Residual compressive strength of cement-based grouting material with early ages after fire

Qingtao Li[a], Lujie Liu[a], Zhaohui Huang[b]*, Guanglin Yuan[a]

[a] State Key Laboratory for Geomechanics & Deep Underground Engineering, School of Mechanics & Civil Engineering, China University of Mining & Technology, Xuzhou, Jiangsu 221116, China

[b] Department of Mechanical, Aerospace and Civil Engineering, College of Engineering, Design and Physical Sciences, Brunel University, Uxbridge, Middlesex UB8 3PH, UK

Abstract

In this paper a comprehensive experimental investigation on the residual compressive strength of cement-based grouting materials after exposed to high temperature is presented. The research focused on the influences of different temperatures, curing ages before and after heating and water mixing ratios on the residual compressive strength of the material. The research indicates that the residual compressive strength of cement-based grouting material reduces significantly after heating. The reduction of the residual compressive strength of the material increases with increasing water mixing ratio. For the specimens exposed to higher temperature, such as 550 ^{0}C, the residual compressive strength cannot recover after heating. The research generated a set of reliable and valuable test data for the researches and practical structural engineers in the field of structural fire engineering.

Keywords: Cement-based grouting material; Curing age; High temperature; Water mixing ratio; Residual compressive strength.

* Corresponding author, E-mail address: zhaohui.huang@brunel.ac.uk (Z. Huang)

RESEARCH HIGHLIGHTS:

- Residual compressive strength of CGM material reduces considerably after heating.
- Residual compressive strength of CGM decreases with increasing water mixing ratio.
- Residual compressive strength of CGM cannot recover after exposed to 550 ^{o}C.
- A set of valuable test data has been generated in this research.

1. Introduction

In recent years, cement-based grouting material (CGM) has been widely used for repairing and strengthening building structures. This is because of CGM has super early strength, fluidity, no shrinkage and convenient for construction [1-3]. Previous researches indicate that the strength of cementitious materials at early ages changes considerable with time. Bentz et al. [4] found that the compressive strengths of concrete (with water cement ratio of 0.425) at early curing ages of 1, 3 and 7 days were 30%, 60%, 74% of the 28 days' strength, respectively. Benaicha et al. [5] found that the compressive strengths of high performance concrete at curing ages of 1, 3 and 7 days were 57%, 62%, 71% of the compressive strength at 28 days, respectively. Kima et al. [6] indicated that the compressive strengths of the concrete (with water cement ratio of 0.4) for curing ages of 1, 3 and 7 days were 41%, 62% and 82% of the compressive strength at 28 days. The experimental results generated by Kocak and Nas [7] indicated that the compressive strengths of the fly ash concrete with curing ages of 2 and 7 days were 43% and 79% of the compressive strength at 28 days, respectively. Madandoust et al. [8] found that the compressive strength of concrete increased with the curing age of the concrete and the strength increase ratio was more significant during the curing ages between 14 and 42 days.

In recent years, there were considerable numbers of fire accidents happened during the construction period of buildings due to some problems related to the organization and management of construction site. For example, a big fire lasted for 4.5 hours happened at the 23 floor on the 25 storeys reinforced concrete building which was just finished concreting for 3 days in Wuhan, China [9]. The temperature within the concrete floor reached 400 ^{o}C. The concrete strength was significantly affected by the fire. Therefore, for assessing the structural safety of the building after fire it is really important to understand the mechanical properties of such early age of concrete after exposed to fire.

Hence, the mechanical properties of early age concrete after exposed to high temperatures have attracted many researchers' attention. Chen et al. [10] conducted an experimental study on the mechanical properties of early age normal-strength concrete after exposed to high temperatures. Wang et al. [11] found that the ultimate bearing capacities of the concrete columns in the age of 14 and 28 days were reduced to 41% and 60%, respectively after exposed to the temperature of 550 ^{o}C.

The test results generated by Ma [12] indicated that the residual compressive strength of fly ash concrete after high temperature increased with the increasing curing age.

At present, some researchers have conducted a number of studies on the mechanical strength of cement-based grouting material after exposed to high temperatures. Yan et al. [13] indicated that the fire resistance of cement-based grouting material is better compared to normal concrete. Yuan et al. [14] found the residual compressive strength of cement-based grouting material after high temperature decreased with increasing water mixing ratio.

Because of the cement-based grouting material has high compressive strength in the early stage of construction, its mechanical properties are considerably different compared to normal concrete. Hence, it is needed to understand the mechanical properties of the early age cement-based grouting material after exposed to fire. This information is very important for structural engineers to assess the structural safety after fire. However, according to the authors' knowledge there are very limited researches on the residual strength of early age cement-based grouting material after exposed to high temperature. Therefore, the main objectives of this research are:

- Conduct a series of tests to investigate the residual compressive strength of cement-based grouting material after exposed to different temperatures.
- Study the influence of temperatures on the degradation of the compressive strength of cement-based grouting material.
- Investigate the influences of different curing ages before and after exposed to high temperatures and water mixing ratios on the residual compressive strengths of cement-based grouting material.
- Generate a set of valuable test data for the fellow researches who develop numerical models and practical structural engineers who conduct repairing and strengthening of reinforced concrete buildings.

2. Test specimens

In this research the cement-based grouting material was provided by Zhengzhou Nuweison Construction Engineering Technology Ltd. The material was high-strength and no shrinkage cement grouting material (CGM-1). Its compositions and properties are given in Tables 1 and 2, respectively. The compositions of additive binding gelled material are shown in Table 3. According to Chinese design code for cementitious grouting material [15], in this research four key design curing ages of 3, 7, 14, and 28 days before heating were adopted. Previous researches [16, 17] indicated that when cementitious materials were exposed to the temperature higher than 600 ^{o}C, the compressive strength of the materials was significantly degraded. The concrete structural members after such high temperature were unrepairable. Hence, three level temperatures of 150 ^{o}C, 350 ^{o}C and 550 ^{o}C were adopted in this research. The research conducted by Yuan et al. [18] indicated that the water mixing ratio of cement-based grouting material is another important factor needed to be considered. In this research three water mixing ratios of 12%, 14% and 16% were used for the cement-based grouting material. The test specimen size is 100 mm x100 mm x 100 mm. The specimens were stored in the structural lab under the conditions of 20 ^{o}C and R.H. = 95% for curing. Before the heating the specimens were naturally dried for one day.

3. Test procedure

In this research, an electrical heating furnace GWD-02A with power of 18 kW was used to heat the specimens. The furnace has computerized temperature control system. For simulating real fire accident, high heating ratio was adopted. Based on the recommendation from previous researches [17, 18], the high heating rate of 10 ^{o}C/min was used for all tests. In order to make sure the temperature within the specimens is uniformly distributed, the specimens were heated to the target temperature then the target temperature was maintained for 90 min. After heating the specimens were cooled down to ambient temperature under natural air cooling condition. Then the specimens were stored in normal lab condition (20 ^{o}C and R.H. = 95%) until total curing time of 28 days (curing time before heating + curing time after heating) to be reached. After that the specimens were loaded to failure to obtain the residual compressive strengths of the specimens. For the loading tests, a YAW-3000 type electro-hydraulic servo pressure tester was used and the loading speed was controlled between 5 kN/s and 8 kN/s [19]. Table 4 summarizes the test conditions of the specimens. For comparison, the specimens of different water mixing ratios at the curing age of 28 days without heating were tested. The compressive strengths of the specimens with the water mixing rates of 12%, 14%, 16% were 73.8 MPa, 67.1 MPa, 61.5 MPa, respectively. For each test three identical specimens were used and the average residual compressive strength of each test was calculated.

4. Test results

4.1. Surface appearance of the specimens after heating

As shown in Fig. 1, after exposed the specimens to the temperatures of 150 ^{o}C, 350 ^{o}C, 550 ^{o}C, the colors of the specimen surface changed from the primary color into brick red and dark red colors. It can be seen that the specimens exposed to the temperature of 150 ^{o}C, there were almost no cracks on the surfaces of specimens. For the specimens exposed to the temperature of 350 ^{o}C, there were some little tiny cracks appeared within the surfaces of the specimens. After exposed to the temperature of 550 ^{o}C, the cracks became more notable. Also for the specimens with higher water mixing ratio there were more cracks resulted from heating.

