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Effective thermal conductivity of foamcrete of different densities

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Abstract

The main purpose of this study is to investigate the thermal conductivity of foamcrete. Various densities of foamcrete samples ranging from 650, 700, 800, 900, 1000, 1100 and 1200 kg/m^3 with constant cement-sand ratio of 2:1 and water-cement ratio of 0.5 were produced. This study was limited to the effect of density, porosity and pore size on thermal conductivity of foamcrete. Hot-guarded Plate method was used to obtain the thermal conductivity of foamcrete at different densities. The porosity value of foamcrete was determined through the Vacuum Saturation Apparatus. In turn to examine the effect of pore size on thermal conductivity of foamcrete, pore size measurements were made under a microscope with a magnification of 60x. Lower density foamcrete translates to lower thermal conductivity. The density of foamcrete is controlled by the porosity where lower density foamcrete indicates greater porosity. Therefore, thermal conductivity changes considerably with the porosity of foamcrete because air is the poorest conductor compared to solid and liquid due to its molecular structure.

Keywords: foamed concrete, thermal conductivity, hot-guarded plate, thermal properties, lightweight concrete, porous material

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1. Introduction

Energy efficiency is a significant issue for high quality housing. Energy not only corresponds to high percentage of the running cost of buildings but it also has a main effect on the thermal comfort of the occupants. These days, the demand for energy efficient design and construction has become progressively more vital with the growing of energy costs and increasing awareness on the effects of global warming. Buildings, as they are designed and used today, contribute to serious environmental problems because excessive consumption of energy and other natural sources. The close connection between energy use in buildings and environmental damage arises because energy-intensive solutions sought to construct a building and meet its demands for heating, cooling, ventilation and lighting cause severe depletion of precious environmental resources.

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One of the methods to decrease the energy content of buildings is through selection of building materials. Strain on conventional energy can be reduced by utilization of low energy materials and efficient structural design. The choice of materials also helps to maximize indoor comfort. For example, 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.

Thermal conductivity, *k*, is the process of the conduction of high-temperature thermal energy within an object or between two objects in contact, which lowers the temperature. In physics, thermal conductivity,*k*, is the property of a material describing its ability to conduct heat. It appears principally 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 in the course of kinetic energy conduction. According to molecular dynamics, an object’s temperature is in a direct proportion to the mean kinetic energy of its composition [1]. Thermal conductivity (W/m K) is the result of thermal diffusibility (cm^2/s), specific heat (J/g K) and density [2] 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 [3]. The thermal conductivities of ordinary heat insulating materials range from 0.034 to 0.173 W/m K [1].

Hence, the utilization of low thermal conductivity building materials is important to decrease heat gain through the envelope into the building in hot climate country like Malaysia. Foamcrete has been acknowledged for its superior performance in thermal insulation and sound insulation characteristics due to its cellular microstructure. The thermal conductivity of foamcrete typically is 5 to 30% of that of normal weight concrete and range from between 0.1 and 0.7 W/mK for dry density values of 600 to 1600 kg/m^3 respectively [4,5]. In practical terms normal weight concrete would have to be 5 times thicker than foamcrete ones to achieve similar thermal insulation [6]. The thermal conductivity of foamcrete with 1000 kg/m^3 density is reported to be one-sixth the value of typical cement-sand mortar [7]. Since foamcrete is made by injecting air into a cement based mixture, the density of foamcrete is directly a function of the air inside foamcrete. Expectedly, the density of foamcrete should play an important role in determining its thermal properties. A reduction in foamcrete density by 100 kg/m^3 results in a lessening in its thermal conductivity by 0.04 W/mK [8].

This study intends to investigate the thermal conductivity of foamcrete of different densities and establish the key factors affecting the thermal conductivity of this material. foamcrete of seven densities (650, 700, 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.

2. Experimental Program

Foamcrete is a relatively new construction material compared to normal strength concrete. The major factor limiting the use of foamcrete in applications is insufficient knowledge of the material performance at elevated temperatures. In building application, load carrying capacity and fire resistance are the most important safety requirements. In order to comprehend and eventually predict the performance of foamcrete based systems, the material properties at ambient temperature and elevated temperatures must be known at first stage. To be able to predict the fire resistance of a building structure, the temperatures in the structure must be determined. For quantification of structural performance, knowledge of the mechanical properties, at elevated temperatures of the material is essential. Foamcrete mechanical properties will be established, including compressive strength, compressive modulus, strain at maximum compressive strength, compressive stress-strain relationship, failure modes, flexural tensile strength and flexural tensile modulus.

