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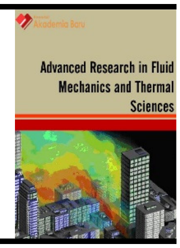

Determination of Thermal Properties of Lightweight Cellular Mortar (LCM) of Different Density Through Guarded Hot Plate Method

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Md Azree Othuman Mydin[1,*], Mohd Nasrun Mohd Nawi[2], Muhammad Arkam Che Munaaim[3], Abdul Aziz Abdul Samad[4], Noridah Mohamad[5], Izwan Johari[6]

[1] Cluster of Technology, School of Housing, Building and Planning, Universiti Sains Malaysia, 11800, Penang, Malaysia
[2] School of Technology Management and Logistics, College of Business, University Utara Malaysia, 06010 Sintok, Kedah, Malaysia
[3] School of Environmental Engineering, Universiti Malaysia Perlis, 02600, Perlis, Malaysia
[4] Jamilus Research Centre, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, Malaysia
[5] Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, Malaysia
[6] School of Civil Engineering, Universiti Sains Malaysia, Engineering Campus,14300 Nibong Tebal, Seberang Perai Selatan, Penang, Malaysia

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ABSTRACT

Currently, the construction industry in Malaysia has shown substantial awareness in employing lightweight cellular mortar (LCM) as a building material. The main advantages of LCM are its outstanding thermal properties, low density, excellent fire resistance performance, exceptional impact resistance and worthy freeze thaw resistance. The application of low thermal conductivity building materials is significant to reduce heat gain through the envelope into the building in hot climate country like Malaysia. Hence, the aim of this study is to determine the effective thermal conductivity of LCM of various densities through Guarded Hot Plate Method. The densities were ranging from 550, 650, 750, 850 and 950 kg/m3 with constant cement-sand ratio of 2:1 and water-cement ratio of 0.45. This study focused on the effects of density, porosity and mortar bubble size on thermal conductivity of LFC. Guarded Hot Plate Method was used to attain the thermal conductivity of LCM of various densities. The porosity value of LCM was determined through the Vacuum Saturation Apparatus. In order to scrutinize the effect of mortar bubble size on thermal conductivity of LCM, bubble size measurements were made under a microscope with a magnification of 50x. From the experimental results, it had shown that lower density LCM decodes to lower thermal conductivity. For instance, the thermal conductivity for LCM reduced from 0.30 to 0.24W/mK and further reduced to 0.19W/mK for corresponding densities of 950, 750 and 550 kg/m3, respectively. The density of LCM is controlled by the porosity where lower density LCM specifies higher porosity. The study also revealed that the dominant void size rises as the LCM density declines due to the higher amount of foam used. For example, from a microscopic analysis of the internal images of the three densities of LCM, the dominant void size of the 550, 750 and 950 kg/m3 density LCM has been determined as 0.76mm, 0.66mm and 0.55mm in that order. Hence, thermal conductivity changes significantly with the porosity of LCM because air is the poorest conductor compared to solid and liquid due to its molecular structure. From the results obtained, it can be concluded that LCM 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.

* *Corresponding author.*
E-mail address: azree@usm.my (Md Azree Othuman Mydin)

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1. Introduction

It should be pointed out that the component of energy competence is a substantial matter for producing high quality housing. Energy not only relates to high proportion of the building running cost but it also has a key influence on the thermal comfort of the building occupants. At the present time, the plea for energy efficient design and construction has developed increasingly more dynamic with the emergent of energy costs and cumulative consciousness on the effects of global warming. In the process of building energy calculations, it is essential to distinguish the thermal properties of the material itself. Hence, the thermal insulation of building envelope plays an important role in energy saving [11]. Recently there is a growing awareness on developing new materials and advanced solutions to cater for the needs of producing excellent performance building material in terms of thermal properties such as thermal conductivity, thermal diffusivity and specific heat capacity. This study will focus on the thermal conductivity of lightweight cellular mortar (LCM).

