Compressive strength and thermal conductivity of metakaolin geopolymers with anisotropic insulations

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Abstract. This research investigated the properties of thermally insulating geopolymer prepared using waste filler (fibreboard and rubber) to act as anisotropic pore/insulation. The geopolymer matrix was synthesised using metakaolin and an alkaline solution consists of sodium hydroxide solution and sodium silicate mixture. Geopolymers with varying content (0, 3, 5 and 7 layers) of coin-shaped fibreboard and expanded polystyrene are produced to examine the anisotropic insulation effect on the material characteristics. The compressive strength and thermal conductivity were determined experimentally. From the results, it is proved that the use of anisotropic insulations can improve the thermal conductivity and minimizing the reduction of compressive strength. Geopolymer incorporated with fibreboard had better performance in terms of strength while geopolymer incorporated with rubber had better thermal conductivity.

1. Introduction

Building and construction is considered as the biggest contributor to the worldwide energy consumption and greenhouse gas emission and many efforts has been done to improve energy efficiency. In light to this matter, insulating concrete has been widely used to reduce energy consumption. Insulating concrete is a material designed to reduce thermal conductivity by incorporating insulating components, such as lightweight aggregates and entrained pores. The presence of pores and the volume ratio helps lowering the thermal conductivity of concrete. Geopolymers have been used to make lightweight concretes with aim of producing more environmentally friendly construction materials compared to the OPC-based concretes [1-5]. Geopolymers are class of environmentally friendly and sustainable inorganic aluminosilicate, firstly introduced by Professor Joseph Davidovits in 1978 [6-11].

Generally, the thermal conductivity decreases as the pore volume increases, while the compressive strength has a direct proportion to the pore volume. Several studies have been done to overcome the contrary behavior between these properties using OPC-based concrete [12,13]. Cabrillac et al. [14] studied the mechanical behavior of an anisotropic porous materials made up of ellipsoidal pores. The study showed that at an equal porosity, a material made up of ellipsoidal pores could be four times as
rigid on a mechanical level in a preferential direction as compared to the material with spherical pores. Chung et al. [15] compared the effect of isotropic and anisotropic pores on materials properties of insulating concrete and discovered that the strength in parallel direction to the flat surface of the ellipsoidal pores is greater compared to the strength of isotropic pores. The thermal conductivity of the anisotropic pores is lower when measured in direction perpendicular to the flat surface of the ellipsoidal pores compared to the isotropic pores. From the study, it is proved that when the anisotropic pore is appropriately arranged in a specific direction, it can be used to reduce the thermal conductivity by minimizing strength loss. Zake-Tiluga et al. [16] also observed similar results when investigated anisotropic behavior of compressive strength in porous ceramic.

Most of the study on anisotropic pores were focused on OPC-based concrete and ceramics. There are limited knowledge of the pore anisotropy using geopolymer. Hence, the objective of this study is to develop thermally insulating materials with mechanical properties suitable for use in structural applications. In this work, rubber and corrugated fibreboard were incorporated in metakaolin geopolymer as anisotropic pores. The influence of directional factor on the compressive strength and thermal conductivity is assessed.

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 fluoroscene (XRF) spectrometer is shown in Table 1. The activator solution was a mixture of sodium hydroxide (NaOH) and liquid sodium silicate (Na$_2$SiO$_3$). The NaOH powder has 99% purity with a density of 2.13 g/cm$^3$ while the liquid Na$_2$SiO$_3$ contains 30.1% SiO$_2$, 9.4 Na$_2$O and 60.5% H$_2$O with a density of 2.4 g/cm$^3$. Corrugated fibreboard (from disposed carton box) and Insulflex (Lan Hoe, Malaysia) made of nitrile rubber were cut into coin-shaped. These insulation materials are denoted here as paper and rubber, respectively.

| Chemical | Wt% |
|----------|-----|
| SiO$_2$  | 55.7|
| Al$_2$O$_3$ | 38.6|
| Fe$_2$O$_3$ | 2.03|
| TiO$_2$  | 0.78|
| CuO      | 0.03|
| ZrO$_2$  | 0.04|
| K$_2$O   | 2.43|
| MnO$_2$  | 0.04|

