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Performance of modified lightweight aggregate concrete after exposure to high temperatures

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Lightweight expanded clay aggregates (ceramsites) were modified by coating a thin layer of alkali-activated fly ash binder. The modified aggregates were used to prepare concrete specimens, which were exposed to room and high temperatures. Spalling of the concrete specimens during heating and their mechanical properties after exposure were tested. Furthermore, hydration products of the alkali-activated fly ash and microscopic structures of the concrete specimens after exposure were also tested. In addition, in situ images of the concrete specimens were collected to demonstrate the formation and propagation of cracks in the specimens with increasing temperature. All the results were compared with results obtained for concretes prepared with normal lightweight aggregate and with crushed limestone. The results show that, unlike the reference concretes, nearly all the modified concrete specimens were intact, even at a temperature of 1200°C, without spalling and retained good mechanical properties. Nepheline was detected in the alkali-activated fly ash after heating at 800°C. Probably as a result of the strengthening of the alkali-activated fly ash coating, high temperatures induced cracks in the modified concrete that extended along the interfacial transition zone, but did not penetrate the interior of the aggregates.

Notation

E	elastic modulus
f_{cu}	cube compressive strength
$f_{cylinder}$	cylinder compressive strength
f_f	flexural strength
f_t	splitting tensile strength
n	total number of specimens
n_{sp}	number of spalled specimens
T_{sp}	temperature at which spalling first occurred

Subscripts

T	temperature
20	room temperature (°C)

Introduction

Lightweight aggregates, such as expanded clay (ceramsite), expanded perlite and pumice, are usually used to prepare lightweight aggregate concrete. One of the main applications of such concrete is in the construction of filler walls of high-rise

buildings, owing to the advantage of its light weight. Fire is a tremendous threat for high-rise buildings, as frequently reported worldwide in recent years. High temperature is well known to cause serious damage to both the macroscopic and microscopic structures of concrete, leading to generalised mechanical decay of the concrete and even detrimental effects at the structural level, owing to concrete spalling (Choi *et al.*, 2017; Gao *et al.*, 2017; Ma *et al.*, 2015, 2018). The deterioration of concrete at high temperature is mainly caused by damage to the binder or aggregates; their influences on the mechanical properties of concrete at high temperature have been reviewed previously (Ma *et al.*, 2015).

Lightweight aggregates are normally formed by volcano eruption or incineration. As a result, they have low heat conductivity and exhibit a high resistance to heat. Therefore, concrete manufactured using such aggregates should deliver improved mechanical properties at high temperature, in comparison with concrete containing normal aggregates (Jiang *et al.*, 2013; Sancak *et al.*, 2008; Tanyildizi and Coskun, 2008;

Turkmen and Findik, 2013; Yoon *et al.*, 2015). Internationally established lightweight aggregates, such as Lytag (2017) and Leca (2017), which are mainly produced from power station ash and expanded clay, respectively, have also brought superior fire resistance to concretes containing them.

However, the occurrence of thermal spalling will extremely limit the resistance of concrete to high temperature (Ma *et al.*, 2015). Thermal spalling of concrete is greatly sensitive to its moisture content (Ma *et al.*, 2015). Jiang *et al.* (2013) point out that high-temperature-induced spalling did not occur when moisture content (calculated by using evaporative water content in a concrete specimen at a certain moment divided by that in the specimen just taken out from the standard curing room) in normal concrete is below 75%, whilst this value for lightweight concrete was 25%. This indicates that spalling of lightweight concrete at high temperature is much more sensitive than normal concrete to moisture content. It is known that the porosity of lightweight aggregates, and consequently the water absorption, is much higher than that of normal aggregates. Therefore, in practice, to minimise water absorption of lightweight aggregates and its effect on the workability and subsequent setting and hardening of the concrete produced, lightweight aggregates are usually pre-saturated before mixing. However, such treatment will bring extra water into the concrete to increase its moisture content, thus increasing the possibility of spalling at high temperature. Although the moisture in lightweight aggregates might evaporate into the atmosphere during concrete service, owing to their highly porous characteristics, lightweight aggregates would also heavily absorb moisture again to induce spalling of the concrete in a fire caused by gas or other fuel (Lindgard and Hammer, 1998). This will extremely limit the super resistance of lightweight aggregate to heat. In many studies (Sancak *et al.*, 2008; Tanyildizi and Coskun, 2008; Turkmen and Findik, 2013; Yoon *et al.*, 2015), researchers did not follow the practical process of presaturating lightweight aggregates before concrete mixing. Jiang *et al.* (2013) dried lightweight concrete specimens at 100°C before exposing them to high temperature, which minimised spalling to a large extent. However, such pre-drying action is impossible in practice.

