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Size effect of sandstone after high temperature under uniaxial compression

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Abstract: Uniaxial compression tests on sandstone samples with five different sizes after high temperature processes were performed in order to investigate the size effect and its evolution. The test results show that the density, longitudinal wave velocity, peak strength, average modulus and secant modulus of sandstone decrease with the increase of temperature, however, peak strain increases gradually. With the increase of ratio of height to diameter, peak strength of sandstone decreases, which has an obvious size effect. A new theoretical model of size effect of sandstone material considering the influence of temperature is put forward, and with the increase of temperature, the size effect is more apparent. The threshold decreases gradually with the increase of temperature, and the deviations of the experimental values and the theoretical values are between 0.44% and 6.06%, which shows quite a credibility of the theoretical model.

Key words: high temperature process; sandstone; size effect; threshold

1 Introduction

With rapid development of nuclear waste treatment and underground coal gasification project, problems of rock mechanics under the influence of high temperature have become a research focus in the field of rock mechanics in recent years [1−3]. Some explorations aiming at the physical and mechanical properties of rock have been done by rock mechanics researchers. KEMPKA and ZIEGLER [4] summarized the physical properties of sandstones after high temperature treatment; RAO et al [5] discussed the in-plane shear crack sub-critical propagation characteristic of rock at high temperature with a newly designed electrically conductive adhesive method; ZUO et al [6] investigated the failure and strength characteristics of sandstone at room temperature up to 300 °C in an internally heated apparatus and tensile load; ZHANG et al [7] analyzed the varying characteristics of marble, limestone, and sandstone at high temperature using the MTS810 rock mechanics servo-controlled testing system; MAO et al [8] investigated the mechanical properties of limestone under the action of temperatures ranging from room temperature to 800 °C and derived the thermal damage equation.

Rock, as a typical kind of heterogeneous material, shows obvious size effect in the mechanical property [9−11]. However, the size effect, as an inherent characteristic of the rock material, is an important factor restricting the strength prediction and evaluation of rock engineering. The so-called size effect refers to the behavior in which the mechanical property of material changes with the size of sample. YOU et al [12−13] discussed the relationship between the heterogeneity and the size effect of rock materials; ZHU et al [14] established the non-linear relationship between the uniaxial compressive strength of brittle rock and the ratio of height to diameter by using the Grey Theory; YANG et al [15] conducted experiments on marble of different heights and put forward an applicable size effect model; ZHANG et al [16] established the statistical model and the regular lambdas of the failure probability and the size effect in strength of quasi brittle materials based on the weakest link model and the defect Poisson distribution assumption; CHEN et al [17−18] conducted a systematic research on the size effect of deformation modulus of jointed rock mass by using the method of finite element analysis; JING et al [19] obtained the relationship between the strength attenuation value and the size of

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pre-damage specimens.

Mechanical property of rock under the effect of temperature is more complex. However, research on the size effect of rock in or after high temperature process is seldom reported. Based on this, the uniaxial compression test of sandstone specimens in different heights and in both natural condition (25 °C) and at high temperatures (200−800 °C) was conducted to study the size effect of sandstone and its evolution with temperature.

2 Test preparation

Sandstone, which is the most typical sedimentary rock, was selected as the test material. The sandstone was collected from the city of Linyi, Shandong province in China, which is dark red in the natural state, has uniform texture, and no obvious texture. The average density is 2.39 g/cm^3 under natural condition and the main minerals are quartz, feldspar, montmorillonite, illite and some small amount of hematite.

The sandstone was processed into cylinder specimens with a diameter of 50 mm and a height of 50−150 mm. Then, the finished cylinder specimens were treated at a high temperature in the GWD-02A high temperature furnace (Fig. 1). The furnace is developed by China Light Industry Institute of Ceramics Kiln Development Center and the temperature adjustment range is between 0 and 1100 °C. During the test, the temperature was chosen as 25 °C (room temperature), 200 °C, 400 °C, 600 °C and 800 °C, and the heating rate was 5 °C/min. When the temperature reached the specified level, we should wait for 60 min in order to ensure that the rock was heated evenly; finally, the samples were cooled to room temperature naturally, and then the cooled samples were conducted with some necessary grinding processes to ensure that the samples at different temperatures have the same ratio of height to diameter for quantitative analysis. The sandstone samples after high temperature processes are shown in Fig. 2.