4.2. Influence of curing age on the residual compressive strength

As mentioned above the results presented in this section are related to the specimens which had total curing age of 28 days (curing time before heating + curing time after heating). Table 5 gives the residual compressive strengths of the specimens ($f_{c,T}$) tested under different conditions.

For analyzing the residual compressive strengths of the cement-based grouting material with different curing ages before heating, the ratio of residual compressive strength after heating is defined as: $f_{c,T}$ / $f_{c,20}$, in which $f_{c,20}$ is the 28 days' compressive strength at ambient temperature. Fig. 2 shows the comparison of the ratio ($f_{c,T}$ / $f_{c,20}$) against different curing ages before heating for the specimens with three water mixing ratios under three exposed temperatures.

As shown in Fig. 2, the residual compressive strengths of the specimens with a 7 days curing age before heating were the highest compared to other curing ages before heating under different exposed temperatures and water mixing ratios. However, the residual compressive strengths of the specimens with 3 days curing age before heating were slightly bigger than the one of 14 and 28 days curing ages before heating. It also can be seen that the residual compressive strengths of the specimens with 28 days curing age before heating were the lowest. The exposed temperature has significant impact on the degradation of compressive strength of cement-based grouting material. For example, as shown in Fig. 2(a), after exposed to the temperature of 150 ^{o}C the residual compressive strengths of the specimens with 3, 7, 14, 28 days curing ages before heating were reduced by 12.9%, 2.9%, 13.1% and 12.9%, respectively compared to the specimens without heating. But, for the specimens exposed to the temperature of 550 ^{o}C, the residual compressive strength of the specimens with 3, 7, 14, 28 days curing ages before heating were reduced by 34.3%, 27.4%, 36.8% and 34.3%, respectively.

In order to deeply understand the test results, the microstructure analyses of the typical heated specimens were conducted. Fig. 3 shows the microstructures of the specimens heated to the temperature of 550 ^{0}C with different curing ages before heating. The specimens had the water mixing ratio of 12%.

For cement-based grouting material the hydration products such as C-S-H gel within the specimen are gradually increased with the extension of curing age before heating. During curing period, due to increasing the degree of hydration, more and more hydration products are generated. Hence, the density and integrate of the material are enhanced as the curing age before heating is increased. For the specimen with a 3 days curing age before heating, the hydration products were relatively less compared to the specimens with the curing ages of 7, 14 and 28 days. Also within the specimen, there was more free water, and relatively less crystal water and larger porosity. The flocculent structure of hydration products was relatively loose and the integrity of the material structure was poor. For the specimens with a 7 days curing age before heating, the hydration products were increased and free water was reduced with crystal water phase increased. Also the porosity of the material was decreased significantly. The flocculent structure of hydration products was denser. However, compared to the specimens with 14, 28 days curing age before heating, the structure of hydration products was still relatively loose and the integrity of the material was not very good. For the specimens with 14, 28 days curing ages before heating, the degree of hydration was considerably increased which further reduced free water, porosity and increased crystal water within the material. Hence, the density of the structure of hydration products was further increased and resulted good integrity of the material.

After the specimens were exposed to high temperature of 550 °C, the dehydration and decomposition of the hydration products within the specimens occurred. The free water, capillary water, gel water and crystal water in the specimens were evaporated due to high temperature. For the specimens with 3, 7 day curing ages before heating, due to relatively loose material structures the water within the specimens was more easily escaped. This resulted considerable less cracks inside the specimens. In contrast, for the specimens with 14, 28 day curing ages before heating, there were considerable cracks formed within the specimens resulted from high water vapor pressure generated within the specimens due to high density of the material.

By detail examining Fig. 3(b) it can be seen that for the specimen with a 7 days curing age before heating, there were a lot of remnants of hydration products within the specimen. These hydration products filled the part of cracks which resulted from high temperature. Compared with Fig. 3(a) it is clear that the remnants of hydration products within the specimen with a 7 days curing age before heating were much more than the one of the specimen with a 3 days curing age before heating. For the specimen with a 3 days curing age before heating, the internal structure was looser due to the thermal decomposition of hydrated cement paste during heating and the water was more easily to escape from the specimen. In contrast, the specimen with a 7 days curing age before heating had high degree of hydration, its internal structure was compact and the water was more difficult to escape from the specimen. Hence, during curing period after heating there was enough water for the cement hydrations to be continued within the specimen. However, there was less water available for continuing cement hydrations for the specimen with a 3 days curing age before heating due to significant loss of water during heating process. Therefore the remnants of hydration products within the specimen were much less compared to the specimen with a 7 days curing age before heating.

Comparing Figs. 3(a), (c) and (d) it can been seen that after heating the hydration products within specimen with a 3 days curing age before heating were more than the one of the specimens with 14 or 28 days curing ages before heating. The specimen with a 28 days curing age before heating had least remnants of the hydration products and more cracks formed within the specimen. Therefore, the residual compressive strength of the specimen with a 7 days curing age before heating was the highest compared to the specimens with 3, 14 and 28 days curing ages before heating. And the residual compressive strength of the specimen with a 28 days curing age before heating was the lowest.

Cement-based grouting material has the characteristics of gaining strength at early curing age. For example, the specimen with a 14 days curing age before heating has completed the hydration for the most of cement paste. During the curing period after heating there were only small parts of cement continuing to hydrate, so the remnants of the hydration products within the specimen were very limited. The level of hydration of the specimen with a 28 days curing age before heating was the highest compared to the specimens with less curing ages. Hence, the hydration within the specimen almost cannot happen during the curing period after heating and there were least residual hydration products within the specimen. Also due to the hydration process within the specimen was almost completed, the material structures had good integrality and internal voids within the material were relatively smaller. Hence, when exposed to high temperature the significant uneven expansions of different composition materials resulted the significant cracks within the specimen. Hence the size of the cracks in the specimen with a 28 days curing age before heating was the largest compared to other specimens (see Fig. 3(d)).

4.3. Influence of exposed temperatures on the residual compressive strength

Fig. 4 shows the relationships of the ratio ($f_{c,T}$ / $f_{c,20}$) against the exposed temperatures for the specimens with different curing ages before heating and water mixing ratios. It is evident that the residual compressive strengths of the specimens were reduced with the exposed temperature increased. The general degradation trends of residual compressive strength were similar for the specimens with three water mixing ratios.

After the specimens exposed to 150 ^{o}C, the free water inside the specimen started to evaporate and some hairline cracks and pores were formed within the specimen. This caused the degradation of the residual compressive strength of the specimens. After exposed to 350 ^{o}C, the incompatibility of thermal expansion of aggregate and cement paste became more significant and the interaction between the aggregate and cement paste was weakened resulted the deduction of the residual compressive strengths of specimens. After exposed to 550 ^{o}C, the C-S-H gel within the specimens decomposed considerably; the dehydration of $Ca(OH)_2$ generated CaO; quartz crystal and quartz were transformed from stable α type to the β type quartz and the volume of the specimens were expensed rapidly [18]. All of these led to the considerably reduction of the residual compressive strength of the specimens.

Fig. 5 shows the SEM images of the unheated and heated (550 ^{o}C) specimens with a 28 days curing age before heating and the water mixing ratio of 12%. From Fig. 5(a) it can be seen that for the specimen without heating the structure of the material was intact and the hydration products were abundant. There were a large number of flocs which were C-S-H gel. The free water, pore water and water of crystallization of the specimens were filled with clusters of hydration products and their internal pore structure, the density of hydration products’ structure was good resulted good integrity of the material. As shown in Fig. 5 (a), flocculent structure was fully filled in the material.

