



Research Paper

The effect of high temperature on tensile strength of sandstone



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HIGHLIGHTS

- This paper reports the variation of tensile strength with temperature (25–900 °C).
- Relationship between tensile strength and total absorbed energy of disc is studied.
- The results indicate four phases in the variation of tensile strength.
- Tensile strength and longitudinal wave velocity are related in quadratic function.
- Tensile strength is closely related to the effect of thermal stress.

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ABSTRACT

Heating at high temperature will make the tensile strength of sandstone change due to the loss of water and minerals and the effect of thermal stress. In this paper, the sandstone samples are heated from room temperature to 900 °C in a high temperature furnace and then are subjected to Brazilian test with a computer-controlled hydraulic universal testing machine. The longitudinal wave velocity, total energy absorbed per unit thickness of disc and mass loss rate are comprehensively investigated. The results show that the tensile strength changes in the following four phases: from room temperature to 300 °C, 300–600 °C, 600–800 °C and 800–900 °C, among which the tensile strength decreases rapidly in the second (300–600 °C) and fourth phases (800–900 °C) owing to the thermal stress that the most conspicuous effect is the expansion of quartz. The changing trends of tensile strength, longitudinal wave velocity and total energy absorbed per unit thickness of disc along with the temperature are similar.

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1. Introduction

Effect of temperature on the physical and mechanical properties of rock is an important research topic in the field of rock mechanics [1]. In many cases, the rock mass may be affected by high temperature, underground coal gasification [2], underground development of deep mine oil and gas storage cavern [3], burial of highly radioactive nuclear waste [4], development of geothermal resources [5,6] and fire in exploitation of underground rock [7–9]. The physical and mechanical properties of rock will change obviously after high temperature, such as the decrease of strength, elastic modulus and longitudinal wave velocity [10,11]. Those changes may cause irreparable loss if there are no good remedial measures. Therefore, the problem of rock engineering in high temperature environment has become the new development of rock mechanics [4].

Many studies have got certain achievements focusing on physical and mechanical properties of rock under high temperature [1–20]. The tensile strength is a key parameter for determining the rock's load bearing capacity, deformation, damage, fracturing and crushing, etc., therefore it is used to analyze the stability and serviceability of rock structures [21]. There are many test methods to determine the tensile strength such as Brazilian tensile strength test [22], flatten Brazilian disc [23], semi-circular bending test [24] and ring test [25]. The Brazilian tensile strength test is widely applied to rock engineering because it is easy to conduct, specimens are easy to prepare and uniaxial compression test machines are quite common [21]. Zhao et al. [8] studied the changing trends of density, longitudinal wave velocity and tensile strength of grit stone after high temperature. Su et al. [16] investigated the effect of temperature and sample size on the tensile strength by carrying out the Brazilian tensile strength test at five temperature levels ranging from 20 °C to 800 °C. Dan and Konietzky [26] carried out a series of Brazilian tests on Mosel slate and simulated the deformation process and failure behavior of the foliated rock samples.

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Liu and Xu [27] used an electro-hydraulic and servo-controlled material testing machine and a split Hopkinson pressure bar to conduct static and dynamic compression and splitting tensile tests in order to make a full study on the static and dynamic mechanical properties of high-temperature-treated granite.

Therefore, the study on tensile strength of sandstone is of great significance in a wide range. Based on the above, by taking the tensile strength as the clue, we analyzed the variations of longitudinal wave velocity, mass loss rate and total energy absorbed per unit thickness of disc with temperature in this paper. Thermal stress at different temperatures was also discussed. This study is expected to provide a scientific basis of high temperature rock mechanics for the prediction and evaluation of the stability and safety of rock mass after high temperature.

2. Experiment preparations and test methods

We obtained the tested samples of sandstone from Linyi, Shandong province. The average density of sandstone samples is about 2.41 g/cm³ and the natural content of water is about 0.07%. The sandstone samples mainly consist of quartz, dolomite/ankerite, feldspar and kaolinite. The procedures of this experiment are shown in Fig. 1. First of all, we cut samples into $\Phi 50 \times 30$ mm disc specimens and numbered in sequence, and then heated them to the specified temperature (25 °C, 50 °C, 150 °C, 200 °C, 250 °C, 300 °C, 350 °C, 400 °C, 450 °C, 500 °C, 550 °C, 600 °C, 650 °C, 700 °C, 750 °C, 800 °C, 850 °C and 900 °C) at the rate of 30 °C/min by a high temperature furnace (type KSL-1100X-L). When the heating process was over, we kept samples at designed temperature for 30 min in order to ensure samples heated evenly, and then let them to cool naturally.

