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Strength, thermal conductivity and sound absorption of cellular lightweight high calcium fly ash geopolymer concrete

Athika Wongkvanklom[1)], Patcharapol Posi*[2)], Pornnapa Kasemsiri[3)], Vanchai Sata[3)], Trinh Cao[4)] and
Prinya Chindaprasirt[3)]

[1)]Department of Civil and Environmental Engineering, Faculty of Science and Engineering, Kasetsart University, Chalermphrakiat Sakon Nakhon Province Campus, Sakon Nakhon 47000, Thailand
[2)]Department of Civil Engineering, Faculty of Engineering, Rajamangala University of Technology Isan, Khon Kaen Campus, Khon Kaen 40000, Thailand
[3)]Sustainable Infrastructure Research and Development Center, Faculty of Engineering, Khon Kaen University, Khon Kaen 40002, Thailand
[4)]Surface Design Consulting Pty Ltd, Suite 11.03, 68 York Street, Sydney, NSW 2000, Australia

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Abstract

In this research, the effects of foam content on mechanical property, thermal property and sound absorption of cellular lightweight geopolymer concrete (CLGC) were studied. The geopolymer mixtures were made with 15 M NaOH solution, sodium silicate/NaOH ratio (NS/NaOH) of 1.00, sand/ash ratio of 1.25, liquid/fly ash ratio of 0.4. The foam contents were varied from 2-12 %wt. The 28-day compressive strength of CLGCs of 2.7-57.8 MPa, unit weight of 844-2100 kg/m^3, water absorption of 1.36-31.25%, porosity of 2.82-49.42%, thermal conductivity of 0.13-1.62 W/mK, and sound absorption coefficients of 0.05-0.5 were obtained. The CLGCs with 4% foam content, 28-day compressive strength of 38.9 MPa and unit weight of 1815 kg/m^3 is suitable for structural lightweight concrete complying to the requirements of ASTM C330/C330M-17a. Whereas the mix with 8 and 10 % foam contents with compressive strengths of 7.60 and 6.1 MPa, and unit weights of 1210 and 1060 kg/m^3 are suitable for use as masonry lightweight concrete block in accordance with ASTM C331/C331M-17.

Keywords: Cellular lightweight geopolymer concrete, Mechanical property, Thermal property, Sound absorption

1. Introduction

Concrete is a composite material and has been used widely in construction. It is composed of three components i.e. cement, water, and aggregate. Certain chemicals can also be added to increase or adjust certain properties of concrete. Generally, the unit weight of concrete is 2200-2400 kg/m^3 [1]. The weight of concrete structure is reduced by the development and use of lightweight concrete. The additives such as foam have been applied to reduce unit weight of concrete. The reduction of dead weight leads to lower cost of construction since the size of all structural members such as column, beam and foundation could be reduced because of lower load. Moreover, the lightweight concrete is low in thermal conductivity compared to that of normal concrete due to the higher porosity of material [2, 3]. The cellular lightweight concrete for structural application with weight not exceeding 1840 kg/m^3 could provide similar strength to normal concrete [4, 5]. Furthermore, cellular lightweight concrete has several advantages such as low cost, environmentally friendly, good workability, and good performances on thermal and acoustic properties [6-9].

Generally, the cellular lightweight concrete is easily manufactured using foaming agent. In recent years due to its properties, foamed concrete is in high demand for use in large scale engineering applications including void filling, providing rigid structure, providing reduced defection under lower loading, providing low density structure and providing enhanced thermal and fire resistance. The application of foamed concrete as a structural material still has some limitations as its strength is generally lower than 20 MPa [10]. In recent years, high strength foamed concrete has been studied and produced. Chen B et al. [11] found that structural high-strength foam concrete with density of 1000-1500 kg/m^3 could be prepared using silica fume (SF), polypropylene (PP) fiber and superplasticizer. The compressive strengths increased from 20.0 MPa to 50.0 MPa when the amounts of SF and PP fiber were increased. The high strength foamed concrete can be utilized as structural material in load-bearing systems such as wall in building. Panesar DK [12] also reported that foamed concrete can be applied for use as wall which can protect both heat and sound.

Recently, it is an environmental concern that the production of Portland cement involves large amount of natural resources viz., material and energy [13]. The manufacturing of aggregate requires the explosion of rock usually from mountain and thus destroys the environment and ecological system [14]. The impact of Portland cement manufacture thus leads to carbon dioxide emissions and greenhouse effect [15, 16]. For these reasons, a new type of more environmentally friendly cementitious material called 'geopolymer' has been developed to supplement the use of Portland cement. Geopolymer is one of the composite materials synthesized from silica

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*Corresponding author. Tel.: +668 9576 7461
Email address: mister_wing@hotmail.com
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and alumina bearing source materials. The formation of amorphous aluminosilicate inorganic polymer involves the activation of silica (SiO_2) and alumina (Al_2O_3) with high alkaline solutions. The reaction of fly ash geopolymer is usually slow and requires some heat curing to accelerate the setting and hardening [17]. The existent of calcium in the mixture is also known to be beneficial to the setting-hardening of the fly ash geopolymer.

