Thermal Performance of Natural Fiber-Reinforced Geopolymer Concrete

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Abstract Malaysia has a hot tropical climate; hence, the energy required to cool buildings increases daily. Therefore, an attempt was made to produce an eco-friendly construction material with good thermal performance. Geopolymer concrete (GPC) reinforced with two different types of natural fibers, kenaf fiber (KF) or coconut fibers (CFs), was introduced as insulation material. The proposed concrete mixtures were subjected to a non-destructive thermal test using a hotbox apparatus. Three panels of 100 mm thick were fabricated; the first panel consists of GPC as control, the second panel consisted of GPC with 1% KF, and the third panel consists of GPC with 0.75% CF. The composite that achieved the best test performance was selected and used to fabricate different thicknesses, 75 and 50 mm. The results showed that the compressive strength of GPC prepared with KF was 2.4 and 5% higher than that of GPC with CF at 7 and 28 days, respectively. Moreover, the thermal conductivity of GPC prepared with KF was more effective than that with CF which was lower by 3.8%, while compared to GPC without fiber, the thermal conductivity of geopolymer kenaf fiber decreased by 7.1%. In addition, the decrease in the thickness of the panel leads to a decrease in the thermal conductivity by 23% and 42% of 75 mm and 50 mm, respectively. In conclusion, the addition of KF to GPC can improve compressive strength and thermal insulation. Hopefully, this compound provides the industry with an alternative material of high thermal resistance for wall panels.

Keywords Geopolymer concrete · Kenaf fiber · Thermal insulation

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1   Introduction

The climate and global warming changes have many impacts on the engineering field and particularly the construction industry. Therefore, many researchers try to find a solution in different ways to decrease temperature effects on buildings and geopolymer is one of the alternative materials. Geopolymers possess distinctive properties such as high strength and resistance to high temperatures, i.e., a good heat insulator. The production of one ton of geopolymer binders produces 0.18 tons less carbon dioxide (CO_2) from the burning of carbon fuel compared to one ton of CO_2 from Portland cement [1]. Geopolymer concrete is an alternative material to normal concrete (made of Portland cement), it is an eco-friendly material consisting of source materials rich in silica and alumina such as fly ash, ground granulated blast furnace slag (GGBS) and metakaolin GPC possess high compressive strength at M14 of sodium hydroxide up to 82 MPa [2]. Utami reported that the thermal conductivity of geopolymer composites was ranging between 0.19 and 0.82 W/m C with an average of 0.421 W/m C, which enabled them to be used as insulator materials. However, although geopolymer composites are similar to OPC in terms of their favorable features, geopolymer binders exhibit brittle behavior and have low flexural and tensile strengths. Utilizing short fibers in the mix is one common and practical technique to increase flexural strength and toughness while reducing the brittleness of the binders [3].

The addition of fibers in brittle matrices is an efficient approach for reducing crack propagation and thereby improving the fracture toughness of the matrix when subjected to load [4]. Different types of fibers have been used as reinforcement in cementitious and geopolymer composites to enhance their flexural capacity and toughness like steel, polypropylene, basalt, sisal, jute, wood, bamboo, coconut, and asbestos [5]. Wang et al. worked on natural fiber-reinforced fly ash geopolymer mortar high calcium. The study showed two kinds of natural geopolymer composites. The authors used coconut and sisal fiber, with a content of 0.5–1.0%. The mechanical, physical, and thermal characteristics of fiber-reinforced geopolymer composites have been examined and compared to the composites prepared with glass fiber and plain geopolymer without fibers. The findings showed that the addendum of natural fibers (sisal/coconut fibers) as reinforcement substances has resulted in serious enhancements in flexural and tensile strength comparable to glass fibers utilization, while there is an initiating decline in dry density, workability, and compressive strength [6]. Irshidat et al. reported that the addition of polypropylene in the range of 0.05–0.2% reduced the thermal conductivity of geopolymer composites. The reduction increased with fiber content due to the ability of the fibers to entrain air or because of the PP fibers' lower heat conductivity value as compared to the geopolymer matrix [7].

