Hindawi Publishing Corporation
Advances in Materials Science and Engineering
Volume 2016, Article ID 5972570, 6 pages
http://dx.doi.org/10.1155/2016/5972570

Research Article

Experimental Research on High Temperature Resistance of Modified Lightweight Concrete after Exposure to Elevated Temperatures

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Received 20 February 2016; Accepted 4 May 2016

Academic Editor: Osman Gencel

In order to improve the spalling resistance of lightweight aggregate concrete at high temperature, two types of modified materials were used to modify clay ceramsite lightweight aggregates by adopting the surface coating modification method. Spalling of the concrete specimens manufactured by using the modified aggregates was observed during a temperature elevation. Mass loss and residual axial compressive strength of the modified concrete specimens after exposure to elevated temperatures were also tested. Concrete specimens consisting of ordinary clay ceramsites and crushed limestone were manufactured as references for comparison. The results showed that the ordinary lightweight concrete specimens and the crushed limestone concrete specimens were completely spalled after exposure to target temperatures above 400°C and 1000°C, respectively, whereas the modified concrete specimens remained intact at 1200°C, at which approximately 25% to 38% of the residual compressive strength was retained. The results indicated that the modified lightweight concrete specimens have exhibited superior mechanical properties and resistance to thermal spalling after exposure to elevated temperatures.

1. Introduction

Lightweight aggregate concrete types are well known for their advantages of being lightweight and fire-resistant and for having high strength. They have wide use in high-rise buildings and large span bridges. Lightweight aggregates, such as pumice, expanded perlite, and clay ceramsite, which are made by burning, naturally have excellent resistance to high temperature [1]. Thus, it is expected that lightweight aggregate concrete types also have high application potential in chimneys, high temperature furnaces, tunnel fireproof layers, and other fire-resistant constructions. Several references claim that the residual mechanical properties of lightweight aggregate concrete types after exposure to high temperatures of 800°C or 1000°C were considerably higher than those of ordinary concrete types [2–7].

However, the spalling resistance of lightweight aggregate concrete types often behaves worse than that of ordinary concrete types in a fire due to the ability of lightweight aggregates to act as water reservoirs for evaporable water [8, 9]. The water in the lightweight aggregates either comes from prewetting of the aggregates, absorption from the fresh concrete, or penetration from the environment [10]. The increased moisture content will lead to both increased pore pressure and an increased temperature gradient during a fire [11]. The higher the moisture content, the higher the spalling probability as the moisture content is greater than a threshold value [12]. Thus, moisture content is the direct factor for the explosive spalling of lightweight aggregate concrete types. If the lightweight aggregate concrete types undergo explosive spalling in fire, their high temperature resistance cannot be fully effective

Table 1: Chemical composition and physical properties of slag cement.

Slag cement	Chemical composition: %							Physical properties	
	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	SO_3	Loss on ignition	Specific gravity	Fineness (45 μm): %
PSA	17.9	54.03	5.26	3.44	1.78	1.7	4.30	3.04	11

Table 2: Physical properties of coarse aggregates.

Aggregate type	Bulk density (kg/m^3)	1 h water absorption: %	Cylinder compressive strength (MPa)	Crushing value (2.5 mm): %
LS	1430	0.5	16.57	7.8
LWA	407	14.5	3.07	47.5
PLWA	410	10.8	2.74	/
GLWA	485	9.2	3.19	/

(a) LS (b) LWA (c) PLWA (d) GLWA

Figure 1: Different types of coarse aggregates.

in fire protection, thus limiting their application in the fire protection of the building structure.

In light of the unstable high temperature behavior of lightweight aggregate concrete types, in this study, two types of materials were used to modify clay ceramsite. The modified clay ceramsites were used to manufacture lightweight concrete types. The spalling characteristics, mass loss, and residual axial compressive strength of the concrete types after high temperature exposure were examined, and the results were compared to those of concrete types manufactured using normal clay ceramsites and crushed limestone.

