Thermal Conductivity of Geopolymer with Polypropylene Fiber

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Abstract. Geopolymer is widely used to replace cement for fire-resistant products. The benefits of geopolymer based on fly ash are cost-effective and easy process production. Lightweight products are needed to minimize dead load for the existing structure. The addition of polypropylene fiber is intended to produce relative lightweight and strong material applied for fire resistance. This research was conducted to obtain thermal conductivity, density, and compressive strength of the geopolymer. The ratio of activator/fly ash (a/f) was varied 40%, 45%, and 50% with addition of polypropylene fibers of 0.5%, 1%, and 1.5% of the fly ash weight. The experimental test was conducted on the 7th day at ambient temperature while concentration of NaOH used in geopolymer synthesis was kept at 10M with a ratio of alkaline activator (Na₂SiO₃/NaOH) of 2. The test results showed that thermal conductivity (λ) is in a range between 0.19-0.82 W/m.C while the thermal conductivity is less than 1 W/m.C. This indicates that the geopolymer can be applied for thermal insulating material. Geopolymer with polypropylene fiber and a/f 50% can be classified as lightweight material with a density around 1.6283-1.7625 gr/cm³. The ratio of a/f 50% produces a compressive strength ranging from 18.14 MPa to 28.42 MPa.

1. Introduction

Geopolymers served environmental protection by recycling low calcium-fly ash and slag furnaces. These geopolymers can be used as building material with excellent compressive strength for infrastructure development and structural applications [1]. Fly ash-based geopolymer is also an alternative material for substituting expensive raw materials, such as metakaolin. This procedure uses a low-cost budget and uses available reagents so that it saves material and cost [2]. The use of fly ash with NaOH and Na₂SiO₃ activators dryed at ambient temperature can reduce environmental problems caused by the overproduction of cement. This combination will produced easy-made and cost-effective geopolymer paste [3]. NaOH concentration has the effect on workability and time setting, while the compressive strength depend on Na₂SiO₃ [4] and the molarity of NaOH [5]. According to Jaya [5], low thermal conductivity and high compressive strength were obtained by using NaOH...
concentration above $10\,\text{M}$. In general, hardened geopolymer paste with polypropylene fiber has a higher strength compared to paste without fiber content [6].

The matrix texture of geopolymer paste was dominated by microporous material while cement paste was dominated by mesoporous material. The microporous material was proven to be thermal-resistance at high temperature indicated by no cracks on the surface, damage or dimensional changes found from laboratory tests. These changes were different from the cement paste which destroyed after high-temperature heating [7]. It was found that additional of carbon and basalt fibers could improve geopolymer thermal properties. Both fibers were shown a good resistance at high temperature applied to wood. These experimental results were shown no fire spread signs, shrinkage and low thermal conductivity [8]. Therefore, fly ash-based geopolymer can be used as eco-friendly fire-resistant building materials, sound and heat insulators, and thermal insulation materials [7,8].

Lightweight products are needed to minimize additional dead load of structures. The addition of polypropylene fiber is intended to produce relatively lightweight and strong geopolymer. The resulting geopolymer is expected suitable for application as fire resistance or thermal insulation. This study examined the properties of fly ash-based geopolymer mixture and polypropylene fiber namely thermal conductivity, density and compressive strength.

2. Materials, Specimens and Test Method

2.1. Materials

2.1.1. Fly ash
Fly ash was obtained from the Paiton power plant which chemical composition is shown in Table 1. Based on XRF test and according to ASTM C618 the fly ash can be classified as type C [9]. The density of fly ash is $1312\,\text{kg/m}^3$ and the specific gravity is 2.46. In this study, the activator/fly ash (a/f) ratio are 40%, 45%, and 50%.

| Chemical Components | SiO$_2$ | Na$_2$O | Fe$_2$O$_3$ | CaO | MgO$_2$ | Na$_2$O | K$_2$O | TiO$_2$ | Cr$_2$O$_3$ | SO$_3$ | LOI |
|---------------------|--------|---------|-------------|-----|---------|--------|-------|--------|------------|-------|-----|
| Fly ash             | 38.79  | 18.21   | 15.2        | 14.61 | 7.18    | 1.76   | 1.23  | 0.95    | 0.22       | 0.59  | 0.69 |

2.1.2. Alkaline Activator
Alkaline activator was produced through a reaction of sodium silicate (Na$_2$SiO$_3$) and sodium hydroxide (NaOH). 10 molarity of NaOH alkaline was made by dissolving NaOH pellets in distilled water. The ratio of Na$_2$SiO$_3$/NaOH was kept constant at 2.