The uniaxial compression test of the sandstone specimens was conducted on the electro-hydraulic servo universal testing machine YNS2000 in China University of Mining and Technology. The maximum test force of this testing machine is 2000 kN. Displacement loading method was used during the uniaxial compression process and the loading rate was 0.1 mm/min. Two rigid plates were put in the upper and lower end portions of the specimens, and the contact surfaces of specimens and the plate were coated with a layer of vaseline lubricant in order to reduce the end friction effect on the experimental results.

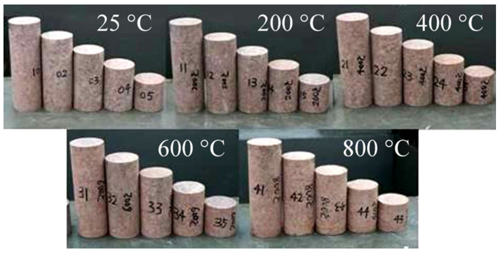

Fig. 2 Sandstone sample

3 Experiment results and analysis

3.1 Physical properties analysis

Figure 3 shows the variation of the diameter, density and longitudinal wave velocity of sandstone with temperature after high temperature processes, where d is diameter, ρ is density, v is longitudinal wave velocity, and T is temperature. The values of all physical quantities are defined as the average value of the physical parameters of sandstone specimens.

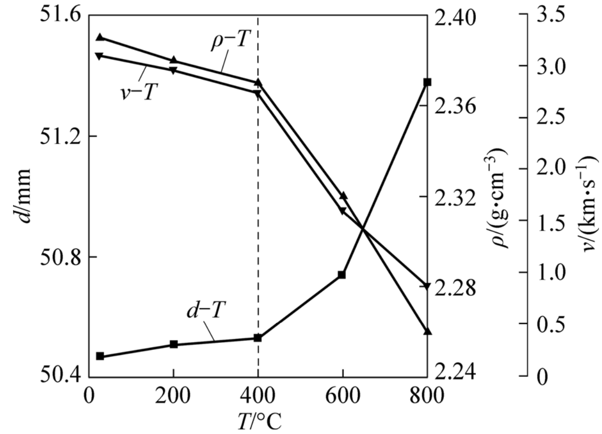

Fig. 3 Relationship of diameter, density and longitudinal wave velocity with temperature

It can be seen from Fig. 3 that along with the gradual rising of temperature, the diameter of sandstone increases gradually, while the density and the longitudinal wave velocity decrease gradually. The overall trend can be divided into two stages:

1) In the temperature range of 25−400 °C, interlayer water and adsorbed water of the mineral detach, and part

Fig. 1 GWD-02A high temperature furnace

of the clay mineral appear a certain thermal expansion. However, part of the process is reversible after cooling and there are small changes in physical properties. With temperature rising from 25 °C to 400 °C, the diameter of sandstone increases from 50.47 mm to 50.53 mm, by 0.12%; while the density decreases by 0.84% from 2.39 g/cm^3 to 2.37 g/cm^3 and the longitudinal wave velocity decreases by 11.83% from 3099.15 m/s to 2732.64 m/s.

2) In the temperature range of 400−800 °C, the water loss basically has completed. The clay mineral has a strong thermal expansion and some minerals in rock melt, accompanied with phase transition, such as quartz transforming from α phase to β phase at around 573 °C, which leads to a large number of micro defects in the rock and the physical properties change dramatically. With the temperature rising from 400 °C to 800 °C, the diameter of sandstone increases from 50.53 mm to 51.38 mm, by 1.68%, while the density and longitudinal wave velocity decrease by 4.64% and 68.14%, respectively, from 2.37 g/cm^3 and 2732.64 m/s to 2.26 g/cm^3 and 870.73 m/s, respectively.

