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SCALE EFFECT OF CEMENT MORTAR SPECIMENS SUBJECTED TO HIGH TEMPERATURES USING UNIAXIAL COMPRESSIVE AND SPLITTING TENSILE TESTS

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In this study, cubic and cylindrical cement mortar specimens were first subjected to high temperatures, then the cubic and cylindrical specimens were taken out and conducted with uniaxial compressive test and splitting tensile test, respectively. The effect of the length to side ratio on the uniaxial compressive properties and the effect of thickness-to-diameter ratio on the splitting tensile properties of cement mortar specimens after high temperature were studied. Test results show that: (1) With temperature increasing from 25 °C (room temperature) to 400 °C, the compressive strength and elastic modulus of cubic specimens with three kinds of side lengths decrease; the decreasing rates of compressive strength and elastic modulus of cubic specimen with side length of 70.7 mm is higher than those of cubic specimens with side length of 100 mm and 150 mm, and the strain at the peak stress of cubic specimens with three kinds of side lengths increase. (2) After the same temperature, the tensile strength of cylindrical specimen decreases with the thickness-to-diameter ratio increasing from 0.5 to 1.0. The decreasing rate of tensile strength of cylindrical specimen with thickness-to-diameter ratio is highest when the temperature is 25 °C (room temperature), followed by that after the temperature of 200 °C, and that after the temperature of 400 °C is the lowest.

Keywords: Cement mortar, high temperature, uniaxial compression, splitting tensile, scale effect

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1. INTRODUCTION

In practical, rock engineering and concrete engineering are inevitably exposed to high temperatures under construction and operation stages, such as fire. Therefore, study of the residual strengths of rocks and concrete materials after high temperature is of great significance for evaluating the bearing performances of rock engineering and concrete structure engineering when subjected to high temperatures. For rocks and concrete materials, the main advantage is of high compression resistance; however, the tensile properties also should be focused on. At present, many researchers have carried out experimental researches on the compressive and tensile properties of rocks and concrete materials after high temperature.

Chan *et al*. [1] investigated the compressive strength and pore structure of high-performance concrete after exposure to high temperature. Li *et al*. [2] experimentally studied the compressive strength of high-strength concrete after fire. Ghandehari *et al*. [3] measured the compressive strength and the splitting tensile strength of high-strength concretes after exposure to elevated temperatures. Ahmad *et al*. [4] studied the effect of high temperature on the residual compressive strength of concrete specimens. Lü *et al*. [5] studied the effect of high temperature on tensile strength of sandstone using splitting tensile test.

Evidently, the scale effect cannot be negligible in the test of mechanical properties of rocks and concrete materials. Many researchers have used cubic samples and carried out uniaxial compression tests on concrete and rock specimens that are not subjected to high temperatures. Yi *et al*. [6] investigated the effect of specimen sizes, specimen shapes, and placement directions on compressive strength of cubic concrete specimen. Yazıcı & Sezer [7] investigated the influence of size and capping type of cylindrical specimens on compressive strength of concrete. An *et al*. [8] studied scale effect on compressive strength of RPC experimentally. Del Viso *et al*. [9] and Sim *et al*. [10] investigated the influence of the shape and of the size of the specimens on the compressive strength of cubic concrete specimens.

The above literatures (Yi *et al*. [6]; Yazıcı & Sezer [7]; An *et al*. [8]; Del Viso *et al*. [9]; Sim *et al*. [10]) mainly focus on the scale effect on the uniaxial compressive mechanical properties of rocks and concrete materials, which were not subjected to high temperature. The scale effect of the splitting tensile properties of rocks and concrete materials is rarely reported. Moreover, studies on the variation of compressive strength with side length of cubic specimen after high temperature and that on splitting tensile properties with length-to-diameter ratio and / or thickness-to-diameter ratio of the cylindrical specimens after high temperatures are also relatively less.