LCM is not a new building material in the construction industry. It was first patented and utilized in year 1923 and a limited scale of fabrication was started a year later. The utilization of LCM in construction industry was very restricted until the late 1970s, when it was on track to be implemented in Holland for ground engineering applications and voids filling jobs. Then, a full-scale assessment on the application of LCM as a trench reinstatement was carried out somewhere in 1987 in the United Kingdom and the accomplishment of this trial had led to the widespread utilization of LCM for trench reinstatement and other applications followed [7]. It should be noted that over the past 30 years, LCM has principally been utilized around the world for soil stabilizing, trench reinstatement, bulk filling, backfill of bridge abutments, pipeline infill component, insulation material for roof tiles, grouting element for tunnel and sandwich fill for precast elements. Nevertheless, in the last few years, there is emerging attention in using LCM as a lightweight non-structural and semi-structural element in buildings to take advantage of its excellent insulation properties. Figures 1, 2 and 3 show some real project utilizing LCM.

Fig. 1. LCM insulation screed was utilized to offer thermal protection for a multi-storey building in Mauritius (www.drn.com.my)

Fig. 2. LCM was poured in sections to prevent loss in density and reduce shrinkage problems in slabs for UEM Building Kuala Lumpur (www.drn.com.my)

Fig. 3. LCM was used as underlayment and slab thickening for airport project in Malaysia (www.drn.com.my)

The 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 lesser embodied energy or lower thermal conductivity has improved the indoor comfort in building. Accordingly, a high level of insulation in any new material development is an indispensable step to an energy efficient design of building. The essential fact of thermal conductivity (*k*) of material is that, for steady flow, the quantity of heat flowing in a unit of time through a plate varies directly as the variance of temperature between the faces of the plate, in a straight line as the cross section of the plate, and contrariwise as the thickness of the plate. This law, which was first specified clearly by Joseph Fourier, the famous French military engineer and mathematician [10]. In general, thermal conductivity can be defined as the process of the conduction of high-temperature thermal energy within an object, which sinks the temperature. As per mentioned by Fourier's Law for heat conduction, when an object is heated at certain temperature, the vibration of the atoms and molecules and the moving of free electrons release thermal energy to the lower temperatures in the sequence of kinetic energy conduction. Conferring to molecular dynamics, an object's self-temperature is in a straight fraction to the mean kinetic energy of its alignment. Thermal conductivity is influence by the density of the material, thermal diffusivity and the specific heat capacity. In addition, it is also influenced by the pore size, pore structure, chemical configuration, moisture content and temperature gradients [4].

Therefore, the use of low thermal conductivity materials in building is really significant in order to reduce heat gain through the building envelope into the interior of building in the hot climate country. As been mentioned earlier, LCM has been recognized for its excellent properties and characteristics in terms of thermal insulation and sound absorption owing to its cellular micro-structure. Based on some previous studies, the thermal conductivity of LCM normally is 10 to 40% of that of normal strength concrete and range from between 0.05 and 0.75 W/mK for dry density values of 500 to 1700 kg/m^3 correspondingly [6]. In applied terms, normal strength concrete would have to be 5 times thicker than LCM ones to attain comparable thermal insulation properties. As LCM is prepared by injecting air into a cement based blend, hence the density of LCM is directly a function of the air bubble inside LCM. For that reason, the density of LCM plays a significant role in defining the thermal properties holistically. A decrease of LCM density by 100 kg/m^3 may result in a decreasing of thermal conductivity by 0.04 W/mK [1]. Hence, this research anticipates to scrutinize the thermal conductivity of LCM of different densities and forming the key factors affecting the thermal conductivity of this material. There are 5 densities (550, 650, 750, 850 and 950 kg/m^3) of LCM will be prepared for this particular study and tested through Guarded Hot Plate Method in order to obtain its thermal conductivity.

2. Materials

The LCM implemented in this study was made of Ordinary Portland Cement (OPC), fine aggregate, water and stable foaming agent. A constant cement-sand ratio of 2:1 and water-cement ratio of 0.5 will be used for all batches of LCM specimens made for this research. It should be pointed out that a water-cement ratio of 0.5 was found adequate to accomplish adequate workability of mortar.

2.1 Cement

Type I ordinary Portland cement, which is produced by CIMA and packed under the brand name "Blue Lion Cement" was used. This cement complies to the Type I Portland cement as in BS 12 [9] Table 1 shows the chemical compositions of the Portland cement used in this study.

