International Journal of Minerals, Metallurgy and Materials
Volume 20, Number 5, May 2013, Page 462
DOI: 10.1007/s12613-013-0752-1

Cellular lightweight concrete containing high-calcium fly ash and natural zeolite

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(Received: 12 July 2012; revised: 3 October 2012; accepted: 10 October 2012)

Abstract: Cellular lightweight concrete (CLC) with the controlled density of approximately 800 kg/m^3 was made from a preformed foam, Type-I Portland cement (OPC), fly ash (FA), or natural zeolite (NZ), and its compressive strength, setting time, water absorption, and microstructure of were tested. High-calcium FA and NZ with the median particle sizes of 14.52 and 7.72 μm, respectively, were used to partially replace OPC at 0, 10wt%, 20wt%, and 30wt% of the binder (OPC and pozzolan admixture). A water-to-binder mass ratio (W/B) of 0.5 was used for all mixes. The testing results indicated that CLC containing 10wt% NZ had the highest compressive strength. The replacement of OPC with NZ decreased the total porosity and air void size but increased the capillary porosity of the CLC. The incorporation of a suitable amount of NZ decreased the setting time, total porosity, and pore size of the paste compared with the findings with the same amount of FA. The total porosity and cumulative pore volume decreased, whereas the gel and capillary pores increased as a result of adding both pozzolans at all replacement levels. The water absorption increased as the capillary porosity increased; this effect depended on the volume of air entrained and the type or amount of pozzolan.

Keywords: lightweight concrete; fly ash; zeolites; compressive strength; microstructure; water absorption

1. Introduction

Lightweight concrete has been widely used in wall panels, masonry blocks, roof decks, and precast concrete units in many building applications. There are many advantageous qualities of lightweight concrete, such as its low density, low thermal conductivity, reduction of dead load, fast building rate, and low haulage cost [1]. The air voids needed to produce lightweight concrete can be obtained using expanded lightweight aggregate materials, such as perlite, blast furnace slag, volcanic ash, and coal bottom ash. The air voids can also be formed in cement paste by adding the prepared foam to the unhardened mixture. Cellular lightweight concrete (CLC) is a well-known low-density product that contains blends of Portland cement, silica, pozzolan, and lime as well as a homogeneous void or cellular structure attained with gas-forming chemicals or foaming agents. Autoclave curing is usually employed for CLC that contains binder ingredients other than, or in addition to, Portland cement [2]. Density control is achieved by substituting macroscopic air cells for all or part of the fine aggregate. Normal-weight coarse aggregates are not usually used, but lightweight aggregates, both fine and coarse, are often found in CLC [3]. After molding, the concrete hardens under normal atmospheric conditions [4].

Since CLC is a porous material with a homogeneous cellular structure, it possesses a number of attractive characteristics, such as good thermal and acoustic insulation, satisfactory workability, and self-flowing properties. Its good thermal and acoustic performance makes it a natural choice as a building construction material. Although

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its mechanical properties are low compared with those of normal concrete, CLC products are used in many applications, such as partition walls and load-bearing walls in low-rise residential buildings [5−6].

Fly ash (FA) is a by-product from the combustion of pulverized coal in power plants. More than 3.5 million tons of coal fly ash is produced in Thailand annually. Using FA as a replacement ingredient in cement is currently a common practice in Thailand because FA improves the properties of concrete and reduces its cost. The high content of amorphous silica, alumina (which comprises more than 70wt%), and fine spherical particles (15 μm in diameter on average) in FA are the primary reasons for its high pozzolanic index. Many researchers have already examined the influence of FA on the properties of concrete, such as compressive strength, sulfate resistance, and durability [7].

Natural zeolite (NZ), a volcanic or volcanogenic sediment material, has a three-dimensional structure, and it is classified as a hydrated aluminosilicate of alkali and alkaline earth cations with uniform pores, grooves, and pits. NZs possess special properties, such as ion exchange, molecular sieves, large surface areas, and catalytic activity, which make this material preferable for large-scale industrial applications[1]. Approximately 40 NZs have been identified over the last 200 years. The most common NZs are analcime, chabazite, clinoptilolite, mordenite, and phillipsite. Based on the recorded production and production estimates, the worldwide production of NZ is approximately 3-4 million tons per year[1].

The current research presents the test results and evaluations of incorporating FA and NZ into preformed foam CLC as a replacement for Portland cement. This information is essential for its wider application to other construction materials.

2. Experimental

2.1. Materials

Type-I Portland cement (OPC), foaming agent, water, FA, and NZ were the materials used. The specific gravities of OPC, FA, and NZ were measured in accordance with ASTM C 188-95(2003) [8], and their particle sizes were measured using laser particle size analysis. These data are provided in Table 1. A scanning electron microscopy (SEM) photo of an OPC particle is shown in Fig. 1(a). FA was obtained from a silo at the Mae Moh Power Plant in northern Thailand. Its SEM photo, which is shown in Fig. 1(b), reveals the spherical shape of the particles. NZ was a clinoptilolite ($(\text{Na,K,Ca})_6(\text{Si,Al})_{36}\text{O}_{72}\cdot 20\text{H}_2\text{O}$). An SEM photo of NZ, which is shown in Fig. 1(c), demonstrates its irregular and crushed-shape particles. Other researchers have also reported similar observations [9]. The chemical compositions of these three materials are listed in Table 2. The foaming agent was synthetic. Fig. 2 shows the particle size distributions obtained using the Malvern Mastersizer Instrument. The particle size of FA is similar to that of cement, whereas that of NZ is smaller.