From this discussion, it can be seen that, owing to either the original moisture in lightweight aggregate concrete or its re-absorption in a fire, such concrete has a high probability of spalling at high temperature. Therefore, it is necessary to propose a method to modify lightweight aggregates to reduce their absorption, thus reducing the possibility of spalling of the concrete at high temperature.

Surface coating is considered to be a useful method to reduce absorption of water by lightweight aggregates, thus reducing the possibility of spalling of the concrete. In our previous investigation (Ma *et al.*, 2018) and the study carried out by Bideci (2016), inorganic polymer compound material and cement + colemanite (a kind of boron mineral), respectively, were used to coat lightweight aggregates to reduce the frequency of spalling. In the former study, the frequency of spalling of lightweight aggregate concrete was reduced by decomposition of the coating material at a lower temperature to generate channels for vapour to escape. By contrast, the coating used in the latter study was applied to strengthen the lightweight aggregates, increasing the resistance of the concrete to high temperature. However, because spalling was not the main concern in the latter study, the experimental design did not consider related procedures. However, probably because Portland cement-based material was used for coating, when the temperature was increased to 600°C, very deep and wide cracks were still found at the surface of the concrete. Researchers (Guerrieri and Sanjayan, 2010; Ranjbar *et al.*, 2014; Rashad and Zeedan, 2011; Thokchom *et al.*, 2012; Zhang *et al.*, 2015) have reported that alkali-activated fly ash has superior heat resistance because the high temperature simply provides a desirable environment for the activation. In this context, such a binder was selected in this study to coat lightweight aggregates, and the thermal spalling and mechanical properties of the concrete containing the coated aggregates after high-temperature exposure were investigated.

Experimental programme

In this paper, lightweight expanded clay aggregates (ceramsites) were precoated using alkali-activated fly ash. The modified ceramsites were used to produce lightweight fly ash aggregate concrete (FAAC). Thermal spalling and the mechanical properties of the concrete after exposure to high temperatures were studied. Furthermore, the formation of hydration products of the alkali-activated fly ash and microscopic structures of the concrete with increasing temperature were also examined in order to understand the role of the alkali-activated fly ash. The macroscopic structure of the concrete was also observed in situ to examine the formation and propagation of cracks in the concrete. Normal ceramsite concrete (NCC) and crushed limestone concrete (CLC) specimens were also prepared as reference for comparison.

Materials

Cement

The cement used to manufacture the concrete specimens was slag Portland cement PSA 32.5, which conforms to Chinese

Table 1. Chemical compositions of cement and fly ash (%)

	SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	MgO	SO ₃	Loss on ignition
Cement	17.90	54.03	5.26	3.44	1.78	1.70	4.30
Fly ash	43.60	3.14	24.03	6.93	2.44	0.30	3.75

Figure 1. Appearance of the coarse aggregates: (a) limestone; (b) ceramsite; (c) modified ceramsite

national standard GB 175-2007 (SAC, 2007). Table 1 gives its chemical composition.

Fine aggregates

Fine aggregates were prepared using three parts of manufactured sand and two parts of mountain sand (by mass), whose fineness modulus, specific gravity and 1 h water absorption were 2.54, 2.72 and 2.3%, respectively.

Coarse aggregates

Normal ceramsites without modification were used to prepare NCC specimens; CLC specimens were manufactured using crushed limestone. The reason for using limestone to manufacture reference concrete was that, compared with siliceous aggregates, limestone with this kind of calcareous aggregate has a higher resistance to heat (Ma *et al.*, 2015). The maximum size of both kinds of aggregate was 30 mm, and they both had a good particle distribution. For the manufacture of FAAC specimens, ceramsites were precoated with alkali-activated fly ash before concrete mixing. A sodium hydroxide solution with a concentration of 8 mol/l was mixed with the fly ash powder, where the ratio between the solution and the powder was 1:2:1. When the alkali-activated fly ash slurry was ready, ceramsite particles were put into a proper amount of slurry for coating. After removing excess slurry from the surface of the particles with a sieve, the coated ceramsites were immediately dried in an oven at 80°C for 5 h (Guo *et al.*, 2016). The chemical composition of the fly ash used is given in Table 1. The appearances of all kinds of coarse aggregates are shown in Figure 1, and their properties are given in Table 2.