3.2 Axial stress strain curves

Figure 4 shows the uniaxial compression stress−strain curves of sandstone specimens after high temperature processes. The following can be indicated from Fig. 4:

1) Figure 4 shows an obvious pressure dense phase with a concave shape in the early loading stage of stress−strain curve due to the existence of the internal micropores, and with the increase of temperature, pressure dense phase becomes more remarkable.

2) Some fluctuations appear before the peak point of the sandstone after high temperature process, which is unclear between 25 °C and 200 °C, but with the increase of temperature, fluctuation is more and more obvious, which is owing to extension and connection of microdefects caused by high temperature treatment [20].

3) At a low temperature, when the axial stress reaches the peak strength point, it experiences a transient decay process, then drops to zero quickly, but the post-peak attenuation stage of sandstone after a high temperature treatment at 600−800 °C is relatively long, which further illustrates that a significant change in the internal mineral composition of sandstone takes place between 600 °C and 800 °C, with phase characteristic transforming.

3.3 Macroscopic mechanical parameters

Figure 5 shows the relationship of macroscopic mechanical parameters (peak strength, peak strain, average modulus and secant modulus) of sandstone with temperature, where λ is the ratio of height to diameter, σ_0 is the peak strength, ε_0 is the peak strain, E is the average modulus, and E_{50} is the secant modulus. It is indicated from Fig. 5 that:

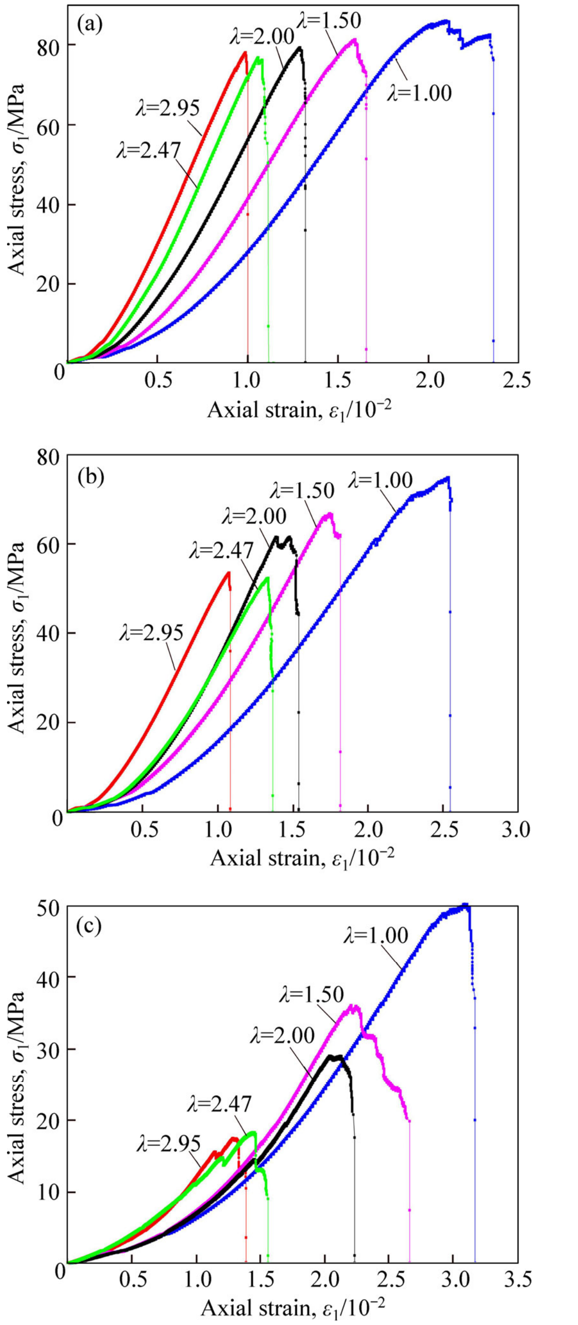

Fig. 4 Axial stress−strain curves of sandstone: (a) T =25 °C; (b) T=400 °C; (c) T=800 °C

