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Effect of different cooling conditions on physical and mechanical properties of high-temperature sandstone

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Abstract: Rock engineering may be subjected to high temperature environment. Different cooling methods of high-temperature rock often lead to significant changes in the physical and mechanical properties of the rock, which will have an important impact on the stability and permeability of rock engineering. Magnetic resonance imaging (MRI), scanning electron microscope (SEM) and uniaxial compression test were used to study the porosity, pore size distribution, peak strength, peak strain, stress-strain relationship and microstructure changes of five temperatures for sandstone samples at 100, 300, 500, 600 and 800℃ under two cooling methods (natural cooling and water cooling). The test results show that: (1) When the rock samples used the natural cooling method, the strength of high-temperature sandstone does not decrease continuously with the increasing of temperature. However, rock samples using water cooling method show continuous decrease of sandstone strength, and the decreasing extent is far greater than that of natural cooling; (2) 500℃ can be considered as the critical value of the influence of different cooling methods on the porosity of sandstone. When the temperature is above 500℃, the water cooling method will cause the rock porosity increase rapidly, and the proportion of pores with large pore diameter (Φ>10 μm) is also higher than that of the natural cooling method. In this consideration, in the field of high-temperature sandstone engineering, the possible seepage hazards should be fully considered when water cooling is used (i.e., fire extinguishing with water after a tunnel is on fire); (3) The SEM test results shows that when the temperature is above 500℃, water cooling promotes the widening and expansion of cracks. When the temperature reaches to 800℃, the pore size of water-cooled sandstone becomes larger, and the fracture is largely developed and connects into a network. This will lead to a substantial increase in water permeability. At the same time, it is one of the reasons for the sharp decrease in rock strength that caused by water cooling at this temperature.

Keywords: sandstone; heat treatment; cooling conditions; pore; MRI; SEM

1 Introduction

High temperature rock mechanics has been involved in many engineering applications such as deep mining of mineral resources, utilization of underground heat source, urban underground space, deep disposal of radioactive nuclear waste, and underground coal gasification. Currently, high temperature rock mechanics has become a hot spot in rock mechanics research[1−2]. Different cooling methods of rock after high temperature treatment will lead to large changes in its physical and mechanical properties, which will affect the stability and permeability of the corresponding rock engineering. For a tunnel project, for instance, a fire occurred in the tunnel and then was extinguished by water. The rock mass of the tunnel is cooled by water, changes of the mechanical properties and its porosity and pore distribution usually affect the stability and water permeability of the tunnel. It is therefore necessary to study the changes in the physical and mechanical properties of rock caused by high temperature and various cooling methods, which is of great significance to the study of rock engineering stability.

At present, the research of high temperature sandstone is mainly focused on the physical properties, mechanical properties, and property change laws. The research methods are mainly laboratory tests, which include acoustic wave test, uniaxial and triaxial compression strength tests, Brazilian splitting test, scanning electron microscope (SEM), polarizing microscope, acoustic emission (AE), and the Split Hopkinson pressure bar (SHPB) test, etc.

Wu et al[3] and Zhang et al[4] conducted laboratory studies on the mechanical properties of sandstone after high temperature using uniaxial compression strength test, and they analyzed the strength and deformation characteristics of sandstone after high temperature treatment. For high porosity coarse sandstone specimens, Su et al[5] studied the change of physical and mechanical properties after high temperature treatment, and they concluded that the reasons for the mechanical property deterioration are the crack expansion and thermal stress. Through a proposed thermal damage factor based on the compaction modulus, Wang et al[6] analyzed the change of the thermal damage factor with temperature and the damage rule of high temperature sandstone could be obtained. Wu et al[7] tested and analyzed the elastic wave velocity and mechanical parameters of