Table 1. Physical properties of the material

Sample	Specific gravity	Median particle size, d_{50} / μm	Blaine fineness / ($\text{cm}^2\cdot\text{g}^{-1}$)
OPC	3.15	14.12	3600
FA	2.02	14.52	4300
NZ	2.09	7.72	11300

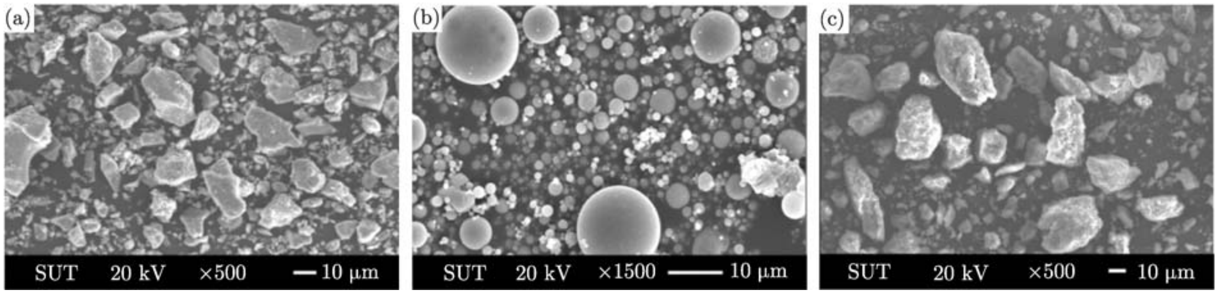

Fig. 1. SEM images of OPC (a), FA (b), and NZ (c).

Table 2. Chemical compositions of OPC, FA, and NZ wt%

Ingredient	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	LOI	$SiO_2 + Al_2O_3 + Fe_2O_3$
OPC	19.85	4.49	3.56	66.96	1.36	—	0.34	2.46	0.98	—
FA	43.87	26.33	10.81	12.69	1.23	—	1.10	2.74	1.23	81.01
NZ	75.32	10.28	2.66	3.95	1.20	0.89	4.29	—	1.41	88.26

Note: LOI—loss on ignition.

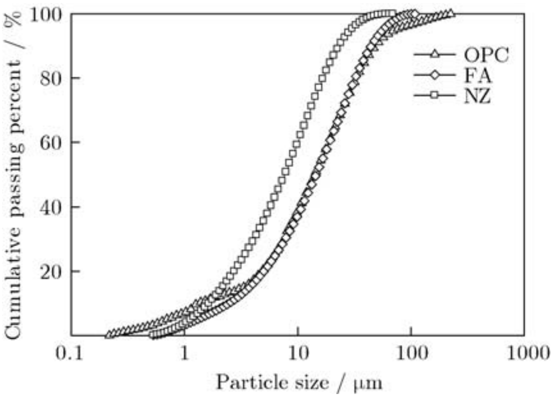

Fig. 2. Material particle size distribution.

2.2. Mix proportions

This experiment studied the effect of the filler contents on the density, setting time, water absorption, and compressive strength of CLC. The OPC was replaced with FA and NZ at levels of 0-30wt%. The mixes were labeled CON, FA10, FA20, FA30, NZ10, NZ20, and NZ30. For example, FA10 denotes the mix with 10wt% FA, and CON denotes the control mix (CLC with only OPC). The mass ratio of water to binder (W/B) of 0.5 was used for all mixtures. The foam required for a CLC density of 800-850 kg/m^3 was obtained per ASTM C 796-04[3]. The concrete mix proportions are provided in Table 3.

Table 3. Mix proportion of CLC

Mix No.	Symbol	Pozzolan replacement / wt%	Mix proportion / (kg·m^{-3})					W/B
			Binder			Foaming agent	Water	
			Cement	FA	NZ			
1	CON	0	665.0	—	—	0.772	332	0.5
2	FA10	10	598.5	66.5	—	0.759	332	0.5
3	FA20	20	532.0	133.0	—	0.746	332	0.5
4	FA30	30	465.5	199.5	—	0.733	332	0.5
5	NZ10	10	598.5	—	66.5	0.760	332	0.5
6	NZ20	20	532.0	—	133.0	0.748	332	0.5
7	NZ30	30	465.5	—	199.5	0.737	332	0.5

The foaming agent was diluted with water at a mass ratio of 1:40. Next, the liquid was pressurized with air at 6 kg/cm^2 and aerated to a density of 45 kg/m^3. OPC and FA (or NZ) were thoroughly mixed using a horizontal mixer. The foaming agent was added and mixed until a uniform paste was obtained. This process usually required approximately 3 min. The samples were poured into molds, and an external vibrator was applied to facilitate compaction. The CLCs were removed from the molds after 24 h, wrapped with a plastic film and placed in a moist room at (23±2)°C. A set of 100 mm×100 mm×100 mm specimens was used for the strength and porosity tests.

