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An Experimental Investigation on Thermal Conductivity of Lightweight Foamcrete for Thermal Insulation

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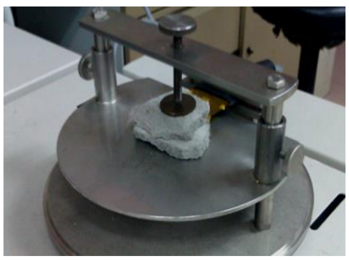
Graphical abstract



Abstract

Presently, the construction industry has shown considerable consciousness in utilizing lightweight foamcrete as a building material. The demand of lightweight foamcrete is becoming higher now where this material has increased many folds in recent years due to its intrinsic economies and advantages over conventional concrete in a range of structural and semi-structural applications. The major specialties of lightweight foamcrete are its excellent thermal conductivity, low self-weight, high impact resistance and good freeze thaw resistance. The aim of this experimental study is to investigate the thermal conductivity property of lightweight foamcrete with various densities. The main parameters that will be considered are density of lightweight foamcrete, the void size and porosity. The lightweight foamcrete samples are made with constant water-cement ratio of 0.5 and cement-sand ratio of 2:1. According to experimental results, lower densities lightweight foamcrete transforms to lower thermal conductivity values. Meanwhile, the density of lightweight foamcrete is controlled by the porosity where lower densities indicate larger porosity values. For this reason, thermal conductivity of lightweight foamcrete changes significantly with the porosity because air is the poorest conductor in comparison to solid and liquid owing its molecular constitution. The measured values of thermal conductivity should provide a useful database for evaluating the thermal performance of lightweight foamcrete structures.

Keywords: Foamed concrete; thermal conductivity; lightweight concrete; porosity; void size

Abstrak

Pada masa ini, industri pembinaan telah menunjukkan keprihatinan yang tinggi dalam menggunakan konkrit ringan berbusa sebagai bahan binaan. Permintaan konkrit ringan berbusa menjadi semakin tinggi di waktu di mana bahan ini telah meningkat berlipat ganda dalam beberapa tahun kebelakangan ini disebabkan oleh keadaan ekonomi yang baik dan intrinsik jika dibandingan dengan kaedah pembinaan konvensional dalam pelbagai aplikasi struktur dan semi-struktur. Keistimewaan utama konkrit ringan berbusa adalah kekonduksian haba yang sangat baik, rendah berat sendiri, rintangan impak yang tinggi dan rintangan pembekuan cair yang baik. Tujuan kajian ini dijalankan adalah untuk menyiasat properti konduktiviti terma konkrit ringan berbusa yang mempunyai ketumpatan yang berlainan. Parameter utama yang akan dipertimbangkan adalah ketumpatan konkrit ringan berbusa, saiz lompang dan aspek keliangan. Sampel konkrit ringan berbusa disediakan dengan nisbah air-simen 0.5 dan simen-pasir 2:1. Berdasarkan kepada keputusan eksperimen yang diperoleh, ketumpatan konkrit ringan berbusa yang lebih rendah akan memberi nilai konduktiviti terma yang rendah. Sementara itu, ketumpatan konkrit ringan berbusa dikawal oleh aspek keliangan di mana ketumpatan yang rendah memberi nilai keliangan yang lebih besar. Atas faktor ini, konduktiviti terma konkrit ringan berbusa berubah dengan ketara dengan keliangan kerana udara adalah konduktor yang paling tidak baik berbanding dengan molekul pepejal dan cecair. Nilai konduktiviti terma yang diukur di dalam kajian ini akan menyediakan pangkalan data yang berguna untuk menilai prestasi konduktiviti terma struktur konkrit ringan berbusa.

