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Influence of Density, Porosity and Void Size on Thermal Conductivity of Green Lightweight Foamed Concrete

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ARTICLE INFO	ABSTRACT
Article history: Received 20 October 2021 Received in revised form 26 December 2021 Accepted 8 January 2022 Available online 14 February 2022 ***Keywords:*** Lightweight foamed concrete; thermal conductivity; void size; porosity	One of the methods to reduce the energy content of buildings is through selection of building materials. Strain on conventional energy can be reduced by employment of low energy materials and efficient structural design. The selection of materials also helps to capitalize on indoor comfort. For instant, the use of materials and components with small embodied energy or low thermal conductivity has enhanced the indoor comfort in building. Thus, a high level of insulation in any new material development is an essential step to an energy efficient design. The main purpose of this study is to investigate the thermal conductivity of green lightweight foamed concrete samples ranging from 650 until 1050 kg/m^3 with constant cement-sand ratio of 1:1.5 and water-cement ratio of 0.5. This study was limited to the influence of density, porosity and void size on thermal conductivity of lightweight foamed concrete. Lower density foamed concrete translates to lower thermal conductivity. The density of foamed concrete is controlled by the porosity where lower density lightweight foamed concrete indicates greater porosity. Hence, thermal conductivity changes considerably with the porosity of lightweight foamed concrete because air is the poorest conductor compared to solid and liquid due to its molecular structure.

1. Introduction

These days, adopting a green environment in the construction industry has been a critical topic in Malaysia for a few back years. It can be seen evidently in the Malaysian Construction Industry Master Plan (2005-2015). There are a few initiatives that government and private sectors in Malaysian to entice the players in the construction industry to embrace with sustainable development and green buildings. The green building intends to decrease carbon footprint and gas emission. To accomplish these agenda, all construction industry players in Malaysia need to fulfil the Green Building Index (GBI) requirements, which is introduced in 2005 to increase the awareness between the construction players and support sustainable construction in the built environment [1]. Furthermore, the global concern of eco-friendly construction has propelled a lot of research on green concrete worldwide. The research that uses materials and processes resource-efficient and

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environmentally throughout the life cycle has been an increase. In some cases, special attention has been given to areas such as concrete mix design, mix material sourcing, construction method, construction technology, and concrete structure maintenance. Thus, it can be concluded that achieving sustainable development in society depends on the significant role played by the industry players [2].

In recent times, the construction industry in Malaysia has shown major recognition in the use of lightweight foamed concrete as a building material due to its many promising characteristics such as lighter weight, easy to fabricate, durable and cost effective. Lightweight foamed concrete is a material consisting of Portland cement paste or cement filler matrix with a homogeneous pore structure created by introducing air in the form of small bubbles [3]. With an accurate control in amount of foam and methods of fabrication, a wide range of densities (500-1600 kg/m^3) of lightweight foamed concrete can be manufactured [4].

This material has so far been applied principally as a filler material in civil engineering works. However, its good thermal and acoustic performance indicates its strong potential as a material in building construction [5]. Indeed, there has been prevalent reported utilization of foamed concrete as structural elements in building schools, apartments, and housing in countries such as Libya, Russia, Brazil, Malaysia, Mexico, Saudi Arabia, Indonesia, Egypt and Singapore. Figure 1 and Figure 2 show some examples of the application of foamed concrete in real project. Lightweight foamed concrete is a complex material which acts in an appropriately multifaceted way. Its properties diverge with age, temperature, and humidity [6]. In addition, at near the beginning ages, heat is generated which may result in considerable temperature increase [7]. It consequently becomes complicated to envisage its behaviour with any real precision, even under controlled conditions, and the use of published information must be cautiously qualified unless the conditions of application are close to those under which the information was obtained [8].

Fig. 1. Lightweight foamed concrete blocks being used in a housing project in Malaysia

Fig. 2. Cast in-situ lightweight foamed concrete wall in Surabaya, Indonesia

Thermal conductivity is the progression of the conduction of high-temperature thermal energy within an object or between two objects in contact, which lowers the temperature [9]. In physics, thermal conductivity is the property of a material describing its capability to conduct heat. It appears primarily in Fourier's Law for heat conduction. When an object is heated, the vibration of the molecules or atoms and the floating of free electrons discharge thermal energy to the lower temperatures during kinetic energy conduction [10].

