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Mechanical Properties and Thermal Conductivity of Fly Ash-Based Geopolymer Foams with Polypropylene Fibers

Ni Komang Ayu Agustini [1,2], Andreas Triwiyono [3,*], Djoko Sulistyo [3] and S Suyitno [4]

1 Civil and Environmental Engineering Department, Gadjah Mada University, Yogyakarta 55288, Indonesia; ni.komang.ayu@mail.ugm.ac.id
2 Faculty of Engineering and Planning, Warmadewa University, Denpasar 80116, Indonesia
3 Department of Civil and Environmental Engineering, Gadjah Mada University, Yogyakarta 55288, Indonesia; djokosulistyo@ugm.ac.id
4 Department of Mechanical and Industrial Engineering, Gadjah Mada University, Yogyakarta 55288, Indonesia; suyitno@ugm.ac.id
* Correspondence: andreas.triwiyono@ugm.ac.id

Abstract: This paper focuses on the effect of polypropylene (PP) fibers on the mechanical properties and thermal conductivity of fly ash-based geopolymer foams. Class C Fly ash (FA) was used as a binder material. A mixture of sodium silicate (SS) and sodium hydroxide (SH) was used as an alkaline activator of the geopolymer binder. The foams were prepared mechanically by mixing the foaming agent with distilled water at high pressure. The foams were added to the geopolymer admixture with volumes of 40% and 60%. A small dosage of PP was varied from 0%, 0.25%, and 0.50% by weight of fly ash (FA). The result showed that the strength of foamed geopolymer rises as the PP fiber content increases. The PP fiber was proven to increase the tensile strength of foamed geopolymer due to the ability of PP fiber to connect the crack and improve the tensile strength. The PP fiber amount in this study significantly affects the thermal conductivity of foamed geopolymer. However, the thermal conductivity in this study has the same properties as lightweight concrete and a little higher than gypsum board.

Keywords: foamed geopolymer; polypropylene; thermal conductivity; mechanical properties

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1. Introduction

Geopolymers are known as a new generation of materials. These materials consist of aluminosilicate powder, which is activated using the alkali solution. Commonly, a by-product of coal combustion (fly ash) or calcinated kaolinite clay (metakaolin) is used as raw materials. The combination of these materials results in the geopolymeric gel binder phase [1]. Davidovits [2] mentioned that geopolymers act similar to zeolites and feldspathoids, which adsorbs toxic chemical waste. The geopolymer matrix helps deactivated hazardous elemental waste and turns it into an adhesive solid.

According to the reaction to high-temperature exposure, many researchers have learned this behavior and stated that the alkali-activated aluminosilicate materials have better fire-resistance than the Portland cement mortar. Davidovits [3] reported that geopolymer materials are mineral materials and act similar to thermosetting organic resins, having thermal stability up to 1200 and 1400 °C. Previous investigations showed geopolymer mortar with metakaolin and fly-ash as raw materials that have a better performance in high temperatures than the Portland cement mortar or the commercial mortar, especially in compressive and bond strength [4].

The concern of expanding sustainable insulation material is increasing. One alternative is foamed geopolymer [5]. Subaer [6] mentioned that a low thermal conductivity is needed when using the geopolymer as an insulation product because it was designed to reduce the protected materials' heat conduction. Decreasing the density of geopolymer results in lower thermal conductivity [7]. The foamed geopolymer is an adequate alternative protection to fire corresponding to their properties, non-inflammability materials and have a low thermal conductivity [8]. The type of foaming agent and its amount significantly affect the lightweight geopolymer's thermal properties. Huang et al. [9] reported that the thermal conductivity of porous fly ash-based geopolymer materials (as low as 0.0564 W/mK) through a physical foaming and non-sintering method. Carabba et al. [10] pointed out that a lightweight mortar with identical properties similar to commercial cement-based ones used as fire protection occurred when the expanded perlite and H_2O_2 were used to produce a lightweight mortar. A combination of surfactant and foam reported by Jaya et al. [11] produced a smaller and narrower pore size distribution. Furthermore, he explained that geopolymer foam could be classified as Class II structural and insulating materials.