In this text, cubic and cylindrical cement mortar specimens subjected to high temperature were first prepared, and then uniaxial compression tests on cubic specimen and splitting tensile tests on cylindrical specimen were carried out. Finally, the effects of sample side length on the uniaxial compressive properties and that of thickness-to-diameter ratio on the splitting tensile properties of cement mortar specimens after high temperatures were studied.

2. EXPERIMENTAL SET-UP

2.1. SAMPLE PREPARATION

Cubic and cylindrical specimens were used in this context. Cement mortar with a water / cement ratio of 0.55 was poured into the cubic mold to prepare for the cubic specimens. Cement mortar with water / cement ratio of 0.45, 0.55 and 0.65 were poured into the cylindrical PVC mold to prepare for the cylindrical specimens. Cement No. 425 employed in this test is produced by the China Building Materials Academy. The ISO standard sand was used in the tests. The particle size of sand ranges from 0.5 mm to 1.0 mm.

There are total 36 cube specimens and 180 cylindrical specimens. The dimensions of the cubic specimens are divided into three types, namely: (1) 70.7 mm × 70.7 mm × 70.7 mm; (2) 100 mm × 100 mm × 100 mm; (3) and 150 mm × 150 mm × 150 mm. The dimensions of cylindrical specimens are divided into five types: (1) 50 mm (diameter) × 25 mm (thickness); (2) 50 mm (diameter) × 30 mm (thickness); (3) 50 mm (diameter) × 35 mm; (4) 50mm (diameter) × 40 mm (thickness); and (5) 50 mm (diameter) × 50 mm. Both the cube and cylindrical specimens were made with cement to sand ratio at 1: 2. The curing environment for specimens is 20 °C and 95% relative humidity for 28 days before high-temperature treatment, which is same as Xiong et al. [11].

Cubic specimens were tested for uniaxial compression test and cylindrical specimens for splitting tensile tests. The splitting loading diagram of cylindrical specimen is shown in Fig. 1.

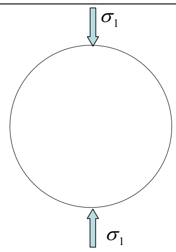


Fig. 1. The splitting loading diagram of cylindrical specimen.

2.2. TEST SEQUENCE

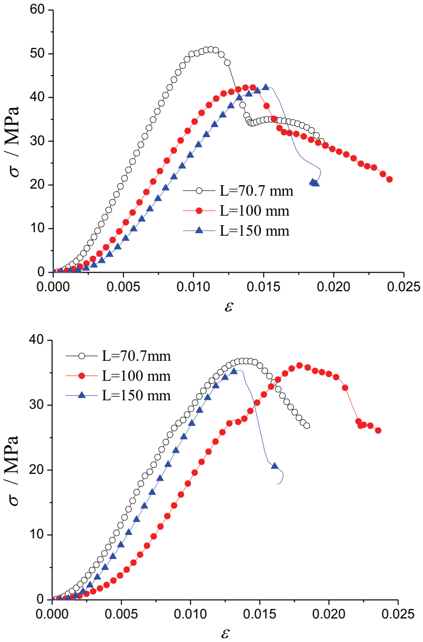
After being cured for 28 days, these cubic and cylindrical specimens were placed at a ventilated place for 7 days to ensure that the surfaces of these specimens were completely dry. Then these specimens were elevated to the peak temperatures of 200 °C, 300 °C and 400 °C at a heating rate of 10 °C /min in the furnace, respectively. After the peak temperature was reached, the cubic and cylindrical specimens were maintained for another 2 h in the furnace, and then they were cooled down to room temperature in the furnace and taken out for testing. After that, uniaxial compression tests were carried out on cubic specimens using WAW-600C universal testing machine after 7 days taken out from the furnace, at a displacement loading rate of 0.6mm / min. And splitting tensile tests can be performed on these specimens using WAW-600C universal testing machine after 7 days taken out from the furnace, at a displacement loading rate of 0.1mm / min.