Table 1
Chemical compositions of Portland cement

Chemical compound	Portland cement
MgO	1.50
Al_2O_3	3.60
SiO_2	16.00
SO_3	3.10
K_2O	0.34
CaO	72.00
Fe_2O_3	2.90
Na_2O	n/d

2.2 Sand

Fine aggregates river sand was used. The sand was dried and sieved through sieve 2.36 mm and treated in accordance with BS 882 to increase the LCM flow features and constancy as in BS12620 [3].

2.3 Water

The water used for this study was potable tap water, free from any dissolved metal or ions that might constrain the setting and hydration process of the LCM mixes. The water was also used to insipid the foaming agent for aeration process.

2.4 Foaming Agent

In order to aerate the base mortar, Noraite PA-1 agent was used which is suitable for LCM densities ranging from 600 to 1600 kg/m^3. Noraite PA-1 was obtained from local supplier Dr-N Technologies Sdn Bhd. Noraite SA-1 is a synthetic foaming agent. This foaming chemical is especially suitable for ready mixed LCM (example for void filling and flat roof insulation) but can also be used in load bearing components. Noraite PA-1 comes from natural sources and has a weight of around 80 gram/litre and enlarges about 12.5 times when used with the foam generator. The stable foam was produced using foam generator Portafoam TM2 System. Its dilution rate is about 1 part of chemical to 33 part of water and provides approximately 430 litres of foam from 1 litre foam agent.

3. Mix Design and Experimental Programme

3.1 LCM Compositions

LCM specimen each measured 200mm x 200mm x 50mm were made at seven different densities namely 550, 650, 750, 850 and 950 kg/m^3. Cement to sand ratio of 1:2, water to cement ratio of 0.5 and foaming agent: water ratio of 1:33 were used in this study. The mix design was chosen for the target density for LCM between 550 and 950 kg/m^3. Densities less than 1000 kg/m^3 were chosen for this study because LCM to be used as non-structural material for building envelope and partitions All the measurements were by weight. Three identical samples were made for each target density and were tested using Guarded Hot Plate Method at 10 days after mixing process. Details for all mix designs are shown in Table 2. The target LCM volume required for each mix design was 0.1 m^3.

Table 2
Mix design of LCM mixes

Target dry density (kg/m^3)	Target wet density (kg/m^3)	Portland Cement content (kg)	Sand content (kg)	Water (kg)	Foam mass (kg)
550	671	36	18	9.0	4.47
650	774	42	21	10.5	4.16
750	877	48	24	12.0	3.85
850	981	54	27	13.5	3.54
950	1084	60	30	15.0	3.22

3.2 Hot-Guarded Plate Tests

The hot-guarded plate has been designed to comply EN 12667:2001 (Thermal performance of building materials and products. It consists of a two specimen guarded hotplate which is sandwiched between two cooling plates. In use, a test specimen is placed between the hotplate and each of the cold plates. The overall test specimen and plate area is 500mm x 500mm with a central metering area of 250mm x 250mm. It should be pointed out that hot guarded plate test is commonly renowned as the main complete method for measurement of the thermal transmission properties of homogeneous insulation materials. The basic hot-guarded plate method consists principally of a hot plate and a cold plate. In a hot-guarded plate test, the test specimen is placed on a flat plate heater assembly consisting of an electrically heated inner plate surrounded by a guard heater. The guard heater is cautiously organized to uphold the identical temperature on both sides of the gap extrication the main and the guard heaters [8].

3.3 Vacuum Saturation Apparatus

Vacuum Saturation Apparatus was used to determine the porosity value of LCM. The measurements of LCM porosity were done on slices of 68mm diameter cores cut out from the centre of 100mm cubes. The LCM samples were dried at 105°C until constant weight had been achieved and then enclosed in the empty and dry vacuum tank. The pressure is depressed to 2500 Pa, which is upheld for 3 hours. This confirms an adequately low pressure in all pores of the samples. While upholding this pressure, the vacuum chamber is gradually inundated with water at 20 °C, at a monitored speed of 50mm/hour, until complete immersion of all LCM specimens. The low flooding speed aids to astound this problem at least moderately, by giving the water the time to be de-aired before entering the LCM sample, though preferably, lower pressures are needed for this procedure. After the flooding, the tank is slowly returned to atmospheric pressure. The water is now forced into the pore system of the LCM, because of the pressure difference between the water surface and the under pressure in the pores [5].