2. Experimental Programmes

2.1. Raw Materials. The cement used in this study was slag Portland cement (PSA 32.5), provided by Hongshi Cements Ltd., Yiliang, Kunming, Yunnan, China. Its chemical composition and physical properties are given in Table 1. Sand with a fineness modulus of 2.54 was used as fine aggregate. Limestones (LS) and clay ceramsite lightweight aggregates (LWA) were used as coarse aggregates. Both the LS and the LWA had particle size ranges of 5 mm to 30 mm and were under continuous grading. Both fine aggregate and coarse aggregates were provided by Chengwei Chemical Building Materials Ltd., Kunming, Yunnan, China.

2.2. Modifications of the Lightweight Aggregates. By adopting the surface coating modification method, two types of materials were used to modify clay ceramsites, that is, modification material I [13] and modification material II [14]. The LS, LWA, modification material I modified lightweight aggregates (PLWA), and modification material II modified lightweight aggregates (GLWA) are shown in Figure 1. The physical properties of the different types of coarse aggregates are given in Table 2.

2.3. Preparation of Specimens. In order to investigate spalling and the compressive performance of the concrete types after exposure to high temperatures, four concrete mixes were prepared, including normal concrete (NC), lightweight aggregate concrete (LWAC), modification material I modified lightweight aggregate concrete (PLWAC), and modification material II modified lightweight aggregate concrete (GLWAC). A water/binder ratio (W/B) of 0.49 was used, and the total volume of aggregates was kept constant for all four mixes. The W/B used can allow the slump of all the mixes to meet the requirement of S2 [15]. The mix proportions of the concrete specimens are given in Table 3. Before mixing, oven-dried LS, LWA, PLWA, and GLWA were presaturated with the water required for their 1 h water absorption and half of the mixing water. The rest of the mixing water was added during the mixing.

After mixing, concrete types were cast into 100 mm × 100 mm × 300 mm prism mould. After demoulding, concrete specimens were cured in a standard curing room at a temperature of 20 ± 2°C and relative humidity above 95% for 28 days. Before the exposure to high temperatures, the extra water on the surface of the specimens was wiped off with a damp cloth.

Table 3: Mix proportions.

Mix	Per cubic meter (kg/m^3) Cement	Water	Coarse aggregate	Sand	28 d compressive strength (MPa)
NC	370	180	1222	658	28.3
LWAC	370	180	317	693	12.6
PLWAC	370	180	318	693	12.8
GLWAC	370	180	378	693	13.2

Table 4: Appearance and spalling statistics of the concrete specimens after exposure to elevated temperatures.

Mix	Temperatures: °C	Appearance Colors	Cracks	Spalling	Spalling statistics $R^{(1)}$: %
NC	20	Slight gray	—	—	66.7
	400	Slight red	Scarce and local	Slight	
	600	Dark red	A small amount of fine cracks	Medium	
	800	Cinereous	Long and wide	Medium	
	1000	Straw white	A large amount of long cracks	Heavy	
	1200	Slight yellow	Numerous and random	Heavy	
LWAC	20	Dark gray	—	—	100
	400	Dark red	Local microcracks	Slight	
	600	Slight red	A certain amount of fine cracks	Medium	
	800	Straw white	Long and wide	Medium	
	1000	Slight yellow	A large amount of long cracks	Heavy	
	1200	Soil yellow	Numerous and random	Heavy	
PLWAC	20	Dark gray	—	—	25
	400	Dark red	Scarce and local	—	
	600	Slight red	Few small shallow cracks	Slight	
	800	Straw white	A certain amount of fine cracks	Slight	
	1000	Slight yellow	Long and wide cracks at edges	Medium	
	1200	Soil yellow	Large amount and located at edges	Medium	
GLWAC	20	Dark gray	—	—	16.7
	400	Dark red	Unclear	—	
	600	Slight red	Scarce and local	Slight	
	800	Straw white	A small amount of fine cracks	Slight	
	1000	Soil yellow	Long and wide cracks at edges	Medium	
	1200	Brownish Yellow	Large amount and located at edges	Medium	

(1) R represents the percentage of the specimens spalled when the target temperature was above 400°C.

