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Performances of Artificial Lightweight Geopolymer Aggregate (ALGA) in OPC Concrete

Rafiza Abdul Razak[1,a], Mohd Mustafa Al Bakri Abdullah[2,b],
Kamarudin Hussin[3,c], Khairul Nizar Ismail[4,d], Djwantoro Hardjito[5,e],
and Zarina Yahya[6,f]

[1,2,3,7]Centre of Excellence Geopolymer & Green Technology (CEGeoGTech), School of Materials Engineering, Universiti Malaysia Perlis (UniMAP), 01000, P.O. Box, D/A Pejabat Pos Besar, Kangar, Perlis, Malaysia

[4]School of Environmental Engineering, Universiti Malaysia Perlis (UniMAP), 02600 Jejawi, Perlis, Malaysia

[5]Civil Engineering Department, Petra Christian University, Jalan Siwalankerto 121-131, Surabaya 60236 Indonesia

[a]rafizarazak@unimap.edu.my, [b]mustafa_albakri@unimap.edu.my, [c]vc@unimap.edu.my,
[d]nizar@unimap.edu.my, [e]djwantoro.h@peter.petra.ac.id, [f]zarinayahya@unimap.edu.my

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Abstract. The non-availability of natural lightweight aggregate and demand are increasing in worldwide, thus new alternatives on producing artificial aggregate should be developed. This paper discussed on the mechanical properties of artificial lightweight geopolymer aggregate (ALGA) made from LUSI mud and alkaline activator in concrete. LUSI means Sidoarjo mud from Indonesia which erupted on 2006 with high volume and impacted an area of almost 770 hectare. The alkaline activator used was combination of sodium hydroxide and sodium silicate. The geopolymer paste formed need to be pelleted and sintered at 950 °C. The results showed that the compressive strength of OPC-ALGA concrete is 41.89 MPa at 28 days of testing with a density of 1760.1 kg/m^3 which can be classified as lightweight concrete. The water absorption of ALGA concrete is 2.77%.

Introduction

The lightweight aggregate results in lightweight concrete and structures, and provide good thermal insulation. The density is mostly depends on the type of aggregate used. The strength is also partially depending on the type of aggregates used for making the concrete [1-2]. Artificial or synthetic aggregate are produced by expanding, pelletizing, or sintering process such as blast-furnace slag, clay [3-5], bottom ash [6-8], fly ash [9-12], shale, sewage sludge [13], steel slag and etc. The commercial lightweight aggregate produced from expansive clays are Leca and Liapor, while from fly ash is known as Lytag.

Sintering is one of the main production processes to obtain lightweight aggregate which is generally used for hardening pellets. In sintering process, the samples of aggregate will be placed in the furnace at high temperature normally more than 1200 °C [7, 11]. However, sintering causes high energy used which may increase the manufacturing cost. But, the lightweight aggregates produced by sintering process give better durability properties such as permeability and corrosion resistance [11].

The demand of lightweight aggregate has increased due to the low density and thermal insulating properties. This has led to the development of artificial lightweight aggregates while reducing the overall cost of the building. So this study was conducted to determine the mechanical properties of artificial lightweight geopolymer aggregate (ALGA) in ordinary Portland cement (OPC) concrete.

Experimental Procedure

Raw Material. The LUSI mud was collected from the eruption site, Sidoarjo, Indonesia and transferred into sealed container. LUSI mud was then dried in the oven at 105 °C for 48 hours. After drying, this material was then crushed and blended to form in ash with particle size less than 300 µm. Alkaline activator also has been used in this study consist of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) solutions. The sodium silicate has a chemical composition of 30.1% SiO_2, 9.4% Na_2O and 60.5% H_2O (modulus SiO_2/Na_2O=3.2), specific gravity at 20 °C = 1.4 g/cm^3 and viscosity at 20 °C = 0.4 Pa s. The sodium hydroxide powder used was of 99% purity and fixed at 12M [14] in this study.