2.1. Materials

The foamcrete 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 foamcrete 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 foamcrete samples made for this study. A water-cement ratio of 0.5 was found satisfactory to attain sufficient workability [9]. In general, the raw materials used are as follows.

2.1.1. ***Cement***

Portland cement obtained from Cima Group of Companies Sdn. Bhd. (Perak, Malaysia) was used in this study. The Portland cement used complies with the Type I Portland cement as in ASTM C150 [10] and BS12 [11].

2.1.2. ***Sand***

Fine sand with additional sieving to remove particles greater than 2.36 mm was used in the mix, to improve the foamcrete flow characteristics and stability as in BS12620 [12].

2.1.3. ***Water***

Through this experimental study tap water was used for the manufacture the foamcrete samples.

2.1.4. ***Surfactants***

The surfactants (foaming agent) used was Noraite PA-1 (protein based) which is suitable for foamcrete densities ranging from 600 to 1600 kg/m^3. Noraite PA-1 comes from natural sources and has a weight of around 80 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 [13].

2.2. Foamcrete compositions

In the current investigation, foamcrete samples each measured 300mm x 300mm x 50mm were made at seven different densities namely 650, 700, 800, 900, 1000, 1100 and 1200 kg/m^3. All foamcrete 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 foam mixture was 2:1:0.5. Three identical specimens were prepared for each density and were tested using hot-guarded plate method at 14 days after mixing. Further details of the mix constituent proportions and the densities are outlined in Table 1. The target foamcrete volume required for each mix design was 0.1 m^3.

TABLE 1: MIX CONSTITUENT PROPORTIONS OF FOAMCRETE MIXES

Target dry density (kg/m^3)	Target wet density (kg/m^3)	Cement:Sand	Water:cement	Portland Cement content (kg/m^3)	Sand content (kg/m^3)	Noraite PA-1 surfactant (m^3)
650	774	2:1	0.5	39	19	0.063
700	826	2:1	0.5	41	21	0.060
800	929	2:1	0.5	46	23	0.055
900	1033	2:1	0.5	52	26	0.050
1000	1136	2:1	0.5	57	28	0.045
1100	1239	2:1	0.5	62	31	0.040
1200	1343	2:1	0.5	67	34	0.035

2.3. Hot-guarded Plate Tests

The HGP test followed the ASTM procedure in reference [14]. 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 basic HGP method consists principally of a hot plate and a cold plate. In a HGP test, the test specimen is placed on a flat plate heater assembly consisting of an electrically heated inner plate (main heater) surrounded by a guard heater. The guard heater is carefully controlled to maintain the same temperature on both sides of the gap separating the main and the guard heaters. This prevents lateral heat flow from the main heater and ensures that heat from the electric heater flows in the direction of the specimen. On the opposite side of the specimen are additional flat plate heaters (cold plate) that are controlled at a fixed temperature selected by the operator. For a given heat input to the main heater, the hot plate assembly rises in temperature until the system reaches equilibrium.

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:

$$k = \frac{W}{A}\left[1 \times \frac{d}{\Delta T}\right] \quad \ldots (1)$$

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.

2.4. Porosity measurements

The porosity value of foamcrete was determined through the Vacuum Saturation Apparatus [15] for all densities considered for this study. The measurements of foamcrete 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:

$$e = \frac{(W_{sat} - W_{dry})}{(W_{sat} - W_{wat})} \times 100 \quad \ldots (2)$$

where e is the porosity (%), W_{sat} is the weight in air of saturated sample, W_{wat} is the weight in water of saturated sample and W_{dry} is the weight of oven-dried sample.

2.5. Pore size measurements

In order to observe the effect of pore size on thermal conductivity of foamcrete, it is necessary to establish the pore size for each density. For the purpose of this study, the specimen preparation for the measurement of the pore size was slightly different then from recommended by ASTM C 457. ASTM C 457 specified the size and thickness of the specimen and length of travel in the linear traverse method (LTM), based on the size of aggregate. 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 pore 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, as follows.

Foremost, the 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-pore walls during polishing, the dried and cooled specimens were vacuum impregnated with slow-setting epoxy. The impregnated specimens were polished as per ASTM C 457. 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 pore size measurement.