Kata kunci: Konkrit ringan berbusa; konduktiviti terma; konkrit ringan; keliangan; saiz lompang

■1.0 INTRODUCTION

Fire resistant barriers play significant role in maintaining Lightweight foamcrete is a vast majority of concrete containing no large aggregates, only fine sand and with very light weight materials containing cement, water and foam. It is categorized as lightweight concrete material having a minimum of 20 per cent by volume of mechanically entrained foam in the mortar slurry. Lightweight foamcrete is created by entrapping numerous small voids of air in cement paste [1]. Mechanical foaming can take place in two principal ways; by pre-foaming a suitable foaming agent with water and then combining the foam with the paste or by adding a quantity of foaming agent to the slurry and whisking the mixture into a stable mass with the required density. The most frequently used foam concentrates are based on hydrolyzed protein or synthetic foaming agents. They are formulated to produce air voids that are stable and capable to resist the physical and chemical forces imposed during mixing, placing and hardening. Lightweight foamcrete is very sensitive to water demand compared to normal concrete. If too little water is added to the mixture, the water will not be sufficient for initial reaction of the cement and the cement will extract water from the foam, causing speedy disintegration of the foam [2]. If too much water is added in the mixture, segregation will happen causing dissimilarity in density. Fresh lightweight foamcrete has the appearance of a light-grey mousse or milk-shake and it is the volume of slurry to foam which dictates the casting density of the lightweight foamcrete. The density of lightweight foamcrete is determined by the ratio of foam to slurry [1]. With proper control in dosage of foam and methods of fabrication, a wide range of densities (400 - 1600 kg/m^3) of lightweight foamcrete can be produced thus providing flexibility for application such as structural elements, partition, insulating materials and filling grades. Table 1 shows the range of densities suitable for different applications.

Lightweight foamcrete is physically has a self-levelling and self-compacting nature where it fills the smallest voids, cavities and seams within the pouring area [2,3]. Lightweight foamcrete is a complex material, which acts in correctly complex way. Its properties deviate with age, temperature and humidity. Additionally, at near the beginning ages, heat is generated which may result in substantial temperature increase. It therefore becomes difficult to foresee its behavior with any real accuracy, even under controlled conditions, and the use of published information must be vigilantly qualified unless the conditions of application are close to those under which the information was acquired [3].

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 [4]. Thermal conductivity (W/m K) is the result of thermal diffusibility (cm^2/s), specific heat (J/g K) and density [5] 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 [6]. The thermal conductivities of ordinary heat insulating materials range from 0.034 to 0.173 W/m K [7].

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 [1]. In practical terms normal weight concrete would have to be 5 times thicker than foamcrete ones to achieve similar thermal insulation [8]. The thermal conductivity of foamcrete with 1000 kg/m^3 density is reported to be one-sixth the value of typical cement-sand mortar [3]. 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 [9].

Table 1 Applications of foamcrete with different densities

Density (kg/m^3)	Applications
300 - 600	Roof and floor insulation against heat and sound and also for interspaces filling between brickwork leaves in underground walls, insulation in hollow blocks.
600 - 900	Production of precast blocks and panels for curtain and partition walls, slabs for false ceilings, thermal insulation and soundproofing screeds in multi-level residential buildings.
900 - 1200	Concrete blocks and panels for outer leaves of buildings, architectural ornamentation, partition walls, concrete slabs for roofing and floor screeds.
1200 - 1800	Precast panels of any dimension for commercial and industrial use, garden ornaments, structural concrete

This research is concerned with exploring the potential of using lightweight foamcrete as an insulation for building. Even though lightweight foamcrete mechanical properties are low compared to normal weight concrete, lightweight foamcrete may be used as partition or light load-bearing walls in low rise residential construction particularly for residential construction. Lightweight foamcrete has very low thermal conductivity, making it a suitable material for building use as insulating or fire resisting material due to its porous internal structure. This study will focus on thermal conductivity of lightweight foamcrete of different densities and establish the key factors affecting the thermal conductivity of this material. Foamed concrete of nine densities (600, 700, 800, 900, 1000, 1100, 1200, 1300 and 1400 kg/m^3) have been be cast and tested at room temperature to acquire its effective thermal conductivity by means of hot-guarded plate method.

■2.0 MATERIALS AND MIX DESIGN

The lightweight foamcrete used in this study was made from ordinary Portland cement, fine sand, water and stable foam and Table 2 lists details of the constituent materials. The main objectives of this research are to determine the thermal conductivity of lightweight foamcrete at room temperature hence only a constant cement-sand ratio of 2:1 and water-cement ratio of 0.5 was used for all batches of lightweight foamcrete samples made for this study.