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sandstone after 20–1 200 ℃ using the wave velocity and the UCS tests. They analyzed mechanical properties such as the dynamic elastic modulus, dynamic Poisson's ratio, and ratio of P to S wave velocity. As the temperature increases, they studied the relations between the temperature and the compressive strength caused by the anisotropic expansion of different mineral particles and the change of the stress-strain curve. Zhang et al[8] studied the pore characteristics and mechanical properties of sandstone at high temperature, and they found that the high temperature would increase the porosity of sandstone and deteriorate the mechanical properties. Using laboratory test method, Zhang et al[9] studied the changes of internal mineral composition, internal structure, and water content of sandstone and granite specimens under high temperature. Through the mercury intrusion porosimetry, Zhang et al[8] studied the change rules of pore characteristics and mechanical properties of rock specimens at different temperatures, and they concluded that the water loss and the decomposition of the mineral particle at high temperature lead to the increasing of rock porosity and the decreasing of mechanical properties. Zhu et al[10] studied the physical and mechanical properties of sandstone with a single fissure under different temperature conditions, and they obtained the law of the compressive strength and other parameters with temperature. Besides, they studied the corresponding temperature threshold values and the threshold of the wave velocity was considered as 100℃, the threshold of mechanical properties was considered as 500℃. Zhao et al[11] studied the changes of the microstructure and mechanical properties of sandstone at 25–900℃ using scanning electron microscopy, X-ray diffraction, UCS test, etc., and they analyzed sandstone pores and mechanical changes under different temperature intervals. The abnormal growth of sandstone strength after 600℃ was also analyzed from the aspects of pore change and mineral reaction.

The cooling methods of high temperature rock mainly include natural cooling, room temperature cooling (water cooling and wind cooling), and ultra-low temperature cooling. Among these three methods, the ultra-low temperature cooling approach uses ultra-low temperature fluid (such as liquid nitrogen) to cool the rock. This method is mainly used for the oil and gas mining industry[12–14].

Using the acoustic wave and the UCS tests, Xi et al[15] studied the ultrasonic velocity, UCS, tensile strength, and elastic modulus of granite specimen after cooling with water within 600℃, and they discussed the relations between these properties and temperature. Wang et al[16] studied the mechanical properties of high-temperature granite after the natural cooling and the rapid cooling using water using the UCS tests, and they discussed the effect of rapid water cooling on the high-temperature residual mechanical properties of granite. Through the UCS test, acoustic emission, image analysis, and other test methods, Kumari et al[17] studied the mechanical properties and fracture behaviour of high-temperature Australian Strathbogie granite under two cooling methods (fast and slow). The test results showed that the thermal damage after cooling would occur when the granite temperature was greater than 400℃. The failure mode of high-temperature cooling granite changed from brittle to quasi-brittle fracture, and the effect of rapid cooling was greater than that of slow cooling. Using acoustic wave and Brazilian splitting tests, Liang et al[18] studied the physical properties of granite at different heat treatment temperatures and the Brazilian splitting characteristics under different cooling conditions. They concluded that the different cooling methods had little effect on the above parameters when the heat treatment temperature was lower than 200℃, but when the temperature was greater than 200℃, the attenuation of the above parameters was accelerated under water cooling condition. In addition, using the acoustic testing, UCS, Brazilian splitting, and pressure pulse attenuation tests, Jin et al[19] studied the mechanical properties and permeability of granite after water cooling under different high temperature conditions, and they summarized change laws of the mechanical properties and the permeability under the water cooling condition of granite specimens at different temperatures. Xi et al[20] explored the evolution law of the mechanical properties of granite with cooling temperature using thermal shock tests. For the same heating temperature of rock specimen, after the rupture using the thermal shock under different temperature cooling media, they found that the UCS, tensile strength, and the cohesion decreased with the increasing of the temperature of the cooling media, while the internal friction angle increased.

Huang et al[21–22] studied the mechanical, acoustic, and wave characteristics of high temperature treated limestone and marble after being cooled by water, and they found that the mechanical properties had a good correlation with the wave velocity or wave characteristics as the temperature changes. Using the UCS, wave velocity, AE, and SEM approaches, Han et al[23] studied the physical and mechanical properties of sandstone at 100–800℃ under water cooling and they obtained the "three-phase features" change rules of acoustic wave velocity decreasing and elastic modulus decreasing under water cooling of sandstone at different temperatures. They also found that the rock ductility did not change too much under UCS tests. Liu et al[24] used approaches of the UCS, AE, SEM to study the macro- and meso-physical properties of red sandstone under cold–heat cycles that ranged from room temperature to 500℃. They analyzed the relation between acoustic emission and cold–heat cycles, as well as the relation between the micro-structure and mineral particles under cold-heat cycles. Zhu et al[25] studied the physical and mechanical properties of high-temperature granite after cooling with water at 500℃, and they found the change rule between the temperature and the physical and mechanical properties of high temperature granite after cooling with water. Han et al[26] also used wave velocity test, UCS test, and AE signal monitoring to study the change rules of different parameters of sandstone after cooling with water in the range of 800℃.

To sum, in the study of high-temperature rock mechanics, there are relatively intensive studies on the changes in physical and mechanical properties of rocks after high temperature. The reaction of rock after high-temperature cooling has also begun to receive attention in recent years.