The pore size were measured according to ASTM C 457 under a microscope with a magnification of 60x on two specimens, prepared as per the procedure described previously, for each foamcrete specimen. Image analysis system consisted of an optical microscope and a computer with image analysis software.

3. Results and discussions

The test results of all foamcrete samples are summarized in Table 2. Further discussions are categorized according to the effect of density, pore size and porosity on thermal conductivity of foamcrete.

TABLE 2: SUMMARY OF TEST RESULTS

Density (kg/m^3)	Thermal conductivity, *k* (W/mK)	Porosity (%)	Effective pore size (mm)
650	0.23	74	0.72
700	0.24	71	0.69
800	0.26	64	0.63
900	0.28	57	0.59
1000	0.31	51	0.55
1100	0.34	47	0.51
1200	0.39	44	0.48

3.1. Effect of density on thermal conductivity

The results show that the thermal conductivity of all foamcrete samples is positively proportionate with the density (Fig. 1). For instance, the thermal conductivity for foamcrete reduced from 0.39 to 0.28W/mK and further reduced to 0.23W/mK for corresponding densities of 1200, 900 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 [16, 17]. As will be discussed in Section 3.2, the density of foamcrete is controlled by its porosity. High density foamcrete will have smaller porosity value compared to the low density thus this will influence the thermal conductivity of this material.

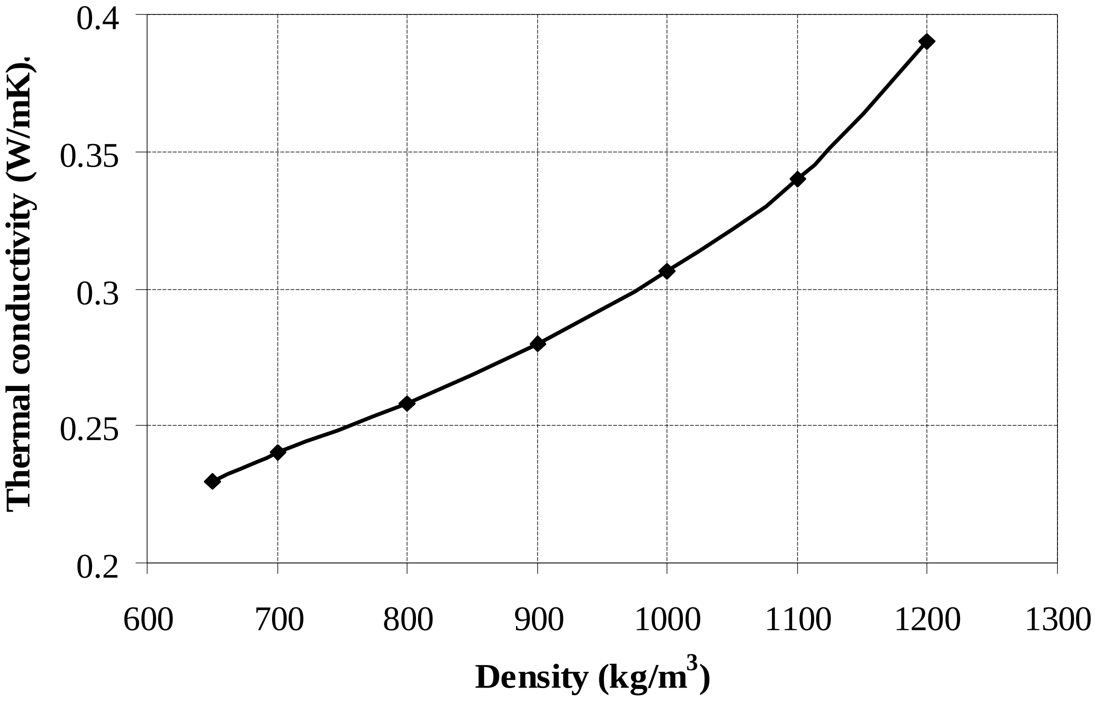

Figure 1: Thermal conductivity of foamcrete at different densities

3.2. Effect of porosity and pore size on thermal conductivity

Fig. 2 shows typical microscopic images of the internal pore structure of the 1000 and 650 kg/m^3 density foamcrete. Clearly the pore sizes are not uniform. However, these two figures do clearly indicate that there is a dominant pore size and that the dominant pore size is primarily a function of the foamcrete density. The dominant pore size tends to increase as the foamcrete density reduces due to the higher quantity of foam used (Fig. 3). For instant, from a microscopic analysis of the internal images of the two densities of foamcrete, the dominant pore size of the 650 and 1000 kg/m^3 density foamcrete has been determined as 0.72mm and 0.55mm respectively.