Fiber materials were used to increase the mechanical properties of materials, especially in foamed material. As the density in foamed material decreases, its effect on their mechanical properties such as tensile strength, compressive strength, spalling or cracking increases. Maras and Kose [12] investigated the PP fibers effect on the mechanical properties of geopolymer composite. The PP fiber was mixed into the admixture in 0%, 0.5%, and 1.0% by volume. Their result showed an enhancement in compressive strength of geopolymer in the addition of PP fiber. Irshidat, Al-Nuaimi, and Rabie [13] reported the thermal and mechanical properties of cement mortars with a varied amount of PP fibers after being heated to elevated temperatures of 150 °C, 200 °C, 450 °C, and 600 °C. The residual compressive strength of cement mortar was increased with the presence of PP. They also showed that the thermal conductivity decreased as the temperature increased. However, the thermal conductivity of the reinforcement mortar was higher than the plain mortar when the temperature reached 200 °C. Jhatial, Goh, Mohamad, Alengaram, and Mo [14] reported that in the range of 0.20%, 0.25% and 0.30% amount of PP fibers in lightweight concrete, the highest compressive strength occurred when the foamed concrete contained 0.20% of PP fibers. They also found that the addition of PP fibers on lightweight-foamed concrete can reduce their thermal conductivity. Won, Choi, Lee, Jang, and Lee [15] reported the optimum mixed proportion of cement composite with PP fibers. A range of PP fibers added was 0 to 0.35% at 0.05% intervals. According to their results, the compressive strength target was successfully reached at 40 MPa at 28 Mpa for all mixtures. The thermal conductivity of the mixture showed a decreasing trend as the amount of the fiber increased. According to Pham et al. [16], the strength of geopolymer concrete with 0.5% PP fibers increased 26% compared to it without PP fibers and decrease while geopolymer concrete contains 1.0% and 1.5% of PP fibers. Thus, this amount of fiber is the most appropriate in this mixture Choi et al. [17] reported that spalling did not occur when eco-friendly fireproof high-strength concrete was exposed to a high temperature. Due to the melted PP fiber creating connecting pores to the outside, the pressure decreased via these pores. According to [18], the polypropylene fibers have a low-temperature melting point of about 170 °C. Around that temperature, the fiber creates channels to allow steam pressure to escape in concrete. This behavior avoids small explosions that cause the spalling of concrete. This study recommended an amount of 0.1 to 0.25% of PP fiber to minimize the spalling.

Various studies to improve the mechanical properties and thermal properties of lightweight materials with PP fiber have been tried by many researchers, mainly in concrete materials. Only a few of them analyze the effect of PP fibers on lightweight geopolymers. The objective of this study investigates the effect of PP fibers on compressive strength, tensile strength, and thermal conductivity of fly ash-based geopolymer foamed materials. These properties have a major role in estimating the capability of foamed geopolymer materials when used as insulator materials. To get more comparability, the thermal conductivity in this study was varied at a range temperature of 50 to 200 °C.

2. Materials and Methods

2.1. Materials

The materials used in this research contained of fly ash (FA), sodium silicate (SS), sodium hydroxide (SH), foam, and PP fiber. Class C fly ash from the Pembangkitan Jawa Bali Paiton Power Station, East Java, Indonesia was used with the chemical composition shown in Table 1. The FA has a density of 2.46 gr/cm^3. The ashes were dried at 100 $\pm$ 5 °C for 24 h and kept in a polyethylene container. Figure 1 shows the SEM Micrograph of fly ash (FA).

Table 1. The chemical component of fly ash (by mass ratio) [19].

Main Components	Proportions (%)
SiO_2	38.90
Al_2O_3	18.21
Fe_2O_3	18.21
CaO	14.61
MgO	7.18
Na_2O	1.76
K_2O	1.23
TiO	0.95
MnO	0.22
Cr_2O_3	0.01
SO_3	0.59
LOI *	0.69

* Loss on ignition at 1000 °C.

