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PHYSICAL PROPERTIES AND COMPRESSIVE STRENGTH OF PRESSED AND CAST FLY ASH GEOPOLYMER

Geopolymers are commonly recognized as sustainable alternatives to OPC and it has broad range of applications. Certain properties of geopolymer such as density are concerned in order to apply in the construction industry. Different densities of geopolymer could be obtained by varying the concentration of the alkaline activator. However, the densities do not differ much. Hence, a different production method of geopolymer can be applied. This study aimed to investigate the physical properties and compressive strength of pressed and cast fly ash geopolymer. The geopolymer samples were prepared by using pressing and casting method. Geopolymer samples without foam addition and with foam addition were prepared in order to achieve different densities of samples. The results demonstrated that the pressed sample has the highest bulk density (2285 kg/m^3) whereas the cast sample with added highest ratio of foam has the lowest bulk density (1293 kg/m^3). The apparent porosity and water absorption result were inversely proportional to the bulk density result. The densest geopolymer obtained the highest compressive strength (61 MPa) and the lightest geopolymer obtained the lowest compressive strength (7 MPa).

Keywords: Fly Ash; Geopolymers; Pressed; Cast; Foaming

1. Introduction

The demand for ordinary Portland cement (OPC) which is one of the vital construction materials is on the rise due to the increasing infrastructure development. However, environmental issues and emissions of greenhouse gases from the production of OPC have been widely reported as the production of one ton of Portland cement emits approximately 0.9 ton of CO_2 into the atmosphere. Geopolymers are commonly recognized as sustainable alternatives to OPC as it is more environmentally friendly [1]. Geopolymers are produced through the polymerization of the aluminosilicate materials in a reaction with an alkaline solution. The aluminosilicates materials that are widely used are metakaolin, fly ash and slag. One of the aluminosilicates materials which is fly ash, has been commonly used as a binder replacement for cement in the construction industry due to its pozzolanic activity, low water demand, lessen bleeding, and low heat evolution [2]. The alkali solution commonly used are sodium hydroxide (NaOH), potassium hydroxide (KOH), and sodium silicate or their combination.

Geopolymer is a novel material that has wide-ranging and numerous applications, however different applications require certain properties of geopolymer. For example, the sound insulating components in construction industry require highly dense structure materials as it can block the sound waves from transmitting from one place to another place whereas sound absorbing or heat insulation components require less dense or porous structure materials [3]. Foamed concretes with densities ranging from 300 to 1600 kg/m^3 have recently been developed and applied for the purpose of void filling, reduction in dead loads and vibration attenuation [4]. This study was performed by using the casting method and pressing method to produce different densities of geopolymers which has been used for various applications in order to stimulate greater application of geopolymer and raise sustainability awareness in the building sector [5].

Casting is the conventional method to produce geopolymers, however it is not porous enough for the sound absorption or heat insulation application, hence foaming agent can be added into geopolymers in order to create a less dense structure. The

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densities can be altered by adding different amount of foaming agent. Meanwhile, pressing method can be applied to produce a highly dense structure geopolymer. The pressing method applies pressure in a single axial direction in order to eliminate the air voids and thus creating a highly compacted structure [6-7]. Hence, geopolymer can be utilised in vast applications by varying its densities by using different production methods. The current literatures have not been focusing on this idea and most of the researchers studied the effect of alkaline activator concentration or the solid to liquid ratio in order to obtain different densities of the geopolymer [8-9]. However, varying the concentration of the alkaline activator to get different densities might face problem like having a very viscous mixture for higher concentration of alkaline activator which limit the flow of geopolymer paste and hence shorten the setting time. The low workability will affect the compaction process and resulting in low density. Meanwhile, low concentration of alkaline activator will provide weak compressive strength [10-11]. Therefore, it is always needed to get the optimum alkaline activator concentration for better geopolymer properties. Nevertheless, one point that must be focused is that there were not much of density variation of the geopolymer by using different concentration of alkaline activator [10,12]. Hence, using different production method could be one of the solutions.

The mechanical and physical properties of cast and pressed geopolymer is one of the important properties in producing construction materials in various applications. In this study, the physical properties and compressive strength of pressed and cast fly ash geopolymer will be investigated.