3.4 Microscopical Determination of Air-Void Size

The test is a quantitative method that determines the air-void size in hardened LCM. The LCM samples of 45 x 45 mm size with a minimum thickness of 15mm were cut from the centre of 2 randomly selected 100 mm cubes using a diamond cutter. Sized LCM samples were then saturated in acetone to stop additional hydration reaction before drying at 105 °C. In turn to safeguard the constancy of the air void walls during the polishing process, the dried and cooled LCM samples were vacuum impregnated with slow-setting epoxy. The impregnated LCM samples were prepared as per ASTM C 457. The air void size were measured conferring to ASTM C 457 under a microscope with a magnification of 50x on two LCM samples, prepared as per the procedure described previously, for each LCM sample [2].

4. Results and Discussions

4.1 Influence of Density on Thermal Conductivity of LCM

Figure 4 summarized the results of thermal conductivity of different LCM densities. It can be clearly seen that the thermal conductivity of all LCM specimens is absolutely proportional with the

LCM density. For example, the thermal conductivity for LCM reduced from 0.30 to 0.24W/mK and further reduced to 0.19W/mK for corresponding densities of 950, 750 and 550 kg/m^3, in that order.

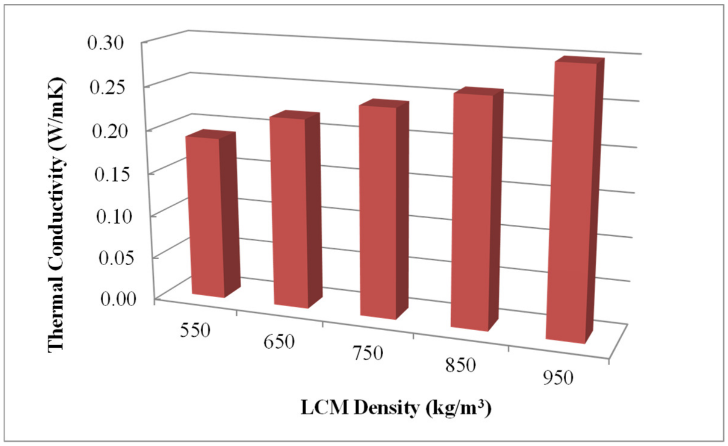

Fig. 4. Thermal conductivity of LCM of different densities

The results had confirmed that lower density LCM transmutes to lower thermal conductivity which is similar to the findings from other researchers in the area of LCM [10]. As will be presented in the next section, the density of LCM is controlled by its porosity. Higher density LCM will have smaller porosity value paralleled to the low density hence this will affect the thermal conductivity of LCM [11].

4.2 Influence of Porosity and Pore Size on Thermal Conductivity of LCM

The microstructures and pore formation of three LCM mixes of different densities are shown in Figure 5, Figure 6 and Figure 7. Evidently the pore sizes are not uniform. However, these 3 figures do obviously specify that there is a dominant void size and that the dominant void size is primarily a function of the LCM density. It should be pointed out that the greater capillary pores present in low densities LCM (550 kg/m^3) are responsible for transporting the moisture content through the concrete, which increases the conductivity. The decrease in the thermal conductivity of higher densities (950 kg/m^3) is due to the increase of void ratio that decreased the unit weight of concrete. Since air is the poorest conductor compared to the solid and liquid due to its molecular structure, it contributes to the lower thermal conductivity in higher densities LCM compared to lower densities LCM.

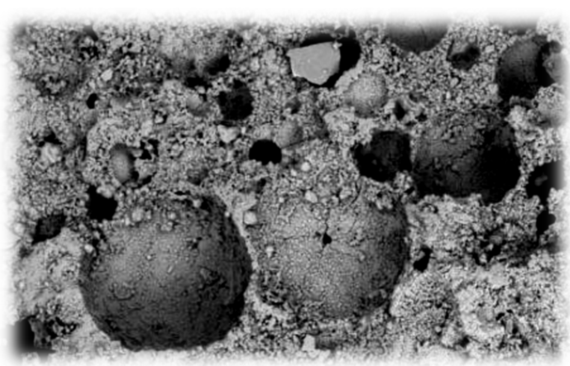

Fig. 5. Formation of voids in 550 kg/m^3 density with dominant void size of 0.76mm

The dominant void size inclines to growth as the LCM density decreases owing to the higher amount of foam used. For example, from a microscopic analysis of the internal images of the three densities of LCM, the dominant void size of the 550, 750 and 950 kg/m^3 density LCM has been determined as 0.76mm, 0.66mm and 0.55mm in that order.

