Porous Metakaolin Geopolymers with Tailored Thermal Conductivity

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Abstract. In this work, a novel lightweight metakaolin geopolymers were produced by using hydrogen peroxide as foaming agent. The influence of the hydrogen peroxide incorporation content (0.25 – 1.25%) on density, compressive strength and thermal conductivity was evaluated. The experimental results show that the density and compressive strength were decrease with increasing content of hydrogen peroxide. However, the thermal insulating properties of the geopolymer foams were improved with increasing content of foaming agent. Geopolymers exhibiting thermal conductivity as low as 0.172 W/mK and a density of 0.5 g/cm³ were produced, showing the potential of these materials in applications requiring lightweight and low thermal conductivity materials.

1. Introduction

The increase in world population has indirectly raised the needs for shelters in the means of the residential building leading to increased energy consumption and greenhouse gas emissions worldwide. In light to this matter, a key criterion for the selection of construction materials is their sustainability. Ordinary Portland cement (OPC) is the most commonly used cementitious building material where the manufacture of OPC releases a great amount of CO₂ into the atmosphere. Hence, the searching for alternative building materials with reduced environmental footprints is becoming important. Lightweight geopolymer appears to be an excellent alternative with good performance and environmental benefits.

Geopolymers are amorphous three-dimensional aluminosilicate binder materials named first by Professor Joseph Davidovits in 1978 [1]. Geopolymers are produced by geopolymerisation reaction that uses aluminosilicate materials and an alkaline activating solution as the primary raw materials [2-4]. The geopolymerisation is a reaction between amorphous silica and alumina rich solids with a highly alkaline solution to form amorphous to semi-crystalline aluminosilicate inorganic polymers.

Porous geopolymers have been the focus of attention in the field of thermal insulation materials because it has shown great potential to many practical applications as a desirable substitute to ordinary Portland cement due to low thermal conductivity. The production of porous geopolymers involves the addition of foaming agents such as aluminium powders and hydrogen peroxide to the geopolymer slurry [5,6].
In this work, lightweight metakaolin geopolymers were produced using hydrogen peroxide (H₂O₂) as foaming agent. The influence of the foaming agent incorporation content on density, compressive strength and thermal conductivity were studied.

2. Experimental

2.1. Material
Metakaolin was used as the Si-Al source material in this work. The metakaolin was obtained by calcining the kaolin at 900 °C for 6 h in the furnace. The chemical composition of metakaolin determined by X-ray fluorescence (XRF) spectrometer is shown in Table 1. The activator solution was a mixture of sodium hydroxide (NaOH) and liquid sodium silicate (Na₂SiO₃). The NaOH powder has 99% purity with a density of 2.13 g/cm³ while the liquid Na₂SiO₃ contains 30.1% SiO₂, 9.4 Na₂O and 60.5% H₂O with a density of 2.4 g/cm³. Hydrogen peroxide solution (diluted from 30 wt% H₂O₂, from Sigma-Aldrich) was selected as chemical foaming agent. Tween 80 (polyethylene glycol sorbitan monoleate, VWR BDH Prolabo, Briare, France) was added as surfactant.

| Chemical | Wt% |
|----------|-----|
| SiO₂     | 55.7|
| Al₂O₃    | 38.6|
| Fe₂O₃    | 2.03|
| TiO₂     | 0.78|
| CuO      | 0.03|
| ZrO₂     | 0.04|
| K₂O      | 2.43|
| MnO₂     | 0.04|

2.2. Preparation of Metakaolin Geopolymer Foams (MkGps)
Geopolymer paste were prepared by mechanically mixing metakaolin and alkaline activator solution. The latter ones were obtained from a solution of 10M NaOH solution (prepared by dissolving sodium hydroxide pellets) and liquid sodium silicate. After that, wet foams were obtained by successively adding surfactant (500 rpm for 1 min) and H₂O₂ (500 rpm for 1 min) into the pastes. The mixing details is shown in Table 2. Immediately after mixing, the wet foams were poured into steel moulds with a dimensions of 50 x 50 x 50 mm. The moulded samples were sealed with a thin film to prevent moisture loss. The samples were cured subsequently in the oven at 60 °C for 24 h. The samples were demoulded and were left for 28 days at ambient temperature prior to compressive strength test and thermal conductivity.