Water

Tap water was applied to mix and cure the concrete specimens.

Preparation of specimens

Mix proportions

As stated in the introduction, the main application of lightweight aggregate concrete is as non-bearing filler walls for high-rise buildings. As a result, according to Chinese standard JGJ

Table 2. Properties of the coarse aggregates

Aggregate	Specific gravity (saturated surface dry condition)	1 h water absorption: %
Limestone	2.38	0.5
Ceramsite	0.82	14.5
Modified ceramsite	0.98	9.2

51-2002 (SAC, 2002a), a strength class of LC10 was chosen as the target in this study. The same water-to-binder ratio, cement content and total volume of aggregates were used to manufacture NCC and FAAC specimens. The CLC specimens also used the same water-to-binder ratio and cement content. Chinese standards JGJ51-2002 (SAC, 2002a) and JGJ55-2011 (SAC, 2011) were used to formulate the mix design of lightweight aggregate concretes and CLC, respectively. Table 3 gives the mix proportions of the concrete mixes studied in detail.

Preparation of specimens

At each temperature, three specimens for each mix were cast for the following tests: (a) a cube compressive strength test with a specimen size of 100 mm × 100 mm × 100 mm; (b) a splitting tensile strength test with a specimen size of 100 mm × 100 mm × 100 mm; (c) a flexural strength test with a specimen size of 100 mm × 100 mm × 400 mm; (d) stress-strain relationship, cylinder compressive strength and elastic modulus tests with a specimen size of 100 mm × 100 mm × 300 mm.

Both the ceramsite particles with and without precoating were presaturated in water before casting. The water content formulated in the mix proportions (detailed in Table 3) did not include the water used for saturation.

After casting, the specimens were cured in moulds; the temperature was maintained at 20 ± 2°C and relative humidity was controlled beyond 95%. The specimens were unmoulded 1 d after casting, and then cured under the same conditions. The total curing duration was 28 d.

Table 3. Concrete mix proportions (kg/m³)

Concrete type	Cement	Water	Fine aggregates	Coarse aggregates
CLC	370	180	658	1222
NCC	370	180	693	317
FAAC	370	180	693	378

Table 4. Slump of the fresh concretes and mechanical properties of the hardened concretes at a curing age of 28 d (room temperature)

Concrete type	Slump: mm	f_{cu} : MPa	$f_{cylinder}$: MPa	f_t : MPa	f_f : MPa	E : GPa
CLC	100	35.1 ± 1.1	29.8 ± 0.9	3.26 ± 0.0	4.80 ± 0.3	23.3 ± 0.4
NCC	80	14.9 ± 0.9	13.3 ± 0.5	1.76 ± 0.1	2.50 ± 0.0	15.4 ± 0.3
FAAC	80	15.2 ± 0.2	13.9 ± 0.6	1.61 ± 0.2	2.50 ± 0.2	14.9 ± 0.8

Heating regime

An electric heating furnace was used in this study to heat the concrete specimens. The specimens were placed in the furnace in an unstressed condition. Ceramic cellular pads with very small section were used to support the specimens at the four corners, allowing all six surfaces of the specimens to be heated during temperature elevation. The temperature was elevated at a rate of 10°C/min to 200, 400, 600, 800, 1000 and 1200°C, respectively. The temperatures were maintained constant for 3 h when the target temperature was achieved, so that a thermal steady state could be obtained in the specimens. After that, the furnace was switched off and the specimens were cooled down slowly in the furnace to room temperature.

Tests

Slump

A slump test was carried out on the fresh concretes following the specifications in Chinese standard GB/T 50080-2002 (SAC, 2002b); the results are presented in Table 4.