This article also uses the same screening method as Xiong et al. [12], three specimens were conducted for each test. The results of compressive strength and splitting tensile strength were calculated by averaging the strengths from three specimens, which are discussed in Section 3 and Section 4. For avoiding imperfection in preparing samples, the result of one specimen was excluded if it exceeds more than 15% of the average value from three specimens, and the average strength was recalculated by other two specimens (Xiong *et al*. [12]).

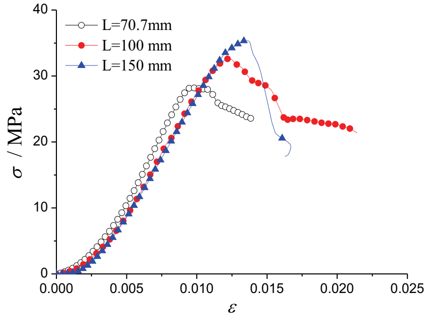
3. ANALYSIS OF UNIAXIAL COMPRESSION TEST RESULTS

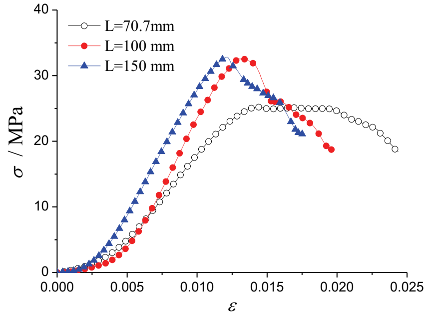
3.1 TRESS-STRAIN CURVE

Under various temperatures, the scale effect on the uniaxial compressive stress-strain curve of cubic specimens is shown in Fig. 2, where L represents the side length of the cube specimen. In the same temperature, the peak stress of cubic specimen will decrease gradually with side length increasing from 70.7 mm to 150 mm.



(a) Room temperature (b) 200 °C





(c) 300 °C (d) 400 °C

Fig. 2. Scale effect on uniaxial compressive stress - strain curve of cubic specimen with various temperatures.

Stress-strain curves were obtained by applying uniaxial compression tests with different temperatures (25°C, 200°C, 300°C and 400°C) on specimens, these curves are mainly composed of compaction stage, linear elastic stage, yielding stage and post-peak softening stage.

3.2 EVOLUTION OF COMPRESSIVE STRENGTH

When the side length of cubic specimen is the same, the linear equation is proposed to analyze the variation of the compressive strength with high temperature, the effect of temperature on the UCS of cubic specimen is shown in Fig.3.

$$\sigma_c = a_1 + a_2 T$$

(1)

where σ_c is the UCS; T is the high temperature; a_1 and a_2 are the fitting parameters.

The fitting results using Eq. (1) are shown in Fig. 3, and the fitting parameters are shown in Table 1.

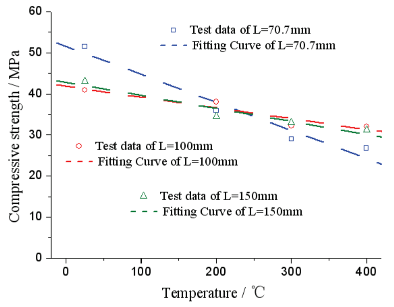


Fig. 3. The fitting results calculated using Eq. (1).

Table 1. Parameters of Eq. (1) when analyzing the variation of UCS of cubic specimen with temperature.

L / mm	a_1	a_2	R^2
70.7	51.597	-0.068	0.953
100	41.816	-0.026	0.90
150	42.784	-0.032	0.925

In Fig. 3, when the temperature is 25 °C, the specimen with a side length of 70.7 mm has the highest compressive strength, the specimen with a side length of 150 mm has the medium compressive strength, and the specimen with a side length of 100 mm has the lowest compressive strength. This is different from the conclusion obtained by Xiong et al. [13]. This is most likely due to that the water-cement ratio of the cubic specimen in this study is 0.55, and the water-cement ratio of the cubic specimen in Xiong et al. [13] is 0.65. In fact, Çelik [14] also found that the compressive strength does not necessarily decrease as the side length increases.