2.3. Compressive strength test

A compressive strength test was conducted at 3, 14, 28, and 60 d in accordance with BS 1881-116 [10]. The results are presented as the averages of three samples.

2.4. Concrete porosity determination

The pore-size measurements of the hardened CLC were determined using mercury intrusion porosimetry (MIP) with a pressure capacity of 228 MPa. The Washburn equation was used to determine pressure [11]. After curing for 3, 14, 28, and 60 d, the samples were obtained by carefully breaking the cube specimens with a chisel. The representative samples of 5 to 10-mm pieces, weighing between 2 and 3 g, were removed from the middle of each specimen. To stop the hydration reaction, the samples were submerged directly into liquid nitrogen for 5 min and vacuumed at a pressure of 0.5 Pa at –40°C for 48 h. This method has been previously used to stop the hydration reaction of cement paste [12-14]. A constant contact angle of 140° and a constant mercury surface tension of 480×10^{-3} J·m^{-2} were used to calculate the pore size.

2.5. X-ray diffraction (XRD)

Dried FA and NZ sample powders were sifted through a No. 100 sieve (150 μm openings). A sample of powder weighing approximately 1 g was used for XRD analysis. The XRD scans were performed for 2θ between 10° and 65° with an increment of 0.02°/step at a scan speed of 0.5 s/step. A quantitative XRD analysis determined the amorphous FA and NZ phases using Bruker's TOPAS software.

3. Results and discussion

3.1. Material properties

The chemical compositions of OPC, FA, and NZ are provided in Table 2. The main chemical component of FA is SiO_2, which accounts for 43.87wt% of its mass. As prescribed by ASTM C 618-03 [15], this sample is a Class F fly ash because the sum of SiO_2, Al_2O_3, and Fe_2O_3 is higher than 70wt%, and the LOI and SO_3 content do not exceed 6% and 5wt%, respectively. NZ has a high SiO_2 content of 75.32wt% and an LOI of 1.41%. The total content of SiO_2, Al_2O_3, and Fe_2O_3 in the NZ is 88.26wt%, which is more than the minimum requirement (70wt%) specified by

ASTM C 618-03 [15] for natural pozzolans.

The XRD patterns of FA and NZ shown in Fig. 3 indicate that the former powder consists primarily of crystalline phases of quartz; for NZ, the common zeolite mineral clinoptilolite is the major crystalline phase, and quartz is contained as a minor phase. Uzal and Turanlı [9] reported a similar result. A quantitative XRD analysis reveals that the contents of amorphous phases in FA and NZ are 78.8wt% and 20.5wt%, respectively. Moreover, the crystalline phase consists of 85wt% quartz and 15wt% mullite for FA and 22wt% quartz and 78wt% clinoptilolite for NZ.

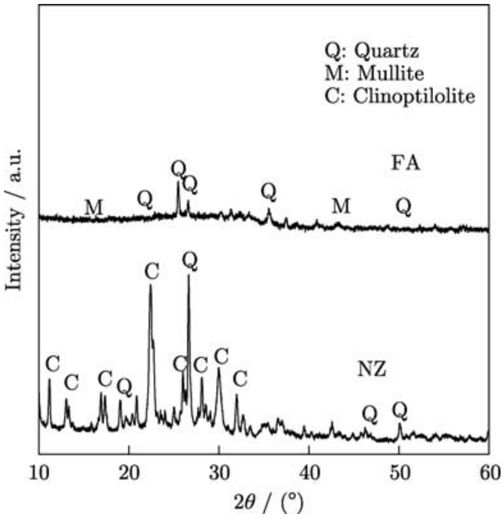

Fig. 3. XRD patterns of FA and NZ.

3.2. Setting time

The initial and final setting times of CLCs containing FA and NZ are presented in Fig. 4. It shows that the setting times prolong as the content of FA or NZ increases. The initial setting times of FA and NZ pastes increase from 5.2 to 14.45 h and from 5.2 to 12.15 h, respectively, whereas the final setting times increase from 13.1 to 23.5 h and from 13.1 to 19.95 h, respectively. The increase of pozzolan content reduces the cement content in the mix. As a result, a delay in the setting time of the cementitious system is due primary to a lower proportion of cement in the blended system. The setting times of the paste that contained NZ are slightly shorter than those of the paste contained FA because the former is a pozzolan with a Blaine fineness of 11300 cm^2/g, whereas the latter has a fineness of only 4300 cm^2/g. The fine pozzolan with a high surface area produces a greater pozzolanic reaction than the coarser pozzolan [16-17].

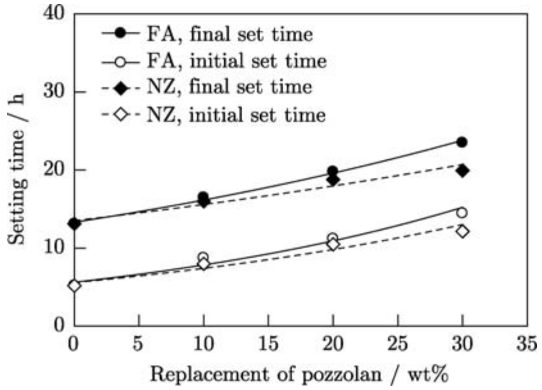

Fig. 4. Effect of FA and NZ on the setting time of CLC.