High calcium fly ash consists of high amount of silica, alumina and calcium oxide and is successfully used in the manufacturing of geopolymer cement with good strength and durability [3, 18, 19]. A number of researches were therefore carried out to improve the properties of high calcium fly ash geopolymer concrete [18-20]. With high calcium content, the reaction resulted in calcium silicate hydrate (CSH) and calcium aluminosilicate hydrate (CASH) coexisted with sodium aluminosilicate hydrate (NASH) [21, 22]. The previously reported element mapping showed that the Ca elements distributed evenly in a similar manner but with less intensity than those of Na elements [21]. The setting and hardening of high calcium fly ash geopolymer was faster than that of low calcium one [23]. This enables the hardening and development of strength of geopolymer cured at ambient temperature.

The high calcium fly ash is a byproduct of burning of lignite coal to generate electricity. The largest power plant at Mae Moh district, Lampang province, Thailand annually generates around 3 million tons of this fly ash. The high calcium fly ash is available in abundant quantity in various part of the world. Therefore, the use of high calcium fly ash as raw material to produce geopolymers is an environmentally friendly option for the production of green concrete.

This research aims examining the feasibility of production of high strength cellular lightweight geopolymer concrete (CLGC). The foam content, unit weight of concrete, mechanical properties, thermal property, and sound absorption are tested for a range of mixes. The information on making and properties of cellular lightweight high calcium fly ash geopolymer should help with the increase use of fly ash and the more environmentally friendly lightweight geopolymer concrete in a sustainable construction industry.

2. Experimental program

2.1 Materials

Materials used in this research consisted of lignite fly ash from Thailand Mae Moh power station, sodium silicate (NS) with 15.32% Na2O and 32.87% SiO2, 15 M sodium hydroxide (NaOH), sand, and foaming agent. A natural protein based foaming agent was used to create foam with density range between 40 and 45 kg/m^3. The compatibility of foaming agent and cement particle is critical to effectively entrain air and a protein foaming agent is thus often preferred [24, 25]. To achieve the required foam, a foaming agent and water at ratio of 1:40 and pressure of 5 bar were used. The physical properties of materials are shown in Table 1.

The fly ash consisted of 36.09% SiO_2, 15.48% Al_2O_3, 14.21% Fe_2O_3, and 22.51% CaO with 0.88% loss on ignition (LOI) as shown in Table 2. Its specific gravity was 2.66 and median particle size was 18.6 µm. The fly ash could be classified as a class C following ASTM C618-19 [26]. Its X-ray diffraction (XRD) pattern is shown in Figure 1. The XRD was performed using Bruker model D8 Advance with ICDD (International Centre for Diffraction Data) database. Figure 2 shows its scanning electron microscope (SEM) image. The shape of fly ash was spherical with smooth surface.

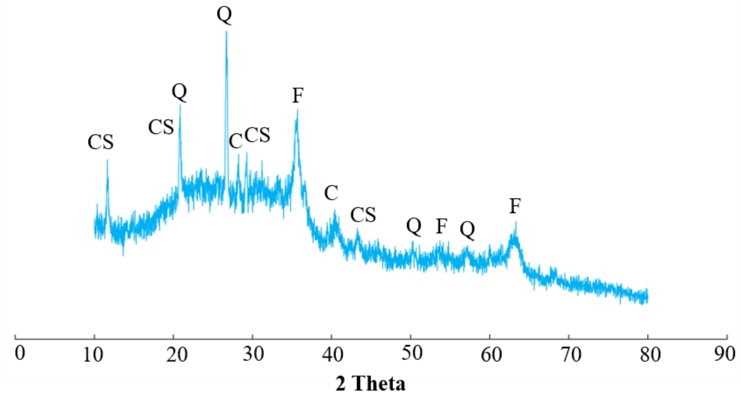

Figure 1 XRD of fly ash F-Maghemite: Fe_2O_3; C-Anhydrite: $CaSO_4$; CS-Gypsum: $CaSO_4.H_2O$; Q-Quartz: SiO_2

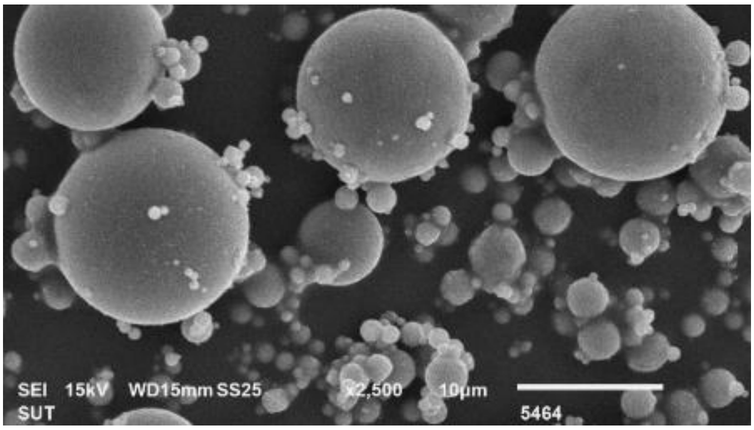

Figure 2 SEM of fly ash

Table 1 The properties of materials

Materials	Fly ash	Sand
Specific gravity	2.66	2.61
Median particle size (μm)	18.6	-
Particle size (mm)	-	0.002-4.75
Fineness modulus	-	2.12
Unit weight (kg/m^3)	-	1680
Water absorption (%)	-	0.48

Table 2 Chemical composition of fly ash

Chemical compositions	Weight (%)
SiO_2	36.09
Al_2O_3	15.48
Fe_2O_3	14.21
CaO	22.51
K_2O	1.62
Na_2O	0.33
SO_3	8.88
LOI	0.88

2.2 Mix proportion

2.2.1 Foam content

The foam agent contents of 2, 4, 6, 8, 10 and 12 % by weight were used to study the properties of CLGCs. The compressive strength, unit weight, water absorption, porosity, thermal conductivity and sound absorption were investigated.