Mechanical properties

After a curing duration of 28 d, the concrete specimens were tested for their cube compressive strength (f_{cu}), splitting tensile strength (f_t), flexural strength (f_f) and stress–strain relationship at room temperature and after the high-temperature heating. The cylinder compressive strength ($f_{cylinder}$) and elastic modulus (E) of the specimens can also be obtained from the results of the stress–strain relationship test. All these tests were carried out by following the specifications in Chinese standard GB/T 50081-2002 (SAC, 2002c). Table 4 gives the strengths and the elastic moduli of the specimens at room temperature.

Spalling

In the process of heating, if sounds of spalling were heard, the corresponding temperature was recorded. When the specimens had cooled down, they were removed from the furnace and the spalling mode was recorded for each spalled specimen. Furthermore, the quantity of the specimens spalled was confirmed and the spalling frequency was calculated.

Hydration products of alkali-activated fly ash

To understand the role of alkali-activated fly ash in FAAC, X-ray diffraction techniques were applied to such a system at room temperature and after heating, with an attempt to determine the evolution of the hydration products of the system with increasing temperature. Alkali-activated fly ash paste was prepared with the same mix proportion and procedure as that used for the ceramic site coating. The same curing regime used for the concrete was used to cure the paste for 28 d. Temperatures of 400°C, 800°C and 1200°C were selected for heating, where the same heating regime as that used for concrete specimens was applied to the paste specimens. The heated specimens at the different temperatures and the specimen kept at room temperature were ground into powder (passing through a 0.08 mm sieve), and the powder samples were immediately analysed using X-ray diffraction.

Microscopic structure

When the concrete specimens were crushed for the mechanical property tests at room temperature and after heating, a number of small and thin fragments, which included both cement matrix and aggregates, were collected. Absolute ethanol was then used to soak the fragments for 3 d to terminate any possible hydration. After drying in a vacuum drying dish, scanning electron microscopy was used to observe the microscopic structure of the fragments.

In situ macroscopic structure

A concrete cube of size 100 mm × 100 mm × 100 mm was manufactured for each mix for in situ macroscopic structure observation. After a curing duration of 28 d under the same regime used for the other concrete specimens, the surfaces of the cube were cut off and a prism of size 40 mm × 40 mm × 80 mm was prepared, which was polished. Furthermore, the prism specimen was put into an electrical furnace with a visible window. The temperature in the furnace was elevated at a rate of 50°C/min from room temperature to an ultimate temperature of 800°C. During the temperature elevation, in situ images of the specimens were collected at 20, 100, 200, 300, 400, 500, 600, 700 and 800°C, using a charged-couple device high-temperature in situ digital image collection system. Because the prism

Table 5. Spalling frequency of concrete specimens at high temperatures

Concrete type	Temperature: °C	f_{cu} test (100 × 100 × 100 mm)		f_t test (100 × 100 × 100 mm)		Stress–strain relationship test (100 × 100 × 300 mm)		f_t test (100 × 100 × 400 mm)	
		n_{sp}/n	T_{sp} : °C	n_{sp}/n	T_{sp} : °C	n_{sp}/n	T_{sp} : °C	n_{sp}/n	T_{sp} : °C
CLC	20	—	—	—	—	—	—	—	—
	200	0/3	—	0/3	—	0/3	—	0/3	—
	400	0/3	—	0/3	—	0/3	—	0/3	—
	600	1/3	488	1/3	492	1/3	547	3/3	502/510/508
	800	1/3	486	1/3	495	2/3	540/542	3/3	498/513/511
	1000	0/3	—	0/3	—	2/3	510/542	3/3	520/542/518
	1200	0/3	—	0/3	—	3/3	533/540/516	3/3	492/517/495
	Spalling frequency: %			11.1			44.4		66.7
	Average T_{sp} : °C			490			534		510
NCC	20	—	—	—	—	—	—	—	—
	200	0/3	—	0/3	—	0/3	—	0/3	—
	400	0/3	—	0/3	—	1/3	387	1/3	387
	600	3/3	416/453/456	3/3	397/450/461	3/3	396/407/412	3/3	412/423/417
	800	3/3	435/444/498	3/3	432/451/456	3/3	402/388/392	3/3	407/386/425
	1000	3/3	408/452/460	3/3	421/434/451	3/3	432/410/391	3/3	445/412/426
	1200	3/3	412/440/462	3/3	441/462/461	3/3	398/421/395	3/3	392/436/414
	Spalling frequency: %			66.7			72.2		72.2
	Average T_{sp} : °C			444			402		414
FAAC	20	—	—	—	—	—	—	—	—
	200	0/3	—	0/3	—	0/3	—	0/3	—
	400	0/3	—	0/3	—	0/3	—	0/3	—
	600	0/3	—	0/3	—	0/3	—	0/3	—
	800	0/3	—	0/3	—	1/3	472	0/3	—
	1000	0/3	—	0/3	—	1/3	437	0/3	—
	1200	0/3	—	0/3	—	0/3	—	0/3	—
	Spalling frequency: %			0.0			11.1		0.0
	Average T_{sp} : °C			—			454		—

