Microwave-assisted Curing of Cellular Lightweight Concrete: A Preliminary Study

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Abstract

Cellular lightweight concrete (CLC) incorporating fly ash (FA) can be cured in only a few hours by using microwave energy and elevated curing temperatures (<100 ^{O}C). The concrete is strengthened by heating through a chemical reaction at a relatively low temperature. In Thailand, high-silica PFA materials can be obtained as industrial waste from electrical power plants. The CLC ingredients are mixed with an appropriate amount of water to obtain the desired consistency. The mixture is compacted in a mold and cured by 2.45 GHz of microwave energy. CLCs produced by this method are strong and relatively inexpensive to make. Thus, this technology could be useful for developing nations.

1. Introduction

The density of concrete may be reduced by introducing stable voids within the hardened cement paste and mortar. In particular, cellular lightweight concrete (CLC) is produced by adding foam containing air bubbles to a concrete mix and trapping the air bubbles within the concrete [1,2].

Air content (>25%) is introduced into a mortar or concrete mix by two principal methods: (1) a preformed foam may be mixed with other constituents in a normal mixer or ready-mixed concrete truck; or (2) a synthetic- or protein-based foam-producing admixture may be mixed with other mix constituents in a high-shear mixer. In both methods, the foam must be stable during mixing, transporting, and placing. The resulting bubbles in the hardened concrete should be discrete, with a size between 0.1 and 1 mm [3]. By controlling the foam dosage, a wide range of densities (400-1600 kg/m^3) of CLC can be obtained for application to structural, partition, insulation, and filling concretes [4].

CLC offers many advantages, such as a high flowability, minimal aggregate consumption, and controlled low strength, for modern construction applications. The low self-weight of CLC allows the supporting structures, including the foundation and walls of lower floors, to be designed at lower cost. Owing to its porous structure, CLC provides a high degree of thermal insulation, leading to considerable material savings [5].

The use of strengthened concrete can minimize construction costs, time, and environmental impacts. High strength may be achieved through the rapid thermal curing of concrete early in the development process. Microwave heating, as one of the most popular approaches for heating dielectric materials, is an established technique with a wide range of industrial applications. A single application of microwave heating will allow the rapid thermal curing of concrete. Moreover, microwave heating has been shown to improve the rate of strength development in concrete compared to conventional thermal curing [6-8].

In this study, we studied the early compressive strength (CS) of microwave-cured CLC mixtures that contained mineral admixtures of fly ash (FA) or limestone (LS) powder. Several power levels and irradiation times were tested.

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2. Experimental

2.1 Materials

Ordinary Type I Portland cement (OPC) complying with ASTM C150 [9] was used in the experiments. Coal–biomass ash (CBA) was obtained from a thermal power plant in Prachinburi province, Thailand, which uses coal and biomass as its main fuels. LS was obtained from an industrial rock-crushing plant located in Saraburi Province. Potable water was used to manufacture the CLC mixtures. The fine aggregate was river sand (nominal max. size = 4.75 mm), which conformed to the requirements of ASTM C33 [10].

Hydrolyzed protein foam was used as the foaming agent. Containments holding the foaming agent were kept airtight and at or below 25 °C. The emulsion was used soon after dilution in 50 parts of potable water.

2.2 Mix proportions

All of the CLC mixtures were designed such that the total cementitious material was replaced with FA or LS powder at 20% by weight. A cement : sand ratio of 1: 1 and a water : powder ratio of 1: 2 were used for all CLC mixtures. Details of the concrete mixes are presented in Table 1.

Table 1 Details of CLC mixtures.

CLC type	Materials [%weight]				w/p
	OPC	CBA	LS	FA	ratio
OPC100	100	-	-	100	0.5
CBA20	80	20	-	100	0.5
LS20	80	-	20	100	0.5

Remark: CLC, cellular lightweight concrete; OPC, ordinary Portland cement; CBA, coal biomass ash; LS, limestone powder; FA, fine aggregate.