It should be pointed out that water-cement ratio of 0.5 was found adequate to reach adequate workability for the lightweight foamcrete mix. Portland cement acquired from Cima Group of Companies Sdn. Bhd. (Perak, Malaysia) was used in this study [10]. Fine sand with additional sieving to eliminate particles greater than 2.36 mm was used in the mix, to enhance the lightweight foamcrete flow characteristics and stability [11].

The foaming agent used was Noraite PA-1 (protein based) which is appropriate for lightweight foamcrete densities ranging from 600 to 1600 kg/m^3. Noraite PA-1 comes from natural sources, 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 TM-2 System as shown in Figure 1. Further details of the mix constituent proportions and the densities are outlined in Table 3. The target foamcrete volume required for each mix design was 0.1 m^3.

Table 2 Constituent materials used to produce foamcrete

Constituents	Type
Cement	Ordinary Portland cement [10]
Sand	Fine sand with additional sieving to eradicate particles greater than 2.36 mm, to improve the foamcrete flow characteristics and stability [11]
Stable foam	Noraite PA-1 (protein based) surfactant with weight of around 70 to 80 gram/litre produce from Portafoam TM2 System. The surfactant solution consists of one part of surfactant to 33 parts of water.

Table 3 Mix constituent proportions of foamcrete mixes

Target dry density (kg/m^3)	Target wet density (kg/m^3)	Portland Cement content (kg/m^3)	Sand content (kg/m^3)	Noraite PA-1 foaming agent (m^3)
600	723	38	19	0.065
700	826	41	21	0.060
800	929	46	23	0.055
900	1033	52	26	0.050
1000	1136	57	28	0.045
1100	1239	62	31	0.040
1200	1343	67	34	0.035
1300	1448	72	37	0.030
1400	1553	77	40	0.025

Figure 1 Portafoam generator TM-2 System

3.0 EXPERIMENTAL SETUP

3.1 Hot-guarded Plate Method

The HGP test followed the ASTM procedure [12]. 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 foamed concrete was Hot Disk Thermal Constants Analyzer Model TPS 2500. The hot disk thermal constants analyzer is an up-and-coming equipment that uses the transient plane source method to determine the in-plane and through-plane thermal conductivity of an anisotropic material in the same test [13]. 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 lightweight foamcrete samples the sensor with the larger radius was used. The thermal conductivities were measured at room temperature of 23ºC. 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 make certain that the assumption of an infinite sample domain was met and that heat was not penetrating entirely 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 [14]. This stacking of disks allowed the generation of more reproducible data. For each formulation, typically 5 different sets of 4 disks (a total of 20 disks) were tested. Figure 2 shows the schematic of samples during testing.

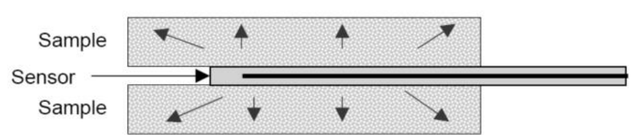


Figure 2 Schematic of samples and sensor for the hot disk

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 [14]. From a theoretical standpoint, the double spiral pattern can be approximated by a series of concentric, equally spaced ring sources. The characteristic heat conduction equation, assuming radial symmetry in the sample, is then given as:

$$(\rho C_p)\frac{\partial T}{\partial t} = k_{in}\frac{1}{r}\left(\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)\right) + k_{thru}\frac{\partial^2 T}{\partial z^2} + \sum_{rings} Q_r\delta(r-r')\delta(z) \tag{1}$$

where ρ is the density of the lightweight foamcrete sample (kg/m^3), C_p is the heat capacity of the sample (J/(kg·K)), T is the temperature of the sample (K), t is the time of the measurement (s), k_{in} and k_{thru} are the in-plane and through-plane thermal conductivities of the sample (W/m·K), δ is the Dirac delta function, r' is the radius of one of the ring sources, and Q_r is the power supplied to that ring per unit length of the ring (W/m). The total power for each ring is proportional to the circumference of the ring $2\Pi r'$, such that the total power supplied for all of the rings is Q (W). This total power Q is an input parameter to the Hot Disk Thermal Constants Analyzer. The first term in Equation 1 represents accumulation of thermal energy, the second term radial (referred to as in-plane in our experiments) heat conduction, the third term axial (referred to as through-plane in our experiments) heat conduction, and the final term is a heat source. The average transient temperature increase of the sensor is simultaneously measured by recording the change in electrical resistance of the nickel sensor [13] according to:

$$\Delta T = \frac{1}{\beta}\left(\frac{R_n}{R_{no}} - 1\right) \tag{2}$$

where ΔT is the change in temperature at time t (K), β is the temperature coefficient of resistance (TCR) of the material (1/K), R_n is the electrical resistance of the nickel at time t (Ω), and R_{no} is the electrical resistance of the nickel at time 0 (Ω). The temperature rise in Equation 2 is correlated with the in-plane and through-plane thermal conductivities through the solution of Equation 1 as:

$$\Delta T = \frac{P}{\pi^{3/2} R\sqrt{k_{in}k_{thru}}} F(\tau) \tag{3}$$

where P is the power dissipation in the probe and F(τ) is a dimensionless time dependent function of τ given by an integral of a double series over the number of rings m:

$$F(\tau) = [m(m+1)]^{-2}\int_0^{\tau} \sigma^{-2}\left[\sum_{l=1}^{m} l \sum_{k=1}^{m} k \exp\left(-\frac{l^2+k^2}{4m^2\sigma^2}\right) I_0\left(\frac{lk}{2m^2\sigma^2}\right)\right] d\sigma \tag{4}$$

A more detailed derivation of Equations 3 and 4 is given by He [14]. Equations 1 through 4 are used to determine the in-plane and through-plane thermal conductivity of the composite being tested. 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:

$$k = \frac{W}{A}\left[1 \times \frac{d}{\Delta T}\right] \tag{5}$$

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. Figure 3 shows the set-up of hot disk thermal constant analyser for thermal conductivity test.

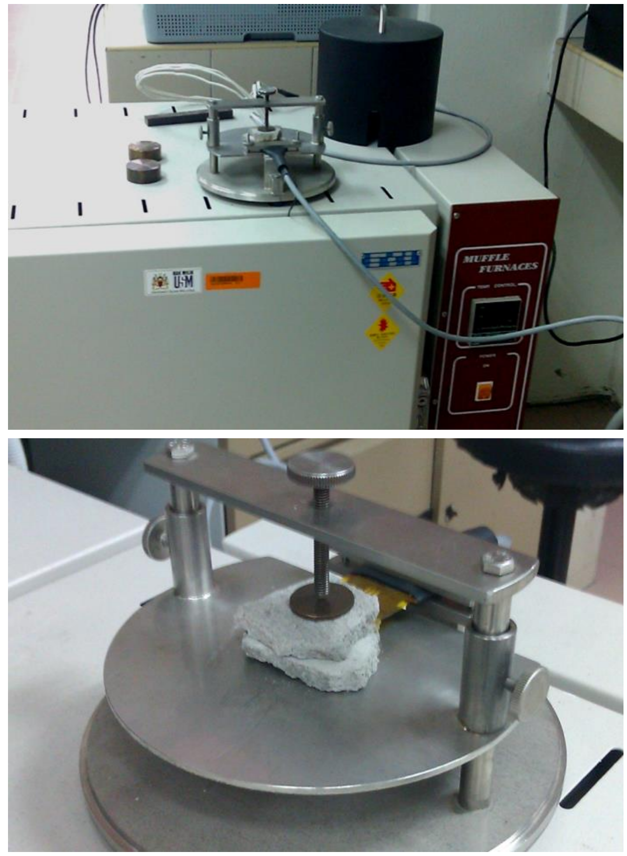


Figure 3 Set-up on hot disk thermal constant analyzer for thermal conductivity test

3.2 Porosity Measurements

There are a few methods available to measure porosity of foamcrete. As far as this paper is concerned, Vacuum Saturation Apparatus [15] will be utilized to determine the porosity value of foamcrete for all densities tested for this study. The measurements of foamcrete porosity were conducted on slices of 68 mm diameter cores cut out from the centre of 100 mm cubes. The specimens were dried at temperature of 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. In order to obtain the porosity value for each foamcrete sample, the following equation was used:

$$\varepsilon = \frac{(W_{sat} - W_{dry})}{(W_{sat} - W_{wat})} \times 100 \tag{6}$$

where ε 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.