3.3. Compressive strength

Table 4 shows the compressive and relative strengths of CON. The compressive strengths of the control mix at 3, 14, 28, and 60 d are 1.81, 2.70, 3.05, and 3.15 MPa, respectively. The compressive strengths of the CLC increase with increasing the curing time due to the hydration reaction that increases the calcium silicate hydrate (C–S–H) product [18]. At 3 d the compressive strength of CLC containing 10wt% FA is slightly higher than that of the control mix at the same time point. This result is due to the proper amount of FA content, which affects the pozzolanic reaction rate and better dispersion and improves the compressive strength of the paste [7, 19-20]. The compressive strengths of CLC containing 20wt% or 30wt% FA are lower than that of the control mix. This result is due to the low OPC content that have been observed in other research [21]. In addition, the compressive strengths of FA30 at 14, 28, and 60 d are lower than those of the other mixes due to the greater amount of FA. FA is a pozzolan, and its pozzolanic reaction is slow compared with that of OPC; thus, the rate of strength development is also slow [19, 22].

Table 4. Compressive strength of CLCs containing OPC, FA, and NZ

Mix No.	Symbol	Compressive strength / MPa				Relative strength to CON / %			
		3 d	14 d	28 d	60 d	3 d	14 d	28 d	60 d
1	CON	1.81	2.70	3.05	3.15	100	100	100	100
2	FA10	1.95	3.17	3.45	3.65	108	117	113	116
3	FA20	1.65	2.75	3.10	3.30	91	102	102	105
4	FA30	1.27	2.15	2.42	2.58	70	80	79	82
5	NZ10	2.19	3.72	4.27	4.51	121	138	140	143
6	NZ20	1.92	3.18	3.66	3.91	106	118	120	124
7	NZ30	0.85	1.56	2.05	2.25	47	58	67	71

The compressive strengths of NZ30 at 3, 14, 28, and 60 d are 0.85, 1.56, 2.05, and 2.25 MPa, respectively. The strengths are weaker than those of the OPC due to the high NZ content and the slower pozzolanic reaction rate of zeolite, which do not significantly contribute to compressive strength [23]. The compressive strengths of NZ10 and NZ20 at 3, 14, 28, and 60 d are 2.19, 3.72, 4.27, and 4.51, and 1.92, 3.18, 3.66, and 3.91 MPa, respectively. These strengths are higher than those of CON at the same time point. The high SiO_2 content (75.32wt%) and NZ fineness (median particle size = 7.72 μm) improve the reaction with $Ca(OH)_2$ to produce an additional calcium silicate hydrate (C–S–H), which improves the compressive strength [1, 24−25].

At the replacement levels of 10wt% and 20wt%, the compressive strengths of CLC containing NZ are higher than those of CLC containing FA, as shown in Table 4. This finding is due to the high purity level (up to 90wt%) of NZ and the high SiO_2 content compared with those of FA. According to Ref. [25], the 28-d strength of zeolite concrete with a replacement level of 15wt% (the optimum) is also 23wt% higher than that of the control mix. As a result, the strength of hardened concrete is improved by incorporating a proper amount of zeolite [1, 16, 19, 26-27]. The optimum replacement level of NZ or FA is 10wt%. For a higher replacement level of 20wt%, the strengths of CLC are slightly reduced compared with those at the optimum replacement level of 10wt%; however, these strengths are still higher than those of the control mix. Replacing cement with FA or NZ affects the compressive strength because the compressive strength significantly increases with time but decreases with increasing the replacement level. Three factors can explain the increased compressive strength of CLC: hydration reaction, filler effect, and pozzolanic reaction. Hydration reaction is directly related to the cement amount in the mix. The filler effect involves the nucleation and packing effects, which depend on the material fineness. The nucleation effect occurs when small particles are dispersed into the cement paste and act as nucleation sites that enhance cement hydration, whereas the packing effect is the result of small particles that fill the voids of the paste [28-30]. Therefore, CLC with pozzolans of high fineness results in a more homogeneous and denser matrix, which increases the compressive strength of the paste.

3.4. Water absorption

The results of CLC water absorption at 28 d are presented in Fig. 5. The water absorption of CON is 30.0wt% at 28 d, whereas those of FA10, FA20, and FA30 are 30.6wt%, 32.5wt%, and 35.3wt%, respectively. The water absorption of CLC containing FA increases as the FA content increases. Kunhanandan Nambiar and Ramamurthy [31] reported similar results when they used Class F fly ash to replace sand at the sand-to-FA ratio of 0-100wt% to obtain foam concrete with the water absorption of 23wt%-30wt%.