The longitudinal wave velocity of samples was measured by RSM-SY5 Wave Detector whose emission voltage is 500 V. Ultrasonic pulse method was used, and sampling interval was 0.5 μ s. The Brazilian test was carried out in our test by a computer-controlled hydraulic universal testing machine (type WES-D1000) which collects the load, time and displacement data automatically. The load at a rate of 0.3 kN/s was measured by an oil pressure sensor and meanwhile a cylindrical capacitor displacement sensor was used to measure the displacement of sandstone samples. The experimental process was performed by the control program which using the data interface with system. In order to obtain more accurate results, the repetitive test was performed 4 times at each temperature and the test values with large discreteness were removed. The average values of tensile strength and longitudinal wave velocity of sandstone samples after different temperatures treated were shown in Table 1.

3. Test results and analysis

3.1. variation of tensile strength

The tensile strength σ_t (MPa) based on Brazilian test is calculated by the formula (1) [28].

$$\sigma_t = \frac{2P}{\pi Dt} \quad (1)$$

where P is the peak load, N; D is the diameter of the disc, mm and t is the thickness of the disc, mm.

The tensile strength of sandstone samples changes significantly along with the temperature (shown in Fig. 2). From 25 °C to 300 °C, the average value of tensile strength decreases a little from 5.69 MPa to 4.62 MPa. At the range of 300–600 °C, the average value of tensile strength decreases with a magnitude of 53.14 percent from 4.62 MPa to 2.38 MPa. From 600 °C to 800 °C, the aver-

age value of tensile strength is just a slight downtrend from 2.38 MPa to 2.21 MPa. In the last phase (from 800 °C to 900 °C), the average value of tensile strength decreases sharply about 75.32 percent from 2.21 MPa to 0.55 MPa.

3.2. Relationship between tensile strength and longitudinal wave velocity

The sound wave can spread in rocks due to the elastic properties. The propagation velocity is influenced by mineral composition, degree of consolidation, porosity, and so on [15]. When rocks subjected to high temperature, internal defects and macro-cracks will grow. The increase of cracks and porosity lead to the decrease of tensile strength and longitudinal wave velocity. For the same material, the relationship between tensile strength and longitudinal wave velocity can be written as [8]:

$$\sigma_t = a(V_p + c)^2 \quad (2)$$

where V_p is longitudinal wave velocity; a , c are the constant.

The results of longitudinal wave velocity and tensile strength are given in Fig. 3. The variations of tensile strength and longitudinal wave velocity versus temperature are similar and can be divided into four phases: room temperature to 300 °C, 300–600 °C, 600–800 °C, 800–900 °C. A quadratic fitting curve of tensile strength and longitudinal wave velocity is fitted with the red¹ curve in Fig. 4, and can be expressed in mathematics as Eq. (3):

$$\sigma_t = 1.597 - 1.772V_p + 0.858V_p^2, R^2 = 0.770 \quad (3)$$

The correlation coefficient of the curve is 0.770, suggesting that the data are fitted well.

3.3. Relationship between tensile strength and total energy absorbed per unit thickness of disc

Load-displacement curves (shown in Fig. 5) of Brazilian disc under different temperatures generally experiences the process of compaction, linear evolution and decline after peak point. The yield step before peak stress is not obvious, showing that the sandstone samples are in a strong brittle failure state. The disc specimens of sandstone lost bearing capacity in a short time after the axial load reaching the peak value. With the increase of axial load, micro-cracks will appear and connect to forming the macro-fissures. Sandstone samples were damaged after axial load reaching the peak value (shown in Fig. 6). The appearance and development of cracks are the macroscopic expression of thermodynamics, which reflects the accumulation and transformation of energy consumption [16]. During the loading process, uniformly distributed load exerted by universal testing machine does work at the disc specimens, which can be entirely transformed into the total absorbed energy of the disc ignoring the external heat dissipation. The load and axial displacement are P_i and l_i respectively when the disc specimens are loaded to the step i . The total energy absorbed per unit thickness of disc (K) is expressed as [16]:

$$K = \int P_i \Delta l_i / t \quad (4)$$

When the total displacement is equal to the limit displacement (displacement corresponding to the peak load), total energy absorbed per unit thickness of disc also reaches the maximum K_0 which decreases gradually with the increase of temperature (shown in Fig. 7). A linear curve of $\sigma_t - K_0$ is fitted with the red curve in Fig. 8, and can be expressed with an equation:

¹ For interpretation of color in Figs. 4 and 8, the reader is referred to the web version of this article.