1) With the increase of temperature, the peak strength, average modulus and secant modulus gradually decrease, but the peak strain increases gradually. Taking the standard cylinder specimens with the ratio of height to diameter of 2.00 for example, when the temperature increases from 25 °C to 800 °C, peak strength, average modulus and the secant modulus decrease by 63.39%, 71.56% and 80.82%, respectively, from 79.23 MPa, 8.86 GPa and 4.85 GPa to 29.01 MPa, 2.52 GPa and

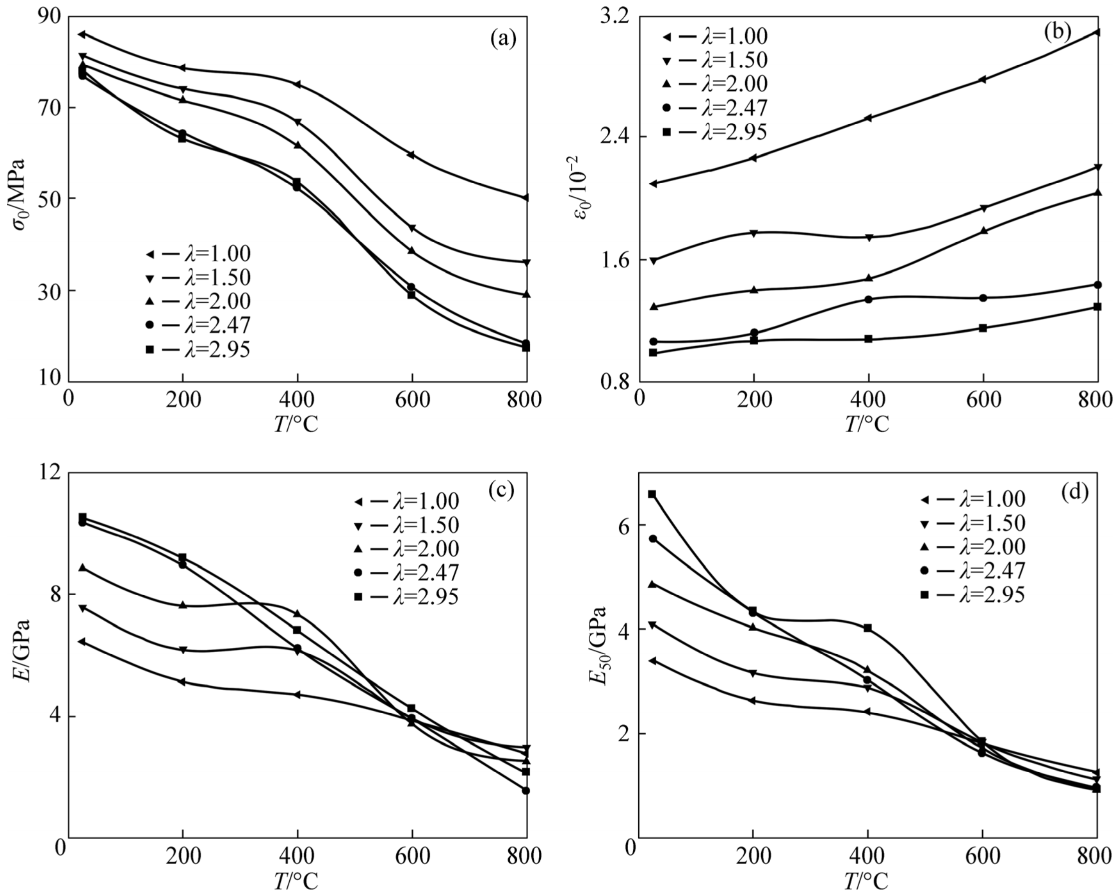

Fig. 5 Variation of macroscopic mechanical parameters: (a) Peak strength; (b) Peak strain; (c) Average modulus; (d) Secant modulus

0.93 GPa, respectively, and peak strain increases from 1.29×10^{-2} to 2.18×10^{-2}, by 68.99%.

2) With the increase of the ratio of height to diameter, peak strength and peak strain gradually decrease. Taking the case at 800 °C as an example, when the ratio of height to diameter increases from 1.00 to 2.95, the peak strength and peak strain respectively decrease from 50.20 MPa and 3.03×10^{-2} to 17.46 MPa and 1.44×10^{-2}, by 65.22% and 52.48%, respectively.