Recently, the inclusion of natural fibers within the geopolymer compound had many benefits because it is an eco-friendly and lightweight material and is effective in thermal insulation [8]. Kenaf fiber is a well-known natural fiber. It consists of cellulose, hemicellulose, lignin, and various compounds that dissolve in water. Lignin,

hemicelluloses, and cellulose were the main compounds [9]. Abirami et al. [10] used 0.25–1% of various types of natural fibers (kenaf and sisal fibers) in the cement composite. The results indicated that adding both fibers improved the compressive and tensile strength by increasing about 6.5% and 12.7%, respectively. Using 1% of sisal or kenaf fibers in the composite obtained the highest mechanical properties than other fiber dosages. Moreover, kenaf fiber-reinforced composite concrete (KFRCC) achieved better compressive strength than using sisal fibers in the composite. Abbas et al. demonstrated that KFRCC showed higher ductility by delaying the formation of cracks under applied compression and flexure loads than the normal composite. There was a large amount of cement matrix and aggregates spalling in the normal sample. Kenaf fibers can act as bridges across microcracks caused by stress, preventing them from diffusing in composites. Depending on their properties, KF prevents the cracks to transfer to the whole composite [11].

Coconut fiber is also a well-known natural fiber used to reinforce geopolymer with excellent properties as reported by abbass et al. The inclusion of coconut fiber in geopolymer matrix improves the properties of the composite, and the tensile strength is enhanced by increasing from 3.6 to 3.89 MPa; however, the inclusion of higher amount of fiber increased the voids content in the matrix [12]. The above-mentioned literature showed that geopolymer composites had good thermal performance and fire resistance. In addition, a positive effect of microfibers on the mechanical properties of the geopolymer composites has been described. Reinforcing geopolymer binders with fibers has been capable to support higher resistance against the crack formation, hence defeating their brittleness problem. However, the current study focuses on the thermal performance of geopolymer with natural fibers such as kenaf and coconut. Additional information from this study will provide better thermal conductivity materials to the construction industry.

2 Experiments

2.1 Materials

The materials used in this research are fly ash (FA), ground granulated blast slag (GGBS) as the binder, alkaline activator, coarse and fine aggregate, kenaf, and coconut fibers. The combination of FA and GGBS was used to produce the geopolymer binder because FA's reactivity is insufficient for alkaline activators to activate it at room temperature, and activation of FA needs a curing temperature of 60–85 °C. Under ambient temperature, curing GGBS enhanced the properties of FA-based GPC, due to the CaO that exists in the GGBS components. Therefore, the use of FA/GGBS-based GPC can conserve energy and provide excellent mechanical properties [13]. The fly ash was used as 60% of the total binder and it was obtained from a coal power plant Green cement company, Malaysia, which satisfied the ASTM C618-15 [14] requirements for low calcium fly ash (class F). On the other hand, the

GGBS was utilized as 40% of the binder. It was designated according to ASTM C 989 [15].

A combination of sodium hydroxide (SH) and sodium silicate (SS) was used as the alkaline solution to activate FA and GGBS. Sodium hydroxide purity is 97–99%. Finally, coarse and fine aggregates are used in producing geopolymer concrete. The river sand was tested for specific gravity and water absorption according to ASTM C128-07 [16] and sieved ASTM C33-03 [17] to the standard specifications. The specific gravity is 2.52 kg/m^3 with an average of about 1.68 water absorption for fine aggregate, while the specific gravity is 2.65 kg/m^3 with an average of about 0.88 water absorption for crushed granite coarse aggregate. In this work, the maximum size of sand retained sieved which was 4.75 mm and coarse 9.5 mm was used. The concrete mixtures were designed with a target slump of higher than 50mm to achieve acceptable workability and compressive strength of 40 MPa at 28 days.

Kenaf fibers were supplied from Lembaga Kenaf Dan Tembakau Negara (LKTN), Malaysia. The fibers were subjected to the alkaline treatment to enhance the fiber properties before being used in the GPC. The fibers were immersed in 6% NaOH solution for 3 h and then washed with water and immersed in the water for 24 h. After 24 h, the fibers were kept to drying at the ambient temperature. The treatment was conducted by following the previous studies [18]. After the treatment, the fibers were cut to a length of 20 mm and added to the GPC mixtures in a content of 1.0% volume fraction [19]. The other type of natural fiber used in this research is coconut fiber, which was also pre-treated by using the alkaline treatment before being used in the concrete mixtures. After the treatment, the fibers were cut to a length of 30 mm and added to the mixtures in a content of 0.75% volume fraction. The length and content of the fibers were chosen by following the study of [20].