Note: Spalling frequency is calculated by using the number of the specimens spalled divided by the total number of the specimens exposed to a temperature $\geq 200^\circ\text{C}$

Figure 2. Appearance of the concrete specimens after heating to 1200°C (from left to right: CLC, NCC, FAAC): (a) specimens of size 100 mm × 100 mm × 100 mm; (b) specimens of size 100 mm × 100 mm × 300 mm; (c) specimens of size 100 mm × 100 mm × 400 mm

specimens were relatively small and cut surfaces were used for observation, moisture in the specimens could easily escape into the atmosphere. In this context, thermal spalling was not considered to occur in such prism specimens, and the purpose of the in situ macroscopic structure observation was simply to evaluate the formation and propagation of cracks in the specimens with increasing temperature.

Results and discussion

Spalling

Table 5 details the number of spalled concrete specimens (n_{sp}) at each temperature and the temperature when spalling first occurred (T_{sp}). Furthermore, a spalling frequency was

calculated for specimens of different sizes, and is also reported in Table 5. Compared with CLC, NCC specimens spalled severely and the spalling started at a lower temperature. As given in Table 2, the 1 h water absorption of ceramsite was 14.5% which was much higher than that of limestone, of 0.5%. As a result, the water content in NCC should be higher than that of CLC. Owing to the vapour pressure (Consolazio *et al.*, 1998), thermal spalling was much more likely to occur for the NCC specimens when they were heated.

However, after the modification, the spalling frequency of FAAC was reduced remarkably, no matter what the size of the specimens. As reported in Table 2, alkali-activated fly ash coating has reduced the water absorption of the ceramsite.

This could be one of the reasons why the spalling frequency of FAAC specimens was greatly reduced. Further, alkali-activated fly ash has superior resistance to heat, as reported in the literature (Guerrieri and Sanjayan, 2010; Ranjbar *et al.*, 2014; Rashad and Zeedan, 2011; Thokchom *et al.*, 2012; Zhang *et al.*, 2015). This could also have contributed to the much lower spalling frequency for the FAAC specimens, and is to be clarified in the following sections.

From Table 5 it also can be seen that, generally, the larger concrete specimens spalled more easily at high temperature. This could be because the thermal difference between inner and outer parts of the concrete is more pronounced for a larger specimen (Ario, 2009).

After 1200°C treatment, photographs of the concrete specimens were taken and are shown in Figure 2. Although a larger quantity of NCC specimens spalled at high temperature (per Table 5), the extent of their spalling was not as severe as that of CLC specimens. This is probably because the initial strength of the latter was higher than that of the former. Nevertheless, during the heating, nearly all the FAAC specimens remained intact, without any clear damage.

Figure 3. Relative f_{cu} of the concrete specimens after exposure to high temperatures

Figure 4. Relative $f_{cylinder}$ of the concrete specimens after exposure to high temperatures

Residual mechanical properties

f_{cu} , $f_{cylinder}$, f_t , f_i and E

Relative values of f_{cu} , $f_{cylinder}$, f_t , f_i and E of the concrete specimens, which were calculated using their values at each temperature divided by their corresponding values at room temperature, are plotted in Figures 3 to 7, respectively. The data plotted are the average values of three specimens, except that spalled specimens were excluded, as they could not be used to provide values for calculation.