Mix Design and Process. The ratio of volcano ash/alkaline activator was 1.7 while the ratio of Na_2SiO_3/NaOH used was 0.4 and kept constant in this study. Geopolymer paste were prepared by mixing volcano ash with the alkaline activator. An alkaline activator consist of sodium hydroxide and sodium silicate was first mixed and stir until homogeneous solution was achieved. The mixing material was mixed for five minutes to obtain a homogeneous paste mixture. The paste need to be palleted then dried at the temperature 60°C for 30 minutes to get the shape of the aggregate. The grain size distribution must meet the ASTM C 330 [15] requirement for the use as artificial aggregate. Then the pelletized ALGA was sintered at 950 °C for 1 hour [14,16]. The control sample concrete was prepared which consist of LUSI mud and water only (without alkaline activator) and sintered at the same sintering temperature of 950 °C.

For concrete mixing process; The dry materials such as ALGA, OPC, and fine aggregate were mixed first. Then, the water will be added to the dry mixing. The mix was then mixed to ensure full mixing of the constituents. The calculation of proportions for each type of material is referred to ACI 211.2. After that, the mixture will be placed in cubes concrete and compacted through three layers. Then, the cubes of concrete were cured in the water until testing day for 1, 3, 7, 14, 28, and 90 days. The performance of ALGA concrete is compared with the control concrete using control aggregate (consist of LUSI mud and water only) produced.

Testing and Analyzing. Aggregate impact value (AIV) test was done to determine the impact value of ALGA and control aggregate as per BS 812. The water absorption has been conducted according to ASTM C140 [19] and for density test has been done according to BS EN 13055-1 [20]. The characterization of ALGA produced were characterized by using X-ray Diffraction (XRD), Scanning Electron Microscope (SEM), and Fourier Transform Infrared (FTIR).

The standard slump test is used according to ASTM C143 [17] to determine the workability of the concrete. The compressive strength of concrete was carried out according to BS EN 12390-3 [18]. Structural lightweight aggregate concrete made with lightweight aggregate must have minimum 28-day compressive strength of 17 Mpa. The density of structural lightweight aggregate concrete should be in the range of 1120 to 1920 kg/m^3. All tests should be done to determine the stability of the artificial lightweight geopolymer aggregate (ALGA) produced in lightweight concrete.

Results and Discussion

Performance of ALGA particle

Density, Water Absorption and Aggregate Impact Value (AIV). The particle density of control sample is 1700 kg/m^3 which higher than the density of ALGA of 1100 kg/m^3. This is due to the existence of pores created in the ALGA produced using geopolymerization methods, thus reducing the density.

The water absorption of control samples is 15.6% which is much higher than water absorption of ALGA with 4.7% only. This is due to some of control samples produced were crack and rupture after sintered at 950 °C as shown in Fig. 1, thus increasing the water absorption. In addition, there is no existence of shell around the control samples to prevent from the absorption of water. However, for ALGA clearly showed the existence of vitrified shell which then reduced the absorption of water.

Fig. 1: Images of control sample

Aggregate impact value (AIV) for control samples is 28.20%. This value has exceeded the limitation of AIV value (25%) to be used in heavy duty concrete. Addition of alkaline activator in ALGA reduced the AIV value significantly to 15.42% which shows high strength compared to control samples. Again, the existence of vitrified shell has strengthened the ALGA with low water absorption produced. Lack of binding ability in control samples without alkaline activator is the best reason for the lower strength produced. Table 1 shows the summary of properties for ALGA using geopolymerization method and control samples.