According to molecular dynamics, an object's temperature is in a direct proportion to the mean kinetic energy of its composition. Thermal conductivity (W/m K) is the result of thermal diffusibility (cm^2/s), specific heat (J/g K) and density and is influenced by its own mineral characteristics, pore structure, chemical composition, moisture, and temperature. The energy performance of a building greatly depends on the thermal conductivity of the building materials which depicts the capability of heat to flow across the material in the presence of a differential temperature [11].

The thermal conductivities of ordinary heat insulating materials range from 0.034 to 0.173 W/m K [12, 13]. This study intends to investigate the thermal conductivity of lightweight foamed concrete of different densities and establish the key factors affecting the thermal conductivity of this material. Lightweight foamed concrete of five densities (800, 900, 1000, 1100 and 1200 kg/m^3) will be cast and tested at ambient temperature to obtain its effective thermal conductivity using hot-guarded plate method.

Essentially, the thickness of normal weight concrete must be five times more than lightweight foamed concrete to accomplish comparable thermal insulation properties. It should be pointed out that lightweight foamed concrete is immensely porous, and its properties reduce with increasing in the number of pores. Variations in the value of density due to pore formation produce significant effect in thermal performance of lightweight foamed concrete. Hence it is important to distinguish the influence of density, porosity and void size on the thermal conductivity of lightweight foamed concrete. The results of this fundamental study could pave the way to produce lightweight foamed concrete of enhanced thermal performance.

2. Materials and Composition

The lightweight foamed concrete used in this study was made from Ordinary Portland Cement (OPC), fine sand, water and stable foam. The main objectives of this research are to determine the thermal conductivity of foamed concrete at ambient temperature therefore only a constant cement-sand ratio of 2:1 and water-cement ratio of 0.5 will be used for all batches of lightweight foamed concrete specimens made for this study.

A water-cement ratio of 0.5 was found satisfactory to attain sufficient workability. Portland cement obtained from Cima Group of Companies Sdn. Bhd. was used in this study. The Portland cement used complies with the Type I Portland cement as in ASTM C150 and BS12. Fine river sand with additional sieving to remove particles greater than 2.36 mm was used in the mix, to improve the foamed concrete flow characteristics and stability as in BS12620.

Through this experimental study tap water was used for the manufacture the foamed concrete samples. The surfactants (foaming agent) used was Noraite PA-1 which is suitable for lightweight foamed concrete densities ranging from 500 to 1600 kg/m^3. Noraite PA-1 comes from natural sources and has a weight of around 75 gram/litre and expands about 12.5 times when used with the foam generator. The stable foam was produced using foam generator Portafoam TM2 System as shown in Figure 3.

Fig. 3. Portafoam TM2 System

Lightweight foamed concrete samples each measured 300 x 300 x 50 mm were made at five different densities namely 650, 750, 850, 950 and 1050 kg/m^3. All lightweight foamed concrete samples were made in house. The cement was mixed with sand and water was mixed in the mixer for a few minutes. Then foam was added gradually until the desired densities were obtained. The ratio of cement, sand and water mixture was 1:1.5:0.5. Three identical specimens were prepared for each density and were tested using Hot Disk^{TM} Thermal Constants Analyzer Model TPS 2500 at 14 days after mixing. Further details of the mix constituent proportion, and the densities are outlined in Table 1. The target lightweight foamed concrete volume required for each mix design was 0.1 m^3.

Table 1
Mix constituent proportions of lightweight foamed concrete mixes

Target dry density (kg/m^3)	Portland Cement (kg)	Sand content (kg)	Water (kg)	Noraite PA-1 surfactant (m^3)
650	24.83	37.24	11.17	0.061
750	28.44	42.66	12.80	0.056
850	32.05	48.08	14.42	0.051
950	35.66	53.49	16.05	0.046
1050	39.27	58.91	17.67	0.041

3. Experimental Set-up

The HGP test followed the ASTM procedure in reference to ASTM C 177. The hot guarded plate test is generally recognized as the primary absolute method for measurement of the thermal transmission properties of homogeneous insulation materials in the form of flat slabs. This steady-state test method has been standardized by ASTM International as ASTM Standard Test Method C 177. The equipment used to determine the thermal conductivity of lightweight foamed concrete was Hot Disk Thermal Constants Analyzer Model TPS 2500.