2.2. Preparation of Metakaolin Geopolymer Incorporated with Anisotropic Insulations
Geopolymer paste were prepared by mechanically mixing metakaolin and alkali activator solution at a ratio of 0.8. The alkali activator was obtained from mixture of 10M NaOH solution (prepared by dissolving sodium hydroxide pellets) and liquid sodium silicate at a ratio of 1.0. The geopolymer paste were set into moulds with dimensions of 100 x 100 x 100 mm. To produce regular arrangement of the insulations, a layer with specific thickness is spread in the mould. Then, the coin-shaped insulations are uniformly distributed as shown in Figure 1 and varied in 3, 5 and 7 layers. The thickness between each insulation layer depends on the total number of layers in the sample. Reference sample also was made without incorporation of coin-shaped insulations. The moulded samples were sealed with a thin film to prevent moisture loss. The samples were left at room temperature for 24 h before demoulding. Subsequently, the demoulded samples were cured in the oven at 80°C for 24 h. The samples were then kept at room temperature for 28 days prior to compressive strength test and thermal conductivity.
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 was measured in two directions which were parallel and perpendicular (Figure 2) to the flat surface of the coin-shaped insulation and tested in accordance to ASTM C109 by using Instron machine series 5569 Mechanical Tester. Room-temperature thermal conductivity was measured in two directions which were parallel and perpendicular to the flat surface of the coin-shaped insulation using a Hot-Disk thermal constant analyser (Hot-Disk AB Uppsala, Sweden). At least 3 measurements were performed to ensure reproducibility.

3. Results and Discussions
Figure 3a presents the compressive strength of geopolymer with 0, 3, 5 and 7 layers of paper and rubber measured in directions parallel and perpendicular to the flat coin-shaped insulations. The compressive strength of the geopolymer decreased upon incorporation of the coin-shaped insulation, when measured in both parallel and perpendicular directions. However, the decrement of strength was more significant in parallel direction (38%) compared to perpendicular direction (86%) regardless of the type of insulation materials. According to Cabrillac et al. [14], when load was applied in the direction parallel to the flat surface of the insulation, the maximum stress is uniformly distributed over the whole sample. However, maximum stress can be found along the edge of anisotropic pores when the load is in perpendicular direction. It is showed that the orientation of anisotropic pores can be used to minimize the strength loss of the geopolymer. Besides, the strength decreases with the increasing...
layers of anisotropic pores, regardless of the directional factor. This is due to the decrease of the weight of the sample which leads to low density sample having low compressive strength (Table 2). Density has a direct relationship with the compressive strength of geopolymer.

Figure 3b shows the thermal conductivity of geopolymer with 0, 3, 5 and 7 layers of paper and rubber measured in directions parallel and perpendicular to the flat coin-shaped insulations. The reference sample has thermal conductivity of 0.213 W/mK. The thermal conductivity decreases upon incorporation of the coin-shaped insulation, when measured in both parallel (20%) and perpendicular (30%) directions, regardless of the type of insulation materials. However, larger reduction can be observed when measured perpendicular to the flat surface of the coin-shaped insulation. This is because less heat transfers through the perpendicular direction due to the disruption of heat flow by the flat surface of the pores [17].

Figure 3. The compressive strength and thermal conductivity of geopolymers with different insulations materials for the parallel and perpendicular directions.

| Samples     | Density (g/cm³) |
|-------------|-----------------|
|             | 0   | 3   | 5   | 7   |
| Reference   | 1.630 | -   | -   | -   |
| Paper       | -   | 1.613 | 1.572 | 1.554 |
| Rubber      | -   | 1.601 | 1.565 | 1.540 |

Figure 4(a-d) showed the microstructure of rubber and paper and also the geopolymer incorporated with paper and rubber. The porous nature of rubber is the most effective to reduce the thermal conductivity while paper is the most beneficial insulation material for larger strength due to fibrous-like and larger strength. The thermal conductivity results suggest that the use of anisotropic insulations can improve the insulation effect of the material. The formation of microcracks at the interface, as shown in Figure 4c was due to the poor adhesion between geopolymer matrix and rubber which causes large strength loss. However, the good adhesion between paper and the geopolymer matrix shown by the proper embedment of paper to the geopolymer (Figure 4d) attributed to the smaller strength loss.