Table 1: Comparison of the properties for optimum ALGA and control sample

Properties	Optimum ALGA	Control sample
Density (kg/m^3)	1100	1700
Water Absorption (%)	4.70	15.60
Aggregate Impact Value (AIV) (%)	15.42	28.20

X-Ray Diffraction (XRD). XRD analyses of control samples compared with ALGA and raw LUSI mud are shown in Fig. 2. It can be seen that the pattern of raw LUSI mud and control aggregate sintered at 950 °C are similar but some of new crystalline peak of SiO_2 has been existed. The highest intensity for control samples has been detected at $2\theta = 26.8°$ associated to quartz (Q), meanwhile it has been shifted to $2\theta = 24.7°$ for ALGA produced using geopolymerization method which associated to sodalite (S). The XRD analysis of ALGA showed major synthesized crystalline phases which identified as sodalite (S) of $Na_4Al_3Si_3O_{12}Cl$, quartz (Q), albite (Al), anorthite (An) and nepheline (N) that strengthen the ALGA produced [21]. These new phases have contributed to the strength of ALGA produced compared with control samples without alkaline activator.

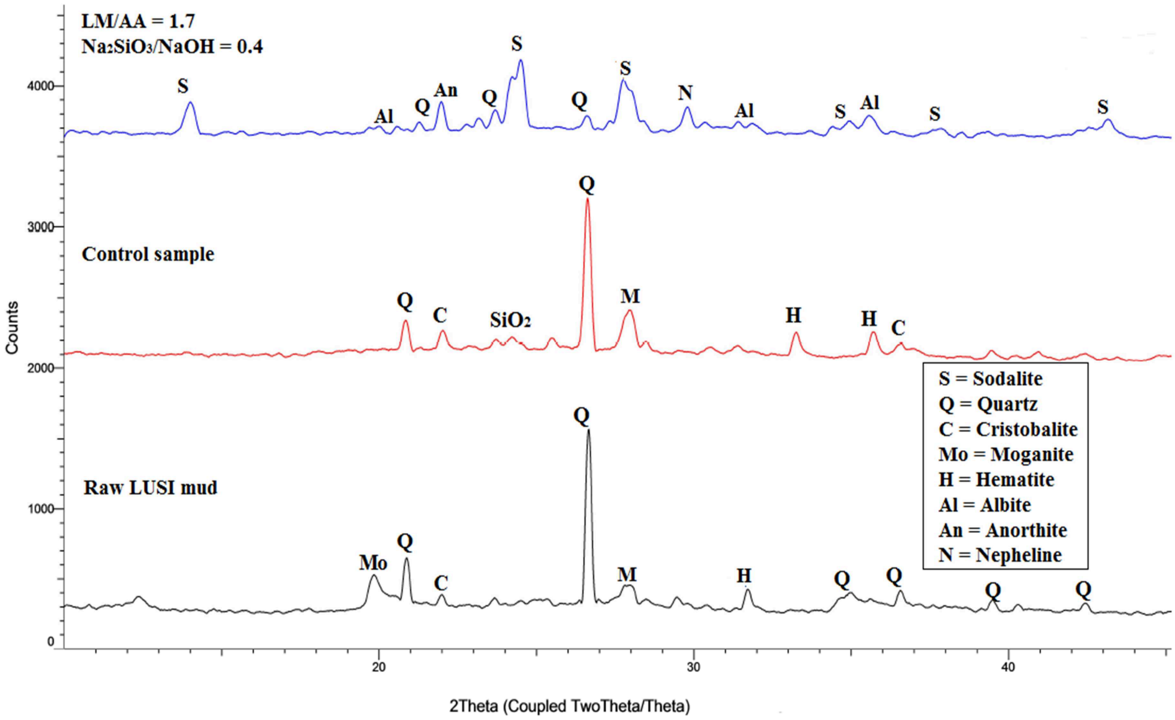
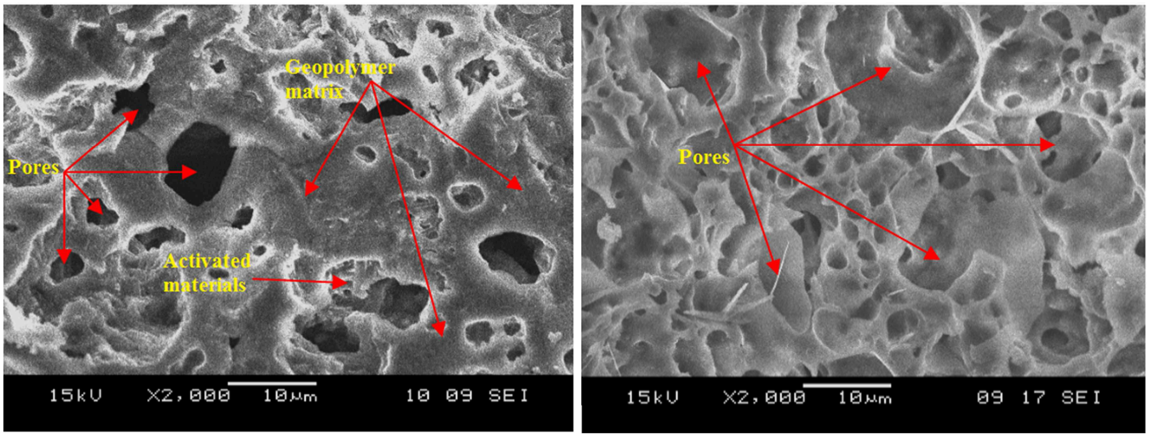