2.2.2 Details of mixing

All mixtures were prepared with 15M NaOH, NS/NaOH ratio of 1.00, sand/ash ratio of 1.25, liquid/fly ash ratio of 0.4. The NS/NaOH ratio of 1.00 was selected as it was reported to give a satisfactory compressive strength for high calcium fly ash geopolymer concrete [13]. The trial mix using low NaOH concentration gave a low strength development and mix with 15M NaOH resulted in satisfactory strength development. Also based on the trial mixes, the sand/ash ratio of 1.25 and liquid to fly ash ratio of 0.4 gave a coherent mixture and satisfactory strength development and they were thus selected. For the mixing, fly ash and NaOH were mixed for 5 min to obtain a uniform color blend. Sand was added and mixed for another 5 min. This was followed by the addition of NS and mixed for 5 min. In the final step, foam was added and mixed for 2 min.

The fresh CLGCs was placed in the molds. The 75x50 mm cylinders were used for the testing of sound absorption. The 100x100x100 mm cubes were for the water absorption, porosity and thermal conductivity determinations. The 50x50x50 mm cubes were for the compressive strength and unit weight. After mixing, the samples were wrapped with plastic sheet and placed in a 25 °C room for 1 hour [13]. The moderate temperatures were used to accelerate the early strength gain. The specimens were put in an oven for curing at 40 °C for one day and 60 °C for two days. The specimens were demolded, wrapped with plastic sheet to prevent moisture loss, and stored in a 25 °C room. From the preliminary test, it was found that the initial curing of 40 °C for one day followed by curing at 60 °C for 2 days produced concrete with volume stability and higher strength than using the high 60 °C from the start of temperature curing.

2.3 Details of test

2.3.1 Compressive strength and unit weight

At the age of 28 days, the 50x50x50 mm specimens were used to determine the unit weight in accordance with ASTM C138/C138M-17a [27] and compressive strength complying to ASTM C109/C109M-20b [28]. The reported compressive strength and unit weight were the average of 3 samples.

2.3.2 Water absorption and porosity

At the age of 28 days, the water absorption and porosity were determined as per ASTM C642-13 [29] and calculated using Eqs. (1) and (2). The reported results were the average of 3 samples.

$$\text{Absorption}(\%) = \left[\frac{\text{B}-\text{A}}{\text{A}}\right] * 100 \tag{1}$$

$$\text{Porosity}(\%) = \left[\frac{\text{C}-\text{A}}{\text{C}-\text{D}}\right] * 100 \tag{2}$$

where; A = mass of oven dry sample in air (g),
B = mass of SSD sample in air after immersion (g),
C = mass of SSD sample in air after immersion and boiling (g), and
D = apparent mass of sample in water after immersion and boiling (g) and SSD stands for saturated surface dry

2.3.3 Thermal conductivity

At the age of 28 days, the thermal conductivity of CLGC was determined using ISOMET 2114 (a portable heat transfer analyzer) based on ASTM D 5930-17 [30]. Similar device was successfully used for testing of cementitious materials [31-34]. The 100x100x100 mm specimens were oven-dried and used for the test. The results were the average of 3 samples.

2.3.4 Sound absorption

At the age of 28 days, the sound absorption of CLGC was measured using an impedance tube testing system (No: BSWA-III-C021-03-0027-IMP) as shown in Figure 3. The sound absorption coefficient was measured using the 75x50 mm cylinder specimen at frequency between 400 and 2,500 Hz. It had been shown that this device was successfully in porous concrete [35, 36]. The testing was done complying to ASTM E1050-19 [37]. The results were the average of 3 samples.