3) With the increase of the ratio of height to diameter, degradation range of peak strength, average modulus and secant modulus along with the temperature gradually increase. When the ratio of height to diameter is 1.00, peak strength, average modulus and secant modulus respectively decrease by 41.59%, 56.74% and 62.83% when temperature rises from 25 °C to 800 °C. But when the ratio of height to diameter is 2.95, those parameters respectively decrease by 77.61%, 79.54% and 86.02%.

3.4 Failure characteristic of sandstone

Figure 6 shows the primary types of failure mode of sandstone samples after high temperature processes with different ratios of height to diameter under uniaxial compression, and the specific distribution is given in Table 1.

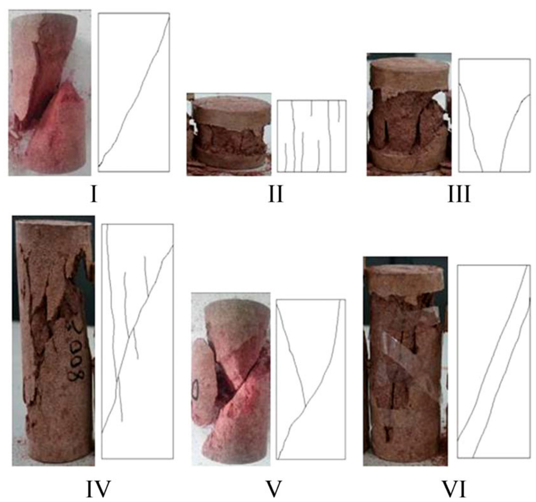

Fig. 6 Failure modes of sandstone

Table 1 Failure mode distribution

Temperature/°C	λ				
	1.00	1.50	2.00	2.47	2.95
25	II	II	I	V	I
200	II	III	I	I	I
400	II	III	I	I	I
600	II	III	V	I	IV
800	II	III	I	VI	IV

1) Shear failure with single shear plane (Type I)

This failure mode is most common, mainly appearing on the sample whose ratio of height to diameter is greater than or equal to 2.00. It attributes to the fact that, when the ratio of height to diameter is large, stress is easy to accumulate on a sloping plane leading to shear failure, and the sample is divided into two cones.

2) Splitting failure (Type II)

This failure mode shows one or multiple-lengthway splitting plane, which mainly appears on the samples with the ratio of height to diameter of 1.00 and some individual samples with the ratio of height to diameter of 1.50.

3) Two symmetrical shear planes failure (Type III)

This failure mode shows two shear planes on both sides of the sample, which presents approximately symmetrical arrangement but they don't intersect with each other. It appears on the samples with the ratio of height to diameter of 1.50 and at a temperature which is equal to or higher than 200 °C.

4) Tensile-shear mixed failure (Type IV)

This failure mode shows a main shear plane accompanied with one or multiple-lengthway splitting plane. It mainly appears on the sample with a ratio of height to diameter of 2.95 and at a temperature between 600 °C and 800 °C.

5) "Y" shear failure (Type V)

This failure mode shows two intersecting shear planes which is very rare. It appears on the individual samples with a ratio of height to diameter between 2.00 and 2.47, such as (T=25 °C, λ=2.47) and (T=600 °C, λ=2.00).

6) Double parallel shear planes failure (Type VI)

This failure mode shows two approximately parallel shear planes which is very rare too, and it appears on only one sample (T=800 °C, λ=2.47).

As the ratio of height to diameter increases, the failure type of sandstone samples gradually develops from tensile failure to shear failure on the whole. Failure form becomes gradually complicated with increasing temperature. At low temperature, blocks of sandstone after damage are relatively regular, but with increasing temperature, the damage degree is sharper. At 800 °C for example, a large number of cracks and peeling appear on the sample surface under compression, and the peeling blocks are fine crumbs.

4 Size effect of sandstone after high temperature process

4.1 Theoretical model

Size effect is a characteristic of rock and big rock structure and its development characteristic is the main factor of rock engineering research. Through many indoor tests, some empirical formulas are concluded by researchers. For example, based on uniaxial compression test of marble with two different grain sizes, YOU and SU [13] summarized the empirical expression of rock cylinder uniaxial compression strength and the ratio of height to diameter; after tests on different height marble samples, YANG et al [15] showed the result that peak strain and elasticity modulus of rock also have noticeable size effect which complies the exponential variation law.