However, as shown in Fig. 5(b), the specimen was heated to 500 ^{o}C. It is clear that the flocs were reduced significantly and there were a lot of cracks formed within the material. That shows a substantial reduction of hydration products after heating to high temperature. This is because of a large number of C-S-H decomposed and the transformations of quartz crystal and quartz from stable α type to the β type quartz as mentioned before. Also the free water, pore water and crystal water within the specimens were all escaped. Especially due to escaping crystallization water from the hydration products, the structure of hydration products became discontinuous which resulted to form cracks within the specimens. Another factor to produce cracks was the non-uniform thermal expansion of aggregate and cement paste at high temperature.

4.4. Influence of water mixing ratios on the residual compressive strength

Fig. 6 shows the relationships of the residual compressive strength ($f_{c,T}$) against water mixing ratios for the specimens with different curing ages before heating and exposed temperatures. From the figure it is evident that the general trends of the influences of water mixing ratios on the degradation of residual compressive strengths are similar for the specimens with different curing ages before heating and exposed to different temperatures. The residual compressive strengths of the specimens were reduced with increasing water mixing ratios.

Fig. 7 shows the SEM images of the specimens of a 7 days curing age before heating, with different water mixing ratios and exposed to 550 ^{o}C. From Fig. 7(a) it is evident that the specimen with water mixing ratio of 12% had more hydration products which filled the cracks resulted from the heating. In contrast, as shown in Fig. 7(c), there were very little hydration products formed and a large number of cracks appeared inside the material. This is because of the density of the specimen with lower water mixing ratio (12%) was larger than the specimen with higher water mixing ratio (16%). So the water within the specimen with water mixing ratio of 12% was difficult to escape from the material which was benefit to form more hydration products after heating. Therefore the residual compressive strengths of the specimens reduced with increasing water mixing ratios.

4.5. Influence of curing ages after heating on the residual compressive strength

In order to investigate the influences of curing ages after heating on the residual compressive strength, another series of tests were conducted for the specimens with a 14 days curing age before heating and three water mixing ratios. The specimens were exposed to temperatures of 150 ^oC, 350 ^oC and 550 ^oC, respectively, then after heating the specimens were stored under normal lab's condition for different curing ages of 1, 3, 7, 14 and 28 days before conducting compressive strength tests. Three identical specimens were tested under each condition and average value was used. As discussed in Section 4.2, the specimens with a 14 days curing age before heating had the lowest residual compressive strengths. This is the reason why 14 days curing age before heating were adopted in this section.

Table 6 gives the residual compressive strengths of the specimens with different water mixing ratios and exposed temperatures under different curing ages after heating. Fig. 8 shows the relationships of the ratio ($f_{c,T}$ / $f_{c,20}$) against the different curing ages after heating for the specimens under different water mixing rations and exposed temperatures. It can be seen from Figs. 8(a) to (c) that the residual compressive strengths of the specimens with a 3 days curing age after heating were the lowest compared to other curing age after heating. The reasons may be explained as the following:

After heating there were a number of small cracks and voids formed inside the material due to the evaporation of moisture and uneven thermal expansions of different compositions of the material. For initial curing period after heating (such as one day) the material cannot absorb enough moisture to produce the hydration products which will fill the gaps of the cracks and voids within the material. Hence, very little of residual compressive strength of the material can be recovered.

After curing age reached 3 days, the moisture was absorbed by the surface of the specimens. The second hydration happened within the surface layer of the specimen due to the water absorption. For example, CaO was extremely easy to absorb moisture to generate $Ca(OH)_2$ and expanded. At the same time the surface part of the pore also expanded due to the water absorption. These caused the expansion of the material closed to surface of the specimen and generated non-uniform deformation within the specimen. Hence, further cracks within the specimen may form during this period. So the residual compressive strength of the specimen was reduced.

After that the residual compressive strengths of the material recovered considerable during the curing ages of 3-14 days. This is because of that more moisture seeped into the specimen and accelerated the formation of hydration products within the material, which filled the gaps of the cracks and voids in the material. Hence, the residual compressive strengths were regained during this period. However, after 14 days of curing age very little of residual compressive strengths were recovered. It is evident that the recovery of the residual compressive strengths of the material is insignificant during the curing period after heating.

5. **Conclusions**

In this research a series of tests were conducted to investigate the residual compressive strength of cement-based grouting materials after exposed to different temperatures. The main parameters considered for the specimens were curing ages before and after heating and water mixing ratios. Based on the test results the following conclusions can be drawn:

- The reduction of residual compressive strength of the specimen with a 7 days curing age before heating was the smallest compared to other specimens with 3, 14, 28 days curing ages before heating. The reduction of residual compressive strength of the specimen with a 28 days curing age before heating was the largest compared to other specimens.
- The residual compressive strength of cement-based grouting material reduces significantly after heating. The higher exposed temperature the more reduction of residual compressive strength of the material.
- The reduction of the residual compressive strength of cement-based grouting material increases with increasing water mixing ratio. However, the influence of water mixing ratio is not very significant.
- The residual compressive strengths of the specimens reduce considerably with a 3 days curing age after heating then gradually recover with 7-14 days curing ages after heating. After 14 days the influence of curing age after heating has negligible influence on the residual compressive strengths of the material. For the specimens exposed to higher temperature, such as 550 ^{o}C, the residual compressive strength cannot be recovered after heating.

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Figure and table captions

Table 1 Mix design of the high-strength cement grouting material (CGM-1).

Table 2 Properties of the high-strength cement grouting material (CGM-1).

Table 3 Chemical composition of additive binding gelled material.

Table 4 The test conditions of the specimens.

Table 5 Residual compressive strengths ($f_{c,T}$) of the specimens tested under different conditions (MPa).

Table 6 The residual compressive strengths ($f_{c,T}$) of the specimens with different water mixing ratios and exposed temperatures under different curing ages after heating (MPa).

Fig. 1 Surface appearance of the specimens after heating.

Fig. 2 Comparison of the ratio ($f_{c,T}$ / $f_{c,20}$) against the different curing ages before heating for the specimens under different conditions.

Fig. 3 The SEM images of the specimens heated to the temperature of 550 ^{o}C with different curing ages before heating.

Fig. 4 The relationships of the ratio ($f_{c,T}$ / $f_{c,20}$) against the exposed temperatures for the specimens with different curing ages before heating and water mixing ratios.

Fig. 5 The SEM images of the unheated and heated specimens with a 28 days curing age before heating and the water mixing ratio of 12%.

Fig. 6 The relationships of the residual compressive strength ($f_{c,T}$) against the water mixing ratio for the specimens with different curing ages before heating and the exposed temperatures.

Fig. 7 The SEM images of the specimens of 7 days curing age before heating, with different water mixing ratios and exposed to 550 ^{o}C.

Fig. 8 The relationships of the ratio ($f_{c,T}$ / $f_{c,20}$) against the curing age after heating for the specimens of 14 days curing age before heating and with different water mixing ratios.

Tables

Table 1 Mix design of the high-strength cement grouting material (CGM-1)

Composition	High-strength cement	Quartz sand	Water reducing agent	Expanding agent
Content（wt. %）	50	48.9	1	0.1

Table 2 Properties of the high-strength cement grouting material (CGM-1)

Density	Fluidity	Vertical expansion rate	Compressive strength (1 day)	Compressive strength (3 days)	Size of quartz sand
2200 kg/m^3	≥300 mm	≥0.02%	≥30 MPa	≥45 MPa	5μ to 5 mm

Table 3 Chemical composition of additive binding gelled material

Composition	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO	TiO_2	Fe_2O_3	LOI
Content (wt. %)	0.38	3.72	7.26	18.99	5.85	0.807	51.49	0.304	2.615	8.59

Table 4 The test conditions of the specimens

<table>
<tr><th rowspan="2">Water mixing ratio (wt. %)</th><th rowspan="2">Heating temperature (^0C)</th><th colspan="2">Total curing age = 28 days</th></tr>
<tr><th>Curing age before heating (day)</th><th>Curing age after heating (day)</th></tr>
<tr><td rowspan="3">12</td><td>150</td><td rowspan="9">3
7
14
28</td><td rowspan="9">25
21
14
0</td></tr>
<tr><td>350</td></tr>
<tr><td>550</td></tr>
<tr><td rowspan="3">14</td><td>150</td></tr>
<tr><td>350</td></tr>
<tr><td>550</td></tr>
<tr><td rowspan="3">16</td><td>150</td></tr>
<tr><td>350</td></tr>
<tr><td>550</td></tr>
</table>