2.2 Mix Proportion

The mix proportion of geopolymer concrete was designed as shown in Table 1.

2.2.1 Preparation of Specimen

In this research, all specimens were prepared from 60% of FA and 40% of GGBS mixed with an alkaline solution which consists of sodium silicate and sodium hydroxide at a ratio of 0.55. The sodium hydroxide molarity used in this study was 14 M. It is important to prepare alkali solution before 24 h of each mixture to ensure that all ingredients are dissolved. The dry compounds: coarse aggregate, fine aggregate FA, and GGBS were mixed in an electric mixer for 3 min. Then, the alkaline solution was added and mixed for 2 min. After that, the natural fiber was added in small batches and mixed for another 3 min to obtain a homogeneous mixture. Then, the fresh mixes were poured into clean molds and then covered until the test day. Three identical cubes were prepared for the compressive strength test and five panels

Table 1 Mix proportion of specimens (Kg/m^3)

GPC mix (Kg/m^3)	FA	GGBS	F. Agg	C. Agg	Ratio S/B	SS	SH	Fiber content	Dimension (mm) ($L \times W \times t$)
(P0) GPC	261	174	710	1065	0.55	170.8	68.3	–	500 × 500 × 100
(P2) GPC + KF	261	174	710	1065	0.55	170.8	68.3	1%	500 × 500 × 100
(P3) GPC + CF	261	174	710	1065	0.55	170.8	68.3	0.75%	500 × 500 × 100
(P4) GPC + KF	261	174	710	1065	0.55	170.8	68.3	1%	500 × 500 × 75
(P5) GPC + KF	261	174	710	1065	0.55	170.8	68.3	1%	500 × 500 × 50

[a] *S* Solution, *B* Binder, *FA* Fly ash, *F. Agg.* Fine aggregate, *C. Agg.* Coarse aggregate

for the thermal conductivity test for three mixes of geopolymer concrete (GPC), geopolymer concrete with kenaf fiber (GPC + KF) and geopolymer concrete with coconut fiber (GPC + CF) with different panels thickness 100, 75, 50 mm according to appropriate insulation thickness in Malaysia is in the range of 18–126 mm [21].

2.3 Tests Procedures

The compression test was carried out according to BS EN12390-3 [22] standard. In total, 18 cubes were tested for compressive strength at 7 and 28 days of ambient curing. The thermal test was carried out using hotbox test apparatus according to ASTM1363-97 [23]. The hotbox test is the method to determine the thermal performance for homogeneous and nonhomogeneous specimens at steady-state conditions for small samples. Hotbox apparatus consists of two boxes one for the metering chamber and the other climate chamber as shown in Fig. 1. The apparatus consists of fans and heating sources as shown in Sections X1 and X2, which contain an internal opening for measuring samples with sizes 500 mm × 500 mm × 100 mm. The box has been surrounded with an isolation material to prevent the heat flux from the hot chamber to the cold chamber to decrease the losses. The samples are placed on the interior opening of the hotbox device where five samples are used with different dimensions and different materials (P0) Control panel geopolymer concrete, (P2) Panel with 100 mm geopolymer with kenaf fiber, (P3) Panel with 100 mm geopolymer with coconut fiber, (P4) Panel with 75 mm geopolymer with

kenaf fiber, (P5) Panel with 50 mm geopolymer with kenaf fiber, the sensors are placed in different places on both hot and cold surfaces of the sample using a thermocouple to monitor the temperature during the test, in addition, the temperature of the cold room should be set by operating air condition before starting the test, and the device is connected to a computer to collect and analyze data to obtain the accurate results of thermal conductivity (K) (W/m K). Values are measured to evaluate the thermal performance of the samples and to obtain results. Thus, the desired results are obtained from this test to obtain an appropriate environment for residential buildings in a hot climate by using a data logger to calculate the thermal conductivity of the samples studied through the general equation stated in Eq. 3. There are three samples prepared with each being square wall panels of 500×500 with 100 mm thickness. Each sample is subjected to the test with repetitive of 3. The geopolymer mixes are made with an addition of 1% by volume of kenaf fiber or with an addition of 0.75% by volume of coconut fibers. Then, the best fiber mix which is kenaf fiber casts on panels with 50 and 75 mm thickness to study their effect on the thermal performance of the geopolymer fiber concrete.