From the test results above, we can know that the size effect also has an influence on the peak strength of sandstone after high temperature process. Based on the variation characteristic of test data and other researchers' empirical formulas [13, 15], a new modified model without dimension is shown:

$$\sigma_0 / \sigma_2 = A\mathrm{e}^{B/\lambda} \tag{1}$$

where σ_0 is the peak strength of a random sample under uniaxial compression, σ_2 is the peak strength of a standard sample under uniaxial compression, λ is the ratio of height to diameter of the sample, and A and B are material parameters. As for the same kind of sandstone material, it is clear that the parameters A and B change with the temperature T, namely, they are the functions of the temperature T: $A(T)$ and $B(T)$.

The absolute value of parameter B in Eq. (1) shows the sensitivity of materials mechanical parameter to size effect. The larger the $|B|$ is, the more obvious the size effect is. Figure 7 reveals that the size effect changes with different values of B. When B is positive, σ_0/σ_2 and λ are negatively correlated; when the B is negative, σ_0/σ_2 and λ are positively correlated.

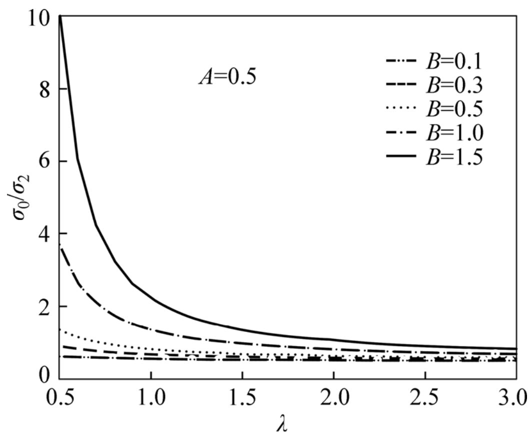

Fig. 7 Influence of parameter B on size effect

Equation (1) shows that when the ratio of height to diameter approaches infinity, σ_0 must reach a fixed value. This threshold shows the peak level of rock strength neglecting size effect and it has really important meaning in rock engineering design. This threshold σ_{0R} is only related to $A(T)$ and mechanical parameter σ_2 of the standard sample:

$$\sigma_{0R} = A(T)\cdot\sigma_2 \ (\lambda \to \infty) \quad (2)$$

In order to validate the applicability of theoretical model, some uniaxial compression test results with different rocks, including marble [14], tuff [14], grey andesite [10] and rocklike material [19], are used. The correlation coefficient R^2, obtained by using Eq. (1) to analyze the test data, is between 0.9172 and 0.9965 with good adaptability. According to the sensitivity characteristic of the size effect, the rocklike material is the most sensitive (B=0.59) and tuff is the least sensitive (B=0.27). The thresholds of marble, tuff, grey andesite and rocklike material are 53.67 MPa, 91.44 MPa, 74.53 MPa and 34.04 MPa, respectively, and that of tuff is the largest.