Fig. 2: XRD analysis of optimum ALGA compared with raw LUSI mud and control sample

Scanning Electron Microscope (SEM). The SEM micrographs of control samples compared with ALGA produced using geopolymerization method are shown in Fig. 3(a) and (b). The ALGA showed more complete geopolymer matrix which contributes to highest strength of samples produced. The pores formed were in the range of 2.5 µm to 6.9 µm in diameter, which give lowest density produced for ALGA (1100 kg/m^3). For control samples, the matrix formed is clearly thinner compared to ALGA produced as shown in Fig. 3(b). This thinner matrix may contribute to the low strength of the aggregate produced.

The pores presented in control samples are higher than ALGA produced with sizes range of 2.5-18.6 µm. It can be concluded that the presence of an alkaline activator as a binder to LUSI mud, making the structure to be more stable with thicker matrix formed, which then contribute to the high strength of ALGA produced.



(a) (b)

Fig. 3: SEM images of (a) ALGA compared with; (b) control sample

Fourier Transform Infrared (FTIR). Fig. 4 shows the FTIR spectra of ALGA and control samples. The bands of 1627 cm^{-1} and 2854cm^{-1} to 3451cm^{-1} arise from the presence of structural water remaining in the geopolymer matrix of ALGA and control samples. The band of 1075 cm^{-1} in the FTIR spectrum of control samples, then shifts to lower frequencies (1011 cm^{-1}) in the FTIR spectra of ALGA assigned to Si-O-Si and Al-O-Si bonding. The absorbance peak at 731 cm^{-1} that appeared at optimum ALGA is assign to stretching vibration of Al-O-Si bonds [22], but absent in the control samples, thus contribute to lower strength as proved by AIV results.