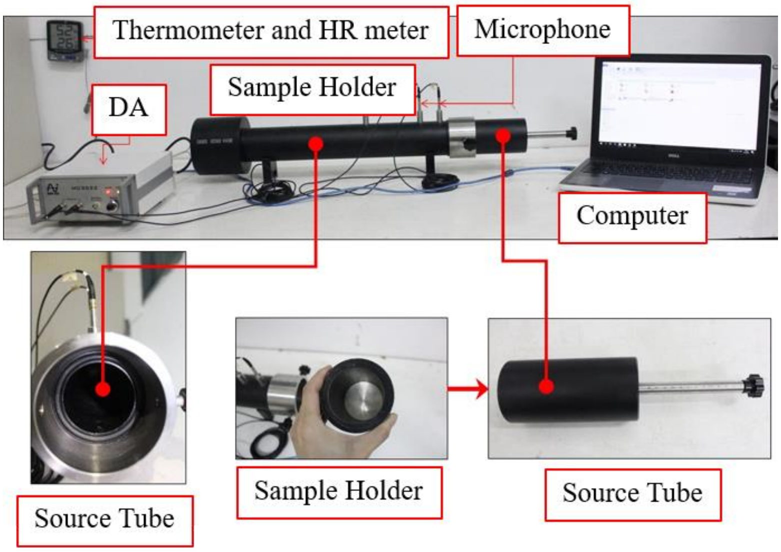

Figure 3 Impedance tube for measured the sound absorption coefficient

3. Results and discussions

3.1 Compressive strength, unit weight, water absorption and porosity of CLGC

The results of compressive strength and unit weight of CLGCs are presented in Figure 4. The overall compressive strength and unit weight ranged from 2.7 to 57.8 MPa and 844 to 2080 kg/m3, respectively. The compressive strengths of mixes with increasing 0, 2, 4, 6, 8, 10 and 12 % foam agent contents were 57.8, 56.8, 38.9, 9.2, 7.6, 6.1 and 2.7 MPa, respectively. At low foam content of 2%, the increase in porosity was small and this thus resulted in only a small reduction in compressive strength to 56.8 MPa. At 4% foam content, the increase in porosity of was still small and this resulted in additional reduction in strength to 38.9 MPa. However, the higher foam content of 6 % resulted in a drastic reduction in strength. The high foam content caused clustering of bubbles and resulted in irregular pores and a significant decrease of compressive strength [38, 39]. The compressive strength values of CLGCs were comparable to the previous reported results [40-42]. The strength of CLGC decreased with the increasing porosity or foaming agent content similarly to the cellular OPC concrete [43, 44].

As the fly ash used in this experiment contained high SO_3 content, the strength of geopolymer concrete could be adversely affected due to the formation of gypsum. However, Phoo-ngernkham et al., (2014) [45] use high calcium fly ash with SO_3 content of 7.29% and obtained satisfactory compressive strength with no problem of swelling. In this experiment, the SO_3 content of fly ash was slightly higher at 8.88 % and no problem of swelling was observed.

The high calcium fly ash was also used to make pervious geopolymer concrete. The strengths of high calcium fly ash pervious concrete with NS/NaOH of 0.5 were 5.4-11.4 MPa for concretes with void volume of 28.8-34.4 % and density of 1680-1820 kg/m^3 [46]. The density of pervious concrete was higher than that of CLGC as it contained coarse aggregate. As discussed earlier, the NS/NaOH ratio of 1.0 is optimum for strength development of high calcium fly ash geopolymer [13] and the use of lower NS/NaOH ratio would result in the reduction in Si/Al ratio and strength.

For the unit weight, the trend of result was similar to that of compressive strength. The unit weight of CLGC decreased with the increase in foam due to the low density of foam (40-45 kg/m^3). The unit weights of CLGCs with foam contents of 0, 2, 4, 6, 8, 10 and 12 % were 2080, 1995, 1815, 1520, 1210, 1060 and 845 kg/m^3, respectively. For structural use, the optimal proportion of foam agent was observed at 4 % with high compressive strength of 38.9 MPa and unit weight of 1815 kg/m^3. This mix is suitable for the manufacturing of structural lightweight concrete. The recommended minimum unit weight for structural lightweight concrete was 1850 kg/m^3 according to C330/C330M-17a [5]. The sample incorporated high foam content showed reasonable range of compressive strengths. With 8 % and 10 % foam agents, the compressive strengths of 7.6 and 6.1 MPa and densities of 1210, and 1060 kg/m^3, respectively were obtained. They are suitable for the masonry lightweight concrete block satisfying the required unit weights of 800-1440 kg/m^3 and compressive strengths of 3.4-17.0 MPa as per ASTM C331-17 [47].

