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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.

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 CO_2 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 μm rather than the particle size greater than 45 μm [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

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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 utilised for the combustion and the daily production of coal ashes is estimated about 1400 t. The combustion of coal is carried out in 2 boilers operating independently. The first or older boiler has a capacity to generate 2 units × 50 MW of electricity, while the second or newer boiler has a capacity to generate slightly more electricity at 2 units × 55 MW. The combustion temperature of coal is set at 540 °C. The cooling system utilised water pumped from river and the flow rate of the cooling system is about 10,275 m^3/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 1680 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 51840 m^3/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 compositions of both fly ash types were 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].

From the vision observation, SFA is darker in shade (*i.e.* grey colour) 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.

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 (Eqs. (1) and 2):

$$K_b = \frac{CaO + MgO}{SiO_2 + Al_2O_3} \tag{1}$$

$$HM = \frac{CaO + MgO + Al_2O_3}{SiO_2} \tag{2}$$

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.

Table 1
Chemical compositions 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_2O_3	25.7	18.1	10.5	5.8
Fe_2O_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_2O	0.7	2.0	5.1	0.3
Na_2O	0.8	0.3	2.7	0.5
SO_3	0.2	0.1	–	2.4
TiO_2	1.3	0.6	–	–
P_2O_5	0.9	0.1	–	–
LOI	0.6	0.5	–	1.0