2. Experimental methodology

2.1. Materials

Class F fly ash powder was used as the aluminosilicate precursor which supplied from Manjung Coal-Fired Power Plant. The chemical composition of fly ash was determined by using X-ray fluorescence (XRF) spectrometer (TABLE 1). One of the alkaline activators used in this study was sodium silicate (Na_2SiO_3) was supplied by South Pacific Chemical Industries (SPCI) Sdn. Bhd. Sodium hydroxide (NaOH) was used as another solid alkaline activator. It was in purified pellets form, and it was supplied by Progressive Scientific Sdn. Bhd. The foaming agent used was polyoxyethylene alkyether sulphate (PAS) and it was mainly composed of 78.6% of CO_3, 11.0% of PdO and 4.2% of CaO.

TABLE 1

Chemical composition of fly ash

Oxides	Weight Percentage (wt.%)
SiO_2	35.63
Al_2O_3	22.83
Fe_2O_3	14.70
CaO	12.17
MgO	4.22
Na_2O	1.85
K_2O	1.75
Sc_2O_3	1.73
P_2O_5	1.22
SO_3	1.21
Others	2.69

2.2. Fly Ash Geopolymers Preparation

To vary the densities of the fly ash geopolymers, pressing and casting methods were used to produce the fly ash geopolymers. Five sets of samples were prepared. To prepare the densest samples, pressing method was used. Fly ash powder was sieved before mixing. Na_2SiO_3 and NaOH were mixed before added with fly ash powder. The ratio of Na_2SiO_3 to NaOH used was 1.5. The fly ash powder was slowly added into the alkali activator solution and mixed for 5 mins to avoid unhomogenized mixture. Solid to liquid ratio was set at 6.0. The mixture for the pressing method was in semi-dry form. After the raw materials were well mixed, the mixture was poured into a stainless-steel cylinder mould and pressed using a hydraulic jack for 2 mins in 5 tons. The samples were wrapped and cured for 28 days.

Another four sets of samples were prepared by using the casting method. Na_2SiO_3 and NaOH were mixed before added with fly ash powder. The ratio of Na_2SiO_3 to NaOH used was 2.5. The fly ash powder was added into the alkali activators solution and mixed for 3 mins. Solid to liquid ratio was set at 2.5. The fly ash geopolymer paste was cast into a cylinder mould with 3.5 cm diameter and 5 cm height. Samples with mould were wrapped with plastic and cured at room temperature for 24 hours. After 24 hours, the samples were demoulded and wrapped again with plastic. Then, the samples were placed and cured at room temperature for another 27 days.

Casting method was also used to produce fly ash geopolymers with lower density and a more porous structure. The mixture was added with foam which prepared beforehand with a foam generator as according to ASTM C796, by using PAS as the foaming agent. Different ratios of foam (1.0, 2.0, 3.0) were added into the geopolymer mixture for 1 min, then cast into the cylinder mould and cured for 28 days. The mix proportion of the fly ash geopolymers was summarised in TABLE 2.

TABLE 2

Mix proportion of fly ash geopolymer

Sample	Solid/ Liquid Ratio	Na_2SiO_3/ NaOH Ratio	Foam/ Geopolymer Paste Ratio	Sample Preparation Method
A	6.0	1.5	N/A	Pressing
B	2.5	2.5	N/A	Casting
C	2.5	2.5	1.0	Casting
D	2.5	2.5	2.0	Casting
E	2.5	2.5	3.0	Casting

2.3. Analysis and Testing Methods

All the analyses and testing were done after 28 days of curing. The bulk density of the fly ash geopolymers were calculated by using Eq. (1).

$$Bulk\ density, \rho = \frac{m}{v} \quad (1)$$

where m is the mass of sample and v is the volume of sample. Meanwhile, testing for apparent porosity and water absorption of fly ash geopolymers were conducted according to ASTM C642 and were calculated by using equations below.

$$Apparent\ Porosity = \frac{M_a - M_d}{M_a - M_w} \times 100\% \quad (2)$$

$$Water\ absorption, Wa = \frac{M_a - M_d}{M_d} \times 100\% \quad (3)$$

where M_d is the mass of dry samples, M_w is the mass of the immersed samples and M_a is the apparent mass of the immersed samples in air.

The compressive strength testing was carried out by using universal testing machine (UTM) by following ASTM C109/C109M. All samples were tested in a load control regime with 5 mm/min of loading rate.