2.3 Mix procedures

Dry ingredients (CBA/LS powder and cement) were fed into the mixer and thoroughly mixed to ensure the even distribution of cement. An appropriate amount of water was added, and mixing was continued. The foam was made beforehand by blending the foam concentrate, water, and compressed air in predetermined proportions in the foam generator, which was calibrated for a specific discharge rate. This foam was added in a measured amount to the slurry of cement, FA, and water in the mixer. The mixture was thoroughly churned or beaten to obtain a foam effect in the concrete. The densities of the CLC mixtures were designed to range from 800 to 1200 kg/m^3.

2.4 Testing procedures

The samples were mixed and cast in cylindrical polyethylene containers of 75 mm (diameter) x 150 mm (height). Figure 1 shows the microwave heating apparatus used in this study. Temperatures were measured by using a shielded type-K thermocouple inserted directly into the sample. The thermocouple output was directed to a controller that regulated the heating power. A domestic microwave oven, with internal dimensions of 310 mm (width) x 190 mm (height) x 280 mm (depth), was used for microwave treatments.

Figure 1 Microwave heating test apparatus.

The heated specimens were kept until early CS testing was performed at 3, 7, and 28 d, in accordance with ASTM C39 [11]. The microwave processing parameters are listed in Table 2.

Table 2 Microwave processing parameters

Processing parameter	Determined value
Application time after mixing	Immediately
Microwave power and duration	100 W for 5, 10, 15 min
	300 W for 5 min
	450 W for 5 min
Compressive strength test	3, 7 and 28 d

3. Results and discussion

3.1 Chemical compositions and physical properties

The chemical compositions and physical properties of OPC, CBA, and LS were analyzed (Table 3). CaO was the predominant chemical component of the materials, with contents of 68.48% and 46.77% in OPC and LS, respectively. SiO_2 was the second-most common component, with a content of 47.39% in CBA. The percentages for loss on ignition were 1.70%, 8.63%, and 39.54% for OPC, CBA and LS respectively.

Table 3 Chemical compositions and physical properties of OPC, BA and LS.

Element	OPC	CBA	LS
Chemical composition (% by mass)			
SiO_2	16.37	47.39	8.97
Al_2O_3	3.85	20.51	1.02
Fe_2O_3	3.48	6.71	0.37
MgO	0.64	1.35	2.38
CaO	68.48	9.05	46.77
Na_2O	0.06	0.63	0.02
K_2O	0.52	1.50	0.13
SO_3	4.00	-	0.33
Physical properties			
Loss on ignition (% by mass)	1.70	8.63	39.54
Particle size distribution (μm)	23.32	30.62	15.63
Specific gravity	3.2	2.39	2.76
Specific surface area (cm^2/g)	610	811	1300

The particle size distributions (PSDs) of OPC, CBA, and LS were determined by laser granulometry (Figure 2), and the morphologies were examined by scanning electron microscopy (SEM) at approximately 1000x magnification (Figure 3a-c).

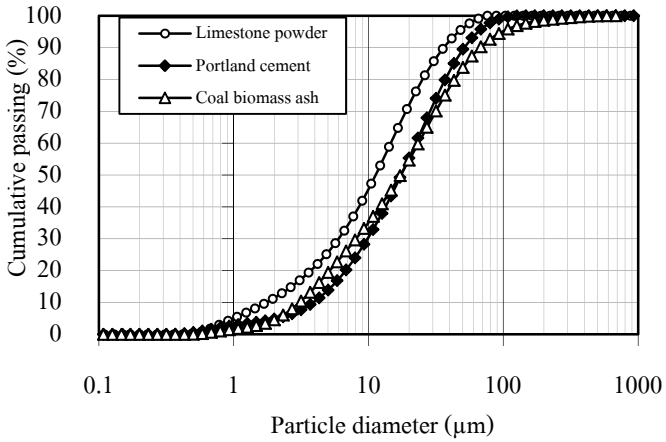
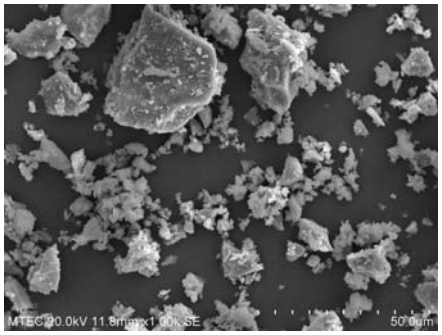
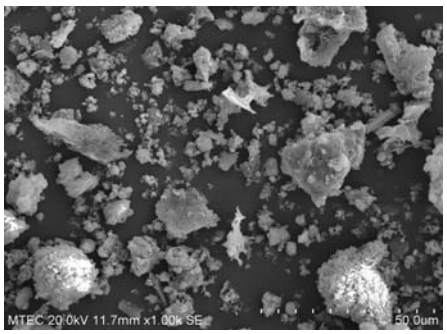


