Correlation between Thermal Insulation Properties with Compressive Strength and Density of Lightweight Geopolymer

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Abstract. This paper reports the results of an experimental work conducted to investigate the correlation between thermal insulation properties with compressive strength and density of lightweight geopolymer prepared by using fly ash as source material and combination of sodium hydroxide and sodium silicate as alkaline activator. The experiments were conducted by varying the ageing time of 3, 7, 28, 60 and 90 days, respectively. The specimens cured for a period of 90 days have presented the highest compressive strength and lowest density accompanied with satisfied value of thermal conductivity. From the results obtained, it was evident that the thermal conductivity had a high correlation coefficient with compressive strength and density.

1. Introduction

Demand is increasing for affordable and lightweight construction materials with superior mechanical properties. Lightweight concrete can be classed according to its unit weight or density, which normally ranges from 320 kg/m³ to 1920 kg/m³ according to the ACI Committee 213 Guide for Structural Lightweight Aggregate Concrete [1]. Lightweight concrete masonry produces some advantages such as reduces the dead load of the building, relatively low thermal conductivity, easy to handle and hence reduces the cost of transportation and handling and also comparatively more durable [2,3]. The challenge in making a lightweight concrete is decreasing the density while maintaining the strength of lightweight concrete. Lightweight concrete masonry could be produced either by using lightweight aggregates (natural lightweight aggregates or artificial lightweight aggregates) or admixtures (air entraining agent or admixtures that develop gases) [4].

Geopolymeric brick are considered as a new technology in which are eco-sustainable masonry units because the possess good mechanical and thermal properties as well as widen the possibilities to recycle waste material to useful products especially for building material [5,6]. Geopolymer lightweight bricks are more sustainable type of the lightweight concrete because of utilization of waste as source materials, manufactured at temperatures below 100 °C, reduces the carbon dioxide emissions and has better resistance to the chemical and fire [7-9].
One of the most popular source materials for production of geopolymer is fly ash. Fly ash is defined as the ‘finely divided residue causing from the burning of powdered coal or ground, which is conveyed from the fire box through the container by flue gases’ [10-11]. The main constituents of fly ash are alumina (Al₂O₃), silica (SiO₂), and iron oxides (Fe₂O₃), with varying amounts of calcium, magnesium, sulphur and carbon [12-14]. The utilization of fly ash as a source material to building and construction materials including cement, concrete, building bricks, and also aggregates is a beneficial approach because it not only transforms the wastes materials into useful materials but it also improves the dumping problems [16]. In the synthesis of geopolymeric materials, utilization of fly ash has been reported by several researchers [15-20].

Existing commercial lightweight concrete also generally possess low thermal insulation properties but has lower strength as compared to lightweight concrete prepared with geopolymer method. In terms of mechanical properties, geopolymer lightweight has enhanced properties without lowering its thermal insulation properties because it is known to have thermal conductivity value within the acceptable market range of 0.4 W/mK to 0.9 W/mK which depends on the density obtained [21].

There is very limited information on the uses of superplasticizer as foaming agent in lightweight geopolymer for concrete masonry applications. Therefore, for this research, the fly ash-based lightweight geopolymer were prepared with pre-form method of foaming agent to study the effects of ageing on compressive strength, density and thermal insulation properties of fly ash-based lightweight geopolymer [22]. The result is very important for the understanding and future improvement for this lightweight material.

2. Experimental

2.1. Material

In the present experimental work, low calcium, class F [22,23] dry fly ash obtained from the coal power station of Cirebon, Indonesia, was used as the raw material. The fly ash was sieved passing a 300 μm sieve to remove foreign materials and coarse particles. The chemical compositions of the fly ash as determined by X-Ray Fluorescence (XRF) analysis are given in table 1.

| Chemical composition | Percentage (%) |
|----------------------|----------------|
| SiO₂                 | 47.28          |
| Al₂O₃                | 16.59          |
| Fe₂O₃                | 20.30          |
| TiO₂                 | 0.86           |
| CaO                  | 6.98           |
| MgO                  | 4.20           |
| Na₂O                 | 0.46           |
| K₂O                  | 0.84           |
| SO₃                  | 1.60           |
| LOI                  | 1.57           |

The foaming agent selected for the research is a synthetic foaming agent named as Polyoxyethylene Alkyether Sulfate. Table 2 stated the properties of foaming agent used in this study. This type of foaming agent is called as surfactant which is easily dissolved in water and will create stable pores. It has a high pH as it is an alkali substance and has the appearance of a brown liquid and manufactured from coconut oil. Table 3 presents the chemical composition of the foaming agent analyzed using X-Ray Fluorescence. The major constituents of foaming agent used in this study are sulfate (SO₃) and palladium oxide (PdO) with 78.60% and 11.0%, respectively.