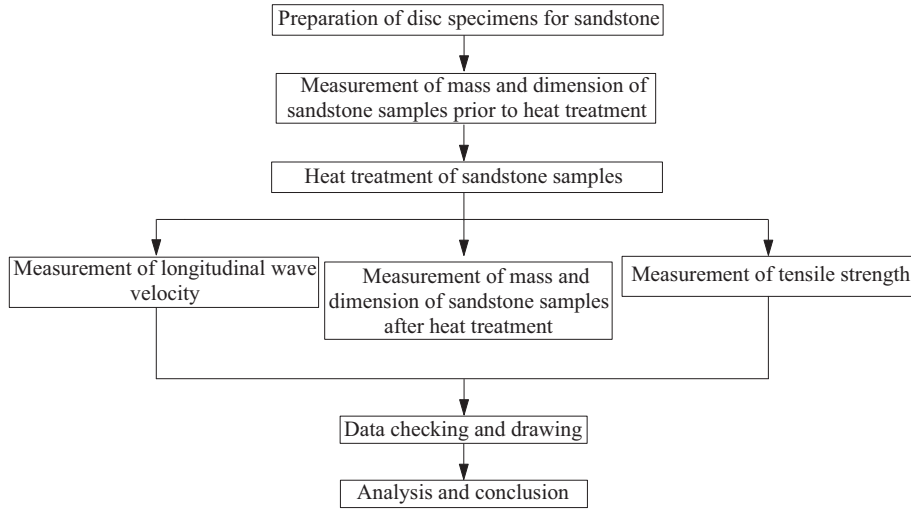


Fig. 1. Test flow.

Table 1

The average values of tensile strength and longitudinal wave velocity of sandstone samples after different temperatures treated.

Temperature/°C	Tensile strength/MPa	Longitudinal wave velocity/km s ⁻¹
25	5.69	3.14
50	5.37	3.05
100	4.89	3.19
200	4.66	3.18
250	4.60	3.14
300	4.62	2.96
350	3.69	3.12
400	3.63	2.82
450	2.50	3.05
500	2.17	2.84
550	2.29	2.57
600	2.38	2.47
650	2.06	2.36
700	2.00	2.30
750	2.09	2.19
800	2.21	1.95
850	0.61	1.19
900	0.55	0.98

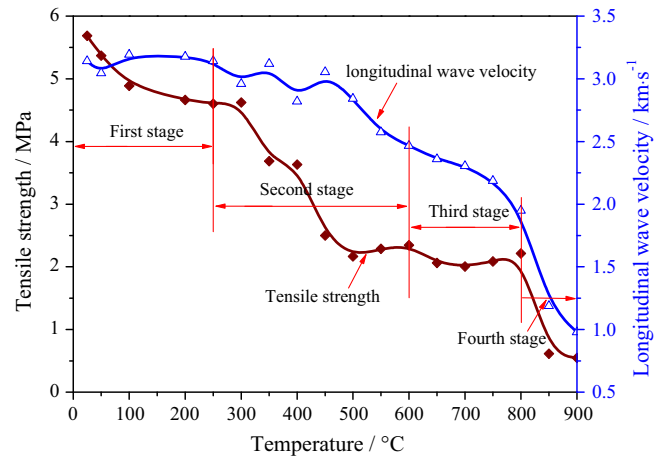


Fig. 3. Variations of tensile strength and longitudinal wave velocity after different temperatures treated.