With temperature increasing from 25 °C (room temperature) to 400 °C, the compressive strength of cubic specimen with three kinds of side lengths will decrease, and the decreasing rate of compressive strength of cubic specimen with side length of 70.7 mm is higher than those of cubic specimens with side lengths of 100 mm and 150 mm.

From Table 1, it shows that the value of parameter a_2 when the side length of 70.7 mm is lower than those values of other two side lengths of cubic specimens.

Due to the smallest size, the temperature distribution inside the specimen with 70.7 mm is more uniform after subjected to high-temperature. This results in the entire specimen being subjected to high temperature effects at the same temperature, and the damage caused by high temperature is also the most serious.

Therefore, the declining rate of compressive strength of specimen with temperature when the length of cubic specimen is 70.7mm is highest among all the side lengths (70.7 mm, 100 mm and 150 mm) of cubic specimens.

The declining rate of compressive strength of cubic specimen with temperature is proposed:

$$\gamma_{cu} = \frac{f_{cu,T}}{f_{cu,RM}} \tag{2}$$

where $f_{cu,RM}$ is the compressive strength of specimens after being cured for 28 days which is not subjected to high temperature; $f_{cu,T}$ is the compressive strength of specimen after high temperature.

In Fig. 4, it is observed that the declining rates of compressive strength of cubic specimen with temperature. The declining rate of compressive strength of cubic specimen with side length of 70.7 mm is significantly higher than that of cubic specimens with side lengths of 100 mm and 150 mm.

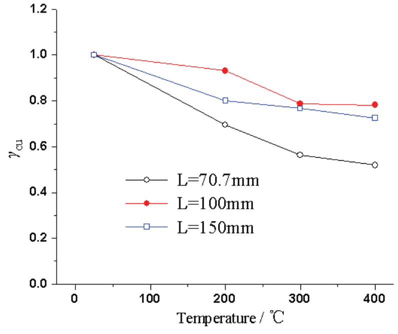


Fig. 4. Variation of declining rates of compressive strength of cubic specimen with temperature and side length.

3.3 EVOLUTION OF STRAIN AT THE PEAK STRESS

When the side length of cubic specimen is the same, the effect of temperature on the strain at the peak stress of cubic specimen is shown in Fig.5.

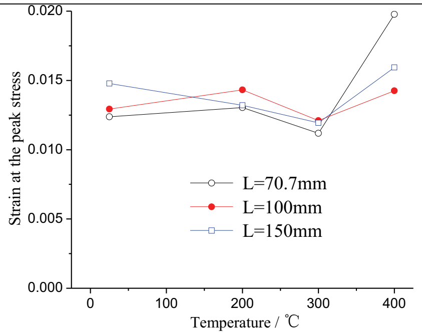


Fig. 5. Variation of strain at the peak stress of cube specimen with temperature and side length.

After specimens are subjected to high temperature, the strain at the peak stress of the specimens with side lengths of 70.7 mm and 100 mm changes similarly with temperature increasing from 25 °C to 400 °C. When the temperature increases from 300 °C to 400 °C, the strain at the peak stress of specimens with these three kinds of sizes increases significantly.

3.4 EVOLUTION OF ELASTIC MODULUS

The elastic modulus is calculated as a secant modulus in this study. The secant modulus is calculated from the origin to a defined point on the stress-strain curve, within 50% of the specimen's peak stress. When the side length of cubic specimen is the same, the effect of temperature on the elastic modulus of cubic specimen is shown in Fig.6.