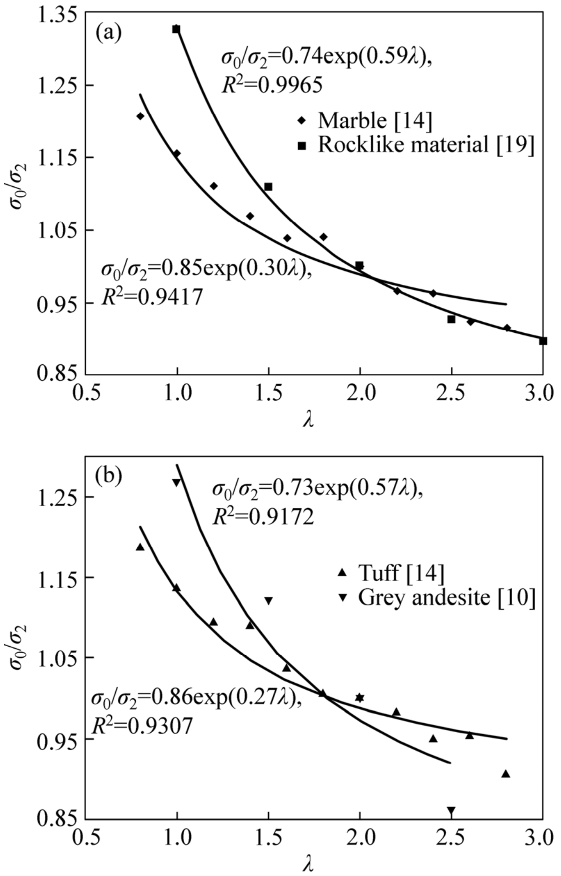

Fig. 8 Theoretical model validation: (a) Marble [14] and rocklike material [19]; (b) Tuff [14] and grey andesite [10]

4.2 Size effect analysis

σ_0/σ_2 is used to indicate the peak strength of sandstone after high temperature process. The experimental value and theoretical curve are shown in Fig. 9, and Table 2 shows the size effect parameter. Correlation coefficient R^2 obtained by experimental value and theoretical model is between 0.8612 and 0.9769, which shows an obvious size effect. When the ratio of height to diameter is between 1.00 and 1.50, σ_0/σ_2 varies in a wide range and the range decreases when the ratio of height to diameter increases.

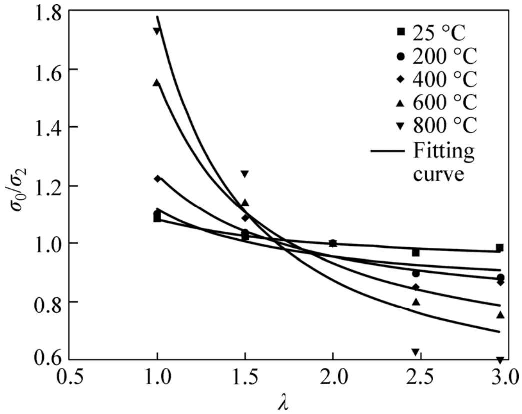

Fig. 9 Experimental value and theoretical curve for size effect of sandstone

Table 2 Size effect parameter

T/°C	A	B	R^2
25	0.92	0.16	0.9573
200	0.82	0.32	0.8612
400	0.74	0.52	0.9165
600	0.55	1.04	0.9769
800	0.43	1.42	0.9286

4.3 Evolution of parameters *A* and *B*

The relationships of parameter A and B with temperature T are shown in Fig. 10, from which we can know:

1) The parameter A decreases gradually with the increase of the temperature, presenting linear characteristics. When the temperature rises from 25 °C to 800 °C, parameter A decreases from 0.92 to 0.43, by 53.26%.

2) Parameter B at 25, 200, 400, 600, 800 °C is respectively 0.16, 0.32, 0.52, 1.04 and 1.42. Parameter B increases with temperature, and size effect highly depends on temperature. The size effect increases with the increase of temperature. By comparing samples with different ratios of height to diameter of 1.00 and 2.95, the peak strength has a difference of 9.28% (7.98 MPa) at 25 °C but 65.22% (32.74 MPa) at 800 °C.

Linear fitting is carried out on the parameter A and B respectively (Fig. 10) and the specific function relations of parameters A, B and the temperature T are obtained. By plugging the relations in Eq. (1), the theoretical model of sandstone material size effect considering the influence of temperature can be gotten:

$$\begin{cases} \sigma_0/\sigma_2 = A(T)\mathrm{e}^{B(T)/\lambda} \\ A(T) = a_1 T + a_2 \\ B(T) = b_1 T + b_2 \end{cases} \quad (3)$$

where a_1, a_2, b_1 and b_2 are undetermined parameters related to material property.