The Hot Disk Thermal Constants Analyzer is an emerging technology that uses the transient plane source technique to measure the in-plane and through-plane thermal conductivity of an anisotropic material in the same test. The sensors used in this test method consisted of a 10µm thick nickel foil embedded between two 25.4 µm thick layers of Kapton polyimide film. The nickel foil was wound in a double spiral pattern and had a radius, R of either 3.189 mm or 6.403 mm.

For the more conductive samples the sensor with the larger radius was used. The thermal conductivities were measured at 23°C. Since the test specimens are anisotropic, this test method is useful for this project. The setup of the Hot Disk Thermal Constants Analyzer apparatus is demonstrated in Figure 4 and Figure 5 shows how the sensor is positioned between two samples of composite material.

Fig. 4. Hot disk thermal constants analyzer apparatus

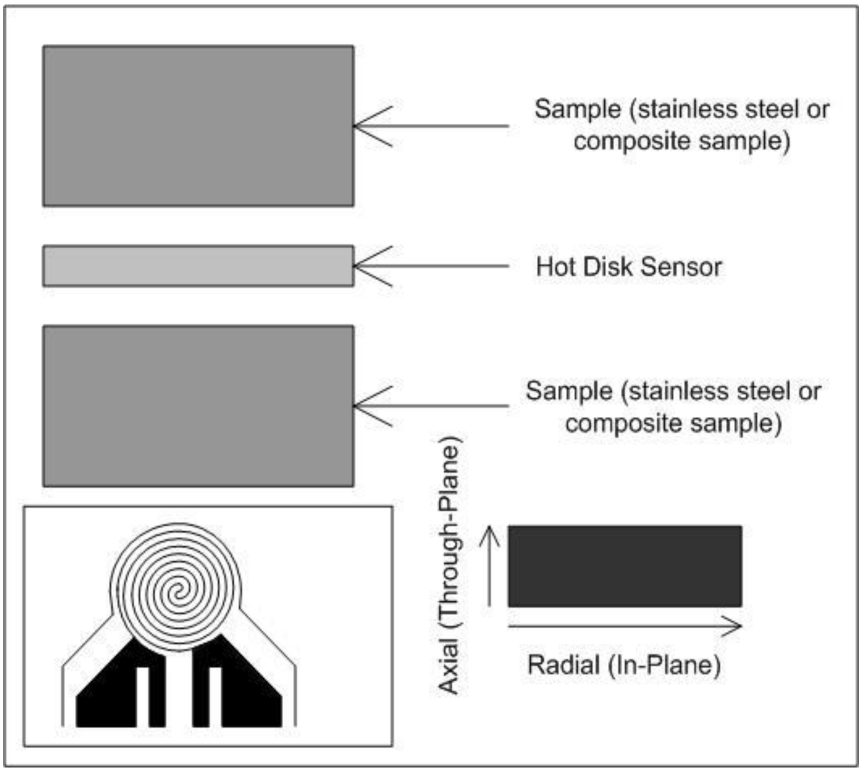

Fig. 5. Schematic of samples and sensor for the hot disk the insert at the lower left shows the double spiral heating element

In this experiment, the samples tested were composite disks with a diameter, D of 6.4 cm and a thickness, x of 3.2 mm. In order to ensure that the assumption of an infinite sample domain was met and that heat was not penetrating completely through the sample in the axial direction, two of these composite disks were stacked together above the sensor and two more stacked below it, giving us a double thickness of sample. This stacking of disks allowed the generation of more reproducible data. The sensor then had a constant electrical current (variable by sample from 0.03W – 1.25W) over a short period of time (variable by sample from 2.5s – 40s) passed through it.