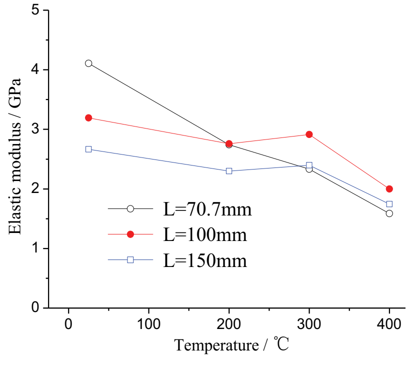


Fig. 6. Variation of elastic modulus of cube specimen with temperature and side length.

When temperature is elevated from 25 °C (room temperature) to 400 °C, the elastic modulus of cubic specimen with three kinds of side lengths decrease.

The declining rate of elastic modulus of cubic specimen with temperature is proposed in this study:

$$\gamma_E = \frac{E_T}{E_{RM}} \tag{3}$$

where E_{RM} is the elastic modulus of specimen after being cured for 28 days that are not subjected to high temperature; E_T is the elastic modulus of specimen after high temperature.

The declining rates of elastic modulus of cubic specimen with high temperature are shown in Fig. 7.

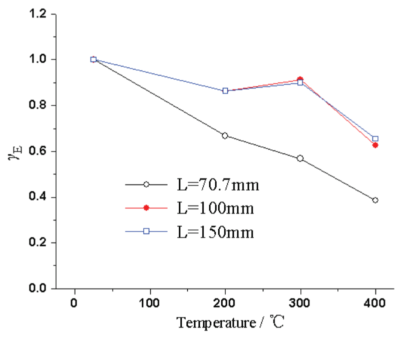


Fig. 7. Variation of declining rates of elastic modulus of cubic specimen with temperature and side length.

It is observed that the declining rate of elastic modulus of cubic specimen with side length of 70.7 mm is significantly higher than that of cubic specimens with side lengths of 100 mm and 150 mm.

4. ANALYSIS OF SPLITTING TENSILE TEST RESULTS

The tensile strength of cylindrical specimen can be calculated as

$$\sigma_t = \frac{2P_{max}}{\pi D t} \tag{4}$$

where P_{max} is the load at failure, σ_t is tensile strength, D is the diameter of cylindrical specimen, t is the thickness of cylindrical specimen.

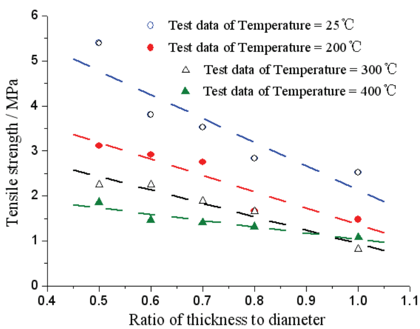
The linear equation is proposed to analyze the variation of the tensile strength with thickness-to-diameter ratio

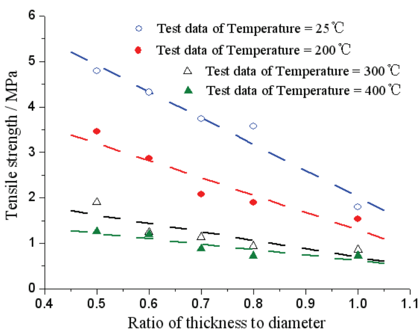
$$\sigma_t = b_1 + b_2\lambda$$

(5)

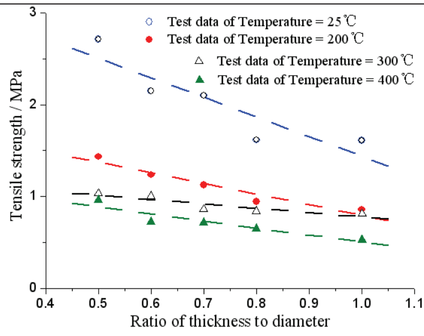
where σ_t is the splitting tensile strength; λ is the thickness-to-diameter; b_1 and b_2 are the fitting parameters.

The fitting results using Eq. (5) are shown in Fig. 8, and the fitting parameters are shown in Tables 2-4.