Table 5 Residual compressive strengths ($f_{c,T}$) of the specimens tested under different conditions (MPa)

Water mixing ratio (wt. %)	Heating temperature (^{0}C)	Curing age before heating			
		3 days	7 days	14 days	28d
12	150	64.3	71.7	64.1	63.3
	350	61.6	67.2	58.6	52.3
	550	48.5	53.6	46.7	45.5
14	150	59.0	65.4	58.2	55.6
	350	53.2	58.7	50.7	50.6
	550	37.4	44.1	36.7	35.7
16	150	55.4	60.5	53.2	51.6
	350	48.2	51.8	47.5	45.7
	550	32.6	38.0	30.6	30.6

Table 6 The residual compressive strengths ($f_{c,T}$) of the specimens with different water mixing ratios and exposed temperatures under different curing ages after heating (MPa)

Water mixing ratio (wt. %)	Heating temperature (^{0}C)	Curing age after heating				
		1 day	3 days	7 days	14 days	28 days
12	150	65.05	60.30	64.59	66.38	65.28
	350	61.20	58.31	57.53	63.45	62.26
	550	52.51	46.65	53.99	51.97	52.65
14	150	57.19	53.26	58.73	60.17	62.64
	350	58.59	51.39	54.97	57.17	59.73
	550	40.55	31.59	36.43	38.94	35.70
16	150	53.14	50.68	56.33	57.73	58.64
	350	51.92	47.98	53.38	56.37	57.54
	550	37.13	28.79	32.13	35.89	37.64

Figures

150 °C　　350 °C　　550 °C

(a) Water mixing ratio = 12%

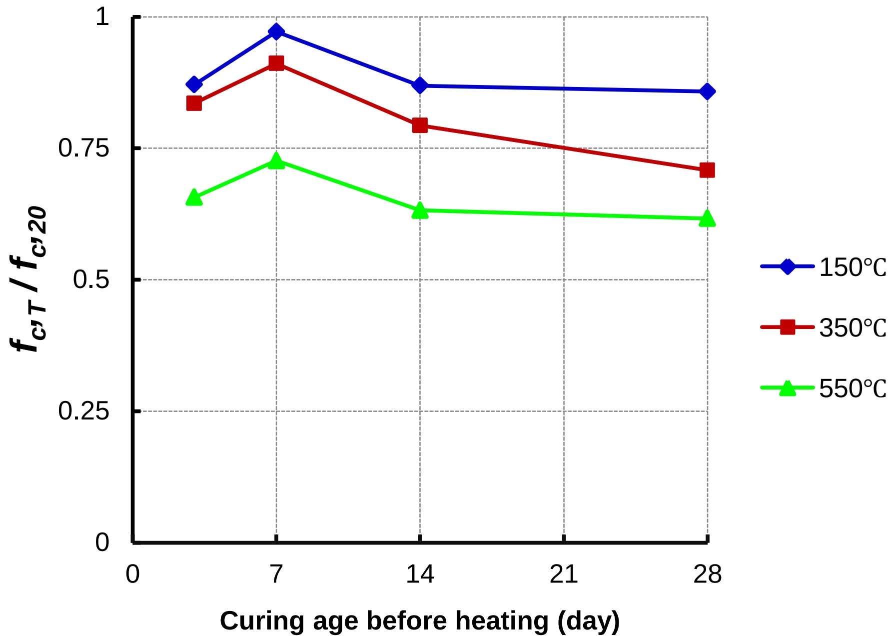
150 °C　　350 °C　　550 °C

(b) Water mixing ratio = 14%

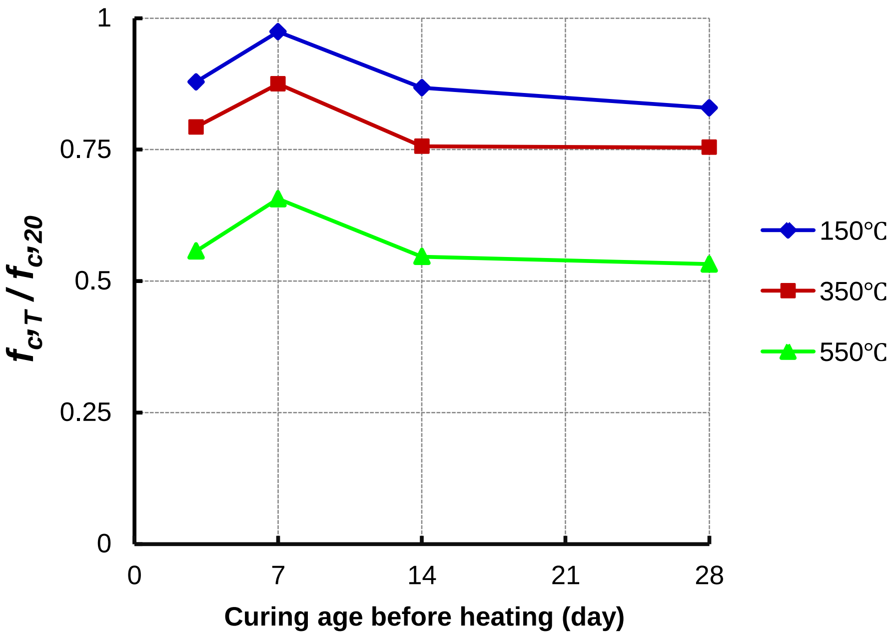
150 °C　　350 °C　　550 °C

(c) Water mixing ratio = 16%

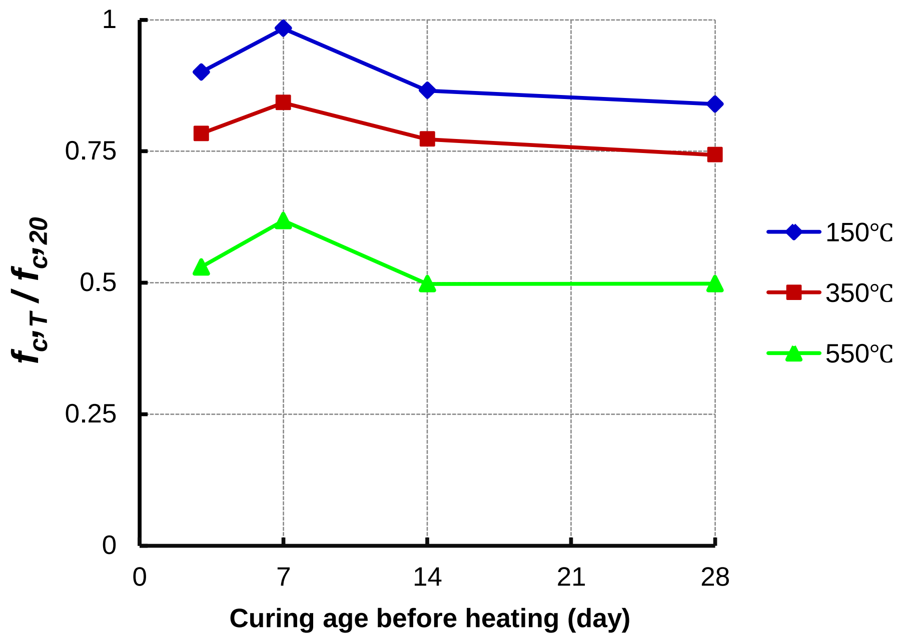
Fig. 1 Surface appearance of the specimens after heating.