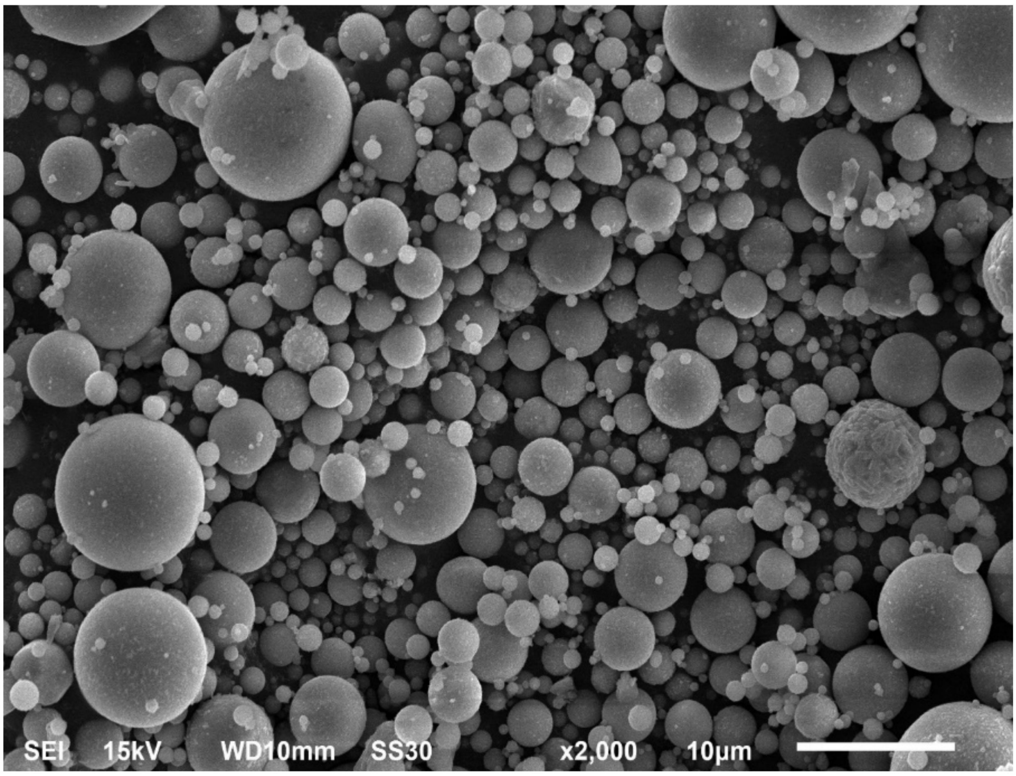

Figure 1. SEM Micrograph of FA.

FA was activated using an alkaline activator by mixing sodium silicate (SS) and sodium hydroxide (SH) solution. SS liquid contains 19.86% SiO_2, 7.89% Na_2O, and 72.25% H_2O, while SH powder has 99 wt.% purity. SH solution of 10 Molar concentration was used in this study by mixing the SH powder and distilled water. All activator solutions were supplied by Brataco Chemica, Tangerang, Banten, Indonesia.

Sika Poro 40 ID (Supplied by Sika Indonesia, Bogor, West Java, Indonesia), with a density of 1.02 $\pm$ 0.02 kg/L was used as a surfactant for foaming admixture. The foamed was made mechanically by mixing the surfactant and the distilled water (1:40 mL) at 5 kPa in generator foam to make a homogenized foam. The foaming admixture was added with a ratio of 40% and 60% from the total volume of geopolymer.

PP fibers (Supplied by Sika Indonesia, Bogor, West Java, Indonesia) have a specified dimension of 12 mm (length) and 18 µm (diameter), specific gravity of 0.91 g/cm^3, tensile strength of 300 to 440 MPa and elastic modulus of 600 to 9000 MPa. The softening point of PP fiber is 160. PP fibers were added with a ratio of 0%, 0.25%, and 0.50% by the mass of fly ash.

2.2. Synthesis of Geopolymer

The geopolymer paste was synthesized with the fixed percentage ratio of alkaline activator with FA at 35%, which has higher mechanical properties and the lowest thermal conductivity in accordance with previous work published by the authors [19]. The molarity of SH was 10 M and mass proportions of SS: SH was kept constant as 1:2. Geopolymer was made by mixing the FA, PP fiber, and the activator for 5 min in Hobart mixer with a speed of 140 rpm. The foaming admixture was added gradually to the slurry at a low speed for 2 min to make the foam spread uniformly. The slurry was poured into various sized molds then cured at a temperature of 23 $\pm$ 2 °C with a humidity of 80 $\pm$ 10%. The detailed mixture for the geopolymer is listed in Table 2.

Table 2. Mixture composition of foamed geopolymer (kg).

Code	FA	SS	SH	Foam (lt)	PP
Geo. paste control	1587.28	370.37	185.18	0.00	0.00
Geo.Foam40%.PP 0%	952.37	222.22	111.11	400.00	0.00
Geo.Foam60%.PP 0%	634.91	148.15	74.07	600.00	0.00
Geo.Foam40%.PP 0.25%	952.37	222.22	111.11	400.00	2.38
Geo.Foam60%.PP 0.25%	634.91	148.15	74.07	600.00	1.59
Geo.Foam40%.PP 0.5%	952.37	222.22	111.11	400.00	4.76
Geo.Foam60%.PP 0.5%	634.91	148.15	74.07	600.00	3.17

2.3. Test Apparatus and Procedure

Compressive strength testing was conducted on a cube sample with a dimension of 50 $\times$ 50 $\times$ 50 mm^3. Samples were tested 7 and 28 days after synthesis using Avery Dennison 20 kN compressive strength test machine according to ASTM C109/109 M [20]. All reported for compressive strength test are the average of measurement of the three samples. Figure 2 shows the specimen and setting up for the compressive strength test. The samples' density was determined from the compressive strength sample by dividing the mass by the volume. All reported for density test are the average of measurement of three samples.