(a) w/c ratio = 0.45 (b) w/c ratio = 0.55



(c) w/c ratio = 0.65

Fig. 8. The fitting results using Eq. (5).

In Fig. 8, when the temperature is the same, the tensile strength of cylindrical specimens with three different kinds of w/c ratios decreases gradually with thickness-to-diameter ratio increasing from 0.5 to 1.0. Su et al. [15] conducted splitting tensile test on red sandstone after high temperature treatment, and the results also showed that the tensile strength of the specimen decreases with increasing thickness-to-diameter ratio after the same high temperature. The experimental results in this paper are consistent with conclusions obtained by Su et al. [15]. The decreasing rate of tensile strength of cylindrical specimen with thickness-to-diameter ratio is highest when the temperature is 25 °C (room temperature), followed by that when the temperature is 200 °C. The decreasing rate of tensile strength of cylindrical specimen with thickness-to-diameter ratio when the temperature is 300 °C is close to that when the temperature is 400 °C, and the decreasing rates of specimens when the temperatures are 300 °C and 400 °C are obviously lower than those of when the temperatures are room temperature and 200 °C. Under same conditions of specimen thickness and high-temperature treatment, the specimen with the water-cement ratio of 0.45 has the highest tensile strength, the specimen with the water-cement ratio of 0.55 has the medium tensile strength, and the specimen with the water-cement ratio of 0.65 has the smallest tensile strength.

Table 2. Parameters of Eq. (5) when analyzing the variation of splitting tensile strength of cylindrical specimen (w / c = 0.45) with thickness-to-diameter.

Temperature / °C	b_1	b_2	R^2
25	7.419	-5.284	0.822
200	5.022	-3.665	0.871
300	3.924	-2.986	0.944
400	2.431	-1.396	0.884

Table 3. Parameters of Eq. (5) when analyzing the variation of splitting tensile strength of cylindrical specimen (w / c =0.55) with thickness-to-diameter.

Temperature / °C	b_1	b_2	R^2
25	7.819	-5.80	0.957
200	5.107	-3.813	0.884
300	2.551	-1.856	0.751
400	1.819	-1.197	0.814

Table 4. Parameters of Eq. (5) when analyzing the variation of splitting tensile strength of cylindrical specimen (w / c =0.65) with thickness-to-diameter.

Temperature / °C	b_1	b_2	R^2
25	3.575	-2.137	0.813
200	1.954	-1.16	0.929
300	1.251	-0.474	0.818
400	1.267	-0.764	0.862

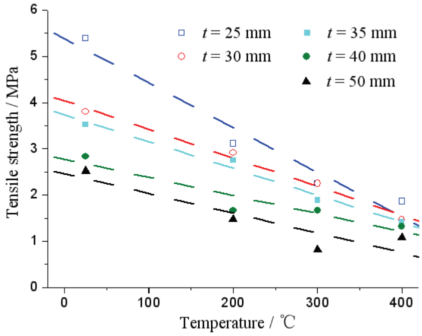
It shows that the value of parameter b_2 under room temperature is lower than those values of other three temperatures. Therefore, the decreasing rate of tensile strength of specimen with thickness-to-diameter at room temperature is highest among the other temperatures.

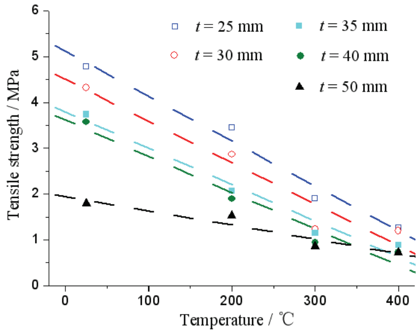
The linear equation is proposed to analyze the variation of the tensile strength with temperature

$$\sigma_t = c_1 + c_2 T \tag{6}$$

where σ_t is the splitting tensile strength; T is the high temperature; c_1 and c_2 are the fitted parameters.