(a) Water mixing ratio of 12%

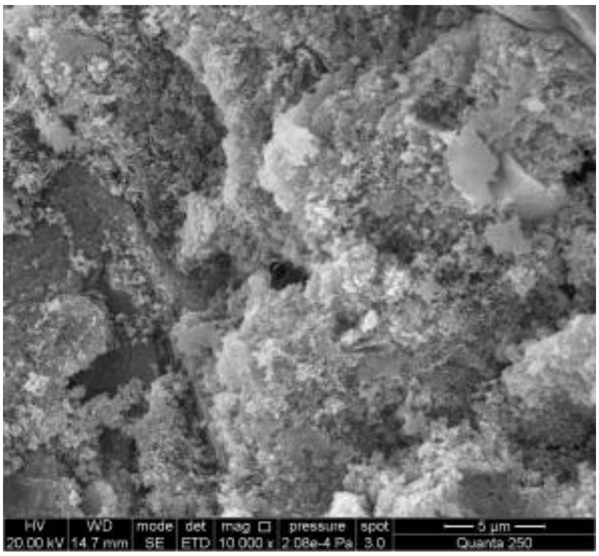


(b) Water mixing ratio of 14%

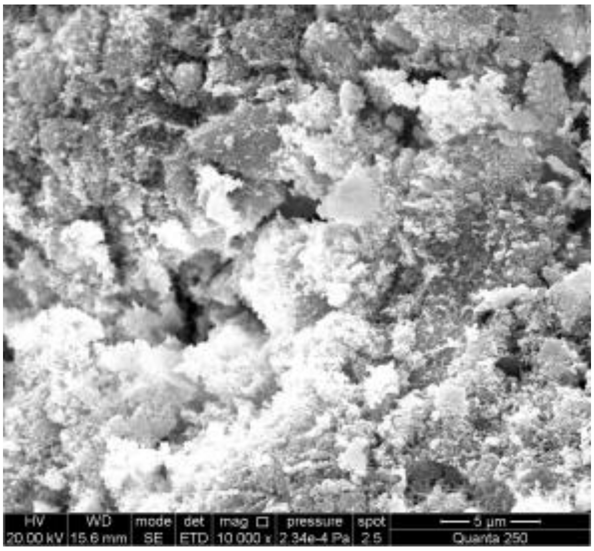


(c) Water mixing ratio of 16%

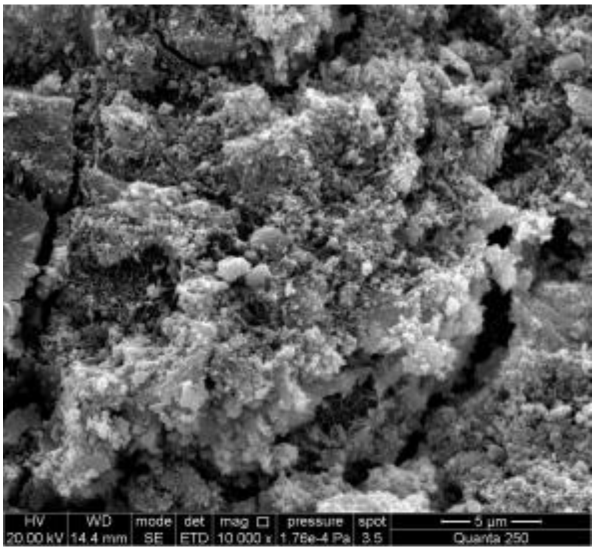
Fig. 2 Comparison of the ratio ($f_{c,T}$ / $f_{c,20}$) against the different curing ages before heating for the specimens under different conditions.