Figure 5. Relative f_t of the concrete specimens after exposure to high temperatures

Figure 6. Relative f_i of the concrete specimens after exposure to high temperatures

Figure 7. Relative E of the concrete specimens after exposure to high temperatures

Figure 8. Stress-strain relationship of the concrete specimens after exposure to high temperatures: (a) CLC; (b) NCC; (c) FAAC

From the figures, it can be seen that after exposure to 1200°C, the values of f_{cu} , $f_{cylinder}$, f_t , f_f and E were 29.8, 36.8, 19.4, 33.1 and 7.2% of the original values, respectively, for the FAAC specimens. However, none of the NCC specimens could survive when the temperature was as high as 600°C. An extremely small number of CLC specimens remained intact after

Figure 9. X-ray diffraction patterns of alkali-activated fly ash after exposure to different temperatures

1200°C, but their mechanical properties were generally not as good as those of the FAAC specimens. Therefore, it can be seen that once thermal spalling of lightweight aggregate concretes could be limited, they could behave very well even at a very high temperature.

Stress-strain relationship

Figure 8 plots the stress-strain relationship of the concrete specimens at room temperature and after heating. As with the strength results, the data plotted are average values obtained for those specimens that remained intact after heating.

From Figure 8 it can be seen that, with the increase in temperature, a flatter stress-strain curve was obtained for all the concrete specimens, indicating that their peak stress generally decreased with the increase in temperature. In addition, the peak stress shifted rightwards as temperature increased, which illustrates the increase of the corresponding strain.

Compared with the CLC specimens, the peak stress of both the NCC and the FAAC specimens was fairly lower, both at room temperature and after exposure to the high temperatures. However the corresponding strain was similar for the different concrete mixes. This indicates that, during the whole temperature evolution, the NCC and the FAAC specimens had a better elastic deformation than the CLC specimen.

X-ray diffraction of alkali-activated fly ash

To explore the chemical changes of alkali-activated fly ash with increasing temperature, X-ray diffraction analysis was

Figure 10. Scanning electron micrographs of the concretes at room temperature: (a) CLC; (b) interfacial transition zone of CLC; (c) NCC; (d) interfacial transition zone of NCC; (e) FAAC; (f) alkali-activated fly ash

conducted of the alkali-activated fly ash paste samples at room temperature and after exposure to 400°C, 800°C and 1200°C, respectively; the patterns at each temperature are shown in Figure 9.

From Figure 9, it can be seen that, at room temperature, the main chemicals of the alkali-activated fly ash were quartz

(SiO₂) and mullite (aluminium silicate), as well as a small amount of haematite. These chemicals were considered to originate from the fly ash (Rashad and Zeedan, 2011); this indicates that the fly ash has not yet been well activated. Similar chemicals were still observed when the temperature increased to 400°C. This could also be a result of an insufficient activation. After 800°C, nepheline (NaAlSiO₄) was formed in the

Figure 11. Scanning electron micrographs of the concretes after exposure to 400°C: (a) CLC; (b) NCC; (c) FAAC; (d) alkali-activated fly ash

system. Other researchers also found similar hydrates for alkali-activated fly ash at room temperature and after exposure to high temperatures (Ranjbar *et al.*, 2014; Rashad and Zeedan, 2011; Thokchom *et al.*, 2012; Zhang *et al.*, 2015).

From Table 5, it is known that the NCC specimens usually spalled around 400°C. However, from this discussion, it can be seen that the fly ash in the FAAC specimens has not been well activated at this temperature. As a result, the structure of the alkali-activated fly ash coating was not dense enough, as shown in Figures 10 and 11, which is to be discussed later. Such a coating could have merely provided channels for the vapour in the ceramsites to escape, reducing the possibility of spalling. Afterwards, the formation of nepheline in this kind of thermally stable mineral could have made the coating denser (Rashad and Zeedan, 2011; Zhang *et al.*, 2015), strengthening the ceramsites to resist further heating.

Microscopic structure

Figures 10 to 12 show scanning electron micrographs of the concrete specimens at room temperature and after exposures to 400°C and 1200°C, respectively.

From Figure 10 it can be seen that, at room temperature, crystalline phases in the CLC specimen orientated in the interfacial transition zone between the cement matrix and the limestone. Cement and alkali-activated fly ash have filled the surface pores of the ceramsite particles for the NCC and the FAAC specimens, respectively. However, probably because the fly ash has not been activated well at room temperature, the microscopic structure of the alkali activated fly ash coating was not sufficiently dense.