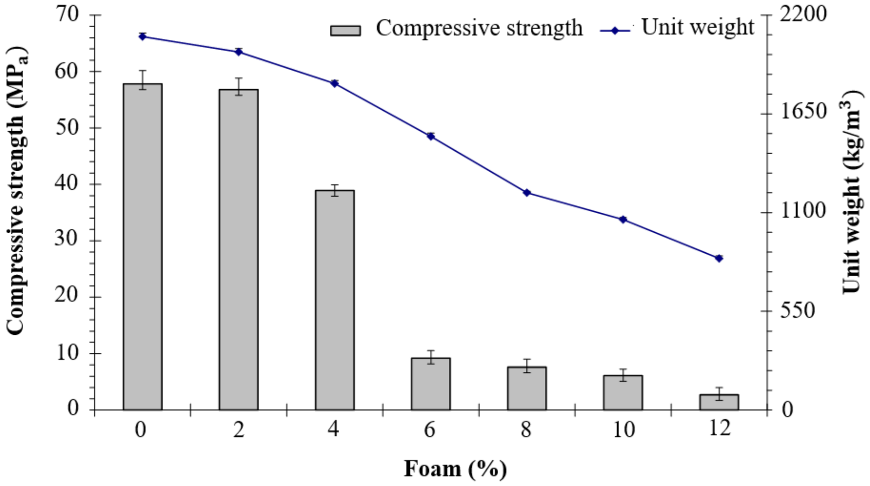

Figure 4 Compressive strength and unit weight of CLGC at 28 days

The water absorption and porosity of CLGCs as shown in Figures 5 and 6 increased with the increasing foam content. The water absorptions at 28 days of CLGCs with foam contents of 0, 2, 4, 6, 8, 10 and 12 % by mass were 1.36, 2.30, 4.50, 6.50, 22.22, 28.20 and 31.25 %, respectively. The corresponding porosity at the age of 28 days were 2.82, 4.42, 7.15, 8.59, 24.05, 30.6 and 49.42 %, respectively. Normally, high water absorption and high porosity of lightweight concrete were observed due to the increased void in cement paste or aggregate [48, 49]. The water absorption and porosity increased with the increase in foam agent due to increased pores and micropores of CLGC as shown in Figure 7. Similar observations were also reported in previous work [50].