2.4. Heating Regime and Test Procedure. Before heating, the specimens in saturated-surface-dry condition were weighed at room temperature. Then, the specimens were placed in an electric furnace under unstressed condition and were heated to 200°C, 400°C, 600°C, 800°C, 1000°C, and 1200°C, respectively, with an increasing rate of 10°C/min. The elevation of temperature was controlled by a programming instrument with precision of 10°C. When the target temperatures were achieved, the temperatures were maintained as constant for 3 h to allow the specimens to reach a thermal steady state. Then, the heated specimens were cooled down slowly to room temperature in the furnace.

During the temperature elevation, the temperatures when spalling occurred were recorded. When the specimens were cooled, they were taken out from the furnace, and any surface changes (i.e., colors, cracks, spalling, etc.) of the specimens due to the high temperatures were recorded as well. The specimens that were still intact (i.e., without spalling) were weighed again followed by crushing for compressive strength test [16].

3. Results and Discussion

3.1. Appearance and Spalling. The appearance and spalling statistics of the specimens after exposure to elevated temperatures are reported in Table 4, and the spalling of the specimens after heating is shown in Figure 2. From Table 4 and Figure 2, it can be observed that no spalling occurred for the concrete specimens when the temperature was below 400°C. When the temperature increased to approximately 450°C, spalling occurred for the concrete specimens to different extents. Based on a statistical calculation, 66.7% of the NC specimens

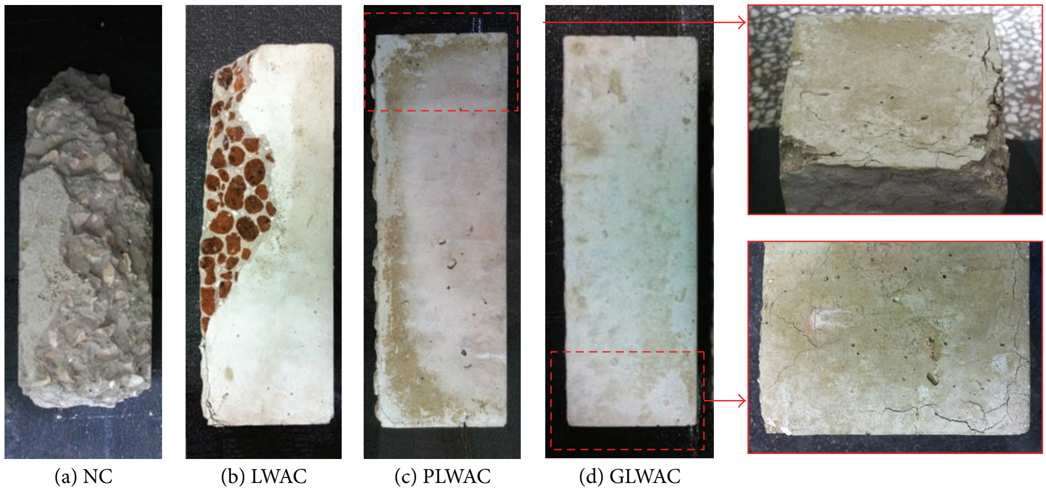

Figure 2: Spalling of the concrete specimens.

were spalled when the temperature was above 400°C; these values for the LWAC, the PLWAC, and the GLWAC specimens were 100%, 25%, and 16.7%, respectively. In general, the extent of the damage caused by spalling was most serious for the NC specimens. Spalling mainly occurred at the edges and corners of the specimens, and a considerable volume of the specimens was broken off from the prisms, as shown in Figure 2(a). The spalling mode for the LWAC specimens was tangential damage at the edges of the specimens, with cracks throughout the lightweight aggregates (refer to Figure 2(b)). However, for the PLWAC and the GLWAC concrete specimens, only mild damage was observed at the corners of the specimens, as shown in Figures 2(c) and 2(d).