The research approaches and methods of rock properties after high temperature cooling are mainly embodied in three aspects: (1) analyze the mechanical property changes of high temperature rock under different cooling methods using the mechanical tests, including strength degradation properties, stress–strain relations; (2) use acoustic wave testing methods to obtain wave velocity changes, and then to analyze the changes of rock internal fractures; (3) analyze the failure mode using the AE and SEM method.

From the literature review, it is found that the research object is mainly focused on granite. There are relatively few studies on sandstone, which are widely distributed, high clay mineral content, high porosity, and reservoir rocks with highly variable and complex properties under high temperature conditions [27].

Sandstone is taken as the research object in this study and different approaches are used such as MRI, SEM, and UCS tests. The porosity, pore size distribution, pore expansion, and internal fracture penetration, strength changes and their correlations are analyzed for the high temperature sandstone that is cooled by two methods: the water and natural cooling. The influence rules and reasons of different cooling methods on the mechanical properties and the permeability properties of sandstone are then discussed, which provides a reference for the stability evaluation, permeability analysis, and similar engineering protection of the high-temperature cooling sandstone engineering.

2 Heating and cooling of rock specimen

2.1 Preparation of rock specimens

The rock specimens were yellow sandstone, which were taken from the Hanzhong area of Shaanxi Province, China. The rock specimens seemed to be in khaki, as shown in Fig. 1. The average density of the rock specimen was 2.19 g/cm^3 in the natural state, the porosity was 13.86%, and the UCS was 50.38 MPa. The rock specimens were processed following the specimen preparation requirements of the International Society for Rock Mechanics (ISRM). For nuclear magnetic analysis, the size of the rock specimen was 25 mm × 50 mm, and the size of the UCS test rock specimen was 50 mm × 100 mm. The rock specimens were numbered as A-*X*-*Y* and B-*X*-*Y*, which were marked on the rock specimens for intuitive distinction purposes during the tests (see Fig. 1). The first letters A and B denoted the natural cooling and water cooling methods, respectively. *X* was 1, 2, 3, 4, 5, and 6 to represent six temperatures of 25, 100, 300, 500, 600, and 800℃, respectively. *Y* was 1, 2, and 3 to represent the number of rock specimen, respectively. To ensure the reliability of the test results, the rock specimens were first unselected if the rock specimen had obvious cracks and other defects, and the rock specimens were then selected if they had similar wave velocity based on the acoustic test method. For each group, three rock specimens were tested and the rock specimens were placed in a dry environment at room temperature prior to the test.

2.2 Heating and cooling of rock specimens

As shown in Fig. 2, the rock specimens were heated by a small box-type resistance furnace with the model of KSL-1200X-J, which was manufactured by Hefei Kejing Materials Technology Co., Ltd. The maximum power of the resistance furnace is 2.5 kW. The maximum working temperature is 1200℃, the long-term working temperature is 1100℃, and the temperature control accuracy is in the range of ±1℃.

Fig. 1 Specimens used in the tests

Fig. 2 KSL-1200X-J box resistance furnace

The heating temperature was set to five groups as 100, 300, 500, 600, 800℃. The temperature was increased at a heating rate of 5℃/min, and the temperature was then kept constant for 2 h after reaching the target temperature to ensure the rock specimens were heated uniformly.

After the rock specimens were heated uniformly, natural cooling in the furnace and rapid cooling in water were then performed, respectively. The final temperature of natural cooling was set as 25℃. For the rapid water cooling way, the heated rock specimens were clipped out of the heating furnace and quickly put them into the pre-prepared 100 L, 25℃ water. The immersion time should not less than 8 h to ensure the full cooling of the heated rock specimens.

3 MRI Test

3.1 Apparatus and test scheme

To obtain the internal pore size distribution and pore changes of the high-temperature sandstone under different cooling conditions, MRI was used to measure the pores of the sandstone at different temperatures under the two cooling methods. The mode of the magnetic resonance imaging analyzer was MesoMR 23-060H-I from the Suzhou Newmag Analytical Instrument Co., Ltd., as shown in Fig. 3.

The rock specimens were evacuated firstly and then saturated with water, so that the pores of the rock specimens were filled with water. During the tests, the forced saturation conditions were: –0.095 MPa of the vacuum degree, 24 hours of immersion. Next, the MRI analyzer was used to measure the nuclear magnetic signal of a standard specimen with known porosity with a certain volume. The correlation between the nuclear magnetic signal intensity and the porosity was then obtained, and the correlation curve was viewed as the calibration curve. Finally, the rock specimens to be tested were placed in the detection chamber, and the unknown porosity rock specimens were then measured based on the calibration curve (as shown in Fig.4).