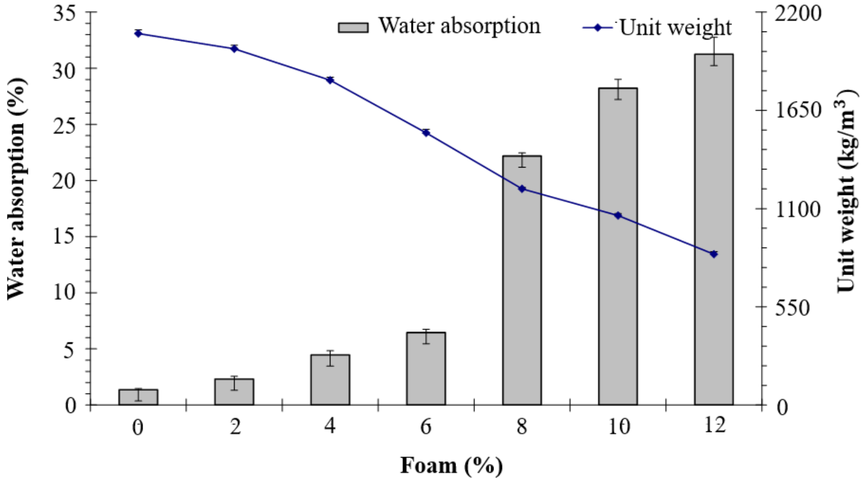

Figure 5 Water absorption of CLGC at 28 days

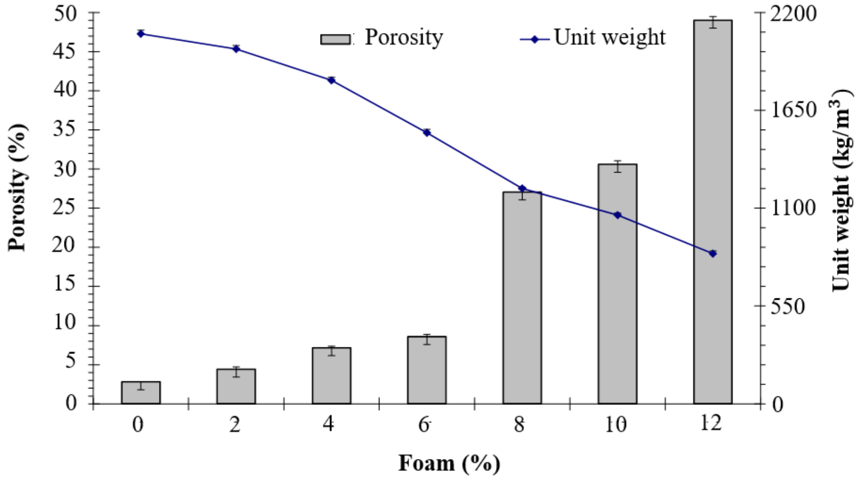

Figure 6 Porosity of CLGC at 28 days

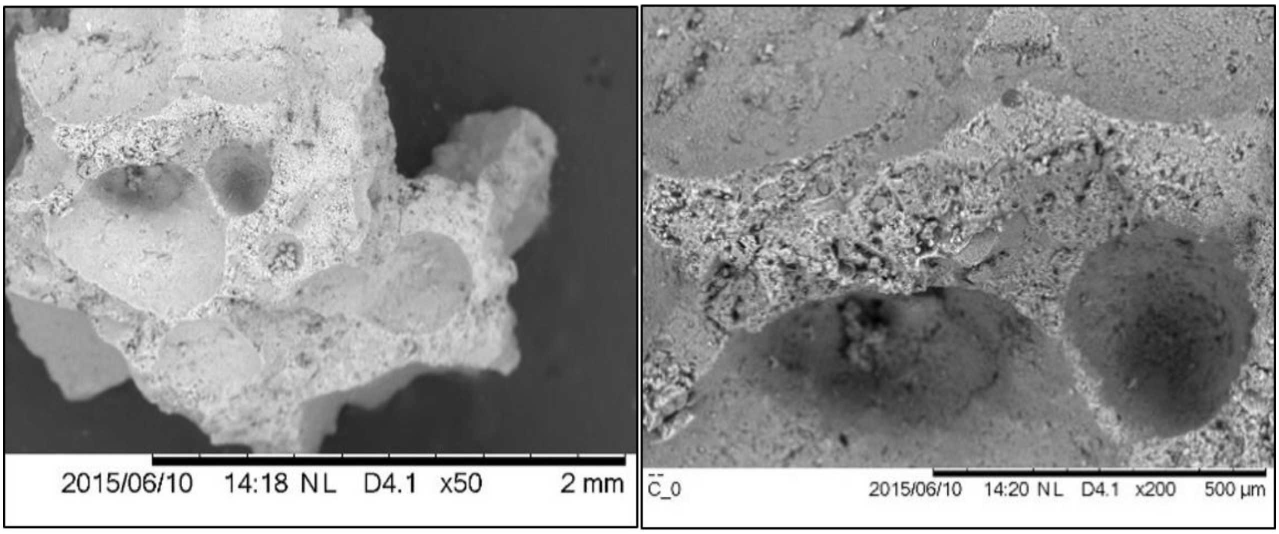

Figure 7 Pores and microspores of 0% foam content of CLGC

3.2 Thermal conductivity

The result of thermal conductivity of CLGCs at dry condition was related to the amount of foam as shown in Figure 8. The thermal conductivity capacity improved with the increase in foam content. This result implied that the CLGC has a greater thermal insulation. The incorporation of foam content from 0 to 12 % into lightweight geopolymer concrete decreased the thermal conductivity capacity from 1.62 W/mK to 0.13 W/mK. The mixes with 8 and 10 % foam showed the thermal conductivity values of 0.50 and 0.36 W/mk. These values were significantly lower than the reported result for normal concrete (1.23 W/mK) [51], and were comparable to the concrete containing lightweight aggregate made from ethyl vinyl acetate waste (0.407-0.489 W/mK with unit weight of 1000-1200 kg/m^3) [49]. The thermal conductivity values of CLGC were reduced with the increase in foam content similar to that of OPC cellular concrete. The obtained thermal conductivity of 0.26-0.35 W/mK for 1000-1200 kg/m^3 density CLGCs were comparable to the reported values of 0.23 and 0.42 W/mK for OPC concrete of the same density [52].

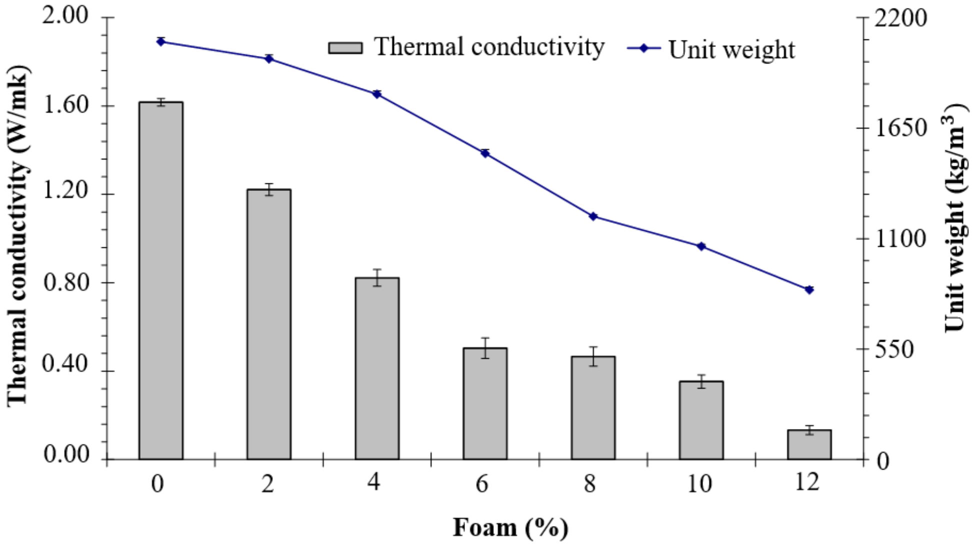

Figure 8 Thermal conductivity of CLGC at 28 days

The relationship between thermal conductivity and unit weight of CLGC is illustrated in Figure 9 and can be expressed in equation (3) with R2 = 0.9206. The thermal conductivity was related to the unit weight of concrete [53-55]. Therefore, the CLGC has a high potential for use as an insulating material that can help save energy of buildings.

$$k = 0.0459e0.0017W \quad (3)$$

where; k is the thermal conductivity in W/mK; and
W is the unit weight of concrete in kg/m^3