2.1.3. Fiber
Figure 1 shows a monofilament polypropylene fiber produced by PT Sika Indonesia, with $0.91\,\text{gr/cm}^3$ density, 12 mm fiber length, 18 micron-nominal fiber diameter, 300-440 MPa tensile strength, and 6,000-9,000 MPa elastic modulus. The ratio of fiber to fly ash weight was varied at 0.5%, 1%, and 1.5%.

![Figure 1. Polypropylene fiber.](image)
2.2. Specimens
In this research three series of specimen were tested to determine thermal conductivity, density, and compressive strength. Each series consists of three specimens. All specimens were made of fly ash, alkaline activator, and polypropylene fiber. Fly ash and polypropylene fibers were mixed manually in dry condition. Alkaline activator was added into the mixture and they were mixed for 5 minutes until homogenous, according to the ASTM C 305 [10]. The mixture was poured into a mold and removed from the mold after 24 hours at ambient temperature. All specimens of fly ash-based geopolymer with variation of material combination are shown in Table 2.

Table 2. The proportion of geopolymer paste with polypropylene fiber by weight per m³.

| No | a/f Ratio (%) | Polypropylene Fiber (%) | Fly ash Kg | Na₂SiO₃ Kg | NaOH Kg | Polypropylene Kg |
|----|---------------|--------------------------|------------|------------|--------|-----------------|
| 1  | 40            | 0.5                      | 1510.71    | 402.86     | 201.43 | 7.55            |
| 2  | 40            | 1.0                      | 1510.71    | 402.86     | 201.43 | 15.11           |
| 3  | 40            | 1.5                      | 1510.71    | 402.86     | 201.43 | 22.66           |
| 4  | 45            | 0.5                      | 1441.20    | 432.36     | 216.18 | 7.21            |
| 5  | 45            | 1.0                      | 1441.20    | 432.36     | 216.18 | 14.41           |
| 6  | 45            | 1.5                      | 1441.20    | 432.36     | 216.18 | 21.62           |
| 7  | 50            | 0.5                      | 1377.80    | 459.27     | 229.63 | 6.89            |
| 8  | 50            | 1.0                      | 1377.80    | 459.27     | 229.63 | 13.78           |
| 9  | 50            | 1.5                      | 1377.80    | 459.27     | 229.63 | 20.67           |

2.3. Test Method

2.3.1. Thermal conductivity test
Thermal conductivity test was carried out with a cylindrical specimen of 4 cm diameter, with variation of 0.2 cm and 0.4 cm thickness, as shown in Figure 2. Thermal conductivity was measured using apparatus machine type OSK 4565-A Tokyo Meter Co.Model HVs - 400000SE according to ASTM E 177 [11]. Temperature investigation in this work was varied at 50°C, 100°C, 150°C, and 200°C.

2.3.2. Density test
A cylindrical specimen of 3 cm diameter with 1 cm thickness, as shown in Figure 3(a), was used for density test. The test was done according to the Archimedes principle according to ASTM D 792 [12]. The specimens were weighed in air and then immersed into a specific liquid to get the volume of specimen. The density was defined as dividing the weight by its volume.

2.3.3. Compressive test
Compressive strength was obtained from compressive test according to ASTM C 109 [13]. Figure 3(b) shows the cube specimen of 5x5x5 cm. The compressive test was executed after 7 day aging using a Compression Testing Machine. The compressive strength was obtained by dividing the maximum load to its cross section area of the original specimen.