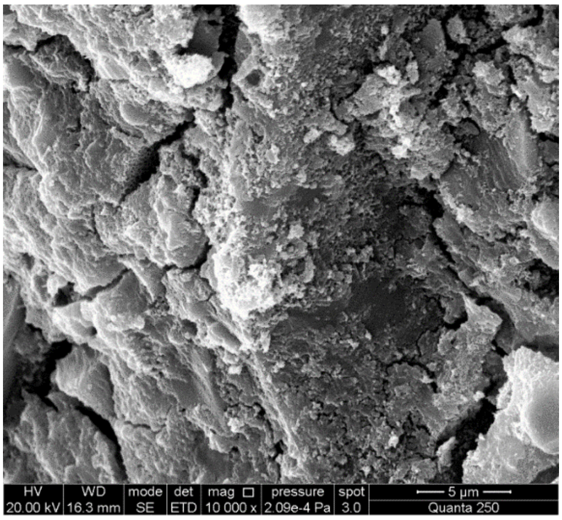
(a) 3 days curing age before heating



(b) 7 days curing age before heating

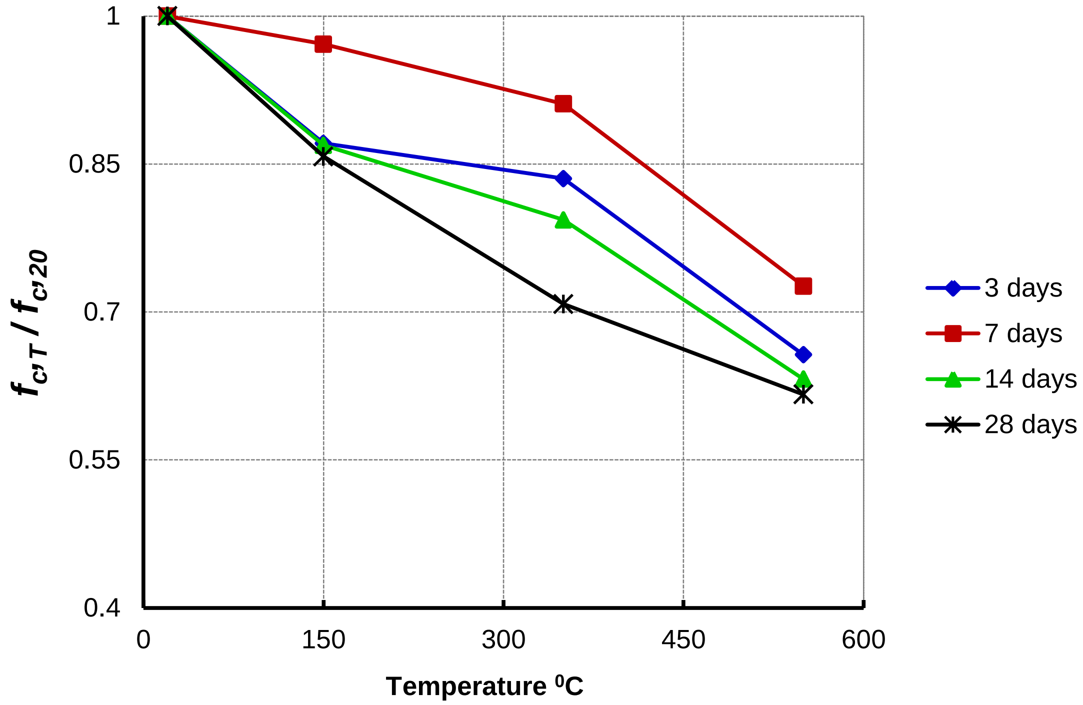


(c) 14 days curing age before heating

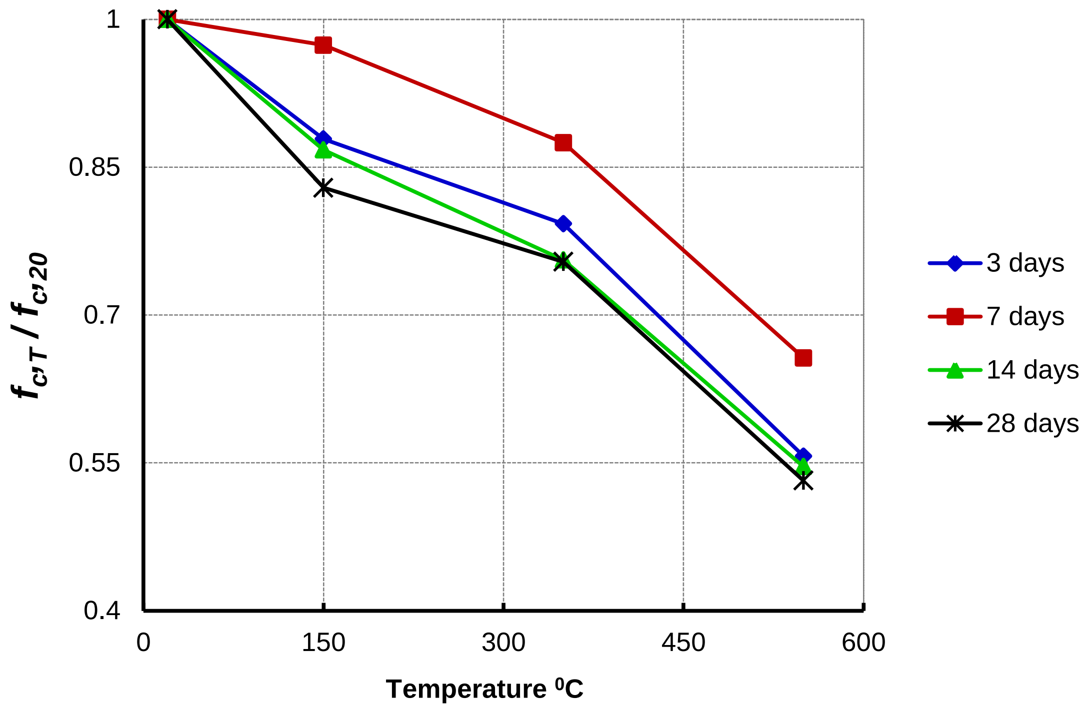


(d) 28 days curing age before heating

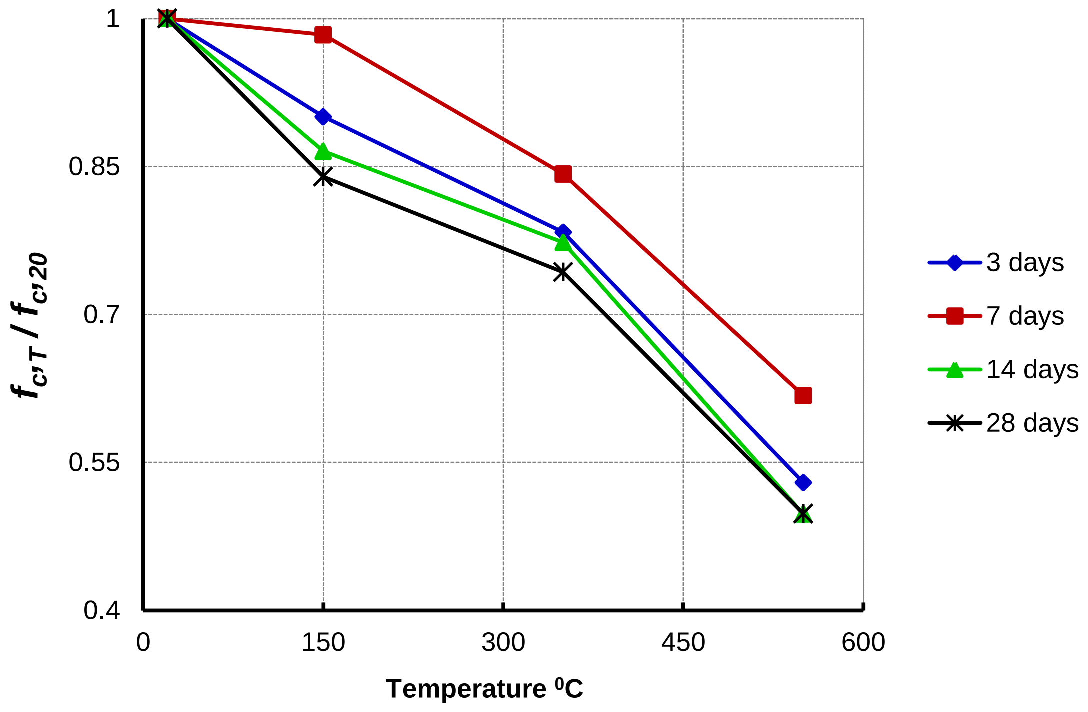
Fig. 3 The SEM images of the specimens heated to the temperature of 550 °C with different curing ages before heating.



(a) Water mixing ratio of 12%

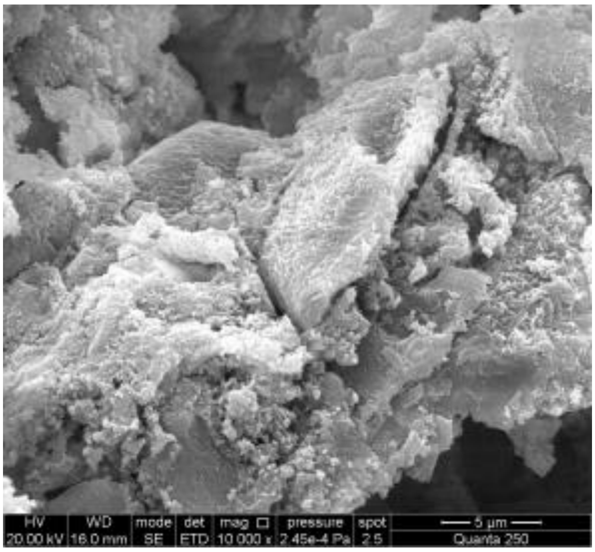


(b) Water mixing ratio of 14%

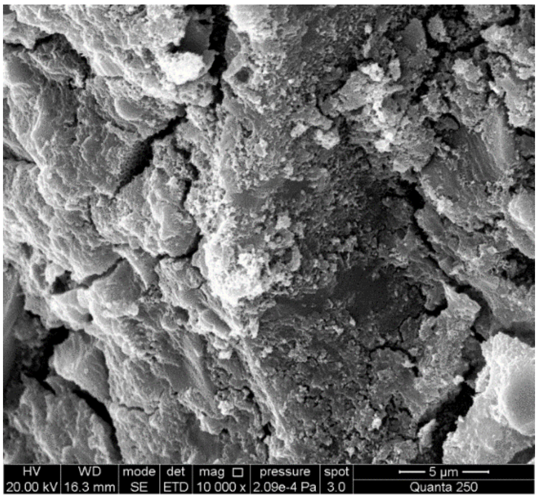


(c) Water mixing ratio of 16%

Fig. 4 The relationships of the ratio ($f_{c,T}$ / $f_{c,20}$) against the exposed temperatures for the specimens with different curing ages before heating and water mixing ratios.