3. Results and discussions

3.1. Bulk Density

Fig. 1 illustrates the bulk density of fly ash geopolymers after 28 days of curing. It shows that the samples prepared by using the pressing method has the highest bulk density which is 2285 kg/m^3. This phenomenon is caused by densification and compaction of the geopolymer mixture when the forces were applied in a constrained area. The unidirectional pressing force during the compaction step releases trapped air in the geopolymer mixture and leads to internal particle motion. Thus, the particle arrangement is changed, which aids the inter-particle interaction and resulting in a well-packed and dense sample [7]. Additionally, the Si^{4+} and Al^{3+} dissociation was enhanced and the reaction rate was increased by an optimal S/L ratio used in the pressing method, where stronger alkali activator content participating in the geopolymer system. The pore fraction is eliminated using this technique, which also involves continuous pressing of alkali-activated aluminosilicates to quicken the breakdown of the precursors and the subsequent polycondensation. Hence, the geopolymer will densify and posses better compressive strength [7,13].

The samples added with highest foam to geopolymer paste ratio has the lowest bulk density which is 1293 kg/m^3. It was clearly shown that the increase in the foam to geopolymer paste ratio would decrease the bulk density of the fly ash geopolymers. Not to mention that the bulk density of the fly ash geopolymers without adding the foam were higher than the fly ash geopolymers that added with foam. This is due to addition of foam into the geopolymer paste would create and trapped tiny air voids in the samples, and thus reducing the bulk density when the foam to geopolymer paste ratio is increased. Similar results were obtained by the study of Ufafa et al. [14]. The density would be significantly affected by the size and amount of the pores [15] which will show in later section.

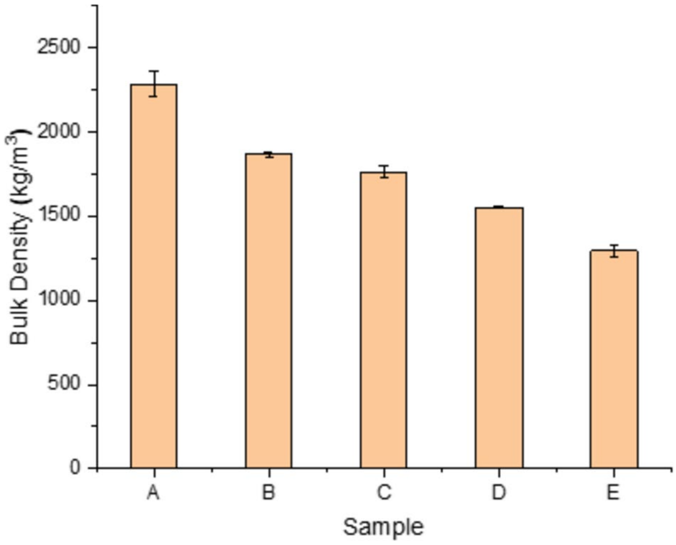

Fig. 1. Bulk density of fly ash geopolymers

3.2. Apparent Porosity and Water Absorption

Fig. 2 presents the apparent porosity and water absorption of fly ash geopolymers. The relationship of bulk density with apparent porosity and water absorption are inversely proportional by comparing to Fig. 1.

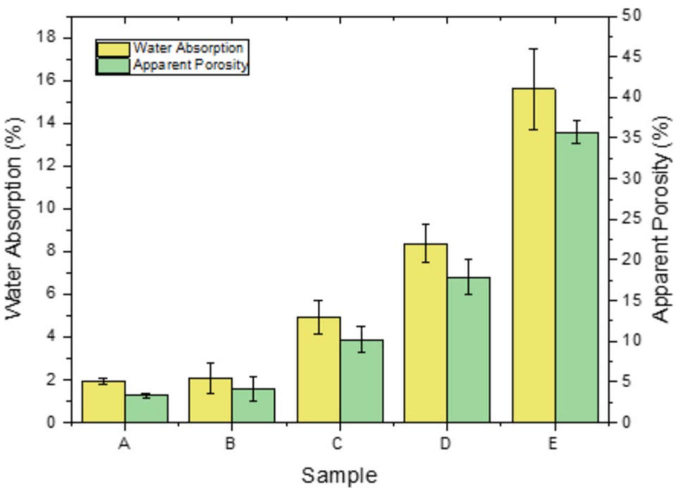

Fig. 2. Apparent porosity and water absorption of fly ash geopolymers

It can be observed that the fly ash geopolymers that prepared by using pressing method has the lowest apparent porosity (3.4%) and water absorption (1.9%) whereas the fly ash geopolymers that produced by using casting method but added with foam

(foam to geopolymer paste ratio = 3.0) has the highest apparent porosity (35.7%) and water absorption (15.6%). As mentioned above, the pressing method aids the removal of trapped air bubbles formed between the particles, thus reducing the porosity of the geopolymer. The sufficient alkali activator content for the pressing method also allows the rate of dissolution and geopolymerisation to increase, which then decrease the porosity of the geopolymer [7].