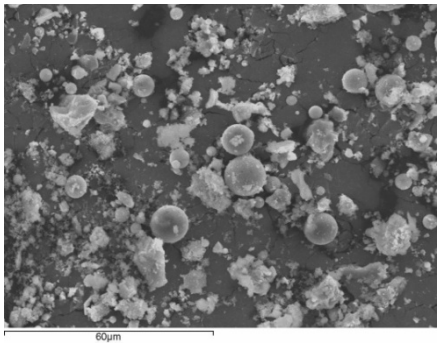
Figure 2 PSD of OPC, CBA, and LS



(a) OPC



(b) CBA



(c) LS

Figure 3 SEM (1000x) of OPC (top), CBA (middle), and LS (bottom).

3.2. Temperature rise

We tested the temperature profiles for normally cured (control) CLC mixtures over a 3-d period (Table 4). The control CLC mixtures included 100% OPC (OPC100) and mixtures in which cementitious material was replaced with 20 wt% CBA (CBA20) or LS (LS20).

The CBA20 mixture showed the lowest temperature among the control mixtures, due to its lower cement content and the pozzolanic behaviour of the ash, which reduced the heat of hydration [12]. In contrast, the LS20 mixture displayed the highest temperature among the control mixtures because LS supplied ions into the phase solution, thereby modifying the hydration kinetics and the morphology of the hydration product [13].

Table 4 Temperature rise in normal cured CLC samples.

CLC Type	T_{Max} (°C)	Time to T_{Max} (h)
OPC100	43.5	10
CBA20	38.3	12
LS20	45.3	8

Table 5 presents the temperature profiles for each microwave power setting and irradiation time during the microwave heating of the CLC mixtures.

The increase in temperature due to heat liberation varied with the application time and power level. The temperature range was 30.0 to 43.9 °C at 100 W, 48.5 to 52.9 °C at 300 W, and 60.8 to 70.3 °C at 450 W. The highest temperature occurred in all mixtures at 450 W after 5 min of microwave heating. The degree of heating was somewhat dependent on the composition and particle size of the mixtures.

Table 5 Temperature rise of CLC samples during microwave heating.

CLC Type	T (°C)	T_{Max} (°C)	Time to T_{Max} (min)
OPC100			
100 W, 5 min	30.3	48.3	18
100 W, 10 min	38.0	48.3	18
100 W, 15 min	43.9	48.3	18
300 W, 5 min	48.5	59.8	7
450 W, 5 min	62.3	70.8	6
CBA20			
100 W, 5 min	30.6	43.1	18
100 W, 10 min	36.5	43.1	18
100 W, 15 min	42.3	43.1	18
300 W, 5 min	52.9	55.4	7
450 W, 5 min	70.3	79.4	6
LS20			
100 W, 5 min	30.0	39.5	16
100 W, 10 min	34.2	39.5	16
100 W, 15 min	38.6	39.5	16
300 W, 5 min	50.8	49.2	6
450 W, 5 min	60.8	69.4	6

3.3 Compressive strength

The apparatus used to measure the CS is illustrated in Figure 4. Table 6 shows the typical CS properties of CLC indicating of the compacted density of CLC for use in quality control.