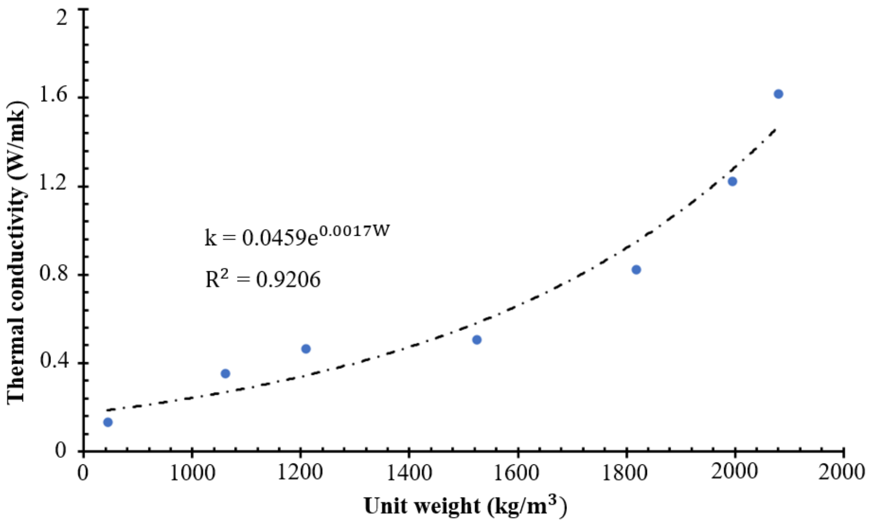

Figure 9 Relationship of thermal conductivity and unit weight

3.3 Sound absorption

Sound absorption is dependent on the sound wavelength and requires a medium such as air, solid, and liquid to move through. Normally, human ears can hear frequencies from 20 - 20,000 Hz. The frequencies above 20,000 Hz are called ultrasound and the frequencies lower than 20 Hz is known as infrasound [37]. There are different properties of sound such as high-low tones, loud-soft sounds, and other qualities of sound depending on the source and the frequency of vibration. These specific properties of sound are frequency, wavelength, and amplitude. Sound absorption takes place when sound waves travel though a medium and sound energy is changed and reduced. Good sound absorber are generally porous materials. The absorption of sound by porous materials is primarily obtained through loss of momentum through the narrow constrictions within the porous materials an index used to indicate the efficiency of each sound absorption material is sound absorption coefficient (α) which can be assessed using transfer function in accordance with ASTM E1050-19 [37].

The main objective of the analytical studies was to calculate the sound absorption coefficient of cellular lightweight geopolymer concrete. The coefficient was measured using an impedance tube and the results are shown in Figure 10. Generally, higher sound absorption coefficients were obtained when the amount of foam agent increased. The results showed that the coefficient increased with the increasing foam content. However, at low at foam contents of 0-4% and unit weight of 1820-2100 kg/m^3, the coefficients were small at 0.04 to 0.12. The increase in sound absorption coefficient was significant when the foam content was 6 %. At foam contents of 6-12%, the coefficients were around 0.09-0.52 with the unit weights of 844-1525 kg/m^3. This corresponded to a significant increase in the porosity of samples at high foam contents as shown in Figure 6. The capability of sound absorption increased when the specific area of voids increased, or unit weight decreased [35]. The sound absorption of CLGCs increased with the increase of foam content due to the increased size and discretion of bubbles [3, 56]. The coefficient increased approximately ten folds from 0.05 to 0.5 when the foam contents increased from 0 to 12%. Similar finding was reported by Zhang et al., [57] on sound absorption coefficients of fly ash-slag geopolymer cellular concrete and OPC cellular concrete that the sound absorption coefficient increased with the increasing foam content.

The results thus indicated that the use of foaming agent was effective in distributing the bubbles and promoting the uniform porosity resulting in enhanced acoustic absorption characteristics.

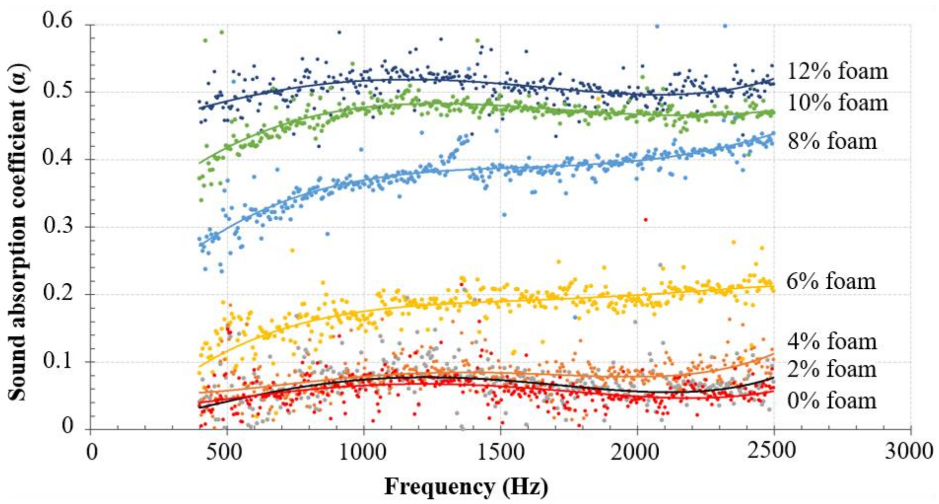

Figure 10 Sound absorption coefficient of CLGC at the age of 28 days

The effects of frequency on sound absorption coefficient of cellular lightweight geopolymer concrete could also be seen as shown in Figure 10. In general, the coefficient at 400 Hz. was lowest and increased with the increase in the frequency up to around 1250 Hz. After this the coefficient remained approximately the same with the exception of the mixes with 6 and 8% foam where the coefficient increased with the increasing frequency. The sound absorption coefficient is related to the volume of pores [35, 58]. As discussed earlier, the reduction in strength started to be significant at the foam contents of 6 and 8% due to the clustering of bubbles and irregular pores. The significant increase in pore volume also increased the sound absorption coefficient significantly. The obtained result was in good agreement with the previously reported results of sound absorption of porous concrete [35, 58, 59].