| Sample name | Surfactant content (wt%) | H₂O₂ content (wt%) |
|-------------|--------------------------|--------------------|
| G1          | 1                        | 0.25               |
| G2          | 1                        | 0.50               |
| G3          | 1                        | 0.75               |
| G4          | 1                        | 1.00               |
| G5          | 1                        | 1.25               |
2.3. Test, Measurement and Characterization
The bulk density of the MkGPs was obtained as the ratio between the mass of the sample and its geometrical volume. The compressive strength of metakaolin geopolymer foam was measured in accordance to ASTMC109 by using Instron machine series 5569 Mechanical Tester. Room temperature thermal conductivity was measured using a Hot-Disk thermal constant analyzer (Hot-Disk AB Uppsala, Sweden). At least 3 measurements were performed to ensure reproducibility.

3. Results and Discussions
Fig. 1 presents the physical appearance of the geopolymer foams (sample G5). The structure of materials is homogeneous where the pores are evenly distributed and have almost the same size in the sample. However, the pore size is varied between different geopolymer foam.

![Figure 1. The exemplary surface of the geopolymer foams (sample G5).](image)

The influence of the foaming agent was investigated by applying five different concentrations of H\textsubscript{2}O\textsubscript{2} to fixed amount of added surfactant, known as Tween 80. Table 3 presents the composition of the examined materials and their characteristics such as density, thermal conductivity and compressive strength (which, dependent on the sample, amounted to 0.36 – 6.00 MPa). As can be seen from the results, the measured density decreases with the increasing concentration of H\textsubscript{2}O\textsubscript{2} content. With the increase amount of foaming agent added to the geopolymer mixture, the number of voids inside the material with air contained could be generated, thus resulting in increase of porosity and the reduction of density and thermal conductivity. Since the bulk density of geopolymer foams needs to be low, and is usually less than 1 g/cm\textsuperscript{3}, it can be concluded that the addition of only 0.25% of H\textsubscript{2}O\textsubscript{2} is certainly too low. The compressive strength and the value of the thermal conductivity were dependent on the density of the geopolymer foams.

| Sample labels | H\textsubscript{2}O\textsubscript{2} content (wt%) | Density (g/cm\textsuperscript{3}) | Thermal conductivity (W/mK) | Compression strength (MPa) |
|---------------|---------------------------------|-------------------------------|-----------------------------|---------------------------|
| G1            | 0.25                            | 1.212                         | 0.298                       | 6.00                      |
| G2            | 0.50                            | 0.814                         | 0.231                       | 2.18                      |
| G3            | 0.75                            | 0.720                         | 0.203                       | 0.66                      |
| G4            | 1.00                            | 0.610                         | 0.187                       | 0.40                      |
| G5            | 1.25                            | 0.500                         | 0.172                       | 0.36                      |
As was expected, the compressive strength of the investigated samples were in correlation with their densities. For instance, the compressive strength of sample G1, which had a density of 1.212 g/cm$^3$, amounted to 6.00 MPa, whereas it was significantly lower, i.e. 0.36 MPa, in the case of sample G5, which had a density of 0.5 g/cm$^3$. The similar trend was reported by Feng, Zhang [7] whereby increasing H$_2$O$_2$ dosage of 0.03 to 0.45 wt% caused the density reduction of the foamed geopolymer from 0.33 to 0.23 g/cm$^3$.

Fig. 3 presents the relationships between the thermal conductivity and the density of the geopolymer foams. The relationship is linear where the lower the density, the lower the thermal conductivity. A research done by Korat and Ducman [8] also obtained similar results where lower density produces a better thermal insulating property of geopolymers.

![Figure 2](image1.png)

**Figure 2.** The relationship between the compressive strength and the density of the geopolymer.

![Figure 3](image2.png)

**Figure 3.** The relationship between the thermal conductivity and the density of the geopolymer.
4. Conclusions
From the research, we can conclude several conclusions which are:

i. The foamed geopolymers can be a promising alternative to other thermal insulating materials

ii. The increasing amount of hydrogen peroxide addition has decreased the density and compressive strength while improving the insulating properties of foamed geopolymers.

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