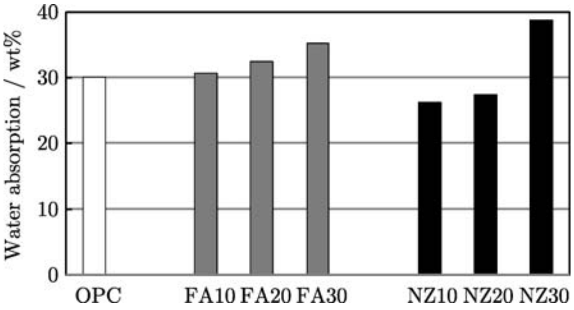

Fig. 5. Water absorption of CLC at 28 d.

The water absorptions of NZ10 and NZ20 are 26.3wt% and 27.3wt%, respectively. These figures are lower than those of CON. This finding is due to the amount of pore bubbles from the foam, which is slightly reduced with the addition of NZ. However, the water absorption of NZ30 is higher (38.8wt%). Other researchers have made similar observations regarding water absorption [25, 32]. This finding is related to the porosity results: a small increase in capillary pores in CLC hence causes a small increase of water absorption.

Fig. 5 shows that the water absorption of CLC containing NZ is more effective than CLC with FA at replacement levels of 0-20wt%. The water absorption of CLC containing 30wt% FA is slightly lower than that containing 30wt% NZ. It is observed that replacing cement with pozzolan in CLC results in the increase of large capillary pores. The result shows that large capillary pores of FA10 and FA20 are higher than those of NZ10, NZ20, and CON. Therefore, an increase of large capillary pores in CLC could influence their water absorption.

3.5. Microstructure of CLC

3.5.1. Porosity of CLC

The porosity results of all CLCs at 28 and 60 d are presented in Table 5 and Fig. 6. The porosity system consists of four types of pores: gel pores or small pores, less than 10 nm; medium capillary pores, 10 to 50 nm; large capillary pores, 50 to 10000 nm; and air void or extra large pores, larger than 10000 nm. Large capillary pores and extra large pores are influential on strength and permeability characteristics, whereas small pores and medium capillary pores are influential on drying shrinkage and creep [33−34]. The total porosities of the control mix, FA10, FA20, and FA30 at 28 d are 52.27%, 48.56%, 50.78%, and 59.32%, respectively. Incorporating 10wt% and 20wt% FA results in the CLCs with reduced total porosity. This result is due to the gradual filling of large pores from factors, such as the hydration reaction, the dispersing effect, the packing effect, and the pozzolanic reaction of FA particles. Small and spherical FA particles fill air voids and decrease the porosity [28, 30]. At 30wt% FA, the total porosity significantly increases, primarily due to the packing effect of FA particles filling the air bubbles, which increases the capillary porosity of CLC. Note that the total porosity and capillary porosity of the CLCs increase, whereas the compressive strength and extra large pores decrease. Other investigations have reported similar findings [7]. The porosity of CLC containing FA at 60 d has a similar trend to that at 28 d.

Table 5. Porosity of CLCs containing OPC, FA, and NZ

Mix No.	Symbol	Porosity at 28 d / %					Porosity at 60 d / %				
		Small	Medium capillary	Large capillary	Extra large	Total	Small	Medium capillary	Large capillary	Extra large	Total
1	CON	0.05	2.84	26.72	22.66	52.27	0.05	2.15	26.93	22.51	51.64
2	FA10	0.28	1.94	38.62	7.72	48.56	0.35	1.86	36.80	7.71	46.72
3	FA20	0.19	2.93	40.51	7.15	50.78	0.20	2.42	40.37	7.56	50.55
4	FA30	0.24	4.39	47.70	6.99	59.32	0.25	3.96	47.67	6.73	58.61
5	NZ10	0.20	4.29	33.88	4.69	43.06	0.21	3.77	31.72	4.55	40.25
6	NZ20	0.38	4.72	34.37	5.34	44.81	0.31	4.40	34.11	5.13	43.95
7	NZ30	0.30	9.26	50.60	9.55	69.71	0.31	7.90	50.49	9.13	67.83