3.3 Pore Size Measurements

The pore size measurements for this research was slightly different compared to the procedure suggested by ASTM C 457 [16]. In ASTM C 457, it indicated the size and thickness of the sample and length of travel in the linear traverse method, based on the aggregate size. All the samples were vacuum-saturated with slow-setting epoxy. In order to make certain uniformity in final results, all the samples were prepared according to similar methods under the same environmental conditions. At first all the sample of 45 x 45 mm in size with a minimum thickness of 15 mm were cut from the centre of two randomly selected 100 mm cubes and then the face of the sample was cut perpendicular to the casting direction. Sized samples were saturated in acetone to impede advance hydration reaction before drying at the temperature of 105°C. To make sure the firmness of the air-pore walls during the polishing work, the dried and cooled samples were vacuum- saturated with slow-setting epoxy. The saturated samples were polished as per suggested in ASTM C 457 [16]. Once the polishing and cleaning works have been completed, all the samples were dried at ambient temperature for 24 hours. After all, an effective size of 40 x 40 mm was taken for pore size measurement. The pore size was measured according to ASTM C 457 under a microscope with a 40 times magnification on two samples, prepared as per the method portrayed earlier. Scanning electron microscopy (SEM) was used to give a detailed view on each of the pore size distributions.

■4.0 RESULTS AND DISCUSSION

Lightweight foamcrete can be fabricated with a wide range of density. Each density gives different result on the properties of this material. Density of lightweight foamcrete influenced by the amount of foam added into the base mix. In this study, different densities of lightweight foamcrete were cast and tested. The test results of all foamcrete samples are summarized in Table 4. Further discussions are categorized according to the effects of density, pore size and porosity on thermal conductivity of lightweight foamcrete.

Table 4 Summary of test results

Density (kg/m^3)	**Thermal conductivity, *k* (W/mK)**	**Porosity (%)**	**Effective pore size (mm)**
600	0.22	77	0.73
700	0.24	71	0.68
800	0.26	64	0.63
900	0.28	57	0.59
1000	0.31	51	0.54
1100	0.34	47	0.50
1200	0.38	44	0.47
1300	0.41	41	0.44
1400	0.45	39	0.42

4.1 Thermal Conductivity-density Relationship

According to Table 4 and Figure 4, it can be clearly seen that the effective thermal conductivity of all lightweight foamcrete samples is proportionate with the density. For example, the thermal conductivity for lightweight foamcrete reduced from 0.45 to 0.31W/mK and further reduced to 0.22W/mK for corresponding densities of 1400, 1000 and 600 kg/m^3, in that order. The hot-guarded plate test results have confirmed that lightweight foamcrete with lower density converts to lower effective thermal conductivity which is equivalent to the findings from the other researcher [17]. As will be shown in Section 4.2, the density of lightweight foamcrete is controlled by its porosity. Higher densities lightweight foamcrete will have smaller porosity value compared to the lower densities hence this will influence the effective thermal conductivity of lightweight foamcrete.

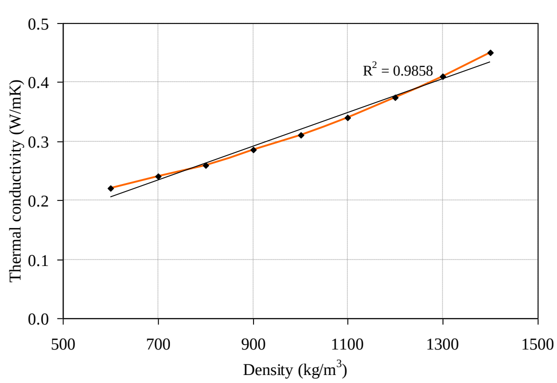


Figure 4 Thermal conductivity-density relation for lightweight foamcrete

With reference to Figure 4, a correlation coefficient of 0.9858 indicates an excellent correlation between the linear regression line and the hot-guarded plate thermal conductivity test results for all densities of lightweight foamcrete.