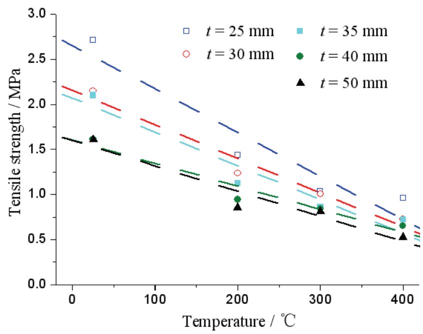
The fitting results using Eq. (6) are shown in Fig. 9, and the fitting parameters are shown in Tables 5-7.





(a) w/c ratio = 0.45

(b) w/c ratio = 0.55



(c) w/c ratio = 0.65

Fig. 9. The fitting results using Eq. (6).

Table 5. Parameters of Eq. (6) when analyzing the variation of splitting tensile strength of cylindrical specimen (w / c=0.45) with temperature.

Thickness / mm	c_1	c_2	R^2
25	5.389	-0.00966	0.953
30	4.038	-0.00618	0.988
35	3.732	-0.00579	0.982
40	2.772	-0.00391	0.889
50	2.461	-0.00427	0.833

Table 6. Parameters of Eq. (6) when analyzing the variation of splitting tensile strength of cylindrical specimen (w / c =0.55) with temperature.

Thickness / mm	c_1	c_2	R^2
25	5.117	-0.00981	0.977
30	4.497	-0.00905	0.936
35	3.791	-0.00793	0.964
40	3.616	-0.00793	0.958
50	1.941	-0.00309	0.908

Table 7. Parameters of Eq. (6) when analyzing the variation of splitting tensile strength of cylindrical specimen (w / c =0.65) with temperature.

Thickness / mm	c_1	c_2	R^2
25	2.653	-0.00483	0.907
30	2.153	-0.00378	0.964
35	2.068	-0.00375	0.930
40	1.601	-0.00255	0.938
50	1.596	-0.00279	0.929

In Tables 5-7, it shows that the value of parameter c_2 when the thickness of specimen is 25 mm is lower than those values of other four thicknesses.

Due to the minimum thickness of the specimen, the temperature distribution inside the specimen with a thickness of 25 mm is more uniform when subjected to high temperature. This results in the entire specimen being subjected to the same high temperature, and the damage caused by high temperature is the most serious. Therefore, the decreasing rate of tensile strength with increasing temperature in 25 mm is the highest among all the thicknesses.

When the tensile strength of specimens with various thicknesses gradually decreases subjected to high temperature from 25 °C to 400 °C. Su et al. [15] carried out splitting tensile test on the red sandstone after high temperature treatment. As the temperature increases from 25 °C to 800 °C, the tensile strength of the specimen increases first and then decreases, and it reaches the maximum value at 400 °C. The test results in this paper are different from Su et al. [15], mainly related to the type of specimen.

5. CONCLUSIONS

1. When the temperature increases from 25 °C (room temperature) to 400 °C, the compressive strength and elastic modulus of cubic specimens with three kinds of side lengths decrease, the decreasing rates of compressive strength and elastic modulus of cubic specimen with side length of 70.7 mm is higher than those with side lengths of 100 mm and 150 mm. The strain at the peak stress of cubic specimens with three kinds of side lengths increase gradually.

2. Under the same temperature, the tensile strength of cylindrical specimen decreases with the thickness-to-diameter ratio increasing from 0.5 to 1.0. The decreasing rate of tensile strength of cylindrical specimen with thickness-to-diameter ratio is highest when the temperature is 25 °C (room temperature), followed by that under the temperature of 200 °C, and that under the temperature of 400 °C is the lowest.

3. The decreasing rate of tensile strength of cylindrical specimen with increasing temperatures when the thickness of specimen is 25 mm is the highest among all the thicknesses.

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LIST OF FIGURES AND TABLES:

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