Figure 4 CS test apparatus.

Table 6 Typical CS properties of CLC [14].

Dry density [kg/m^3]	Compressive strength [MPa]
400	0.5–1.0
600	1.0–1.5
800	1.5–2.0
1000*	2.5–3.0*
1200	4.5–5.5
1400	6.0–8.0
1600	7.5–10.0

According to the British Cement Association [15], CLC mixtures with densities between 400 and 1600 kg/m^3 should display CS values of approximately 1 to 10 MPa. As shown in Table 6, the control CLC mixtures were designed with densities ranging from 800 to 1200 kg/m^3 and produced average strengths in the range of 2.5 to 3.0 MPa at 28 days (for an average density of 1000 kg/m^3). Thus, the minimum strength of our samples should be more than 2.5 MPa, consistent with the recommended CS range. Although numerous factors can affect the CS of the CLC, the density of the freshly placed CLC should give a reliable indication of the expected strength.

The CS values of the CLC mixtures microwave-irradiated at various power levels and exposure times were determined, as shown in Table 7.

Table 7 Compressive strength (MPa) test results.

CLC Type	3 d	7 d	28 d	Criteria
OPC100				
100 W, 5 min	2.31	2.68	3.23	>2.5
100 W, 10 min	2.52	2.91	3.55	>2.5
100 W, 15 min	2.53	2.91	3.58	>2.5
300 W, 5 min	2.24	2.58	3.18	>2.5
450 W, 5 min	2.20	2.55	3.14	>2.5
CBA20				
100 W, 5 min	1.88	2.19	2.82	>2.5
100 W, 10 min	2.99	3.38	3.86	>2.5
100 W, 15 min	2.02	2.33	3.03	>2.5
300 W, 5 min	2.00	2.32	3.00	>2.5
450 W, 5 min	1.89	2.22	2.85	>2.5
LS20				
100 W, 5 min	0.24	0.28	0.36	<2.5
100 W, 10 min	0.23	0.27	0.35	<2.5
100 W, 15 min	0.23	0.26	0.34	<2.5
300 W, 5 min	0.17	0.21	0.26	<2.5
450 W, 5 min	0.17	0.21	0.26	<2.5
Control (Normal curing)				
OPC100	4.55	5.01	5.88	>2.5
CBA20	2.67	2.94	3.84	>2.5
LS20	2.32	2.58	3.25	>2.5

The CS results of the 100% OPC and 20% CBA CLC mixtures were higher than the required 2.5 MPa at all irradiations and power levels. However, the CS for the 20% LS CLC mixture was lower than the required 2.5 MPa.

For the 100% OPC CLC mixtures, treatment at 100 W for 15 min increased the 28-days strength by 43.2% when compared to the required criterion of CLC [14], but the CS decreased with increasing exposure to heating power at 300 and 450 W. Similarly, for the 20% CBA CLC mixtures, treatment at 100 W for 10 min increased the strength when compared to the required criterion [14] by 54.4%, but the CS decreased with increasing exposure to heating power at 300 and 450 W. The lowest CS results were observed for the 20% LS CLC mixtures, for which 5 min of irradiation at 300 and 450 W decreased the strength by 89.6% compared to the criterion [14].

4. Conclusions

Based on the results of this study, the following conclusions may be drawn:

1. The temperature and heating time were important parameters for microwave curing of cementitious CLC.

2. The LS20 mixture quickly reached its maximum temperature, whereas the CBA20 mixture took a longer time to reach a lower peak temperature.

3. The optimum heating condition for the OPC100, CBA20, and LS20 mixtures was 100 W for 15 min or less. Heating for more than 5 min at 300 or 450 W was unsuitable for microwave curing.

4. The CS of microwave-cured (100 W, 10 min) CBA20 mixtures at 3 d was increased by more than 12% compared to the CS of conventionally cured CLC at 3 d.

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