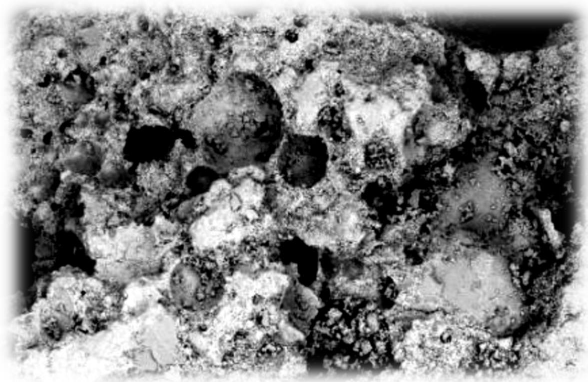

Fig. 6. Formation of voids in 750 kg/m^3 density with dominant void size of 0.66mm

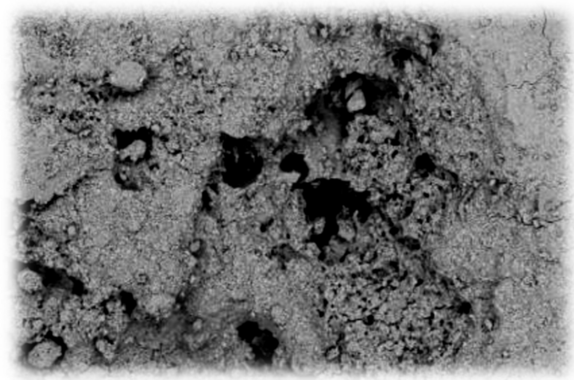

Fig. 7. Formation of voids in 950 kg/m^3 density with dominant void size of 0.55mm

It should be pointed out that the density of LCM is directed by the porosity or amount of air content inside the LCM cement matrix. It can be seen from Figure 8 that lower density of LCM designates larger porosity value or greater amount of air contained (larger void size). As a result, thermal conductivity changes considerably with the porosity of LCM because air is the poorest conductor compared to solid and liquid due to its molecular structure [12].

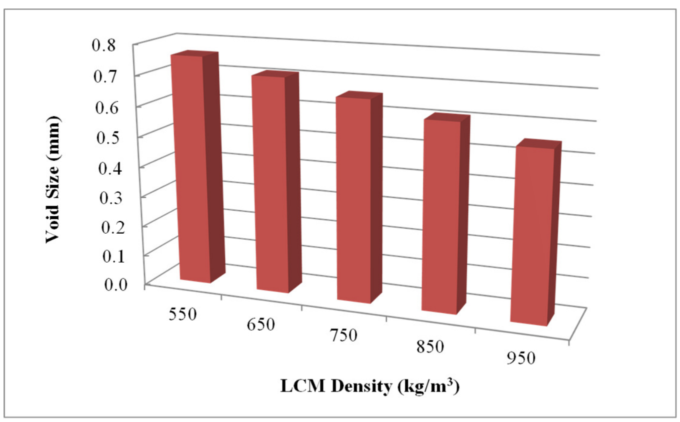

Fig. 8. Effective pore size of LCM at different densities

5. Conclusion

This research focuses on experimental investigation to determine the thermal conductivity of LCM of different densities and the influencing factors on the thermal conductivity through the Hot-Guarded Plate method. As LCM is made by injecting air into cement slurry, the density of LCM is directly a function of the porosity inside the LCM. Hence the density of LCM plays a vital role in determining the thermal conductivity of LCM. Lower density LCM specifies greater porosity. From the experimental results, thermal conductivity changes prominently with the porosity of LCM because air is the poorest conductor in comparison with solid and liquid due to its molecular structure. Lower density LCM interprets to lower thermal conductivity. The dominant void size of LCM is principally a function of the LCM density where it inclines to upsurge as the LCM density decreases due to the greater amount of foam in the base mix.

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