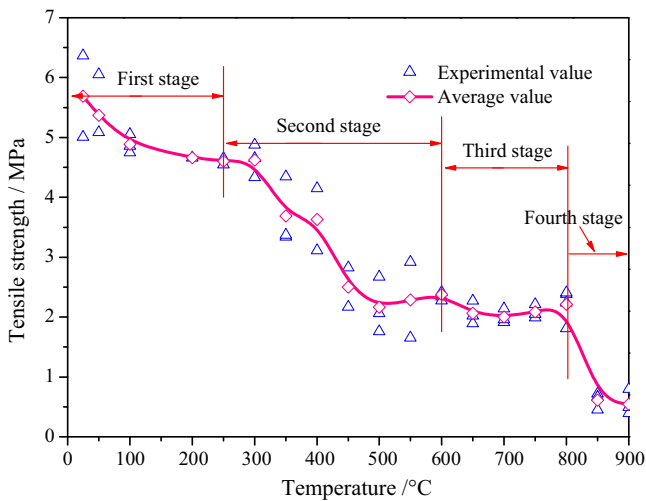


Fig. 2. Variation of tensile strength after different temperatures treated.

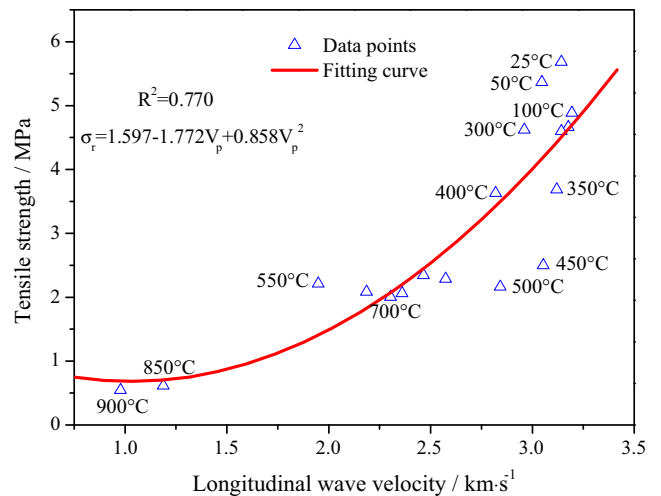


Fig. 4. The quadratic fitting curve of tensile strength and longitudinal wave velocity.

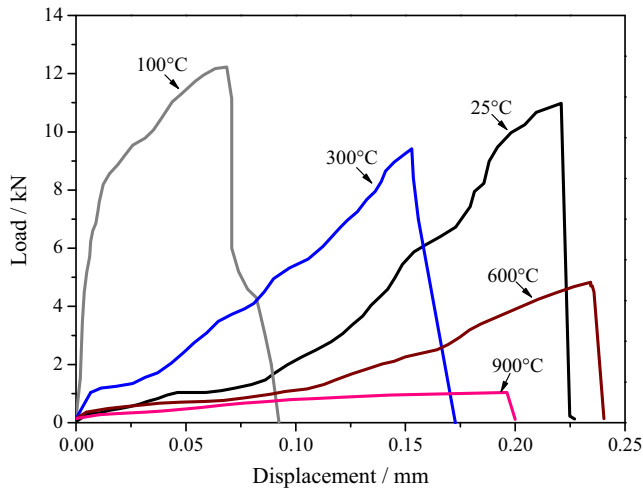


Fig. 5. Load-displacement curves of Brazilian disc.



Fig. 6. The damage of Brazilian disc.

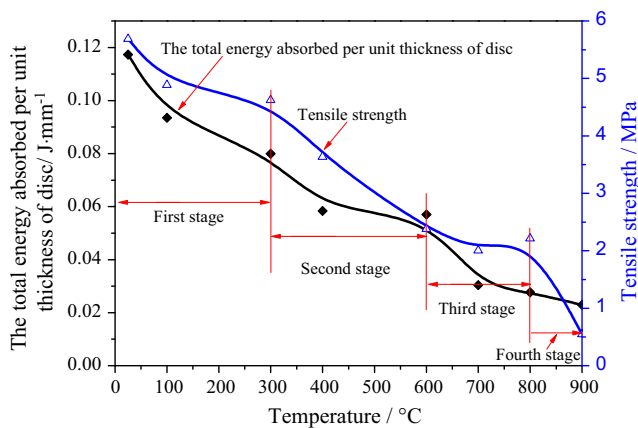


Fig. 7. Variations of tensile strength and total energy absorbed per unit thickness of disc (K_0) after different temperatures treated.

$$\sigma_t = 0.282 + 48.683K_0, R^2 = 0.950 \quad (5)$$

The correlation coefficient of the curve is 0.950, suggesting that the data are fitted very well. Therefore, the variations of tensile strength