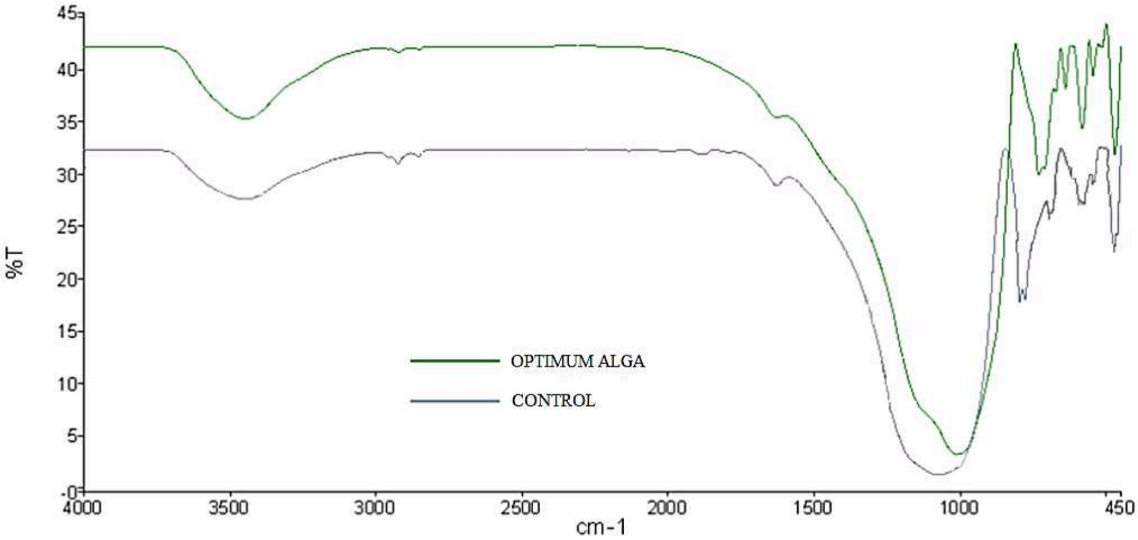


Fig. 4: FTIR spectra for optimum ALGA compared with control sample

Performance of OPC-ALGA Concrete

Workability. A high quality concrete should be within acceptable workability in the fresh condition and develops sufficient strength. The workability of fresh concrete was determined immediately after mixing the concrete. The slump value of OPC-ALGA concrete is 65 mm which is acceptable workability. This low workability is affected by the absorption of water from ALGA due to existence of pores. The bigger the value of slump indicating the better the workability produced and the concrete flows easily while free from segregation [23].

Density. The average density of ALGA concrete is 1760.1 kg/m^3, meanwhile the density of control concrete (control samples without alkaline activator) is 1870.7 kg/m^3. The percentage difference is 6.3% only, however, both samples can be classified as lightweight concrete according to ASTM C330 [15] which stated that the density of lightweight concrete should be less than 1920 kg/m^3.

Water Absorption. The 24 hour water absorption for ALGA concrete is 2.77%, meanwhile the water absorption for control sample is 7.30% which is higher than ALGA concrete. This is due to the pores that are higher in control sample compared to ALGA as proved by SEM images in Fig. 4.32. This value of water absorption is still lower than lightweight aggregate concrete produced by Erhan et al. [24] with 11.7% water absorption using sintered fly ash aggregate with bentonite at 1100 °C.

Compressive strength. The compressive strength of OPC-ALGA concrete and OPC control concrete at 1, 3, 7, 14, 28, and 90 days of testing are shown in Fig. 1. The result shows that the compressive strength of OPC-ALGA concrete is higher than OPC control concrete, indicating that the geopolymer in ALGA plays significant effect to the high strength of OPC-ALGA concrete produced. The development strength of OPC-ALGA concrete is increasing by ages. On early ages of 1, 3, 7 and 14 days, the OPC-ALGA concrete showed higher compressive strength compared to the OPC control concrete. At 28 days, the compressive strength of OPC-ALGA concrete is 41.89 MPa, meanwhile the compressive strength of OPC control concrete is 18.76 MPa with 123.3% lower than OPC-ALGA concrete. Then, the compressive strength of OPC-ALGA concrete is gaining 10.38% at 90 days of testing with 46.24 MPa.