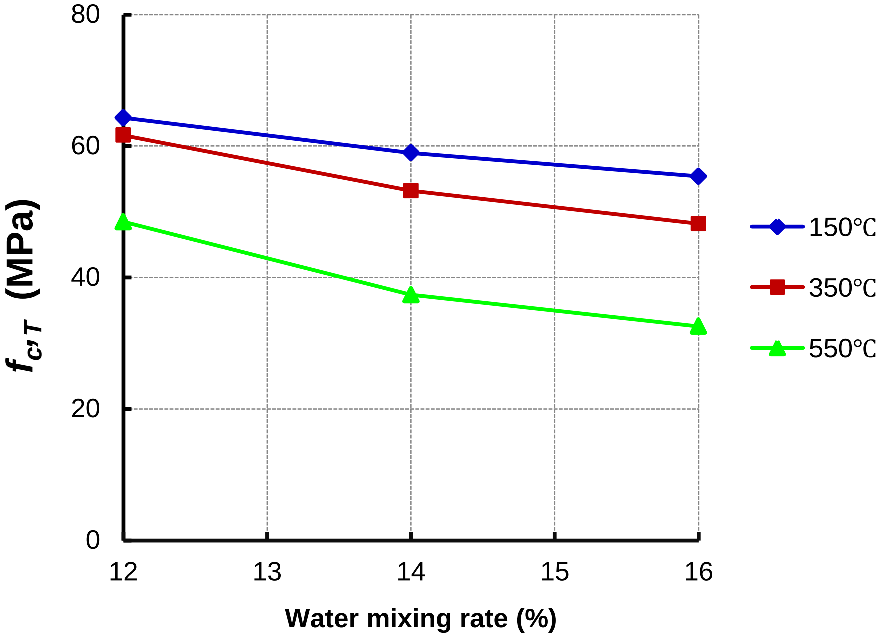


(a) The specimen without heating

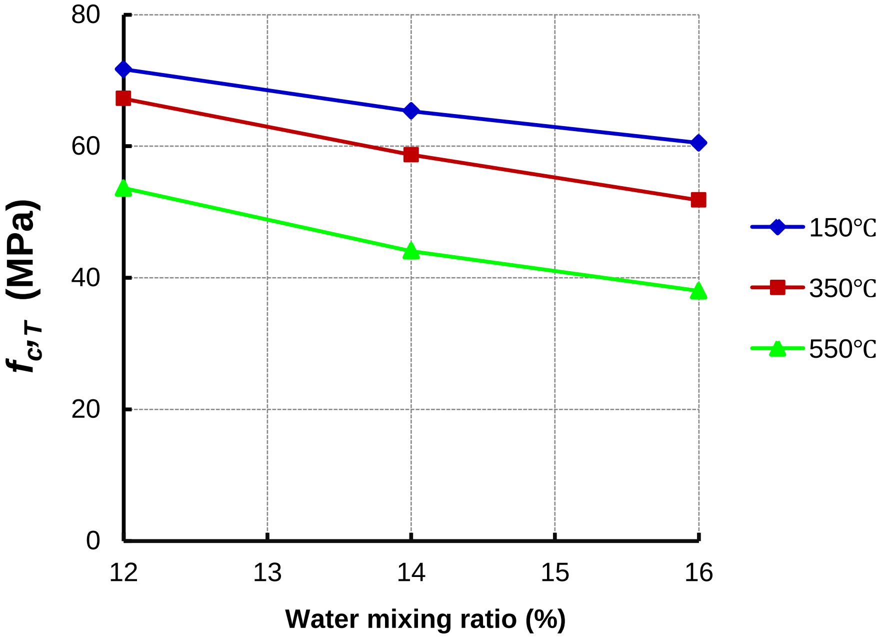


(b) The specimen heated to 550 ^{o}C

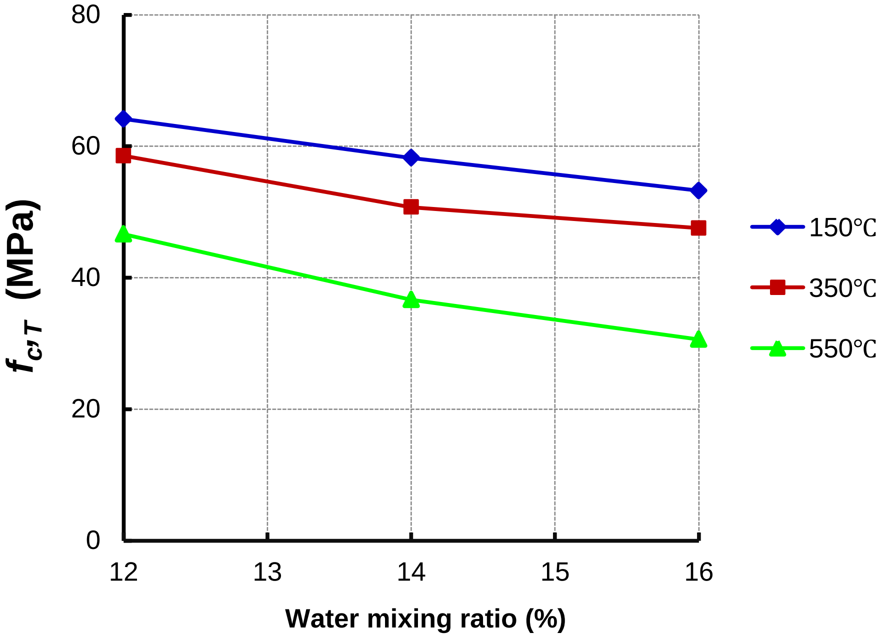
Fig. 5 The SEM images of the unheated and heated specimens with a 28 days curing age before heating and the water mixing ratio of 12%.



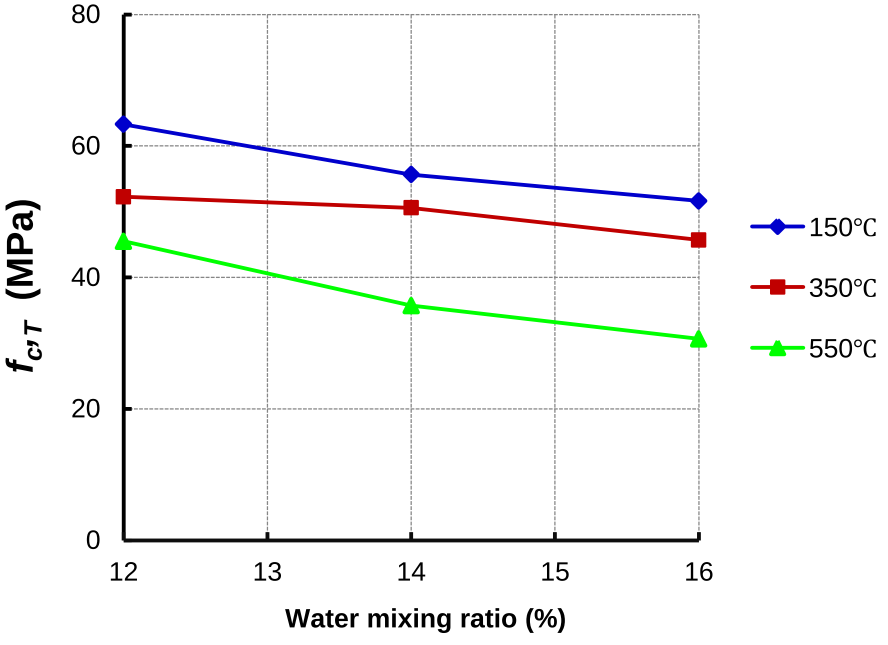
(a) 3 days curing age before heating



(b) 7 days curing age before heating

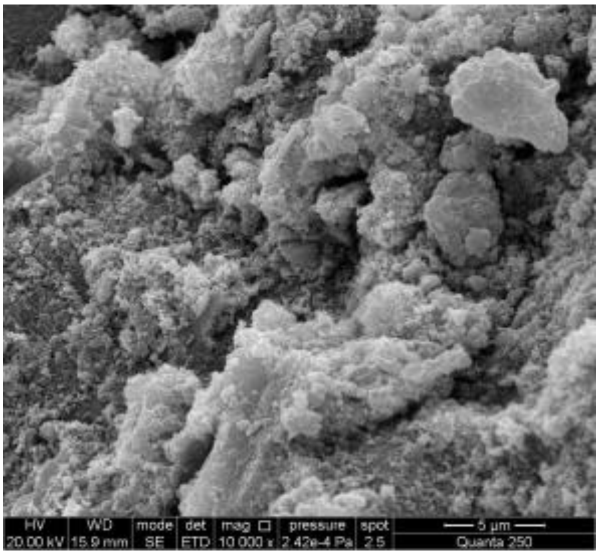


(c) 14 days curing age before heating

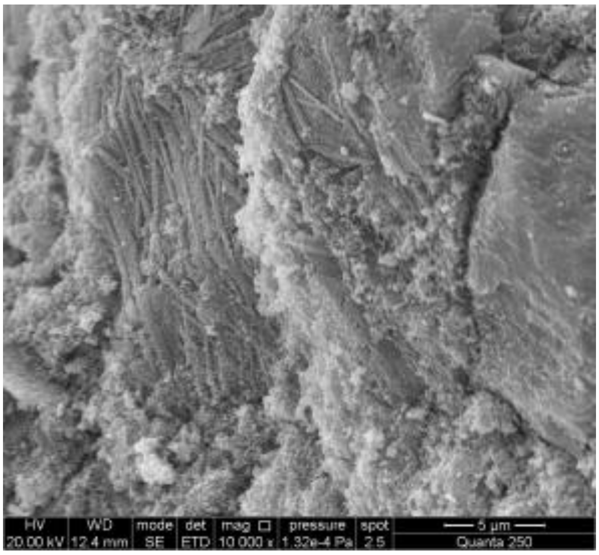


(c) 28 days curing age before heating

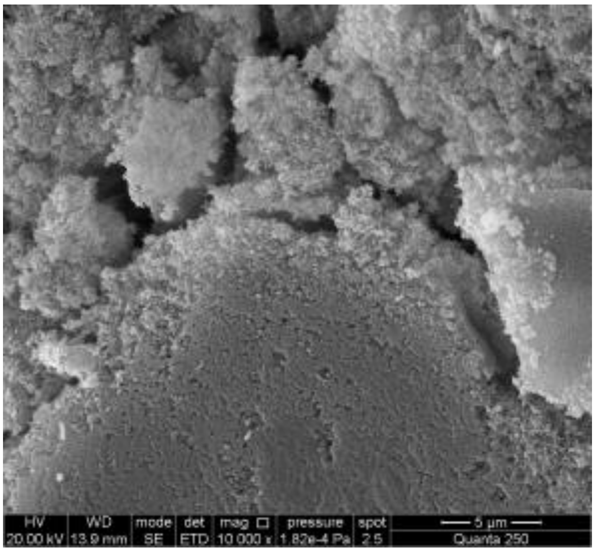
Fig. 6 The relationships of the residual compressive strength ($f_{c,T}$) against the water mixing ratio for the specimens with different curing ages before heating and the exposed temperatures.