Fig. 3 MesoMR23-060H-I magnetic resonance imaging analyzer

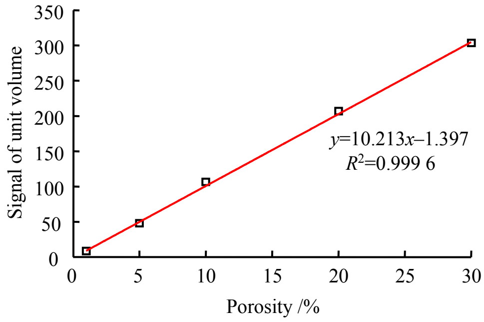


Fig. 4 Calibration curve

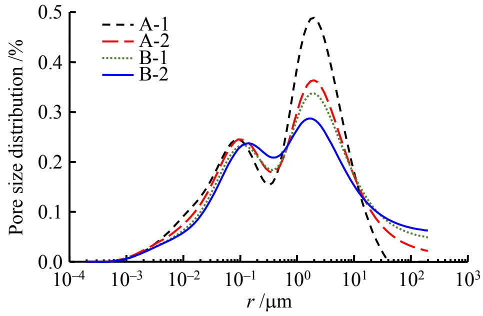
3.2 Pore size distribution

MRI could be used to detect the signal intensity of water in each pore, as well as the signal intensity of water in the total pores. The ratio between them can characterize the proportion of pores with different sizes to the total pores within the rock, that is, the pore size distribution. To avoid errors caused by the measurement of different rock specimens, each rock specimen was measured firstly at 25℃, and the specimen was then heated to a pre-set temperature and cooling thereafter, and MRI was used to measure the pore size distribution again. The measured data was the average value of the three rock specimens. The final pore size distribution of each rock specimen is shown in Fig.5, where the axial r is the pore size.

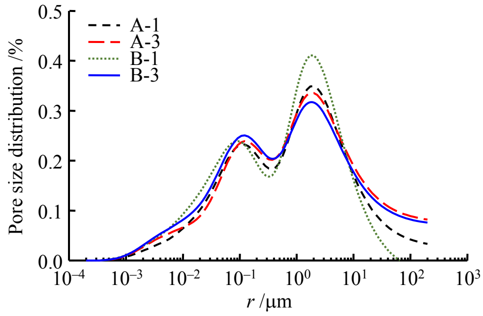
Based on the temperature range intervals, the pore size distribution of rock specimens can be divided into three groups:

In the first group (100℃), for the natural cooling method, it is seen that the proportion of small and medium pores (≤10 μm) decreases, and the proportion of large pores (>10 μm)[8] increases. This means that the internal small and medium pores in the sandstone specimen decrease and the large pores increase after the heating treatment. While for the water cooling method, the reduction ratio of small and medium pores and the increasing ratio of large pores are both lower than that from the natural cooling, which indicates that the water cooling could cause the internal pores of the rock to partially contract due to the rapid cooling process.

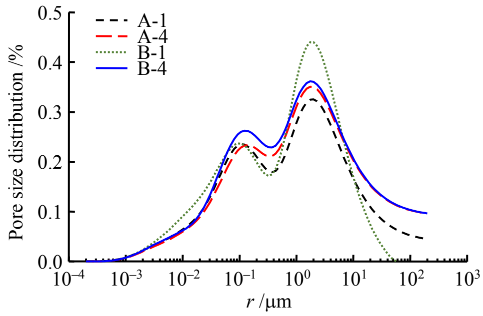
In the second group (100–600℃), within this temperature range, as can be seen from Fig.5, the curve differences between the two cooling methods do not show a large variation. From the curves, it is seen that



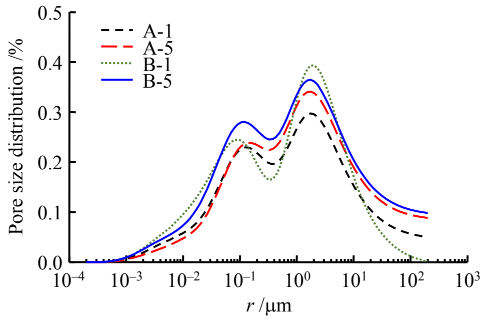
(a) Comparison of two cooling methods for heat treatment at 100℃