From Table 4, it can be observed that, due to the prewetting treatment of the lightweight aggregates, the moisture content of the LWAC specimens should be higher than that of the NC ones, and the LWAC specimens were more prone to spall. However, the extent of the damage caused by spalling was smaller for the LWAC specimens. The modifications of the lightweight aggregates greatly reduced the risk of thermal spalling. This may be attributed to the following reasons: (1) the water absorption of the lightweight aggregates was reduced after the modifications (refer to Table 2), as well, leading to a lower moisture content in the concrete specimens, thereby reducing the spalling risk of the modified lightweight concrete types during heating; (2) with the increase of temperature, parts of modification material I could be melted gradually below 400°C to form microcracks, connecting the existing capillary pores to provide a channel for the escaping of water vapor, thus reducing the risk of the PLWAC specimens to spall [13]; (3) modification material II exhibited a superior performance at high temperature [14]. Therefore, the aggregates in the GLWAC specimens were enhanced, and the performance of the GLWAC specimens at high temperature was improved.

3.2. Mass Loss. Figure 3 shows the mass loss of the concrete specimens at different temperatures. Due to the spalling of the LWAC specimens after 400°C and of the NC specimens after 1000°C, the mass loss test could not be conducted for these two mixes above these temperatures. Normalized mass loss was calculated by using the following equation:

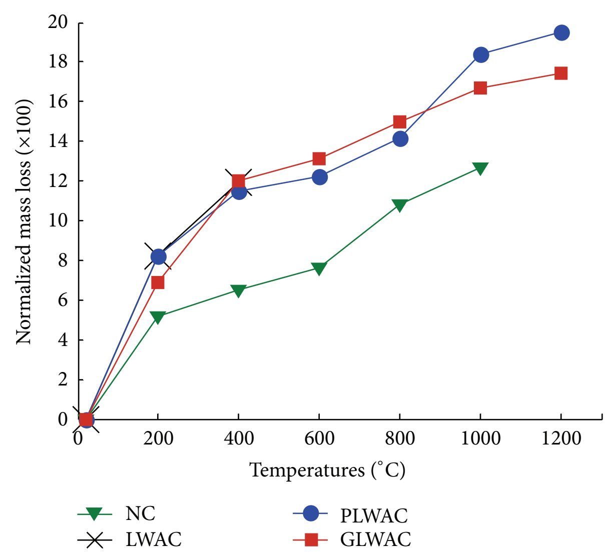

Figure 3: Mass loss of the specimens after being heated.

$$N_{\mathrm{ml}} = \frac{M_{\mathrm{o}} - M_t}{M_{\mathrm{o}}} \times 100, \tag{1}$$

where N_{ml} is normalized mass loss; M_{o} is the original weight at room temperature; M_t is the weight at a given temperature.

From Figure 3, it can be observed that the mass losses of the concrete specimens increased to different extents with the increase of temperature. Furthermore, the mass losses of the concrete specimens manufactured using lightweight aggregates were much larger than those of the NC specimens at all the temperatures. Therefore, it is considered that evaporation of water may be the main cause for the mass loss of the concrete specimens as more water could have been introduced into the lightweight concrete types at the beginning of

Table 5: Compressive strength of the concrete specimens after exposure to elevated temperatures.

Mix	Compressive strength (MPa)						
	20°C	200°C	400°C	600°C	800°C	1000°C	1200°C
NC	28.3	24.2	22.3	14.1	12.8	11.7	/
LWAC	12.6	12.4	11.4	/	/	/	/
PLWAC	12.8	11.8	10.7	8.9	8.0	5.3	3.3
GLWAC	13.2	11.9	12.1	8.8	7.8	6.2	4.9

the mixing. Due to the modifications of the lightweight aggregates, the water absorption of the PLWA and the GLWA was lower than that of the reference lightweight aggregates (refer to Table 2). Therefore, it was expected that the mass losses of the modified concrete types should be lower than that of the reference lightweight concrete. This was true for the GLWAC specimens. However, the mass loss of the PLWAC specimens was similar to that of the LWAC specimens. The reason for this could be attributed to the melting of modification material I at approximately 200°C–400°C to increase the mass loss of the PLWAC specimens. When the temperature increased to approximately 400°C, although a larger amount of water was involved in the LWAC specimens, the escape of water was much difficult (which may be the reason why the LWAC specimens spalled completely at such temperature). Therefore certain amount of water could be still retained in the specimens, which reduced their mass loss. Compared to the PLWAC specimens, the greater mass losses of the GLWAC specimens at both 600°C and 800°C may be the result of the solidification of the matrix of modification material II [14]. The higher mass loss of the PLWAC specimens after 800°C could be due to the decomposition of modification material I.

