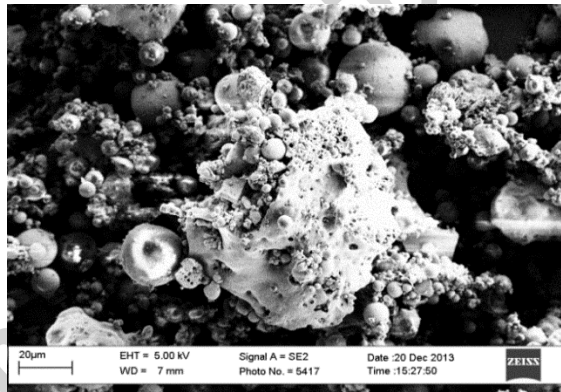
(c) GFA- smooth sphere and rounded in shape (magnification to 20 μ m)



(d) SFA- less rounded in shape and appear with some angularities (magnification to 20 μ m)



(e) SFA- irregular grain (magnification to 10 μ m)



(f) SFA- irregular grains in which some are greater in size than those spherical particles (magnification to 20 μ m)

Fig. 5. SEM on GFA and SFA

4.6. Liquid to ash ratio

It is observed that SFA requires higher ratio of liquid to ash but the compressive strength obtained is lower than GFA. Although higher amount of alkaline solution should be able to leach more silica and alumina from the fly ash and consequently enhances the geopolymerisation process, it is not the case as observed on SFA performance. It could be due to higher usage of alkaline solution that may obstruct the water evaporation and the structure formation [36]. Other than that, fly ash with mostly amorphous phase enhances the leaching capability of SiO_2 and Al_2O_3 [37]. It is believed that the better amorphous phase of

GFA than SFA demonstrates greater leaching capability and enhances the geopolymerisation between the alkaline solution and fly ash, thus increasing the compressive strength.

4.7. Sand with SSD condition

It is worth mentioning that the effect of sand condition on geopolymer strength is significant as shown in Fig. 6. For samples using sand without SSD condition, the strength increments from 1 day to 7 days were 4% and 3% for GFA and SFA respectively. As free moisture exists in sand without SSD condition, it weakens the concentration of alkaline solution. Additionally, this free moisture is not involved in the chemical reaction of geopolymer because the geopolymerisation is activated by the alkaline solution, unlike cement the strength development is built up through water hydration. Therefore, it is believed that the free moisture in the samples have evaporated when subjected to heat drying in the oven. This will subsequently weaken the matrix formed and cause a decrease in strength.

The strength increments of samples using sand with SSD condition after 1 day to 7 days were 17% for GFA and 31% for SFA. As free moisture is eliminated from sand with SSD condition, the actual concentration of alkaline solution is completely used for the geopolymerisation thus higher compressive strength can be obtained.

The strength increments for samples using sand with SSD condition from those samples without SSD condition after 1 day were 15% and 14% for GFA and SFA samples whereas it was found to be 29% and 45% after 7 days respectively. The strength increment of SFA samples was approximately 16% higher than GFA sample after 7 days.

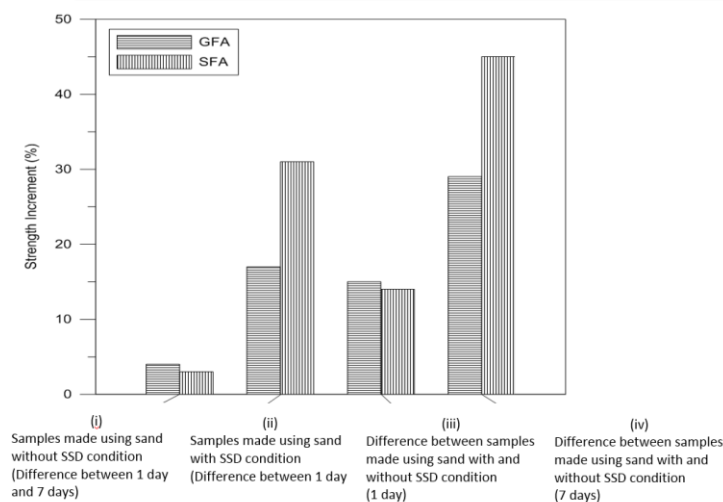


Fig. 6. Strength increment of geopolymer using sand with and without SSD condition