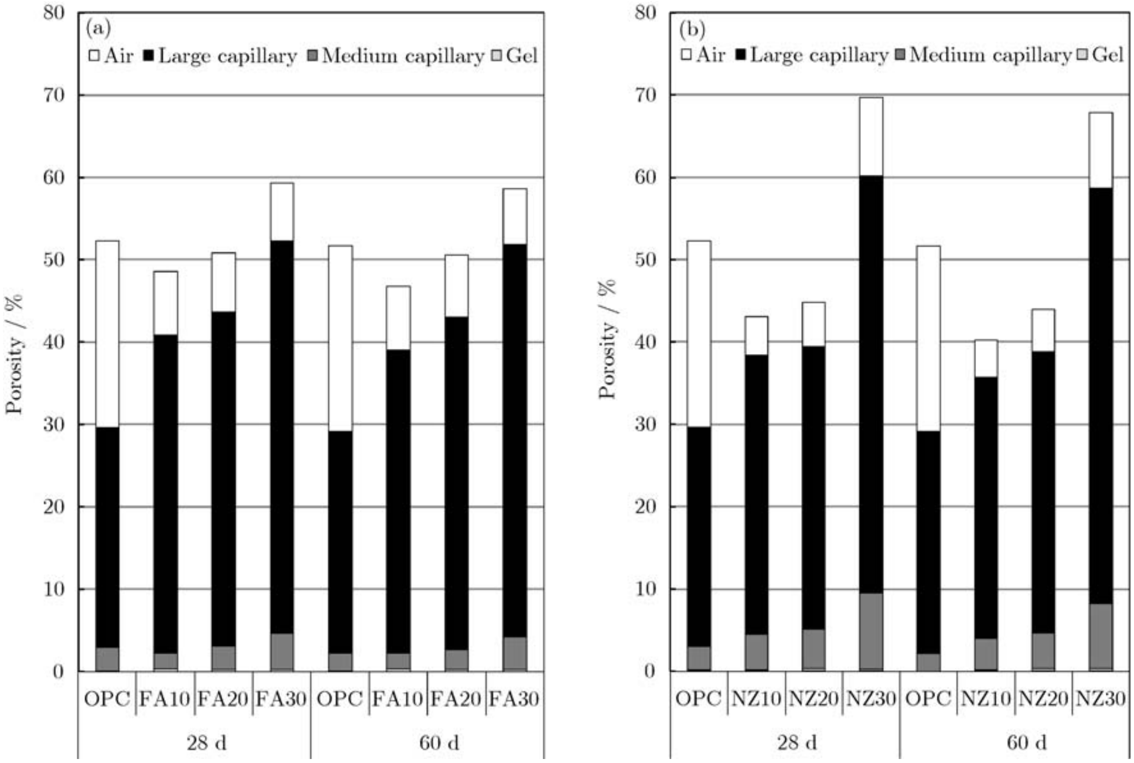

Fig. 6. CLC porosity with admixtures FA (a) and NZ (b).

As shown in Fig. 6, the total porosity of CLCs containing NZ10 and NZ20 are smaller than that of OPC concrete at all replacement levels and times. It is because NZ is more effective at reducing pore size due to a better dispersing effect, packing effect, and pozzolanic reaction of finer NZ particles. The small NZ particles fill the pores and decrease the porosity [9, 27].

Compared with FA, high-fineness NZ has a faster pozzolanic reaction and a better filler effect at reducing the voids of CLC. However, a considerable decrease in the total porosity of NZ10 occur 28 d later, primarily due to the decrease in large capillary pores. This decrease might be associated with the pore system becoming denser as a result of the additional formation and growth of the pozzolanic reaction products [9, 27].

The 10wt% incorporation of pozzolanic materials decreases the total porosity due to the filling effect and pore refinement. The total porosity of OPC concrete is 52.27%, whereas those of FA10 and NZ10 are 48.56% and 43.06%, respectively. The total porosity of NZ10 is reduced more than that of FA10 due to its finer particles. The increase in pozzolan content to 20% and 30% increases the total porosity. The reduced OPC content and hydration products offset the filling effect. The extra large pores of CLCs containing pozzolans are reduced, whereas the small pores, medium capillary pores, and large capillary pores increase. The filling effect reduces extra large pores and increases small pores, medium capillary pores, and large capillary pores. All pores other than small pores increase significantly for 30% pozzolans. Again, this result is due to the reduced amounts of OPC and hydration products. Other investigations also reported similar findings [7]. The pores exhibit a similar trend at 60 d compared with that at 28 d.

As shown in Table 5 and Fig. 6, the incorporation of higher CLC replacement levels of both FA and NZ results in greater gel porosity compared with that of the control mix at all times. CLC with NZ exhibits increased gel porosity, which suggests that CLC with NZ is more effective than that with FA, and this is due to the better dispersion, packing effect and pozzolanic reaction in the blended cement paste. Other researchers have reported similar results [7, 16].

3.5.2. Effects of FA and NZ on the pore size distribution of CLC

The cumulative pore volumes of CLCs with FA and NZ are shown in Figs. 7 and 8. The cumulative pore volumes of the control mix at 28 and 60 d are 0.454 and 0.452 mL/g, respectively. These values decrease with curing time due to the hydration reactions and the increase of the C–S–H product [14, 23].

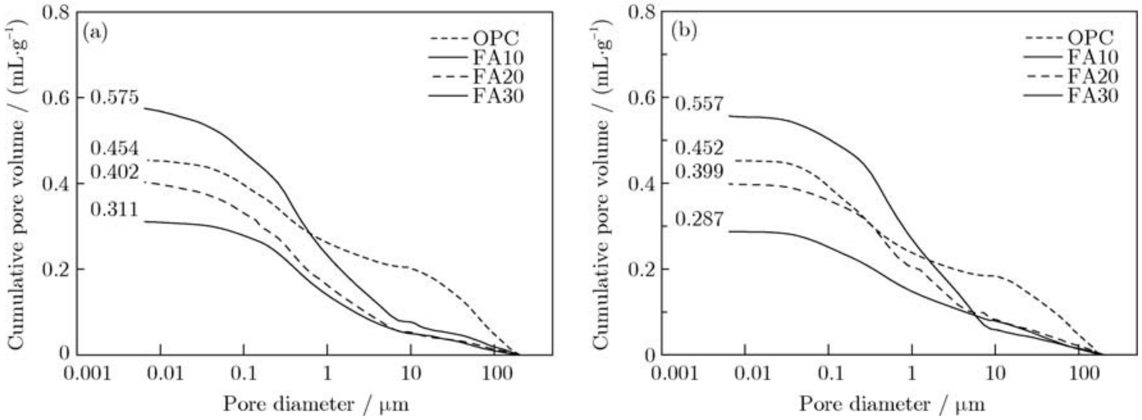

Fig. 7. Relationship of cumulative pore volume and pore diameter of CLC containing FA: (a) 28 d; (b) 60 d.