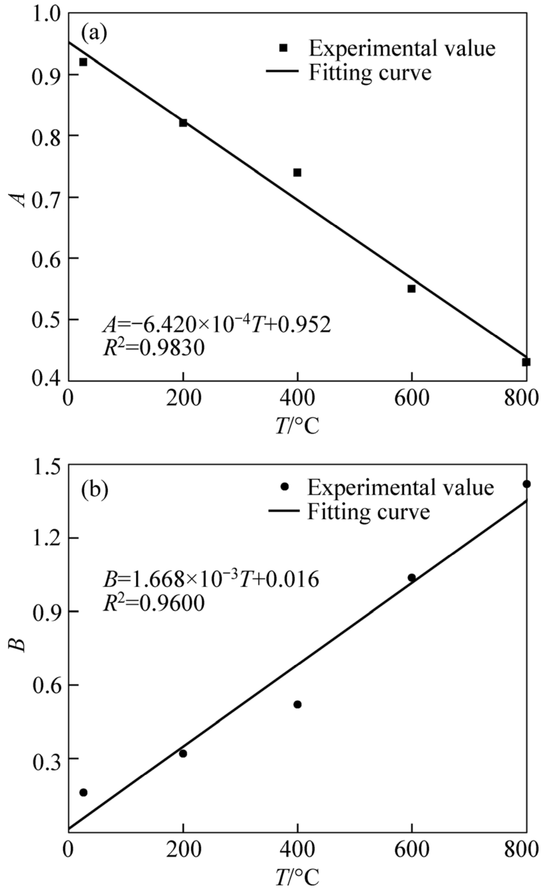

Fig. 10 Relationship of parameter A and B with temperature T: (a) $A-T$; (b) $B-T$

4.4 Evolution of threshold limit value σ_{0R}

Changing curves of the threshold limit value σ_{0R} along with the temperature T are shown in Fig. 11, and the specific values are presented in Table 3. It can be seen from Fig. 11 and Table 3 that deviation of the experimental values and the theoretical values are between 0.44% and 6.06%, with high alignment, which further illustrates the accuracy of the size effect model considering the influence of temperature in this work.

The threshold σ_{0R} decreases gradually with the increase of temperature T, presenting almost linear characteristic, which is obviously corresponding with Eq. (3). As the temperature increases from 25 °C to 800 °C, the experimental values and theoretical values show a decrease from 74.16 MPa and 72.89 MPa to 12.72 MPa and 12.47 MPa, by 82.85% and 82.89%, respectively.

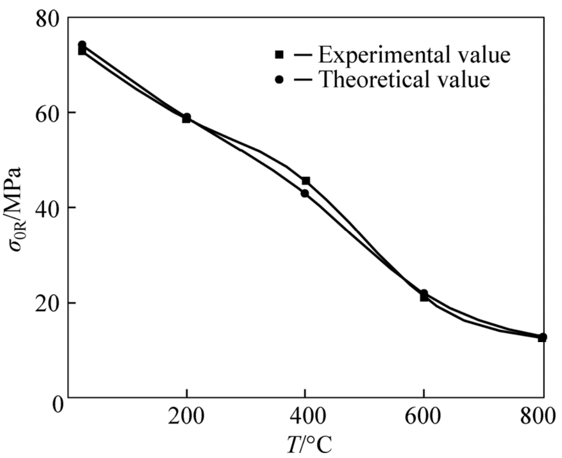

Fig. 11 Relationship between threshold and temperature

Table 3 Threshold limit value σ_{0R}

T/°C	Experimental value/MPa	Theoretical value/MPa	Deviation/%
25	72.89	74.16	1.74
200	58.64	58.90	0.44
400	45.54	42.78	6.06
600	21.17	21.82	3.07
800	12.47	12.72	2.00

5 Conclusions

1) Density, longitudinal wave velocity, peak strength, average modulus and secant modulus of sandstone all decrease with the increase of temperature, while diameter and peak strain increase gradually.

2) With the increase of the ratio of height to diameter, peak strength of sandstone decreases gradually while the decreasing trend becomes smooth, presenting obvious size effect, in which way can the size effect model of sandstone considering the influence of temperature be obtained.

3) Size effect of sandstone material becomes more apparent as the temperature rises, however, the threshold σ_{0R} decreases gradually, and decreasing amplitudes of experimental value and theoretical value are 82.85% and 82.89% between 25 °C and 800 °C.

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