The density of foamcrete is governed by the porosity or amount of air content inside the material. It can be seen from Fig. 4 that lower density of foamcrete indicates larger porosity value or greater amount of air contained (larger pore size). As a result, thermal conductivity changes significantly with the porosity of foamcrete because air is the poorest conductor compared to solid and liquid due to its molecular structure.

(a) 650 kg/m^3 density

(b) 1000 kg/m^3 density

Figure 2 Pore sizes of foamcrete for 650 and 1000 kg/m^3 densities

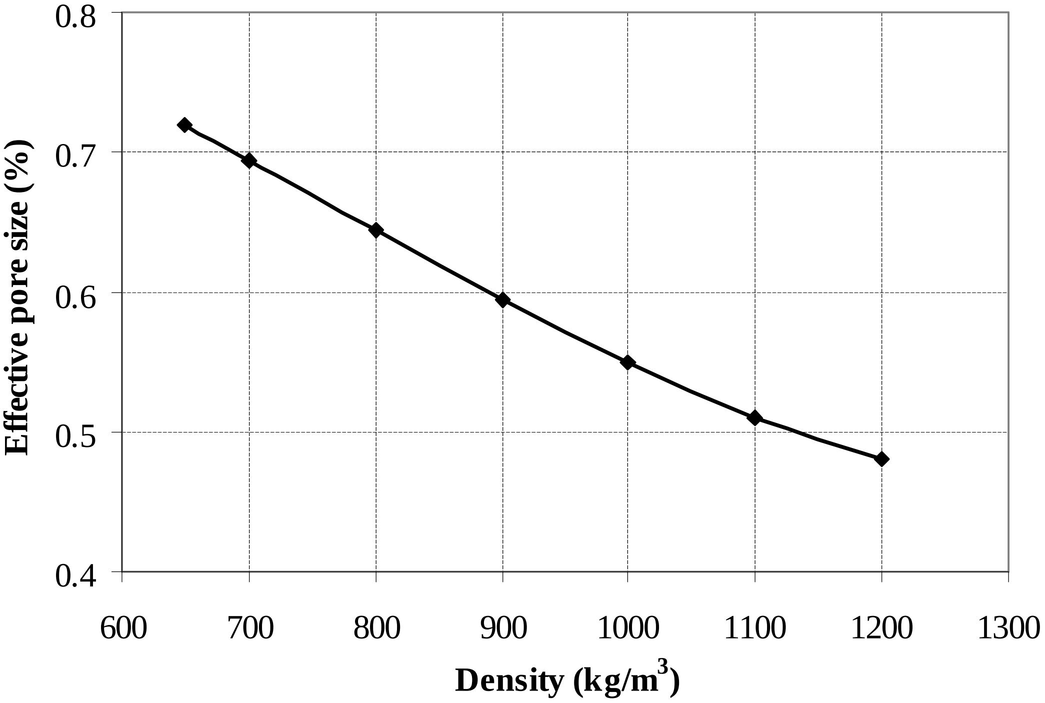

Figure 3 Effective pore size of foamcrete at different densities

4. Conclusion

An experimental study was conducted to determine the thermal conductivity of foamcrete of different densities and the influencing factors on the thermal conductivity through the Hot-Guarded Plate method. Based on test results, the following conclusions may be drawn:

1. Since foamcrete is made by injecting air into a cement based mixture, the density of foamcrete is directly a function of the air (porosity) inside foamcrete. Therefore the density of foamcrete plays an important role in determining its thermal conductivity. Lower density foamcrete indicates greater porosity.
2. Thermal conductivity changes noticeably with the porosity of foamcrete because air is the poorest conductor in comparison with solid and liquid due to its molecular structure.
3. Lower density foamcrete translates to lower thermal conductivity.
4. The dominant pore size of foamcrete is primarily a function of the foamcrete density where it tends to increase as the foamcrete density reduces due to the higher quantity of foam.

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