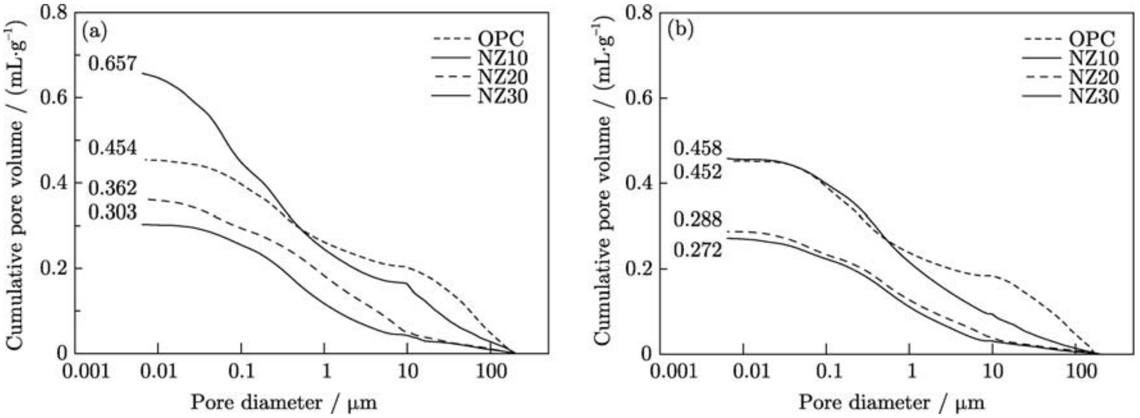

Fig. 8. Relationship of cumulative pore volume and pore diameter of CLC containing NZ: (a) 28 d; (b) 60 d.

As shown in Fig. 7, the cumulative pore volumes of CLC containing 10wt% FA are 0.311 mL/g at 28 d and 0.287 mL/g at 60 d. These figures are lower than those of the control mix and CLC containing 20wt% or 30wt% FA. As shown in Fig. 8, the cumulative pore volumes of CLC containing 10wt% NZ are 0.303 mL/g at 28 d and 0.272 mL/g at 60 d. FA and NZ are effective pozzolans with successful pozzolanic reactions. Incorporating a proper amount of pozzolan fills voids, reduces porosity, and increases the density of the paste [14, 16]. The SiO_2 and Al_2O_3 in pozzolanic materials react with $Ca(OH)_2$ to produce C–S–H and C–A–H, which results in a reduction of $Ca(OH)_2$ content by pozzolanic reaction [23, 27]. The results also reveal that the cumulative pore volumes of concretes containing NZ are smaller than those containing FA. This finding suggests that NZ is slightly more effective than

FA at reducing porosity.

3.5.3. SEM observations

The morphologies of the fractured surfaces of CLCs at 28 d are shown in Figs. 9 and 10. The pores of the control mix are clearly shaded circles of various sizes with relatively smooth surfaces. The pore sizes vary from less than 50 μm to 600 μm. Another researcher reported a similar observation [32].

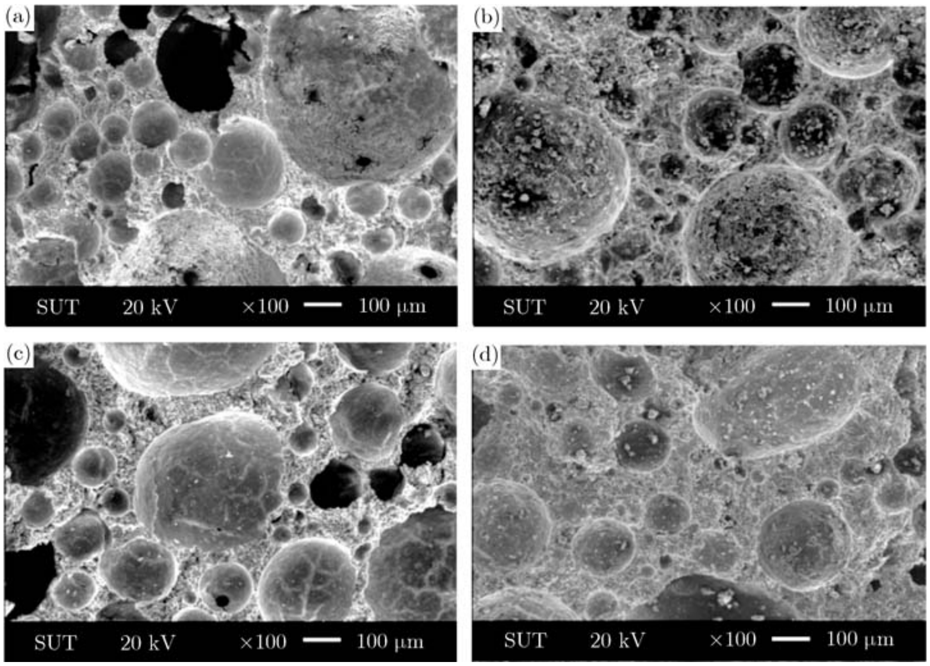

Fig. 9. SEM images of the fractured surfaces of CLCs containing FA at 28 d: (a) OPC; (b) FA10; (c) FA20; (d) FA30.