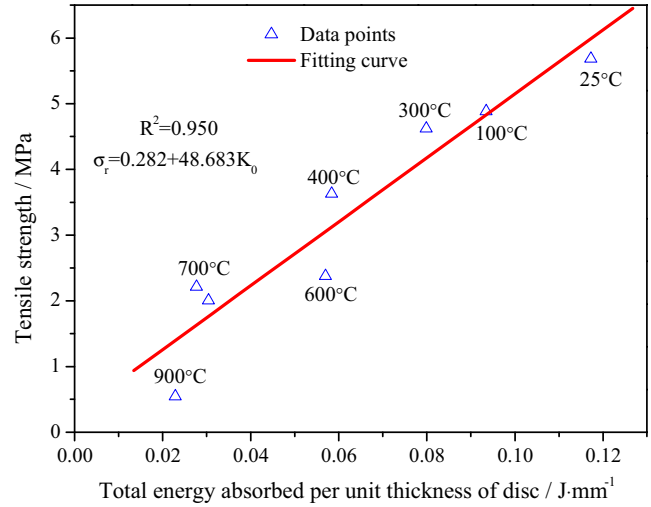


Fig. 8. The linear curve of tensile strength and total energy absorbed per unit thickness of disc (K_0).

and total energy absorbed per unit thickness of disc along with the temperature are consistent.

4. Discussions

There are many factors (i.e. porosity, filling medium of pore, water content) that mainly depend on the mineral composition and structure characteristics affecting the physical and mechanical properties of rocks. The sandstone is a heterogeneous body with different minerals which have different thermal expansion coefficient at high temperature, forming the thermal stress [1]. The maximum value of thermal stress often occurs at the junction of mineral particles. The connection of interface between the mineral particles is broken if the thermal stress reaches or exceeds the ultimate strength. Therefore, the micro-fissures would extend and develop, and it would be partially retained even if the sandstone samples are cooled down to room temperature. At the same time, it is known that the absorbed water would escape around 100 °C; the bounded water escape between 100 °C and 300 °C; crystal water would escape below 400 °C; and structural water of mineral would escape above 300 °C [12,15,29]. With the increase of temperature, the decomposition of minerals in rocks also leads to an increase in internal structural defects. The physical and mechanical properties of sandstone change in different degrees by those factors above.

Tensile strength, longitudinal wave velocity and total energy absorbed per unit thickness of disc with temperature may be divided into four phases.

- (1) 25–300 °C. In this phase, the quality of sandstone decreases a little bit (as shown in Fig. 9) due to the escape of free and combined water. The voids in sandstone would increase simultaneously, which could accommodate the deformation caused by the expansion of mineral grains. Therefore, the tensile strength, longitudinal wave velocity and total energy absorbed per unit thickness of disc are just a slight downtrend.
- (2) 300–600 °C. In this phase, structural water and crystal water in minerals evaporate, such as dehydroxylation of kaolinite at approximately 541 °C [30,31]. At the same time, the most conspicuous effect of the thermal stress between mineral particles is the expansion of quartz, leading to new cracks. The volume expansion rate of quartz is nearly linear before 300 °C, but presents an exponential growth from 300 °C to