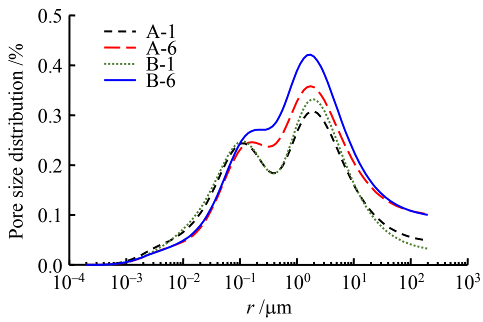
(b) Comparison of two cooling methods for heat treatment at 300℃



(c) Comparison of two cooling methods for heat treatment at 500℃



(d) Comparison of two cooling methods for heat treatment at 600℃



(e) Comparison of two cooling methods for heat treatment at 800℃

Fig. 5 Pore size distributions of heat-treated sandstone under different cooling conditions

the pore size tends to become large within the rock after heating. Under the water cooling method, it is found that the trend of the curve becomes proportion decreasing of the medium pore size, and proportion increasing of the small and large pore sizes.

In the third group (600–800℃), the curve trends of both the natural cooling and water cooling are similar after heating. It is seen that the pore size inside the rock becomes larger for both two cooling methods. While compared to the natural cooling method, the proportion of large pores are larger under the rapid water cooling method. This observation could result from the large temperature gradient at 600–800℃ when compared to that at 25℃, and thermal stress will be generated inside the rock specimens. When combined with the scanning electron microscope (SEM) results, after high temperature treatment, rapid water cooling will lead to a sharp increase of internal cracks and more obvious cracks will grow within rock specimens that are associated with thermal stress inside. In this consideration, even if a certain proportion of the pores are contracted during the water cooling, the pore size distributions still appear as an increase of the large pores which has a larger proportion than that from the natural cooling.

3.3 Porosity

Table 1 shows the average porosity measured using MRI under different working cases. It should be noted that 25 ℃ means that no heating treatment was performed, and thus no water cooling treatment was conducted.

Table 1 Average porosity in different working cases

Heat treatment T /℃	Porosity /%	
	Natural cooling	Water cooling
25	13.86	—
100	12.96	13.20
300	14.96	14.39
500	15.66	15.35
600	15.79	16.17
800	15.97	17.48

To accurately characterize the influence of different cooling conditions on the porosity and to avoid errors caused by the difference of the initial pores of different rock specimens, the average porosity change rate of three rock specimens is used to denote the porosity change caused by different cooling methods. The porosity change rate δ is defined as:

$$\delta = \frac{n_2 - n_1}{n_1} \times 100\% \quad (1)$$

where n_1 is the specimen porosity at 25 ℃; n_2 is the specimen porosity after cooling.

The porosity change rate of the heat-treated sandstone with temperature under different cooling methods is shown in Fig. 6. It can be seen from Fig. 6 that:

(1) When the heating temperature of the sandstone specimen is relatively low, $\delta < 0$, that is, when compared with the rock specimen at 25℃, the porosity of the rock decreases after the treatment of heating and cooling. The porosity decrease of the heat-treated rock is mainly caused by the expansion of mineral particles and the closure of partial pores[11, 28].

(2) When the heat treatment temperature T>100℃, the porosity change rates show an increasing trend for the sandstone specimens under the two cooling methods, which indicates that the rock micro-cracks and micro-pores are initiated and extended as the heat treatment temperature increases, and the porosity increases significantly at this heating temperature stage. Besides, when the heat treatment temperature T< 500 ℃, it is found that the two cooling methods have little effect on the total porosity of sandstone.

(3) When the heat treatment temperature T>500℃, the porosity change rate of sandstone basically keeps the same rate under natural cooling, while the porosity change rate of sandstone continues to increase under the water cooling. The temperature gradient generated by high-temperature rapid cooling is much higher than that from a stable heat flow. This large temperature gradient will cause thermal shock inside the rock, which would intensify the generation and development of micro-cracks and fractures[16]. The porosity is hence to increase at a higher rate. In this consideration, 500℃ can be viewed as the critical temperature value of the influence of different cooling methods on the sandstone porosity. When the sandstone projects are in a high temperature environment of T>500℃ and the water cooling method will be used (such as fire extinguishing in tunnels), the hazard caused by the rapid increase of porosity should be fully considered.