Figure 2. Thermal conductivity specimen.
3. Results and Discussion

3.1. Thermal Conductivity

Figure 4 to 7 show the thermal conductivity from the measurements. All variance show fluctuated trend of thermal conductivity at low temperature. The thermal conductivity of samples with all a/f ratios and addition of polypropylene fiber shows similar trend. The results indicate that in a temperatures range of 50°C-200°C, insignificant differences of thermal conductivity were observed. Previous studies showed that, the thermal conductivity at low temperature of 120°C was a function of the conductivity of gels and pores caused by water evaporation [14]. It was reported in other study that high water content causes thermal conductivity to increase [15]. The thermal conductivity of samples in the present work was in a range of 0.19-0.82 W/m.C with an average of 0.421 W/m.C. Since the value is less than 1 W/m.C all geothermal synthesized in the present work is applicable and suitable as thermal insulating materials [16].

Figure 4. Thermal conductivity of geopolymer with polypropylene fiber (%) at temperature 50°C.

Figure 5. Thermal conductivity of geopolymer with polypropylene fiber (%) at temperature 100°C.

Figure 6. Thermal conductivity of geopolymer with polypropylene fiber (%) at temperature 150°C.

Figure 7. Thermal conductivity of geopolymer with polypropylene fiber (%) at temperature 200°C.
3.2. Density

Addition of polypropylene fibers by 0.5-1.5% shows whether the ratio of a/f affects the density of the geopolymer paste. As shown in Figure 8, the density decreases by the increasing a/f ratio. Addition of polypropylene fiber equal or more than 1% lead to formation of geopolymer with a density between 1.6283-1.7625 gr/cm$^3$. It indicates that the geopolymer paste can be classified as a lightweight product based on ASTM C567 (1140-1840 kg/m$^3$) [17]. Figure 10 shows that a decrease of density and compressive can be resulted from increasing of a/f ratio. Similar to previous study, compressive strength decreases with decreasing geopolymer density [6,18]. The decrease in density is due to an increase of pore volume in the specimens which consequently decreases the compressive strength [19]. Addition of polypropylene fiber in the paste will replace the amount of fly ash while added number of pores in the material. The pores are trapped between groups of fiber in a fresh matrix which causes a reduction in density in the hardened paste [6]. Moreover, water evaporation from the activator compounds also causes formation of pores which can reduce the density [20].

![Figure 8. The density of geopolymer with polypropylene fiber.](image)

3.3. Compressive strength

The compressive strength of fly ash-based geopolymers after 7 day aging is shown in Figure 9. The highest compressive strength is produced from the sample with a/f ratio of 40% which strength ranges in 23.63-33.41 MPa. The lowest compressive strength is produced from 50% a/f ratio samples with a strength in a range of 18.14-28.42 MPa. According to previous study, the strength of geopolymers significantly reduced when the a/f ratio is more than 40% [21]. The increasing ratio of a/f will reduce compressive strength of the resulting geopolymer by about 8%-13% with addition of polypropylene fiber by amount of 0.5-1.5%. Increasing a/f ratio will increase the amount of NaOH in the mixture, which causes the increasing number of pores and reduction of compressive strength. The presence of more NaOH will contributed to more OH ions available in the the mixture. OH ions will react with calcium to form Ca(OH)$_2$ and therefore decreases strength of the product [4].

In addition, polypropylene fibers affect significantly on the decrease of the compressive strength by an average of 25%. The decrease of compressive strength is due to shrinkage effect and weak fiber interface contact, which potentially breaks the bonds in geopolymer matrix [6]. Other research reported that the addition of more than 1% fiber will decrease mechanical properties of the products [6,18]. Reduction of fly ash and Na$_2$SiO$_3$ in the geopolymer mixture will reduce the compressive strength [4].
4. Conclusion
In general, geopolymer paste with some variation of polypropylene fiber addition could lower thermal conductivity of the product that make it suitable for thermal insulation application. According to the experimental results, conclusion can be drawn:

1. The thermal conductivity of all specimens range between 0.19-0.82 W/m.C with an average of 0.421 W/m.C is recommended as an insulator material.
2. The additional of polypropylene fiber doesn’t affect on the thermal conductivity.
3. The ratio a/f 40% is preferable to make high compressive strength (23.63 – 33.41 MPa), but the density is not classified as a lightweight material.
4. The ratio a/f 50% is preferable to produce lightweight material although it has low compressive strength (18.14-28.42 MPa).

Further investigation is needed to identify the strength and behaviour of the product during and after heating at high temperature.

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