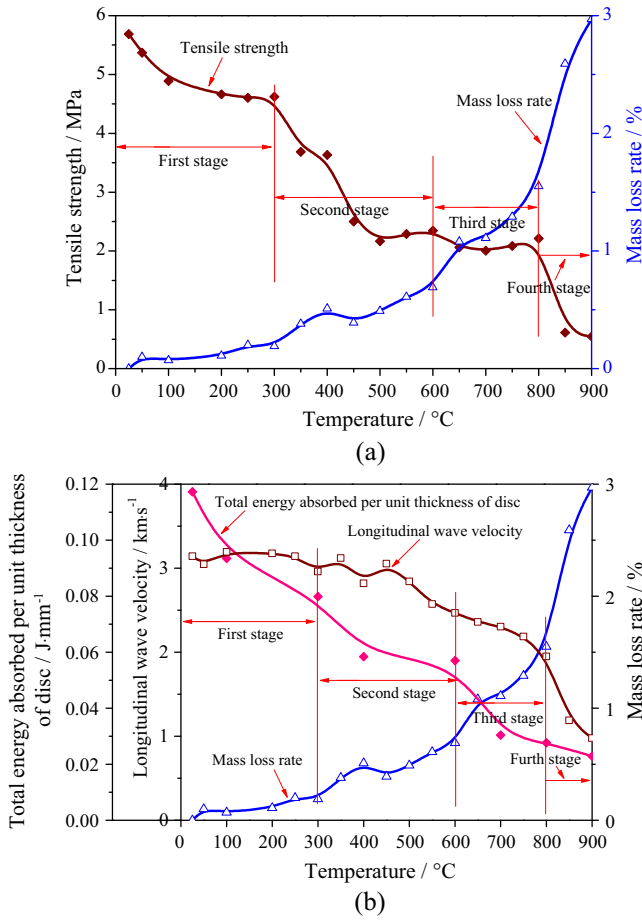


Fig. 9. Variations of tensile strength, longitudinal wave velocity, total energy absorbed per unit thickness of disc and mass loss rate after different temperatures treated. (a) Variations of tensile strength and mass loss rate after different temperatures treated. (b) Variations of longitudinal wave velocity, total energy absorbed per unit thickness of disc and mass loss rate after different temperatures treated.

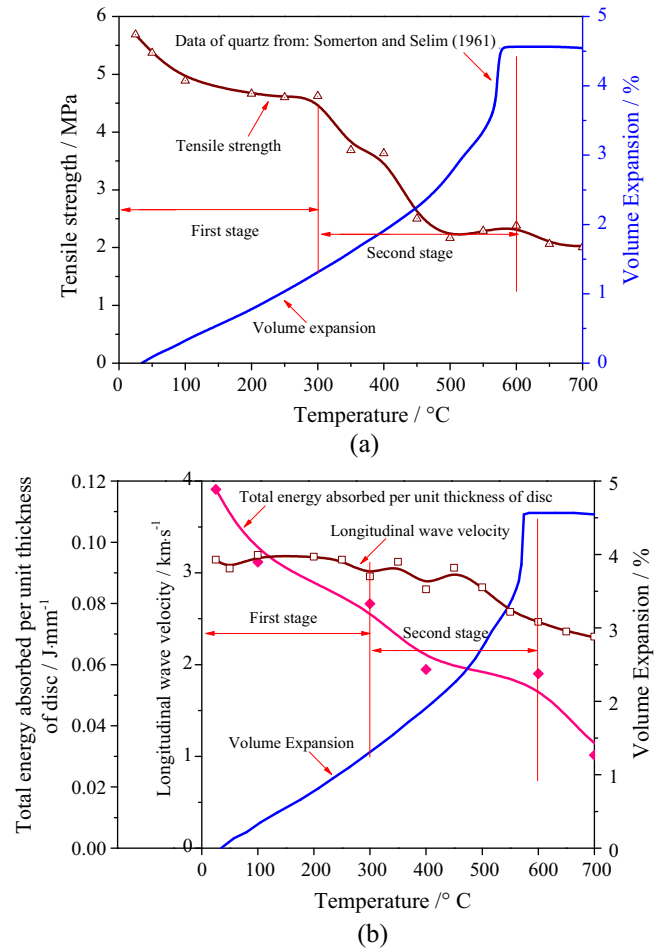


Fig. 10. Variations of tensile strength, longitudinal wave velocity, total energy absorbed per unit thickness of disc and volume expansion after different temperatures treated. (a) Variations of tensile strength and volume expansion after different temperatures treated. (b) Variations of longitudinal wave velocity, total energy absorbed per unit thickness of disc and volume expansion after different temperatures treated.

600 °C (as shown in Fig. 10). Specifically, quartz has a phase transformation at approximately 573 °C (from α phase to β phase) which makes the volume of quartz increase sharply. The micro-fissures would develop and extend, and it would be partially retained though beta quartz would return to alpha quartz when cooled down to room temperature. Therefore, the tensile strength, longitudinal wave velocity and total energy absorbed per unit thickness of disc decrease rapidly.