$$U = Q/(A(T_2 - T_0))\text{in}\left(w/°C\,m^2\right), \tag{1}$$
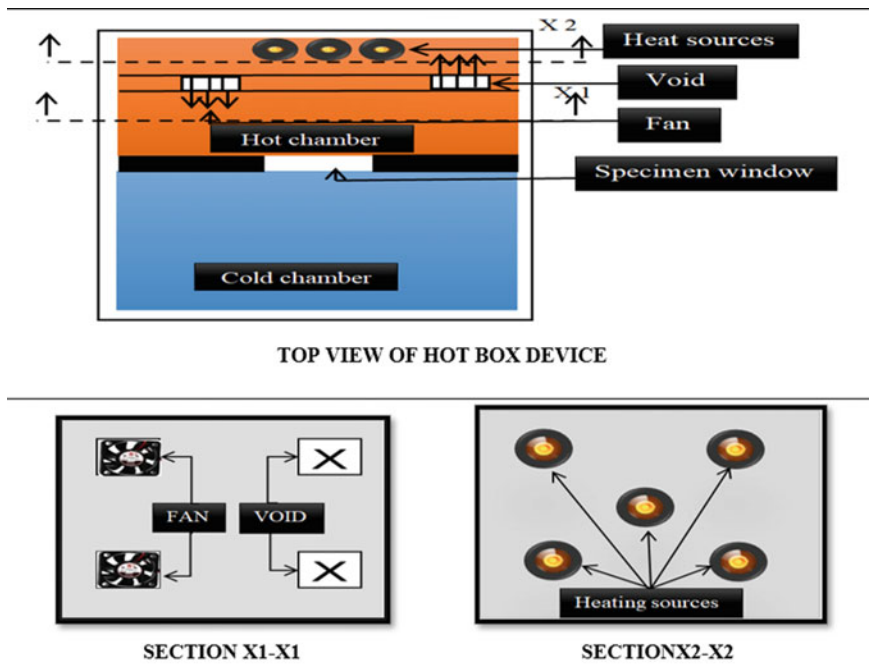
where

Fig. 1 Scheme view of hotbox apparatus

U: thermal transmittance; Q: represents heat flow rate (W) an exposure area perpendicular to heat flow (m^2), T_2: temperature of the hot side with Kelvin (K), T_0 temperature of cold side (K). After calculating the U-value, the thermal resistance and conductivity were determined using the following equations:

Thermal resistance (R):

$$R = 1/U \text{ in} (°C \, m^2/w). \tag{2}$$

Thermal conductivity (K):

$$K = d/R \text{ in} (w/m \, k), \tag{3}$$

where
d: the specimen thickness (m).

2.3.1 Environmental Temperature

The environmental temperature was recorded using hotbox apparatus. Before the test, the temperature in both the hot chamber and climate chamber is necessary to reach a steady-state condition between 1000 and 1400 min as mentioned in ASTM C1363-97 [23]. The temperature in the cold chamber is at constant of approximately 17–18 °C and in the hot chamber was 70–77 °C. Both temperatures are within limits of between −40 and 85 °C. Figure 2 shows the steady condition which was maintained in the apparatus until 1440 min (24 h), which fulfilled the standard requirements.
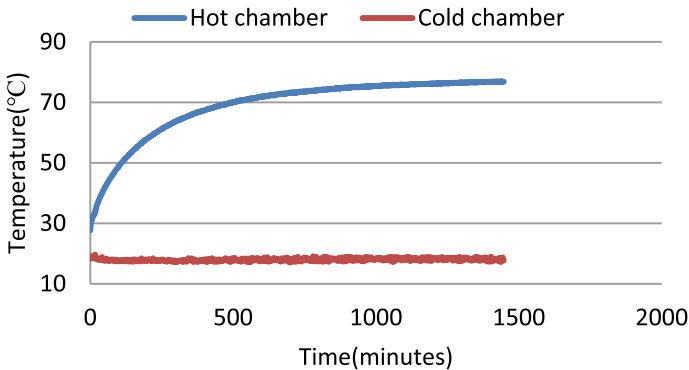