(a) Water mixing ratio of 12%

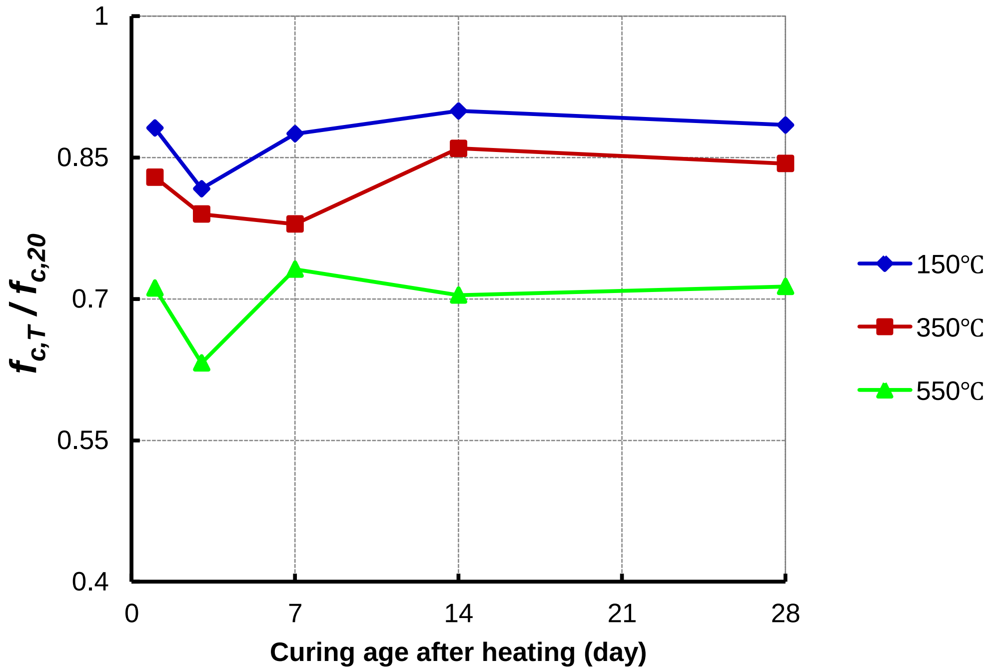


(b) Water mixing ratio of 14%

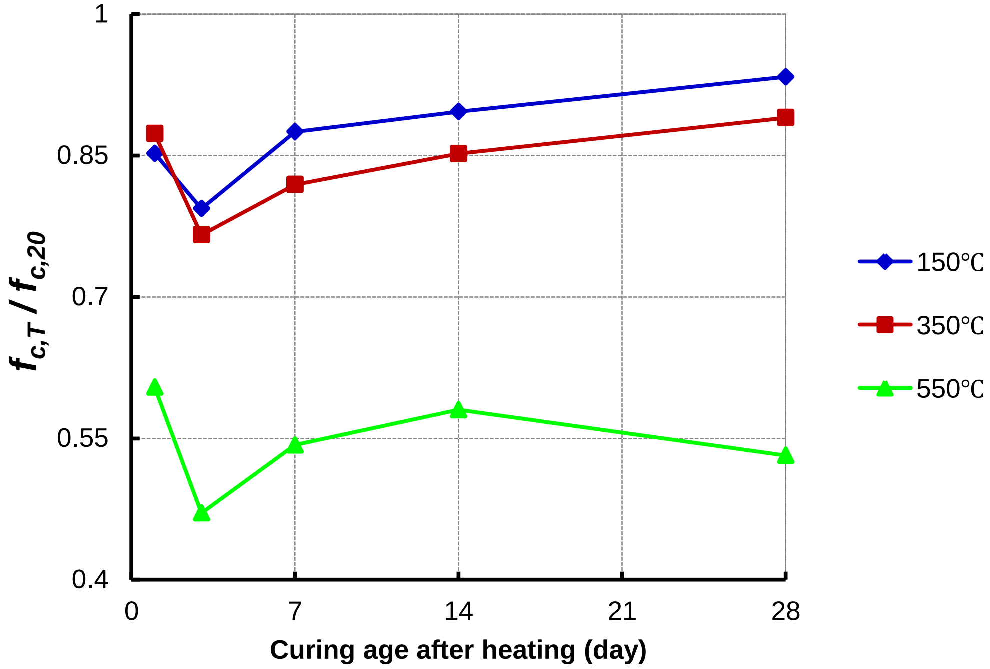


(c) Water mixing ratio of 16%

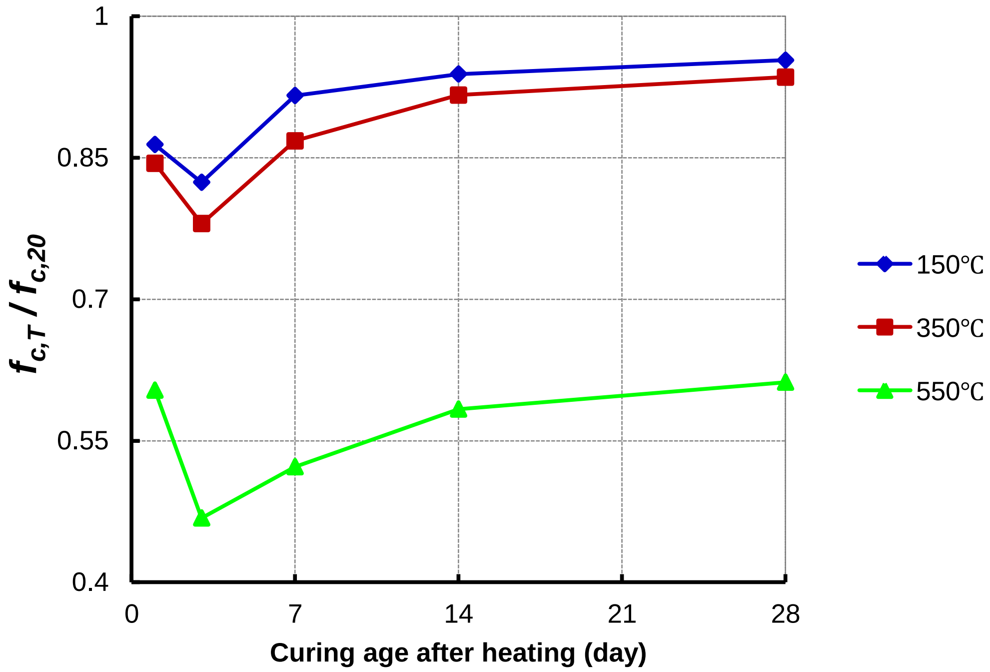
Fig. 7 The SEM images of the specimens of 7 days curing age before heating, with different water mixing ratios and exposed to 550 °C.



(a) Water mixing ratio of 12%



(b) Water mixing ratio of 14%



(c) Water mixing ratio of 16%

Fig. 8 The relationships of the ratio ($f_{c,T}$ / $f_{c,20}$) against the curing age after heating for the specimens of 14 days curing age before heating and with different water mixing ratios.