The generated heat dissipated within the double spiral was conducted through the Kapton insulating layer and into the surrounding sample, causing a rise in the temperature of the sensor and the sample. The final hot plate temperature depends on the electrical power input, the thermal resistance of the specimen and the temperature of the cold plate. The average thermal conductivity, *k*, of the specimen is determined from the Fourier heat flow equation as follow:

$$k = \frac{W}{A}\left[1 \times \frac{d}{\Delta T}\right] \tag{1}$$

where *W* is the electrical power input to the main heater, *A* is the main heater surface area, *ΔT* is the temperature difference across the specimen, and *d* is the specimen thickness

In sequence to scrutinize the effect of void size on thermal conductivity of foamed concrete, it is necessary to obtain the void size for each density. Mixtures from this study, however, do not contain any coarse aggregate but consist of high amounts of air (foam). To ensure the stability of the air void walls during polishing, particularly in weaker specimens (lower density), all the specimens were vacuum-impregnated with slow-setting epoxy. To ensure consistency in results, all the specimens were prepared using similar techniques under the same environmental conditions.

The porosity value of foamed concrete was determined through the Vacuum Saturation Apparatus for both densities considered for this study. The measurements of foamed concrete porosity were conducted on slices of 68mm diameter cores cut out from the centre of 100mm cubes. The specimens were dried at 105°C until constant weight had been attained and were then placed in a desiccator under vacuum for at least 3 hours, after which the desiccator was filled with de-aired, distilled water. The porosity was calculated using the following equation:

$$\varepsilon = \frac{(W_{sat} - W_{dry})}{(W_{sat} - W_{wat})} \times 100 \tag{2}$$

At first, the foamed concrete specimens of 45 x 45 mm size with a minimum thickness of 15 mm were cut from the centre of two randomly selected 100 mm cubes using a diamond cutter. The face of the specimen was cut perpendicular to the casting direction. Sized specimens were saturated in acetone to stop further hydration reaction before drying at 105 °C. To ensure the stability of the air-void walls during polishing, the dried and cooled specimens were vacuum impregnated with slow-setting epoxy. After polishing and cleaning, the specimens were dried at room temperature for 1 day. Finally, an effective size 40 x 40 mm was considered for void size measurement.

The void sizes were measured under a microscope with a magnification of 60x on two specimens, prepared as per the procedure described previously, for each foamed concrete specimen. Image analysis system consisted of an optical microscope and a computer with image analysis software.

4. Results and Discussions

The thermal conductivity test results of all foamed concrete samples are shown in Table 2. Further discussions are categorized according to the effect of density, void size and porosity on thermal conductivity of lightweight foamed concrete.

Table 2
Summary of lightweight foamed concrete thermal conductivity test results

Density (kg/m^3)	Thermal conductivity, *k* (W/mK)	Porosity (%)	Effective void size (mm)
650	0.233	69	0.732
750	0.241	61	0.694
850	0.253	55	0.644
950	0.281	50	0.584
1050	0.322	46	0.505

4.1 Dependence of Density on Thermal Conductivity of Lightweight Foamed Concrete

The results show that the thermal conductivity of all lightweight foamed concrete specimens is positively proportionate with its density (Figure 6). For instance, the thermal conductivity for lightweight foamed concrete reduced from 0.322 to 0.253W/mK and further reduced to 0.233W/mK for corresponding densities of 1050, 850 and 650 kg/m^3, respectively. The results have confirmed that lower density transforms to lower thermal conductivity which is comparable to the findings from other researchers [14]. As will be discussed in the next section, the density of foamed concrete is controlled by its porosity. High density lightweight foamed concrete will have smaller porosity value compared to the low density and therefore this will influence the thermal conductivity of this material [15].