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Table 2. Properties of foaming agent (Polyoxyethylene Alkyether Sulfate)

| Particulars               | Properties          |
|---------------------------|---------------------|
| Appearances               | Brown liquid        |
| Specific gravity          | 1.15 to 1.20        |
| pH at 20°C                | 6.5 – 7.5           |
| Foaming agent dilution    | Dilution ratio of 1:10 - 1:40 |
| Chemical formula          | C12H25SO4           |
| Molar mass                | 288.372 g/mol       |

Table 3. Chemical composition of foaming agent (Polyoxyethylene Alkyether Sulfate)

| Chemical composition | Percentage (%) |
|----------------------|----------------|
| SiO₂                 | 1.80           |
| SO₃                  | 78.60          |
| K₂O                  | 1.60           |
| CaO                  | 4.20           |
| Sc₂O₃                | 0.10           |
| CuO                  | 2.20           |
| PdO                  | 11.00          |
| OsO₂                 | 0.90           |

For the alkaline activator, a combination of sodium hydroxide and sodium silicate solution was used. Sodium hydroxide in a form of pellets with 97% purity and Sodium silicate solution was supplied by South Pacific Chemicals Industries Sdn. Bhd. (SPCI), Malaysia with the chemical compositions SiO₂ 30.1%, Na₂O 9.4%, and H₂O 60.5% has been used in this study.

2.2. Sample Preparations

The alkaline activator solution was prepared by mixing a Na₂SiO₃ solution with NaOH solution and stir until achieve their homogeneity for at least 5 minutes. The alkaline solution was prepared at least 24 hours prior to use with constant ratio of Na₂SiO₃/NaOH of 2.5, by mass for all samples. In this research, the concentration of NaOH solution used is 12M due to the study done by [23] where they have found that this concentration give the highest in compressive strength.

Foaming agent was prepared according to the standard ASTM C 796 [24] by using preformed method. The foam is prepared by using a foam generator. The superplasticizer is diluted with water in foam generator to make a pre-foaming solution and then the pre-foaming solution is expanded with air (from air compressor) into foam. The pressure used for air compressor was kept constant at 0.5 MPa. The bubbles are stable and capable to resist the chemical and physical forces insisted during mixing, molding and curing of the lightweight geopolymer.

2.3. Design of Mix Proportions

In the determination of the effect ageing time of lightweight geopolymer using foaming agent, several fixed parameters and variable parameters were considered. The mix designs for this determination are given in the table 4. The lightweight geopolymer were synthesized according to the given ratio and cured in the oven at 80 °C for 24 hours. After cured in the oven, all the cube samples were removed from the mould and allowed to cool at room temperature at 3, 7, 28, 60 and 90 days of ageing for testing.
Table 4. Mix design for lightweight geopolymer at different ageing time

| Description                      | Mix design |
|----------------------------------|------------|
| Ratio of Na$_2$SiO$_3$/NaOH      | 2.5        |
| Ratio of fly ash/alkaline activator | 2.0        |
| Ratio of foaming agent/water     | 1/10       |
| Ratio of foam/geopolymer paste   | 1.0        |
| Foaming agent used (ml)          | 500        |

2.4. Mixing, Moulding and Curing Process of Lightweight Geopolymer

The lightweight geopolymer were produced using pre-foamed method where the superplasticizer (foaming agent) was prepared first using foam generator before adding to the geopolymer paste. The geopolymer paste was manufactured by mixing fly ash and alkaline activator solution at a given fly ash to alkaline activator mass ratio in a laboratory mixer.

In the laboratory mixer, the NaOH solution and Na$_2$SiO$_3$ solution were mixed first for 5 minutes to prepare alkaline activator solution. Then the fly ash was added to the alkaline activator solution and continues mixing for another 5 minutes until the mixture homogeneous to get the geopolymer paste. Certain amount of foaming agent is added to the geopolymer pastes to produce lightweight geopolymer paste. The lightweight geopolymer pastes are then poured into (50 × 50 × 50) mm cubic moulds. Samples are sealed and left at room temperature for 24 hours before placed in the oven for curing process. After 24 hours, the samples were cured in the oven at given temperatures and time based on parameters used, and then removed from the oven and kept sealed in room temperature until the day of testing.

2.5. Testing for Lightweight Geopolymer

The compressive strength test for lightweight geopolymer was carried out according to [25, 26] by using Universal Testing Machine (UTM), Shimadzu Japan, UH-1000 kNI at the rate of load speed 0.6 N/mm$^2$/s. The lightweight geopolymer samples were tested at 3, 7, 28, 60 and 90 days and three samples are tested to evaluate the average strength.