4.2 Porosity-density Relationship

The density of lightweight foamcrete is governed by the porosity or amount of air content inside the material. It can be seen from Figure 5 that lower density of lightweight foamcrete signifies larger porosity value or greater amount of air contained (larger void size). As a result, the effective thermal conductivity transforms considerably with the porosity of lightweight foamcrete because air is the poorest conductor compared to solid and liquid due to its molecular structure. According to Figure 5, a correlation coefficient of 0.9647 signifies a good correlation between the linear regression and the measured porosity of lightweight foamcrete.

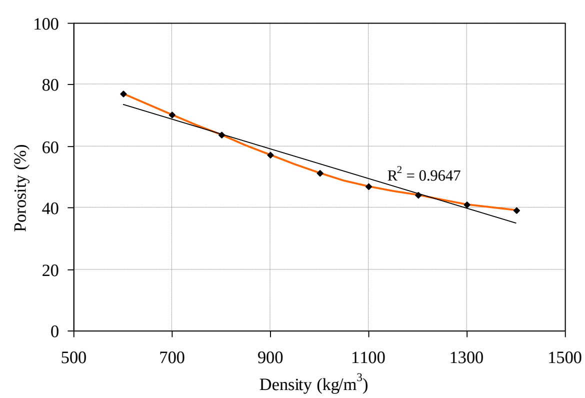


Figure 5 Porosity-density relation for lightweight foamcrete

4.3 Effective void size-density Relationship

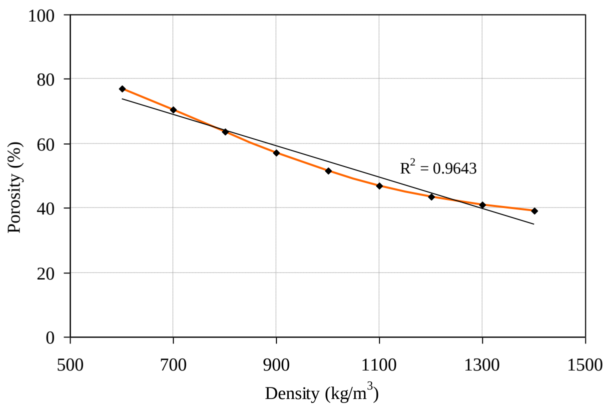
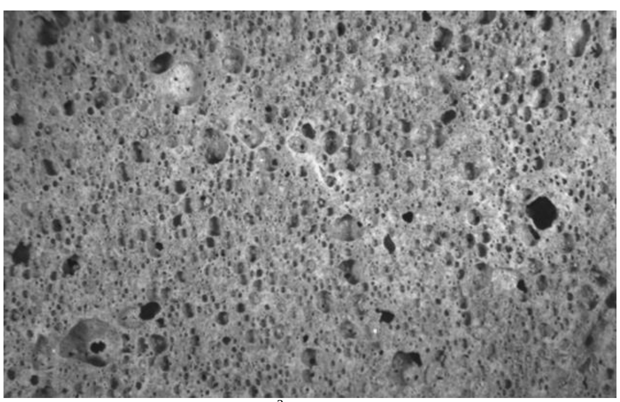
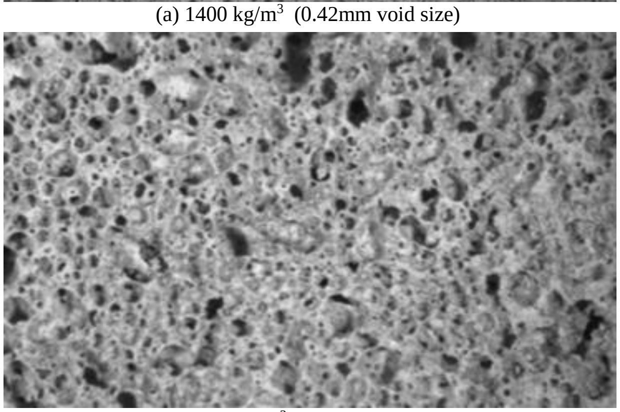