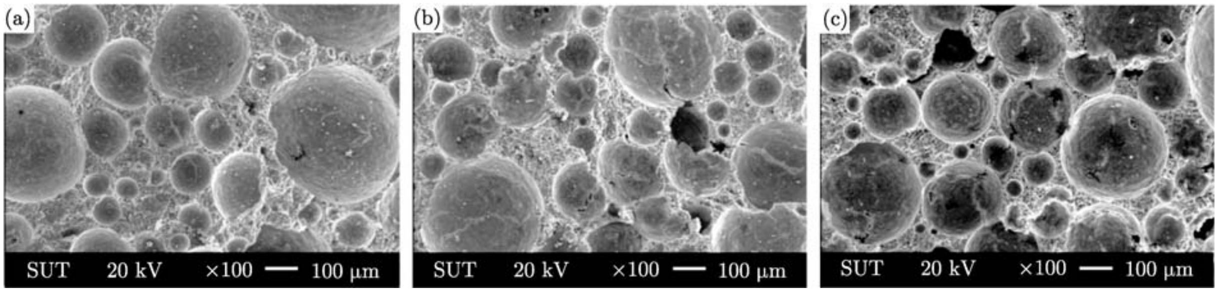

Fig. 10. SEM images of the fractured surfaces of CLCs containing NZ at 28 d: (a) NZ10; (b) NZ20; (c) NZ30.

Figs. 9(b)-9(d) display the SEM images of CLCs containing 10wt%, 20wt%, and 30wt% FA, respectively, which have completely different microstructures from the control mix (Fig. 9(a)). Clearly, the pores are more uniform than those of the control mix because FA facilitates the distribution of air voids by preventing them from merging and overlapping [35]. The pore sizes of these CLCs range from less than 50 μm to 400 μm. In addition, the pore size decreases as the FA replacement level increases [14]. Furthermore, some microcracks are detected at the pore surfaces (Figs. 9(c) and 9(d)). Drying shrinkage and mechanical stresses that occurred during sample preparation probably induce these features.

Figs. 10(a)-10(c) display the SEM images captured from CLCs containing 10wt%, 20wt%, and 30wt% NZ, respectively. Clearly, these pore sizes are slightly more uniform than those of CLCs containing FA. The pore sizes range from less than 50 μm to 300 μm. Fig. 10(a) shows that there are several closed pores, which demonstrates that CLC with 10wt% NZ have low water absorption [36]. In addition, the pore size decreases as the NZ replacement level increases (Fig. 10(c)).

SEM observations reveal that the pores of CLCs containing NZ are denser than those of CLCs containing FA at the same replacement level (excluding the 30wt% replacement level) and control mix. This effect is due to cement hydration and pozzolanic reactions [14, 26]. Numerous large pores are observed with 30wt% pozzolan replacement, which reflects the high total porosity and low strength of these CLCs, due primarily to their low OPC content and reduced hydration products.

4. Conclusions

CLCs with OPC partially replaced by FA or NZ with a density of approximately 800 kg/m^3 can be produced with relatively good compressive strength. NZ is slightly more reactive than FA and enhances the strength of CLC. The optimum replacement level for both FA and NZ is 10wt%, which, compared with CON, results in the 28-d compressive strength increasing by 113% and 140%, respectively. A replacement level of 20wt% results in decreased strength; however, these CLCs are still stronger than the control mix.

CLCs containing NZ set slightly faster than those containing FA. This finding is due to the high fineness of NZ, which also has a higher surface area and a greater pozzolanic reaction. The increase in pozzolans also prolongs the setting time of CLCs with NZ compared with the control mix due to the lower content of OPC.

The capillary porosity of CLCs containing FA and NZ increases as the replacement level of both types of pozzolans increases. Moreover, water absorption is primarily related to capillary porosity. The water absorption increases as the capillary porosity increases, which decreases the compressive strength.

The reduction of air voids in CLCs with density control is due to replacing OPC with pozzolans. The pozzolans cause a filler effect and refine the pore-size structure of the paste. This effect changes larger pores into smaller ones. Thus, the total porosity and cumulative pore volumes of CLCs containing FA and NZ are less than those of OPC.

Acknowledgements

The authors acknowledge the financial support of the Rajamangala University of Technology Isan, Thailand, for a grant originating from the Strategic Scholarships for Frontier Research Network, which supports the Joint Ph.D. Program and Thai doctoral degree. Thanks are also extended to the Thailand Research Fund (TRF) for financial support originating from the TRF Senior Research Scholarship (No. RTA5480004), as well as the TRF New Researcher Scholarship (No. MRG5280178).

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