- (3) 600–800 °C. In this phase, many minerals would melt [32] and metallic bonding would fracture (such as Ca–O, K–O, Na–O, and Al–O) [33]. Meanwhile, the decomposition of dolomite and generation of CO₂ increase the porosity [31] and reduce the quality of sandstone rapidly (as shown in Fig. 9). Therefore, the tensile strength, longitudinal wave velocity and total energy absorbed per unit thickness of disc continue to decrease.
- (4) 800–900 °C. In this phase, the thermal stress continues to increase. Quartz has a phase transformation from β phase to β -tridymite phase at approximately 870 °C, which makes the volume of quartz increase by 16%. At the same time, a large amount of micro-fissures increase and connect to forming the macro-fissures (as shown in Fig. 11), which makes mineral particles on the surface and the edge of cracks of specimens fall off. The quality of sandstone

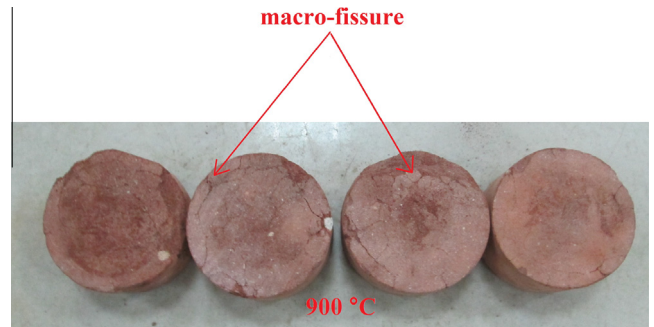


Fig. 11. Sandstone samples at 900 °C.

decreases rapidly (as shown in Fig. 9). Therefore, the tensile strength, longitudinal wave velocity and total energy absorbed per unit thickness of disc decrease sharply. Zhang et al. [34–35] had also confirmed the acute reduction of rock strength after 800 °C.

Zhao et al. [8] and Liu and Xu [27] had also studied the variation of rock's tensile strength versus temperature (as shown in Fig. 12). Compared to our test results, their research presented important

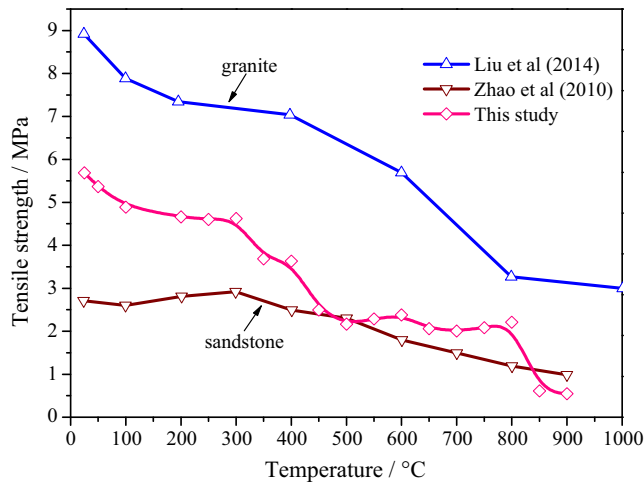


Fig. 12. Variations of tensile strength versus temperature.

similarities. Especially in the first two phases, tensile strength decreased a little from room temperature to 300 °C and decreased rapidly from 300 °C to 600 °C. Generally speaking, when sandstone subjected to high temperature, these factors (i.e. loss of water, decomposition of minerals and thermal stress) would work together and make internal defects grow, contributing to the decrease of tensile strength.

5. Conclusion

In order to study how the tensile strength of sandstone varies after high temperature, Brazilian test was conducted, with the focus of such study of its variation with temperature as longitudinal wave velocity, total energy absorbed per unit thickness of disc and mass loss rate. The following conclusions can be drawn:

- (1) Temperature has a significant impact on the tensile strength of sandstone, which is related to the loss of water and minerals and the effect of thermal stress. The changing trends of tensile strength, longitudinal wave velocity and total energy absorbed per unit thickness of disc are similar.
- (2) The variation of tensile strength with temperature can be divided into four phases: from room temperature to 300 °C, 300–600 °C, 600–800 °C, 800–900 °C. The first phase corresponds to the escape of free and combined water. Between 300 °C and 600 °C, the most conspicuous effect of the thermal stress is the expansion of quartz, contributing to the rapid decrease of tensile strength. The melt of minerals, decomposition of dolomite and fracture of metallic bonding are demonstrated as the sustained reduction of tensile strength from 600 to 800 °C. Finally, tensile strength decreases sharply due to the formation of macro-fissures above 800 °C.

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