Both compressive strengths of GFA and SFA have been observed to increase with curing age. This observation could be due to some unreacted fly ash particles, which earlier on did not manage to undergo geopolymerisation during heat curing in oven that continued to react with the alkaline solution when being cured at room temperature. Also, it could be due to the reaction on the reactive fine particle size of fly ash which consequently improved the bonds in geopolymer over the curing age [38].

The strength increments of SFA over the curing age were observed to be 14% higher than GFA. This suggested that the rate of geopolymerisation for SFA samples was initially slower and mainly developed its strength with the curing age. SFA which has relatively larger particle size may need longer period for dissolution of fly ash particles to build up the strength. Therefore, better strength development was observed at later stage.

5. Conclusions

Fly ash from Sarawak (SFA) was used to assess its potential in making geopolymer and the results were compared with Gladstone fly ash (GFA) from Australia. The results obtained from the experiments showed that SFA-based geopolymer developed lower compressive

strength (55 MPa) than geopolymer using GFA (62 MPa) after 7 days. The factors affecting SFA geopolymer obtained lower compressive strength than GFA are listed as below:

1. SFA and GFA behave very differently in nature. Besides the different color (brownish on GFA whereas grey on SFA), all the chemical elements on GFA are higher than SFA with the exception of K_2O and MnO . The large quantities of MnO content on SFA reduce the quality index of fly ash by 2 times as compared to GFA, i.e. 0.6 for GFA and 0.3 for SFA.
2. The effect of LOI on geopolymer strength can be neglected due to low LOI content on both fly ashes (<1%).
3. GFA shows better amorphous phase than SFA. The faster flow rate of cooling system at Gladstone Power Plant than Sejangkat Power Station (approx. 5 times) enhances the amorphous nature of GFA.
4. The PSD of GFA is predominantly smaller than 24 μm whereas SFA is predominantly smaller than 40 μm , both comprising 90% of the total fly ashes. The finer particles on GFA have better ability to have more closely packed particles to enhance the filler effect and better reactivity. It also acts as 'nucleation sites' to develop strength.
5. The morphology studies show that SFA has been observed to be less rounded in shape and appear with some angularities whereas GFA has been observed to consist mainly of smooth spherical particles and less irregular grains. The former type increases the liquid demand for workability but reduces the strength development; inversely, the latter type increases the ball bearing and lubricant effect for workability also enhancing the strength development.
6. SFA samples have higher strength increment of approx. 14% than GFA samples over the curing age. It has suggested that the geopolymerisation of SFA was initially slower and the strength development was built up at later stage.

This paper shows that Sarawak fly ash can be a potential construction material for producing Sarawak fly ash-based geopolymer. With benchmarking against the well-developed Gladstone fly ash-based geopolymer, factors that influence the strength capability of Sarawak fly ash-based geopolymer can be effectively improved to achieve the desired strength performance.

Acknowledgments

The first author would like to express her sincere gratitude to the Centre for Sustainable Infrastructure (Hawthorn Campus) and Swinburne Sarawak Research Centre for Sustainable Technologies for giving her the opportunity to travel to Melbourne to conduct the experiments. The authors would like to also acknowledge the financial support from the Melbourne Sarawak Research Collaboration Scheme. The assistance, guidance and support rendered by Mr. Brian Lynch and Ms. Chandani Tennakoon during the collaboration project are gratefully acknowledged.

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Highlights

- Geopolymer produces lower carbon footprint and this leads to cleaner production.
- Strength of geopolymer made using fly ash from Malaysia and Australia are studied.
- Both types of fly ash vary in chemical contents, mineral phase and particle size.
- Geopolymer made using Malaysia fly ash show lower strength but has great potential.