The tensile strength test on the "8" shape was conducted as per ASTM C 307-03 [21] at 28 days using ELE 8 kN tensile strength machine loaded at a rate of 5 mm/min. All reports for the tensile strength tests are the averages of the measurements of the three samples. Figure 3 shows the specimen and setting up for the tensile strength test.

Thermal conductivity testing was conducted to comply with ASTM C 177 [22] closely. A set of cylindrical samples with thickness dimensions of 2 mm and 4 mm (40 mm diameter) were tested using thermal conductivity measuring apparatus (HVS-40-200 SE from Tokyo, Japan) at varying temperatures (50 °C, 100 °C, 150 °C, and 200 °C). All reported thermal conductivity results are the average measurement of two samples. Figure 4 shows the specimen and setting up for the thermal conductivity test.

(**a**) (**b**)

Figure 2. Compressive strength test (**a**) and the specimen (**b**).

(**a**) (**b**)

Figure 3. Tensile strength test (**a**) and the specimen (**b**).

(a)

(b)

Figure 4. Thermal conductivity test (**a**) and the specimen (**b**).

3. Results and Discussion

3.1. Foam Effect on Compressive Strength of Geopolymer

Figure 5 presents the compressive strength and density of the foamed geopolymer at 7 and 28 days. In general, all compressive strength of the specimen increased with age. For the geopolymer control, the strength was 9.10 MPa at 7 days, and it rose 105% by age to the value of 18.69 MPa at 28 days. The development of geopolymer gels increases with the increase of curing time and affects the strength. The compressive strength tends to decrease at 7 days by 0.63 and 0.29 times from the control geopolymer when the geopolymer contains 40% and 60% foam, respectively. Different trends slightly occurred with the compressive strength, which tends to increase about 1.26 times, and then drop drastically by 0.41 times from the control geopolymer at 28 days. This increment may be due to the non-uniform distribution of being foamed while casting the sample into the mold. However, by introducing the porosity into the geopolymer, the compressive strength tends to decrease. The instability of the solid structure and the addition of air void as porosity was the reason for the strength reduction [23,24].

3.2. Fiber Effect on the Compressive Strength and Density of Geopolymer

Figure 6 shows the PP fiber effect on the compressive strength of both 40% and 60% foamed geopolymer. It can be seen that the mechanical strength rises gently with the addition of PP fibers. An enhancement of PP fiber content was observed to give a significant effect at 7 days compressive strength. However, a minimal decrease of compressive was observed when 0.50% PP fiber contained in foamed geopolymer. At 7 days curing time, the strength of 40% foamed geopolymer show an increase at 205% times and 271% times when the PP fibers were at 0.25% and 0.50%, respectively, compared to without PP fibers. The strength of 60% foamed geopolymer shows the same trend, which tends to rise as the PP fiber content increases. However, at 28 days curing time, both 40% and 60% of foamed geopolymer contain PP fibers of 0.25% and 0.50% with a similar trend. First when 0.25% PP fiber were included in the foamed geopolymer the strength tended to rise, but this strength dropped slightly when PP fiber content was 0.5%.