The dry density of lightweight geopolymer can be calculated by the formula as shown in Eq. 1 below. Cubic samples (50 x 50 x 50) mm were used for the density measurements. The reported density results were come from the average of three samples measurement.

$$\rho = \frac{M}{V}$$ (1)

Where,

$\rho$ = Dry density
M = Mass of sample
V = Volume of sample

The thermal insulation test was determined using transient plane source (TPS) method on a Hot Disk Thermal Constants Analyzer at ambient conditions. In this experiment, the samples were tested on cylindrical specimens with the thickness of 30 mm and 40 mm in diameter at room temperature. To achieve a relatively precise result, each pair of samples was measured three times to get the average value. In this study, the TPS method is used to measure the thermal conductivity, thermal diffusivity and specific heat of lightweight geopolymer samples. It has become an ISO Standard (ISO22007-2) for rapidly and precisely measuring thermal transport properties of lightweight geopolymer samples.
3. Results and Discussions

3.1. Correlation between Thermal Conductivity with Compressive Strength and Density of Lightweight Geopolymer

Figure 1 shows the relationship between the thermal conductivity and the compressive strength of lightweight geopolymer at different ageing time. The thermal conductivity is strongly influenced by the compressive strength of lightweight geopolymer with $R^2$ value of 0.967. In general, the compressive strength of lightweight geopolymer decreases with a decrease of thermal conductivity, and also results in a decrease in density of lightweight geopolymer.

![Figure 1](image-url)  
**Figure 1.** The relationship between thermal conductivity and compressive strength of lightweight geopolymer

The correlation between the thermal conductivity and density of lightweight geopolymer at various ageing time is plotted in figure 2. The relationship is linear with $R^2$ value equal to 0.9499, where the thermal conductivity is directly related to the density of lightweight geopolymer. High correlation coefficient values ($R^2$) shows in figure 2 indicate that density has an important effect on thermal conductivity properties. The reduction of thermal conductivity value is noticed when the density of lightweight geopolymer declined. This is affected by increasing the total air voids which results in a lower density which favours a reduced thermal conductivity. This is due to the decreasing of the volume of permeable voids and density of microstructure in the geopolymer matrix [27,28].
The fly ash-based lightweight geopolymer can thus be regarded as excellent thermal insulation building materials for their low thermal conductivity and relatively low thermal diffusivity. A good insulator material has a low thermal conductivity and thermal diffusivity because the materials could reduce the energy loss and stabilize the temperature with the surroundings. However, the specific heats value should be high because the materials are able to absorb more heat before it transfer the heat to the surroundings [29,30]. Thermal insulating materials play an important role in reducing the energy constraint, and hence reduce greenhouse gas emissions.

3.2. Correlation between Thermal Diffusivity with Compressive Strength and Density of Lightweight Geopolymer

The relationship between thermal diffusivity and compressive strength of lightweight geopolymer is presented in figure 3. The thermal diffusivity decreased with the decreasing compressive strength of lightweight geopolymer. The determination coefficient, $R^2$ is equal to 0.9647. High correlation coefficient values indicate that strength has an important effect on thermal diffusivity of lightweight geopolymer. High thermal diffusivity in concrete masonry material will ensure its temperature to equivalent with the surroundings.
Figure 3. The relationship between thermal diffusivity and compressive strength of lightweight geopolymer

An attempt was made to correlate density of lightweight geopolymer with thermal diffusivity at different ageing time. Figure 4 explained the linear correlation between thermal diffusivity and density of lightweight geopolymer at different ageing time. It can be seen that as the ageing time increases, the density and therefore the thermal diffusivity of lightweight geopolymer decreases. Similarly, there is a strong correlation between thermal diffusivity and density of lightweight geopolymer. The graph for the density versus thermal diffusivity was plotted and joined with a best fit line. The compressive strength and thermal diffusivity were found to reduce with a decrease in the density of lightweight geopolymer. This is due to the samples have higher content of air voids created from the foaming agent thus reducing the rate of heat transfer through the sample [31-33].

Figure 4. The relationship between thermal diffusivity and density of lightweight geopolymer
4. Conclusions
Thermal insulation test were carried out to investigate the thermal efficiency of fly ash-based lightweight geopolymer at different ageing time (3 days, 7 days, 28 days, 60 days and 90 days). From the results obtained, it was evident that the thermal conductivity had a high correlation coefficient with compressive strength and density. Thermal diffusivity and thermal conductivity of lightweight geopolymer materials are associated to the pore volume that indicated to the lower strength and density. The lightweight geopolymer cured until 90 days produced lowest thermal conductivity of 0.63 W/mK, lowest thermal diffusivity of 0.26 mm²/s and satisfied value of specific heat (2.5 MJ/m³K). For the insulating construction materials, the lower thermal conductivity and thermal diffusivity, the better their thermal insulation. So that, less energy required for the building to cool down and consequently save energy and cost. The samples obtained in present work shows potential in application of wall insulation materials.

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