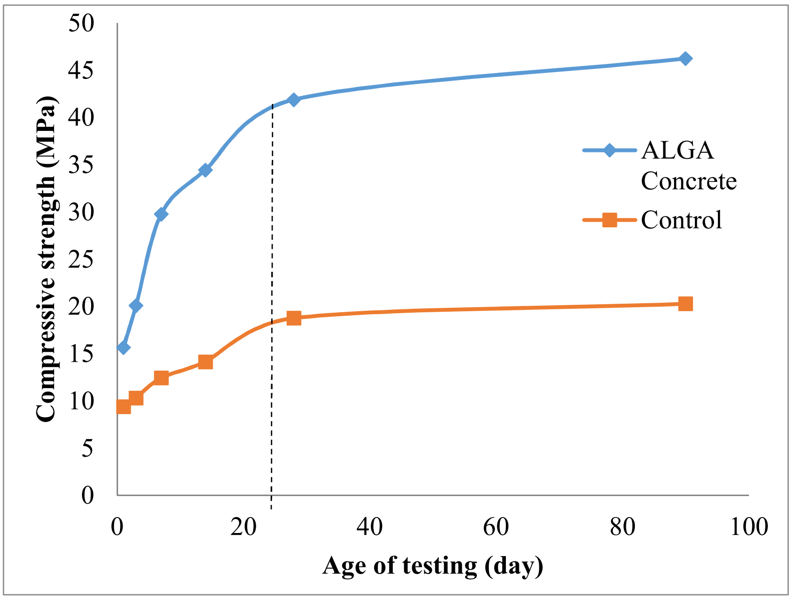


Fig. 1: Compressive strength of OPC-ALGA concrete and OPC control concrete at various ages of testing

It is well known that the interfacial zone between the hydrated cement paste and aggregates is the system's weakest point [25]. Fig. 2 showed the image of the cross section of ALGA surface and cement paste that well interlocked between each other. The cement paste is seen to enter a crushed grain of the ALGA, thus forming interlock between ALGA and cement paste which has strengthened the position of ALGA when loading is applied to the concrete [25].When water is added to the mixture, the ALGA starts to absorb due to porous structure. In this condition, any build-up of water around the ALGA grains is prevented, since the water is absorbed into the grains so that the interfacial zones become narrower and increase the density, thus increasing the compressive strength.

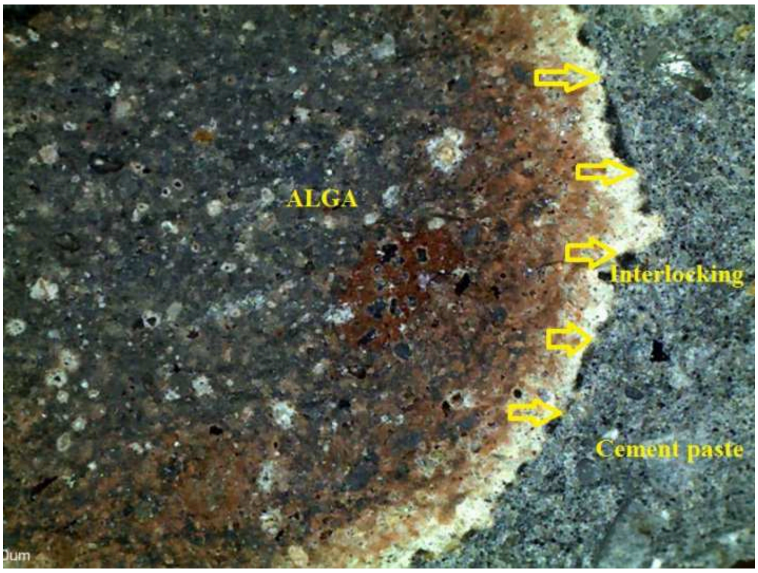


Fig. 2: The interlocking of cement paste and ALGA

Conclusion

The performance of OPC-ALGA concrete is excellent with high strength of 41.89 MPa at 28 days of testing with a density of 1760.1 kg/m^3 which can be classified as lightweight concrete. The water absorption of ALGA concrete is 2.77%. The finding from this study will be as new reference to be commercialized as lightweight aggregate and applied in the lightweight concrete. Furthermore, this finding also will give a new alternative to the Indonesian government for controlling or reducing the high quantity of LUSI mud.

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