The porosity of foamed geopolymer is made up of both internal and entrained void spaces. Hence, when higher amount of foam was added into the geopolymer paste, more air bubbles were impregnated into the fly ash geopolymer sample and causing the apparent porosity and water absorption to increase. Not to forget that when more foams are added, it will form the interconnected pores and allow water to flow which later cause the water absorption to increase.

In addition, the measure of open porosity is determined by the water absorption result [12]. Hence, the capillary pore volume, which regulates the strength and density of geopolymers will then affect how much water is absorbed. The presence of foam resulted in the creation of the pore structure and the expansion of the geopolymer paste, increasing the likelihood of producing a lighter material which can be proved by the result in Fig. 1 [14]. The research work of Mastura et al. [16] showed the similar trend where increasing in the amount of foam would induced an increase in pore size, which helped to raise the water absorption value. Moreover, water flow in the geopolymer samples can be promoted as the occurrence of interconnected pores increase when more amount of foam was added. In turn, increasing the water absorption. The most significant difference between this method and pressing method is that the former one is to create more pores, where the latter one is to diminish the pores.

3.3. Compressive strength

Fig. 3. presents the compressive strength of the fly ash geopolymers. The compressive strength of the fly ash geopolymers mainly increases with the density and it is known that when the porosity of the matrix decreases, the mechanical strength of the geopolymers increases. The densest fly ash geopolymer prepared by using pressing method obtained the highest compressive strength which is 61 MPa. This is due to the compactness and density of the fly ash geopolymer are greatly improved by the application of pressing force which removed the trapped air between the particles. The applied pressure that quickens the polycondensation process will also induce the gel formation and hence giving higher compressive strength due to stronger structural bonding [7,13].

Inversely, the lightest fly ash geopolymer which prepared by adding foam (foam to geopolymer paste ratio = 3.0) attained the lowest compressive strength which is 7 MPa. This is because the presence of pores due to addition of foam into the geopolymer caused the formation of polymer cluster linkage and sample structure to be weakened and formed destructive cracks which lead to poor compressive strength [16-17]. The irregular surface of the geopolymer which due to the pore creation also resulted the strength distribution to be uneven along the geopolymer surface and thus reducing its compressive strength [14]. Bulk density, apparent porosity and compressive strength all are interrelated. Increase pores in the geopolymer structure by adding foam will reduce the bulk density which results in lower compressive strength, formation of polymer cluster linkage weakens and destruction cracks.

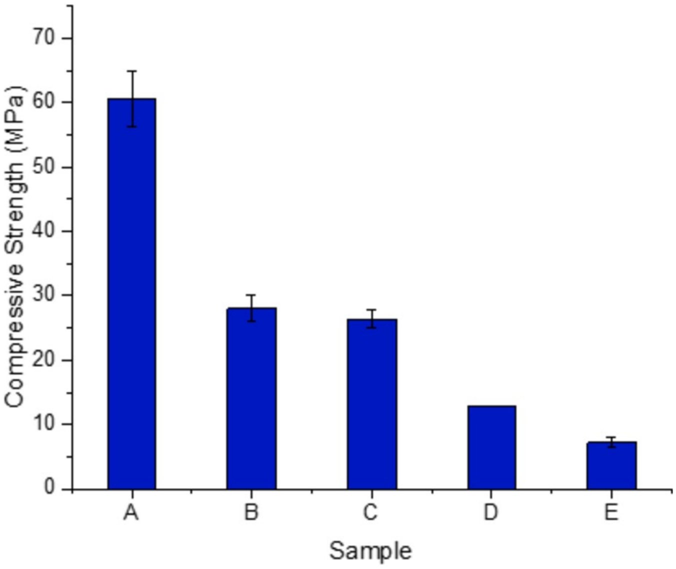

Fig. 3. Compressive strength of fly ash geopolymers

4. Conclusions

This research presented an investigation on the physical properties and compressive strength of pressed and cast fly ash geopolymer. Geopolymer is a novel material that has wide-ranging and numerous applications, however different applications require certain properties of geopolymer. This can be achieved by varying its densities through different production method in order to match with the suitable applications. The following conclusions have been drawn:

- The samples that prepared by using the pressing method possessed the highest bulk density which is 2285 kg/m^3 whereas the samples that prepared by using casting method with added foam (foam to geopolymer paste ratio = 3.0) has the lowest bulk density which is 1293 kg/m^3.
- Fly ash geopolymers that prepared by using pressing method has the lowest apparent porosity (3.4%) and water absorption (1.9%). Meanwhile, the fly ash geopolymers that produced by using casting method but added with highest amount of foam has the highest apparent porosity (35.7%) and water absorption (15.6%). The apparent porosity and water absorption result were inversely proportional to the bulk density result.
- The densest fly ash geopolymer which prepared by using pressing method obtained the highest compressive strength

which is 61 MPa whereas the lightest fly ash geopolymer prepared by adding foam (foam to geopolymer paste ratio = 3.0) attained the lowest compressive strength which is 7 MPa.

In the current work, only the physical and mechanical properties were studied. Hence future studies regarding the morphology and phase analysis could be carried out in order to evaluate the changes of the pores size, pores distribution and phases that present in the geopolymers.

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REFERENCES

[1] L. Li, L. Shi, Q.Y. Wang, Y.J. Liu, J.F. Dong, H. Zhang, G.M. Zhang, Constr Build Mater. **237**, 117564 (2020).

[2] H.Y. Zhang, G.H. Qiu, V. Kodur, Z.S. Yuan, Cem. Concr. Compos. **106**, 103483 (2020).

[3] H.M. Zhang, Building Materials in Civil Engineering, Woodhead Publishing, United Kingdom (2011).

[4] M.R. Ahmad, B. Chen, Compos. Part B Eng. **171**, 46-60 (2019).

[5] A.L. Almutairi, B.A. Tayeh, A. Adesina, H.F. Isleem, A.M. Zeyad, Case Stud. Constr. Mater. **15**, 733 (2021).

[6] F. Lemoisson, L. Froyen, Fundam. Metall. 471-502 (2005).

[7] S.W. Ong, C.Y. Heah, Y.M. Liew, M.M.A.B. Abdullah, L.N. Ho, L.W.L. Chan, W.E. Ooi, N.A. Jaya, Y.S. Ng, J. Mater. Res. Technol. **15**, 3028-3046 (2021).

[8] S.Y. Kwek, H. Awang, C.B. Cheah, Materials (Basel) **14**, 4253 (2021).

[9] N. Doğan-Sağlamtimur, A.B. H Öznur Öz, T. Vural, E. Süzgeç, IOP Conf. Ser.: Mater. Sci. Eng. **660**, 012003 (2019).

[10] S.V. Patankar, Y.M. Ghugal, S.S. Jamkar, Indian J. Mater. Sci. **2014**, 1-6 (2014).

[11] H.T. Ng, C.Y. Heah, Y.M. Liew, AIP Conf. Proc. **2045**, 020098 (2018).

[12] A. Abdullah, K. Hussin, M.M.A.B Abdullah, Z. Yahya, W. Sochacki, R.A. Razak, K. Bloch, H. Fansuri, Materials (Basel). **14**, 1111 (2021).

[13] N. Ranjbar, A. Kashefi, G. Ye, M. Mehrali, Constr. Build. Mater. **231**, 117106 (2020).

[14] U. Anggarini, S. Pratapa, V. Purnomo, N.C. Sukmana, Open Chem. **68**, 629-638 (2019).

[15] K. Dhasindrakrishna, K. Pasupathy, S. Ramakrishnan, J. Sanjayan, Cem. Concr. Res. **138**, 106233 (2020).

[16] W.M.W. Ibrahim, K. Hussin, M.M.A.B. Abdullah, A.A. Kadir, L.M. Deraman, A.V. Sandu, Rev. Chim. **68**, 1978-1982 (2017).

[17] H.T. Ng, C.Y. Heah, Y.M. Liew, M.M.A.B. Abdullah, C. Rojviriya, H.M. Razi, S. Garus, M. Nabialek, W. Sochacki, I.M.Z. Abidin, Y.S. Ng, A. Sliwa, A.V. Sandu, Materials (Basel). **15**, 4085 (2022).