Fig. 2 Average hot and cold air temperature profiles in the hotbox apparatus

3 Results and Discussion

3.1 Compressive Strength

The compressive strength is a very important characteristic of concrete. It is to confirm whether the concrete fits its designated purposes and to determine the concrete quality. In this study, the compressive strength of the GPC control sample and geopolymer with natural fiber was tested by a compressive test machine using a specimen of 7 and 28 days, and the results are presented in Fig. 3. The average compressive strength at 7 days for the GPC control mix is 47.5 MPa and at 28 days is 69.8 MPa. It is observed that by increasing the curing time, the compressive strength increased by 46.9%. Besides, the addition of natural fibers decreased the compressive strength at both testing ages. The compressive strength of geopolymer concrete with kenaf fiber (GPC + KF) is 45.9 MPa at 7 days and 60.7 MPa at 28 days. This shows that the addition of kenaf fibers decreased the compressive strength of GPC by 3.3% at 7 days and decreased by 13% at 28 days. On the other hand, the compressive strength for GPC mixed with coconut fiber (GPC + CF) at 7 days is 44.8 MPa and at 28 days is 57.6 MPa. The reduction in the strength of GPC with the addition of natural fiber could be attributed to the increased voids that formed in concrete [24]. It can be also observed that the compressive strength of GPC mix with kenaf fiber was better than the compressive strength of GPC mix with coconut fiber by 2.4% at 7 days and by 5.1% at 28 days.
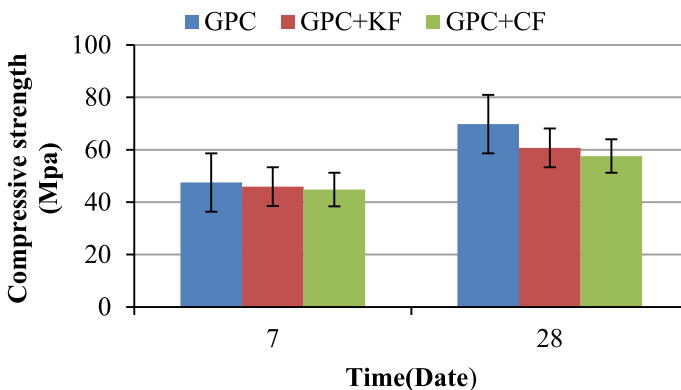

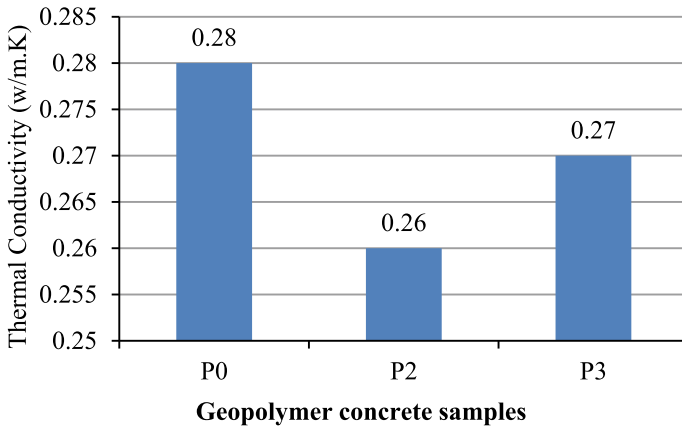**Fig. 3** Compressive strength for geopolymer concrete with kenaf and coconut fibers

Fig. 4 Thermal conductivity of geopolymer with kenaf (P2) and coconut (P3) fibers