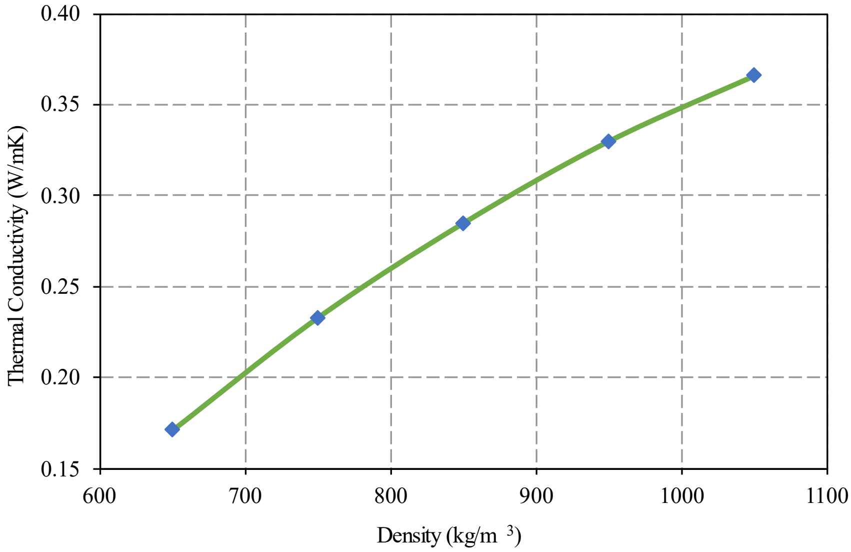

Fig. 6. Thermal conductivity of foamed concrete of different densities

4.2 Dependence of Porosity and Void Size on Thermal Conductivity of Lightweight Foamed Concrete

Figure 7 and Figure 8 visualize typical microscopic images of the internal void structure of the 650 and 1050 kg/m^3 density lightweight foamed concrete respectively. Clearly the void sizes are not uniform. However, these two figures do clearly indicate that there is a dominant void size and that the dominant void size is primarily a function of the lightweight foamed concrete density [16]. The dominant void size tends to increase as the lightweight foamed concrete density reduces due to the higher quantity of foam used (Table 2).

Fig. 7. Void size and distribution of lightweight foamed concrete of 650 kg/m^3 density

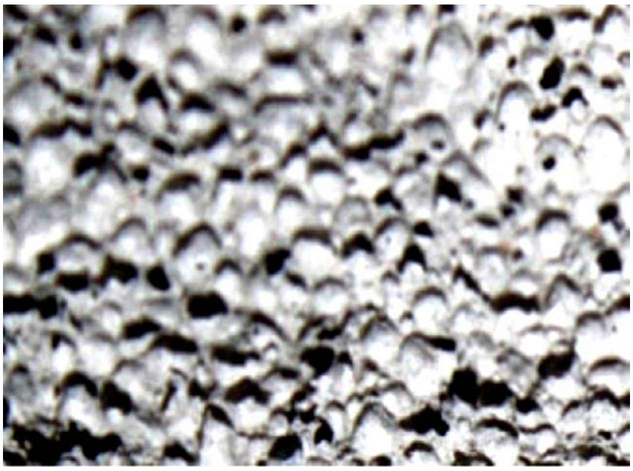

Fig. 8. Void size and distribution of lightweight foamed concrete of 1050 kg/m^3 density

For instant, from a microscopic analysis of the internal images of the two densities of lightweight foamed concrete, the dominant void size of the 650 kg/m^3 and 1050 kg/m^3 densities lightweight foamed concrete has been determined as 0.732mm and 0.505mm respectively. Figure 9 demonstrates the relationship between the density of lightweight foamed concrete and the effective void size The density of lightweight foamed concrete is governed by the porosity or amount of air content inside the material [17]. It can be clearly seen from Figure 10 that lower density of lightweight foamed concrete indicates larger porosity value or greater amount of air contained (larger void size). As a result, thermal conductivity changes significantly with the porosity of foamed concrete because air is the poorest conductor compared to solid and liquid due to its molecular structure [18, 19].