After heating to 400°C, probably owing to the inconsistency of deformation between the cement matrix and the limestone (Ma *et al.*, 2015), cracks were clearly observed in the interfacial transition zone of the CLC specimen. Ceramsite is much weaker than limestone. The cement that filled in the surface pores of the ceramsite particles could have connected the cement matrix and the ceramsite particles in the NCC specimen, so that there was not a clear boundary between the two. Probably owing to this good connection, it was difficult for vapour in the ceramsite particles to escape through the strengthened surface, resulting in the spalling of the concrete, as reported in Table 5. The fly ash in the FAAC specimen has

Figure 12. Scanning electron micrographs of the concretes after exposure to 1200°C: (a) CLC; (b) NCC; (c) FAAC; (d) alkali-activated fly ash

not been well activated, even at 400°C, as discussed previously. As a result, from the scanning electron micrograph, it can be seen that the microscopic structure of the alkali-activated fly ash coating was not dense enough, and clear cracks appeared in the interfacial transition zone. However, such a loose structure and cracks might have provided channels for the vapour in the ceramsite particles to escape, reducing the possibility of spalling of the FAAC specimens.

With an increase in temperature to 1200°C, the cracks in the interfacial transition zone of the CLC specimen enlarged further. However, the cracks originating in the cement matrix of the NCC specimen extended into the inner volume of the ceramsite particles because ceramsite is not as strong as limestone. The fly ash in the FAAC specimen has obtained an improved activation after heating to 800°C, as discussed previously. As a result, the alkali-activated fly ash coating could have protected the ceramsite particles against the penetration of cracks from the cement matrix to the inner volume of the particles. Instead, the cracks in the FAAC specimen developed along the interfacial transition zone, but to a smaller extent than those in the CLC specimen.

In situ macroscopic structure

In situ images of the concrete specimens at room temperature, 400°C, 600°C and 800°C were collected, respectively, as shown in Figure 13. Because the specimens were sufficiently small and images of section surfaces were taken, spalling could not occur for all the specimens. In this context, the purpose of this test was only to demonstrate the cracking modes of the different concrete specimens, where thermal spalling was not considered. The cracks induced by heating are marked on the images using red lines.

As shown in Figure 13, fine cracks were first observed in the cement matrix of the CLC specimen when the temperature raised to around 400°C. With further increases of temperature, to 600°C and 800°C, the cracks in the cement matrix extended through sand particles and developed further, along the edge of the limestone particles. It should be noted here that the cracks in the limestone particle (the one on the right bottom) had been there at room temperature and, therefore, could be ignored in the discussion although they expanded further with increasing temperature. For the NCC specimen, when the temperature was below 600°C, the cracks in the specimen were

Figure 13. In situ images of the concrete specimens at the different temperatures: (a) CLC; (b) NCC; (c) FAAC

not clearly seen. After that, cracks started to appear in the cement matrix and then penetrated through the ceramsite particles when the temperature was increased to 800°C. Owing to the strengthening of alkali-activated fly ash at high temperature, the cracks originating in the cement matrix of the FAAC specimen did not penetrate through the ceramsites, but extended along the edge of the ceramsite particles instead.

Conclusions

Based on the materials and the test procedures used in this paper, the following results were found.

- The use of alkali-activated fly ash to precoat ceramsites extremely reduced the spalling possibility of the ceramsite concretes.

- After exposure to 1200°C, the FAAC specimens still had good f_{cu} , $f_{cylinder}$, f_t , f_f and E .
- With the increase in temperature, the peak stress of the FAAC specimens reduced and the corresponding strain increased; this behaviour was similar to that of the CLC and NCC specimens.
- After exposure to 800°C, nepheline was formed in the hydrates of alkali-activated fly ash. The formation of this thermally stable phase could greatly improve the performance of such a system at high temperature.
- Heat-induced cracks appeared first in the cement matrix of the CLC specimen and then extended along the edge of the limestone particles. However, cracks in the NCC specimen could penetrate through the ceramsite particles. Alkali-activated fly ash protected the ceramsite particles in the FAAC specimen against cracking penetration; cracks in

the concrete evolved in a similar way as those developing in the CLC specimen.

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