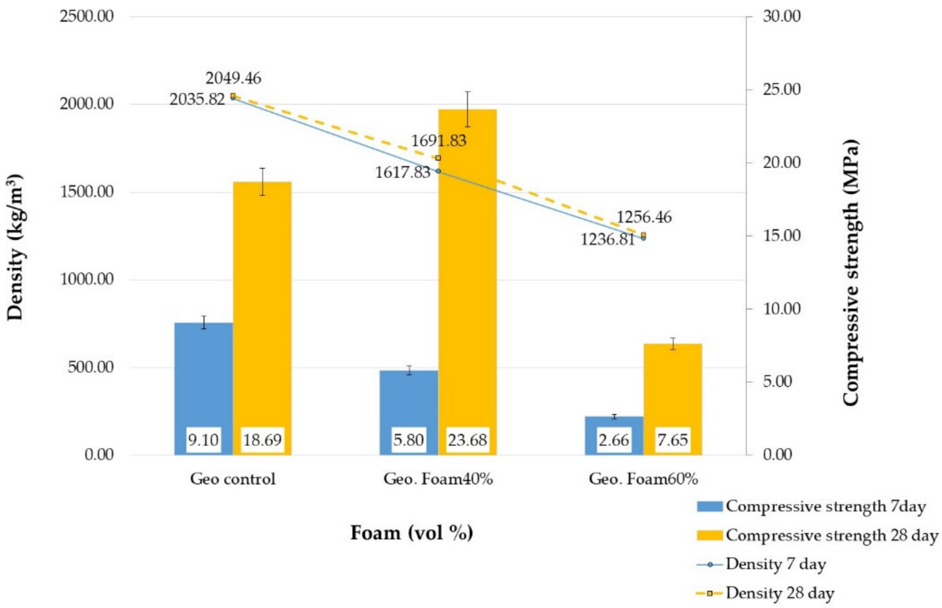

Figure 5. Compressive strength of foamed geopolymer.

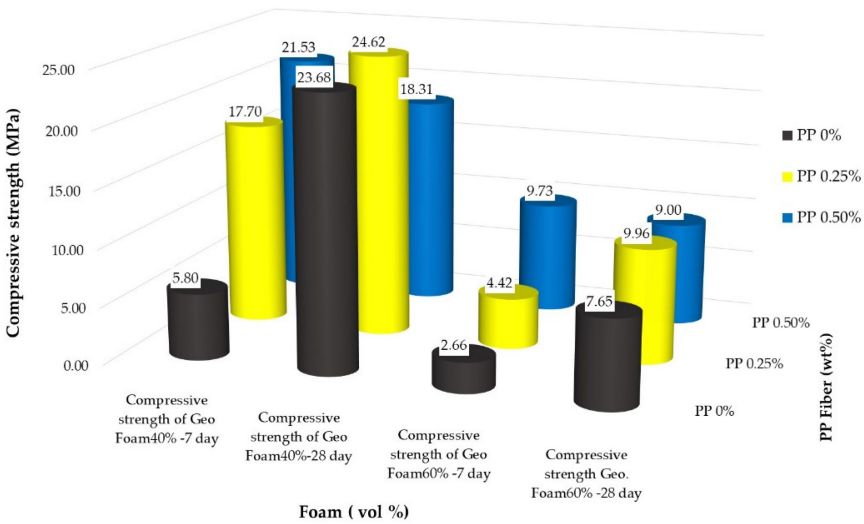

Figure 6. The effect of PP fiber on the compressive strength of foamed geopolymers.

The rise in compressive strength of foamed geopolymer is caused by the bonding mechanism between the PP fibers and geopolymer matrix, where the PP fibers fill up the void from the air. The use of PP fibers beyond optimum dosages can also reduce the strength. According to [14], the PP fibers may have the properties of a hydrophobic material, which tends to retain water and create voids. Besides that, the higher dosage of PP fiber can obstruct the void and can cause weaknesses in the bonding between the matrix and the PP fibers.

The strength reduction in 40% and 60% foamed geopolymer of PP fibers at 0.5% also corresponds with their dry density. A minimal increase in the density of foamed geopolymer was observed at 0.25% dosage of PP fiber, and the density slowly decreased when 0.50% amount of PP fiber was contained in geopolymer. As shown in Figure 7, the dry density of fiber reinforcement geopolymer decreased slightly around 5.3% and 4% compared to the dry density of foamed geopolymer without PP fibers, respectively. Pham et al. [16] reported that the strength of fiber-reinforced geopolymer concrete was improved at 0% and 0.5% of PP fiber and decreased at the amount of 1.0% and 1.5%. Previous works also showed [15,25,26] that the increased amount of PP fibers decrease the rate of strength development. Even though the geopolymer matrix itself is strong locally, the interaction with PP fibers does not result in the same behavior.