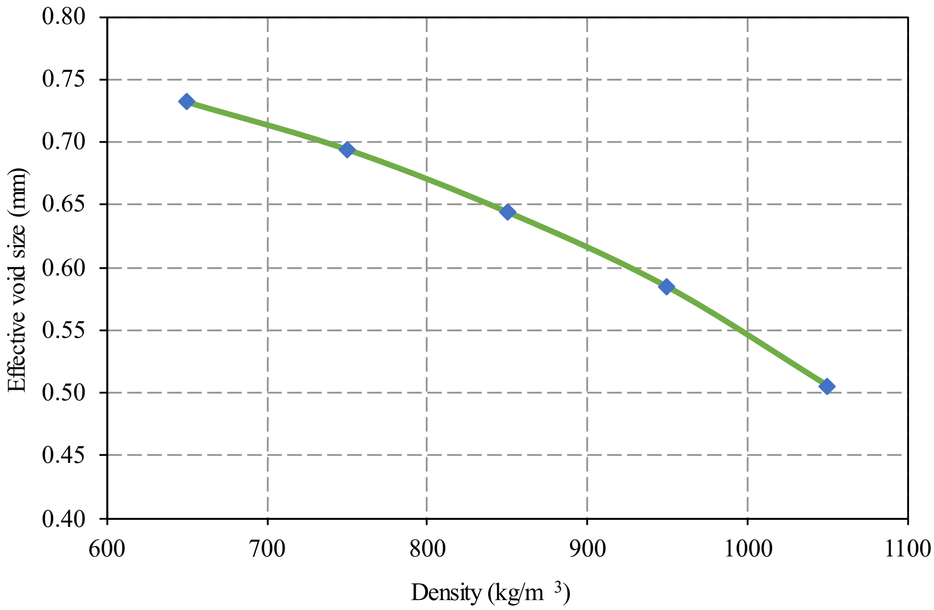

Fig. 9. Effective void size of lightweight foamed concrete of different densities

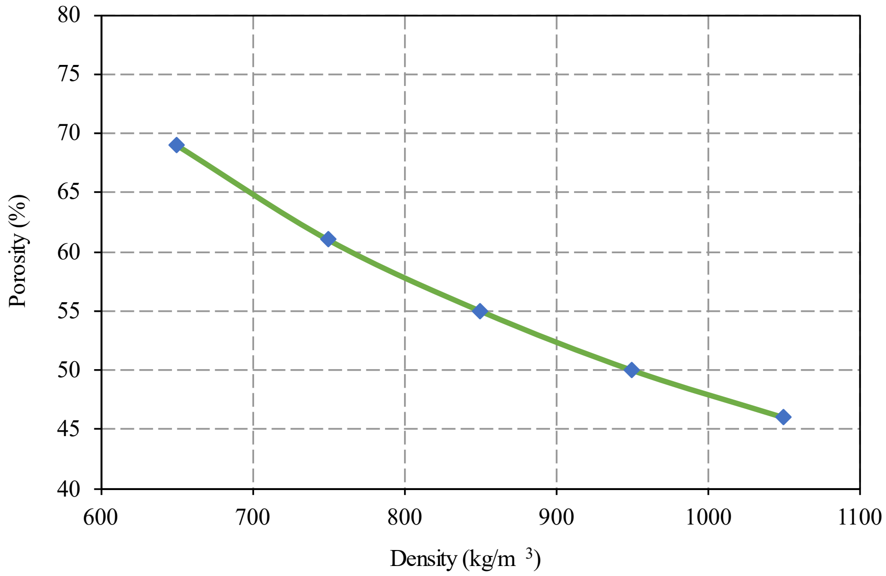

Fig. 10. Porosity of lightweight foamed concrete of different densities

5. Conclusion

An experimental study was conducted to determine the thermal conductivity of lightweight foamed concrete of different densities and the influencing factors on the thermal conductivity through the Hot disk thermal constants analyzer method. As lightweight foamed concrete is produced by injecting air into a cement-based mixture, the density of lightweight foamed concrete is directly a function of the air (porosity) inside the foamed concrete. For that reason, the density of foamed concrete plays an important role in determining its thermal conductivity. Lower density lightweight foamed concrete indicates greater porosity. It should be pointed out that the thermal conductivity changes noticeably with the porosity of foamed concrete because air is the poorest conductor in comparison with solid and liquid due to its molecular structure. Lower density foamed concrete translates to lower thermal conductivity. The dominant void size of lightweight foamed concrete is primarily a function of the lightweight foamed concrete density where it tends to increase as the foamed concrete density reduces due to the higher quantity of foam.

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