3.2 Effect of Natural Fiber on Thermal Performance

The thermal performance of geopolymer concrete is presented in Fig. 4. As shown, the plain GPC (P0) allows direct heat transfer and has attained the highest thermal conductivity of 0.28 W/m K. However, the addition of natural fibers (kenaf or coconut) slightly decreased the thermal conductivity to 0.26 and 0.27 W/m K for the composites prepared with kenaf fiber (P2) and that prepared with coconut fiber (P3), respectively. This indicates an improvement of about 7.1 and 3.6% for P2 and P3, compared to P0 of the same thickness. This shows that using kenaf fiber with geopolymer concrete achieved a lower thermal conductivity than coconut fiber. This may be due to the hollow and cellular nature of kenaf [25] that traps the air in voids and prevents the heat to transmit from the heat source to the material. The results of the current study showed improvement in heat conductivity as compared to works reported by Aprilia et al. [26] and Sample et al. [27] of geopolymer concrete. However, both kenaf and coconut fibers are used for thermal isolation purposes as they are less than 1 W/m K [28]. Moreover, the thermal conductivity for 1% of kenaf fiber with geopolymer concrete reported excellent results around 0.28 W/m K compared with the thermal conductivity of 1% of kenaf fiber around 0.93 W/m K, and this proved that geopolymer concrete can be a good insulator for buildings [26]. Comparing it with a brick wall, the geopolymer concrete 0.28 W/m K is lower by 65.5% than the brick wall of 0.811 W/m K as reported by Balaji et al. [29].

3.3 Effect of Different Thicknesses on Thermal Performance

The thickness changes of wall panels have an important influence on thermal performance. The results as shown in Fig. 5 are based on Eq. (3). Panels P4 and P5 are
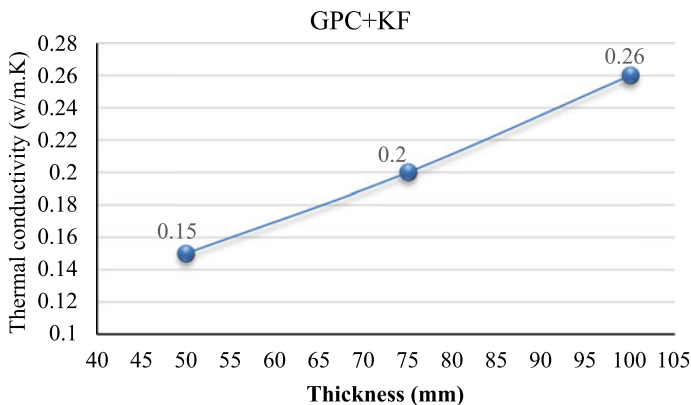
Fig. 5 Relationship between thermal conductivity and thickness of panels

the same materials that consist of geopolymer concrete mixed with kenaf fiber with different thicknesses are 75 and 50 mm. Panels P4 and P5 have thermal conductivity around 0.2 and 0.15 W/m K, respectively. The panel P4 with 75 mm thickness showed an improvement by 28.6%, while the panel P5 with a thickness 50 mm showed an improvement by 46.4% compared with the P0 with a thickness of 100 mm (no fiber specimen). If compared to P2 , a 100mm thickness specimen of GPC with KF, panels P4 improved about 23.1% for 75 mm thickness and P5 of 42.3% for 50 mm thickness. When reducing the thickness of the wall, the thermal conductivity value decreases according to Fourier's law as shown in Fig. 5.

4   Conclusion

This study is an attempt to achieve a better thermal performance of walls using an eco-friendly material made of geopolymer and natural fibers. The two fibers, kenaf and coconut, are compared by using the hotbox method. The following conclusion can be drawn:

1. The addition of fibers reduced the compressive strength of geopolymer, but the kenaf fiber exhibited lesser reduction than the coconut fiber. However, it is insignificant as both are in a range of 60 MPa at 28 days and 40 MPa at 7 days.
2. The addition of natural fibers with geopolymer concrete as an insulating material achieved a great reduction of the heat transmitted through the walls. This is proven by the thermal test, where the geopolymer concrete resistance is 0.28 W/m K.
3. Kenaf fibers have proven more effective in thermal insulation than coconut fiber, where the thermal conductivity of kenaf fibers blended with geopolymer concrete was 0.26 W/m K.

4. The reduced thickness of the wall causes a lower value of the thermal conductivity of the panel.

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