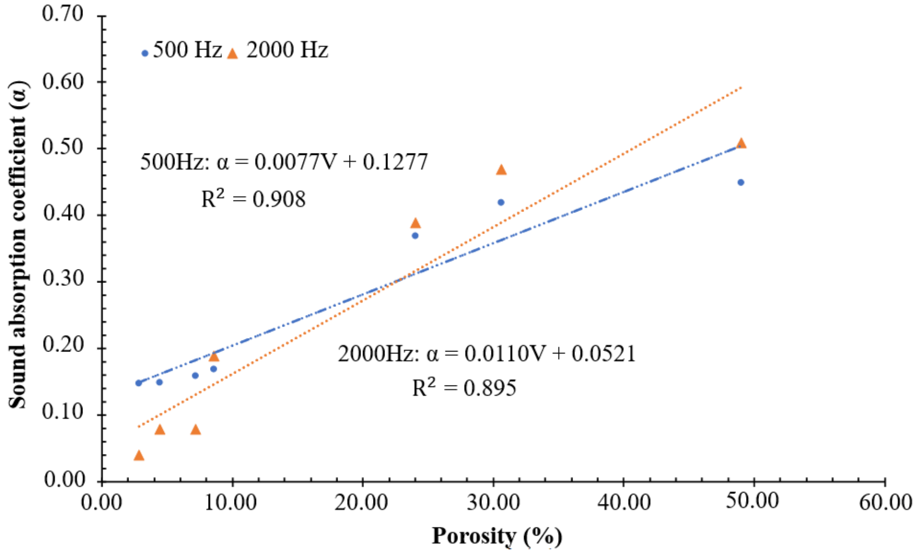

Figure 11 Relationship between porosity and sound absorption coefficient of CLGC at 28 days

The relationships between the porosity and sound absorption coefficient are shown in Figure 11. Equations (4) and (5) were formulated to fit the sound absorption coefficient at 500 Hz and 2000 Hz, respectively. The R2 values were reasonably high at 0.908 for equation (4) and 0.895 for equation (5). The sound absorption coefficient increased with the increase in porosity confirming that the sound absorption coefficient depends on the porosity of concrete [60].

$$500\text{Hz}: \alpha = 0.0077V + 0.1277 \tag{4}$$

$$2000\text{Hz}: \alpha = 0.0110V + 0.0521 \tag{5}$$

where; α is the sound absorption coefficient; and
V is the porosity of concrete in %

The good sound absorption characteristic of CLGC concrete thus offers the possibility for its use where acoustic performance is required.

3.4 Cost comparison

The cost of geopolymer concrete is higher than the cost of the OPC concrete with similar strength [61] due to primarily the high cost of alkali and silicate solutions. From the material prices of the Comptroller General's Department, Ministry of Finance, Thailand (2020), the materials viz., fly ash, sand, sodium silicate, NaOH and foam for 1 m3 CLGC (8% foam, unit weight of 1200 kg/m^3) cost 512, 160, 3243, 922, 1 and 452 Baht, respectively totaling 5289 Baht (176 USD, 1 USD=30 Baht). While the materials viz., cement, sand, water, and foam for 1 m3 OPC cellular concrete cost 1031, 160, 2 and 452 Baht, respectively totaling 1645 Baht (55 USD). It should be noted here that the cost of CLGC was higher due partly to the fact that it was at the laboratory scale and the OPC cellular concrete is at a commercial level.

4. Conclusions

The effects of foam content on mechanical and thermal properties, and sound absorption of cellular lightweight high calcium fly ash geopolymer concrete (CLGC) were studied. Based on the obtained data, the following conclusions can be drawn.

Foamed concrete with compressive strength of 32 to 50 MPa can be produced with geopolymer concrete made with Mae Moe Fly ash. Lower strength foamed geopolymer concrete can also be made readily. This lightweight concrete is applicable for use as wall panel with required thermal and acoustic properties or as a lightweight structural member.

1) The properties of CLGC were affected by the foam content in the mixture. The unit weight and compressive strength decreased with the increasing foam content, and the water absorption and porosity increased as expected.

2) The thermal conductivity of CLGC decreased with increasing foam content. The relationship between thermal conductivity with unit weight could be formulated with equation k = 0.0459e0.0017W.

3) The sound absorption coefficients of CLGC increased with the increasing foam content. The samples with foam content of 8 and 10 % by weight showed the sound absorption coefficients of 0.28-0.48 between the frequencies of 400 and 2500 Hz. These values confirmed the suitability of cellular lightweight high calcium fly ash geopolymer concrete for use as a sound absorbing material in accordance with ASTM E1050-19.

4) The CLGC with 4 % foam content is suitable for structural lightweight concrete with unit weight of 1815 kg/m^3 and relatively high compressive strength of 38.9 MPa satisfying the requirements of ASTM C330/C330M-17a. The samples with foam contents of 8 % and 10% were suitable for the production of masonry lightweight geopolymer concrete block with density and strength complied with the requirements of ASTM C331-17.

5. Acknowledgement

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