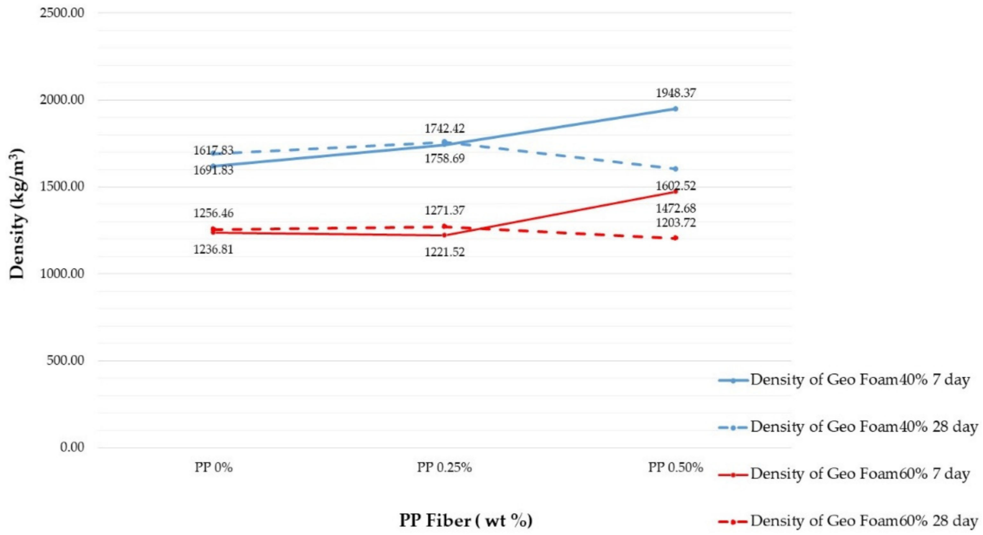

Figure 7. Dry density of fly ash foamed geopolymer with different PP fibers.

3.3. PP Fibers Effect on Tensile Strength of Foamed Geopolymers

Figure 8 shows the PP fiber effect on the tensile strength of foamed geopolymers. A significant increase in tensile strength was observed when the geopolymer contains foamed and PP fiber compared with the control geopolymer. The enhancement was observed more than 10 times from the control geopolymer. The result shows that the trend tends to increase with the amount of PP fiber contained in the foamed geopolymer. The tensile strength of 40% foamed geopolymer with reinforced increases 6.7% and 44.6% compared to without the PP fibers. This similar trend was shown for the tensile strength of 60% foamed geopolymer, which increases as the fiber is included in the matrix. This may be due to the cohesiveness between the fibers and the geopolymer matrix, which improves strength. Besides that, the high tensile strength properties of PP fibers give a major contribution to the tensile strength of geopolymers. According to [27], the increase in tensile strength occurred when PP fiber from 0.3% to 0.5% was added into the geopolymer specimen. This is a consequence of the fiber's ability to connect the cracks and prevent the crack-face separation whenever cracks occur and spread. A similar trend has been reported, for example [28], which confirmed that the addition of the ideal hemp fiber content makes an incredible enhancement in the tensile strength of the geopolymer composite.

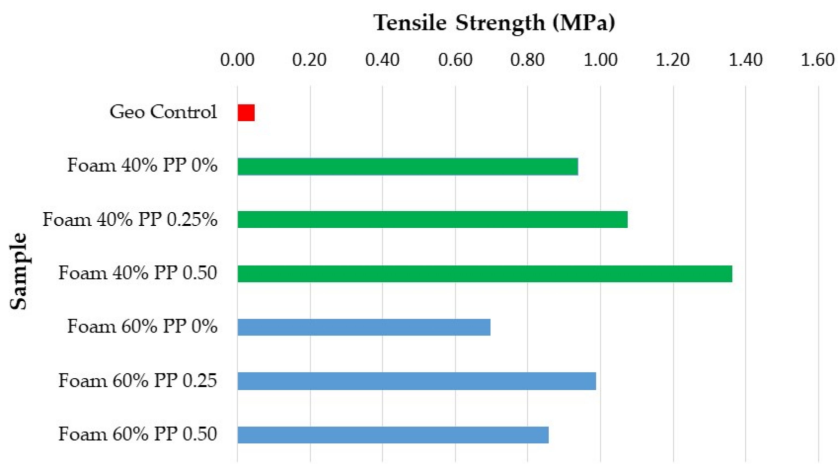

Figure 8. Tensile strength of foamed geopolymer.

3.4. PP Fiber Effect on Thermal Conductivity of Foamed Geopolymer

The thermal conductivity of foamed geopolymer is shown in Figure 9. As can be seen from Figure 9, the control geopolymer has a high thermal conductivity along with temperature compared with its porous geopolymer. After introducing the foam, the geopolymer was observed to show a decrease in thermal conductivity. The density seems to have a significant effect on the thermal conductivity of the geopolymer. It is well known that porosity is the main effect of thermal conductivity [29]. The enhancement of porosity in the geopolymer matrix lowers the volume of the framework structure, because the thermal conductivity of the framework is higher compared to the air within the voids, therefore the affecting the high thermal conductivity of the control geopolymer [30–32]. A similar trend was reported for porous geopolymer with the increased amount of H_2O_2 [24], which causes an enhancement of the voids inside the material and reduces their density and thermal conductivity.