The geopolymer showed a very promising thermal properties compared to other thermally insulating building materials produced using lightweight aggregates and entrained air. For example,
metakaolin geopolymer foams has a thermal conductivity of 0.091 W/mK at a strength of 0.3 MPa [18]. Lightweight geopolymer composites has a thermal conductivity of 0.12 W/mK at a strength of 2 MPa [3], however are not designed for load bearing purposes. This highlights the excellent properties of geopolymer obtained in this study with a thermal conductivity of 0.150 W/mK produced for when geopolymers with rubber as anisotropic insulation, measured in perpendicular direction with compressive strength of 16.34 MPa when measured in parallel direction. The properties of the geopolymer obtains in this study are within the range for structural and insulating lightweight materials based on ACI committee [19].

![SEM images](image_url)

**Figure 4.** SEM images of a) rubber, b) paper, c) geopolymer incorporated with rubber and d) geopolymer incorporated with paper.

4. **Conclusions**

From the research, we can draw several conclusions which are:

I. The compressive strength is higher when measured parallel to the flat surface of the coin-shaped insulation, while thermal conductivity is smaller when measured in perpendicular direction to the flat surface of the coin-shaped insulation.

II. The compressive strength and thermal conductivity were improved compared to the geopolymer foams with isotropic pores.

III. Increasing the number of insulation layers decrease the thermal conductivity and compressive strength regardless of the insulation materials type.

IV. Rubber is the most effective to reduce the thermal conductivity due to the porous nature, while paper is the most beneficial insulation material for higher strength due to fibrous-like and larger strength.

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**References**

[1] Bai C, Li H, Bernardo E and Colombo P 2019 *Ceram Intl* **45** 7196-7202.
[2] Wongsa A, Zaetang Y, Sata V and Chindaprasirt P 2016 Constr Build Mater 111 637-643.
[3] Colangelo F, Rovillo G, Ricciotti L, Ferrandiz-Mas V, Messina F, Ferone C, Tarallo O, Cioffi R and Cheeseman C R 2018 Cement Concrete Comp 86 266-272.
[4] Hamzah H N, Al Bakri Abdullah M M, Yong H C, Zainol M R R A and Hussin K 2015 Key Eng Mater 660 298-304.
[5] Hamzah H N, Al Bakri Abdullah M M, Yong H C, Zainol M R R A and Hussin K 2015 Mater Science Forum 841 59-64.
[6] Davidovits J 1991 T Therm Anal 37 1633-1656.
[7] Abdullah M M A B, Hussin K, Bnhussain M, Ismail K N, Yahya Z, Razak R A 2012 International Journal of Molecular Sciences 13(6) 7186–7198.
[8] Heah C Y, Kamarudin H, Bakri A M M Al, Luqman M, Nizar I K 2011 Australian Journal of Basic and Applied Sciences 5(7) 1026–1035.
[9] Liew Y M, Heah C Y, Li L yuan, Jaya N A, Abdullah M M A B, Tan S J, Hussin K 2017 Construction and Building Materials 156 9–18.
[10] Al Bakri Abdullah M M, Jamaludin L, Kamarudin H, Binhussain M, Ruzaidi Ghazali C M, Ahmad, M I 2013 Advanced Materials Research 686 227–233.
[11] Cheng-Yong H, Yun-Ming L, Abdullah M M A B, Hussin K 2017 Scientific Reports, 7 (November 2016) 1–11.
[12] Shahedan N F, Abdullah M M A B, Mahmed N, Kusbiantoro A, Binhussain M, Zailan S N 2017 AIP Conference Proceedings 1835 1 020046.
[13] Shahedan N F, Abdullah M M A B, Mahmed N, Kusbiantoro A, Bouissi A 2018 AIP Conference Proceedings 2030 20294.
[14] Cabrillac R, Bruno F, Anna-lise B, Helene D and Sophie O 2006 Const Build Mater 20 286-295.
[15] Chung S Y, Elrahman M A and Stephen D 2016 Energ Buildings 125 122-129.
[16] Tiluga Z, Svinka I R and Svinka V 2014 Key Eng Mater 604 153-156.
[17] Chung S Y, Elrahman M A and Stephan D 2017 Int J Concr Struct M 11 573-584
[18] Bai C and Colombo P 2017 J Mater Res 32 3251-3259.
[19] Committee, A.C.I., Specifications for Structural Concrete for Buildings (ACI 301-72). ACI Journal Proceedings, 1972. 69.