Figure 6 Effective void size-density relation for lightweight foamcrete

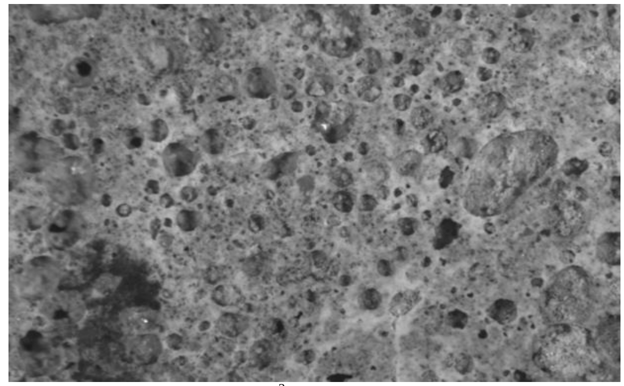
With reference to Table 4 and Figure 6, it can be noticeably seen that the effective void size of all lightweight foamcrete samples is absolutely proportionate with the density. For instance, the void size for lightweight foamcrete increased from 0.42mm to 0.54mm and further reduced to 0.73mm for corresponding densities of 1400, 1000 and 600 kg/m^3. Figure 7 shows typical microscopic images of the internal pore structure of the 1400, 1200, 900 and 600 kg/m^3 density lightweight foamcrete. Clearly, the pore sizes are not uniform. However, these four figures do evidently signify that there is a dominant pore size and that the dominant pore size is primarily a function of the lightweight foamcrete density. The dominant pore size tends to increase as the lightweight foamcrete density reduces due to the higher quantity of foam used.



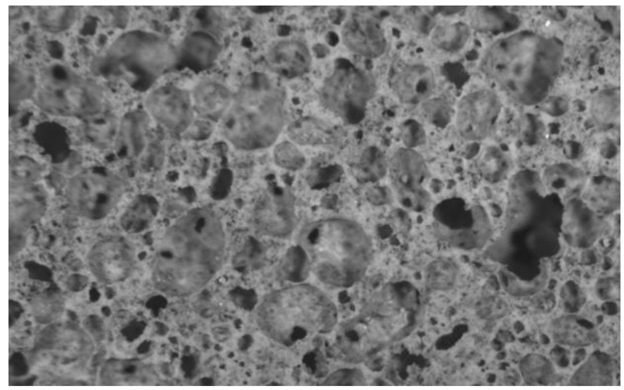
(a) 1400 kg/m^3 (0.42mm void size)



(b) 1200 kg/m^3 (0.47mm void size)



(c) 900 kg/m^3 (0.59mm void size)



(d) 600 kg/m3 (0.73mm void size)

Figure 7 (a-d) Void sizes for different densities of lightweight foamcrete

As can be seen on Figure 6, a correlation coefficient of 0.9683 designates an excellent correlation between the linear regression line and the effective void size of lightweight foamcrete.

■5.0 CONCLUSION

This research focuses on experimental studies to establish the thermal conductivity of lightweight foamcrete of different densities ranging from 600 to 1400 kg/m^3 via Hot-Guarded Plate method and the factors affecting the thermal conductivity of foamcrete. From the experimental results, the following conclusions may be drawn:

1) Density of lightweight foamcrete is directly a function of the porosity as foamcrete is fabricated by injecting air into cement slurry.
2) The lower density lightweight foamcrete signifies larger porosity value; hence density plays an important role in determining the thermal conductivity of foamcrete.
3) Given that air is the poorest conductor in comparison with solid and liquid due to its molecular structure, the thermal conductivity changes perceptibly with the porosity of lightweight foamcrete
4) Lower density foamcrete transforms to lower and improved thermal conductivity.
5) Void size of foamcrete tends to amplify as the foamcrete density reduces due to the higher quantity of foam. It should be pointed out that the dominant void size of foamcrete is predominantly a function of the lightweight foamcrete density

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