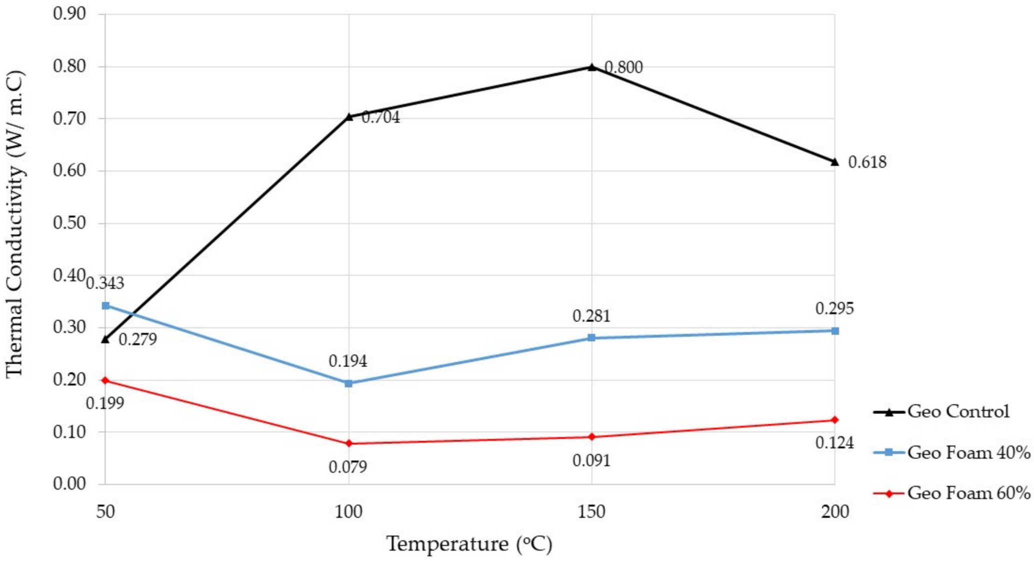

Figure 9. Thermal conductivity of foamed geopolymer.

The effect of PP fibers on the thermal conductivity of foamed geopolymer are shown in Figures 10 and 11. Both 40% and 60% foamed geopolymer has a different thermal conductivity trend regardless of the similar amount of PP fibers. As shown in Figure 10, when 40% foamed geopolymer contains 0.25% PP fiber at the temperature of 50 °C, the thermal conductivity increases almost 123% from the foamed geopolymer without reinforcement. This value drops significantly at a temperature of 100 °C, and has the lowest thermal conductivity when the temperature rises to 200 °C. Although it only rises about 45% at 50 °C compared with pure foamed geopolymer, the thermal conductivity of 40% foamed geopolymer with 0.5% PP fiber has the highest thermal conductivity in the temperature range 100–200 °C. In contrast, Figure 11 show that 0.25% PP fiber gives the highest thermal conductivity throughout the temperature of 60% foamed geopolymer. The increase occurred up to 277%, while 0.5% PP only increases as much as 4.7% compared without the pure foamed geopolymer.