3.3. Relative Residual Compressive Strength. Compressive strengths of the concrete specimens at room temperature and the elevated temperatures were reported in Table 5, and the relative results were plotted in Figure 4. The relative residual compressive strength is defined as the ratio between the residual compressive strength at a given temperature and the compressive strength at room temperature. Due to the occurrence of spalling, the compressive strength tests were not conducted for the LWAC specimens after 400°C and for the NC specimens after 1000°C, respectively. From Figure 4, it can be observed that, with the increase of temperature, the residual compressive strength of all the specimens declined. When the temperature was below 400°C, more than 80% of the compressive strength was retained for the concrete specimens. When the temperature was above 400°C, the LWAC specimens spalled completely, and the residual compressive strength for the other concrete specimens began to dramatically decrease. When the temperature further increased to 1200°C, the NC specimens spalled completely, whereas the PLWAC and the GLWAC specimens still had 25% and 38% of the compressive strength retained, respectively.

From Figure 4, it also can be seen that the lightweight concrete specimens always had higher residual compressive strength than the NC specimens after exposure to the elevated temperatures. It is known that the heat conductivity of

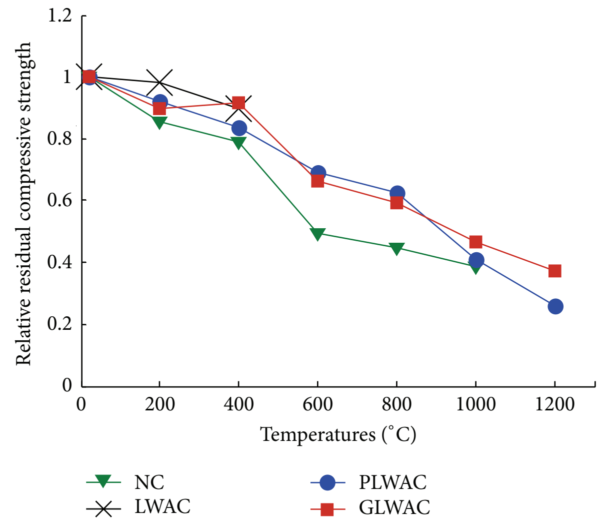

Figure 4: Relative residual compressive strength of the concrete specimens after exposure to elevated temperatures.

lightweight aggregates is lower than that of limestone aggregates [17, 18]. As a result, the temperature rise in lightweight aggregate concrete specimens is at least 15%–20% lower than that of ordinary concrete specimens at high temperature [19]. In this context, compared to the NC specimens, the influence of high temperature on the compressive performance was smaller for the concrete specimens with lightweight aggregates. Furthermore, the materials used to modify the lightweight aggregates may have changed the bonding properties between the cement matrix and the lightweight aggregates. Compared to the reference lightweight concrete specimens, such changing would likely have resulted in different mechanical behavior for the modified concrete specimens. This issue will be explored and detailed in further work.

When the temperature was above approximately 800°C, the decrease in the compressive strength of the PLWAC specimens was clearer than that of the GLWAC specimens. The reason for this may be attributed to the decomposition of modification material I in the former, whereas the solidification of modification material II at high temperature could allow the strength of the latter to remain at a relatively high level.

4. Conclusions

Based on the experimental programme adopted in this study, the following conclusions could be drawn:

(i) The modified lightweight aggregate concrete specimens had much lower risks and extents of spalling after exposure to elevated temperatures. The reasons for this could be attributed to the reduced water absorption, the melting of parts of modification material I in PLWAC specimens, and the improved high temperature resistance of modification material II in GLWAC specimens.

(ii) After 1200°C, the PLWAC and the GLWAC specimens still had 26% and 38% of the compressive strength retained, respectively, exhibiting superior resistance to high temperature.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

Acknowledgments

The authors gratefully acknowledge the financial supports from the National Science Foundation of China (Grant no. 11562010), the China Postdoctoral Science Foundation (Postdoctoral no. 150039 and Grant no. 2015M572646XB), and the Talent Introduction Project of Kunming University of Science and Technology (Grant no. KKSY201406112).

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