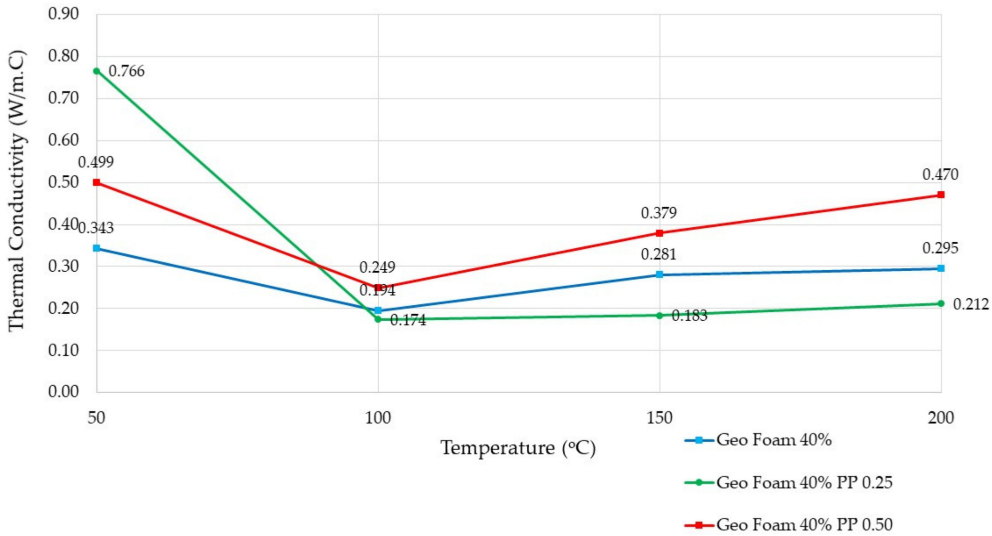

Figure 10. Thermal conductivity of 40% foamed geopolymer with varied PP fiber.

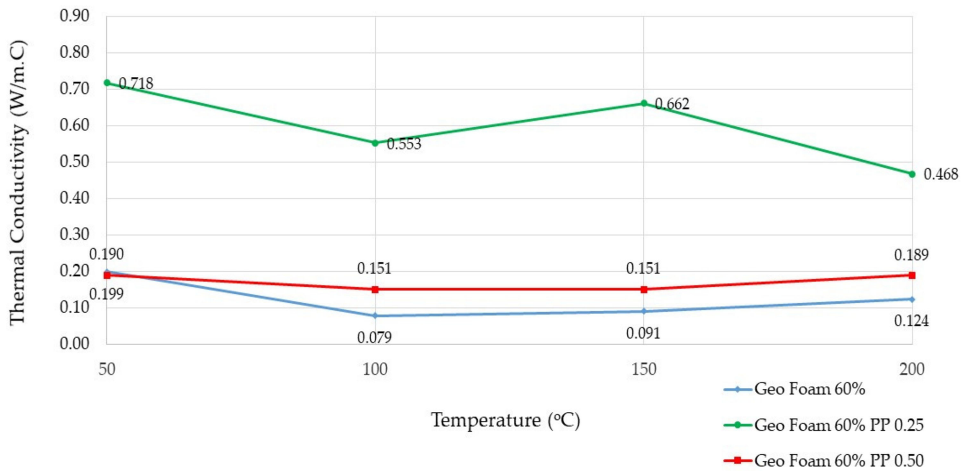

Figure 11. Thermal conductivity of 60% foamed geopolymer with varied PP fiber.

Although PP fiber has a relatively small density (around 0.91 g/cm^3), the PP fibers amount in this study has a significant effect on the density of foamed geopolymer. Generally, adding the PP fiber into the foamed geopolymer will increase their density, thus resulting in higher thermal conductivity. When the temperature was raised, the PP fiber melted and created an extra void inside the foamed geopolymer matrix. Generally [13], this void can allow the steam to release due to the dehydration process and weaken the internal pore pressure. A similar trend was reported [13] using PP fibers in cement mortar compared to without the fiber-reinforced at temperatures of 150 °C, 200 °C, 450 °C, and 600 °C. Fiber-reinforced cement mortar has greater thermal conductivity compared to plain mortar especially when the temperature is above 200 °C. The thermal conductivity in this study has the same properties as lightweight concrete (density of 1800 kg/m^3, the thermal conductivity of 0.6–0.8 W/m°C) and a little higher than gypsum board (density of 800 kg/m^3, the thermal conductivity of 0.2 W/m °C) [33].

4. Conclusions

In this study, foamed geopolymer with or without PP fibers was produced and tested experimentally. The foam was created mechanically and mixed into the geopolymer with volume proportions of 40% and 60% and the PP fiber dosage varied from 0%, 0.25%, to 0.50%. The mechanical properties observed included mechanical and tensile strength. The thermal conductivity was tested at a certain range temperature. The result showed that introducing porosity can reduce their compressive strength. However, when PP fibers fill up the void, the bonding between the PP fibers and the geopolymer matrix becomes strong and it increases the strength of foamed geopolymer. The PP fiber was proven to increase the tensile strength of foamed geopolymer due to the ability of PP fiber to connect the crack and improve the tensile strength. Although PP fiber has a small density, The PP fiber amount in this study gives a significant effect on the increased of the thermal conductivity of foamed geopolymer. However, the thermal conductivity in this study has the same properties as lightweight concrete (density 1800 kg/m^3. the thermal conductivity 0.6–0.8 W/m°C) and a little higher than gypsum board (density 800 kg/m^3. the thermal conductivity 0.2 W/m°C).

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