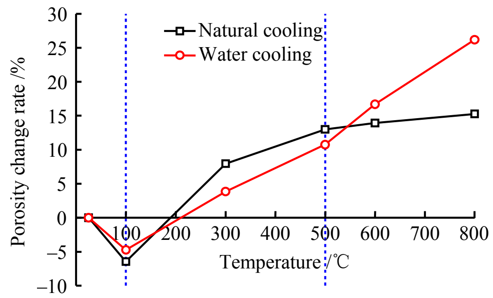


Fig. 6 Porosity change rates of heat-treated sandstone under different cooling conditions

4 Uniaxial compression strength test

4.1 Test equipment and scheme

Once the rock specimens cooled by water were dried, a series UCS tests was conducted for the rock specimens under the two cooling methods. Three rock specimens were tested at each pre-set temperature and the average UCS value was taken as the test result. A GAW-2000 PC controlled electro hydraulic servo rigid pressure testing machine was used in this study, as shown in Fig.7. The maximum load is 2 000 kN. The displacement extensometers were used to measure the axial and radial strains during the tests. The initial pressurization rate was controlled at 500 N/s during the compression process. When the test curve was observed to reach the yield stage, deformation control was then used. The loading rate was controlled to 0.01 mm/min until the specimen was broken.

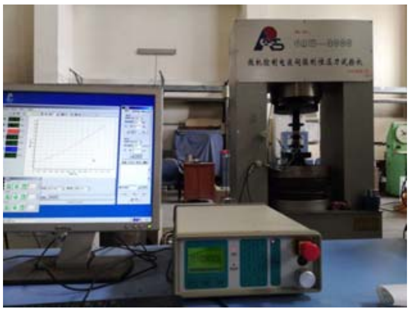


Fig. 7 Rigid pressure testing machine

4.2 UCS test results

Table 2 shows the peak strength value of each rock specimen under the UCS test. It should be mentioned again that each peak strength value is the average value of three rock specimens. Because the rock specimens are not heated or cooled in the water at the case of 25℃, similar to the porosity in Table 1, the peak strength is the UCS under the natural state. Figure 8 shows the UCS variation trend of test specimens.

Table 2 Peak strength of uniaxial compression

Heat treatment T /℃	Peak strength of UCS /MPa	
	Natural cooling	Water cooling
25	50.38	—
100	52.24	41.72
300	55.69	40.96
500	42.70	29.40
600	56.92	26.76
800	49.55	17.34

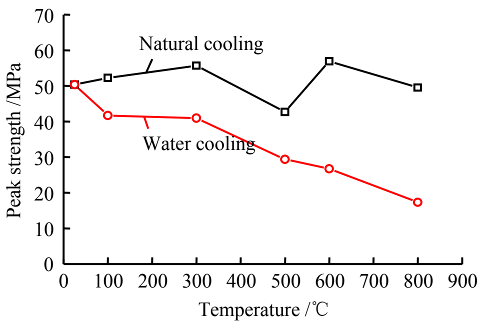


Fig. 8 Variation trend of strength under different cooling conditions

It is seen from Table 2 and Fig.8 that:

(1) When the rock specimens treated at a lower heat temperature (T < 300℃) are cooled using the natural cooling condition, strength values of sandstone are basically similar to the sandstone strength under the normal temperature. When the temperature T > 300℃, the heat treatment has a large influence on the strength of sandstone. The rock strength shows a change of first decreasing, then increasing and final decreasing again, which is related to the internal mineral phase transformation and cracks development within the sandstone[11].

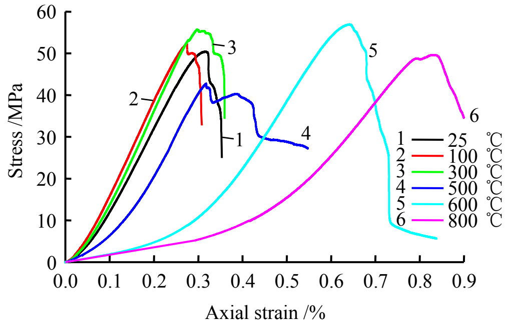
(2) When the rock specimens are cooled using the water cooling condition, it is observed that all the strength values of heat-treated sandstone are lower than that of sandstone at 25℃. Besides, as the heat treatment temperature rises, the sandstone strength continues to decrease. When the heating temperature is at 800℃, the strength decreases by 33.04 MPa compared with the sandstone strength at 25℃. The decreasing amplitude is about 65.6%, which indicates that the rapid water cooling of heat-treated sandstone would lead to a violent interaction within the rock specimens. In the meantime, a strong thermal shock would occur. The higher the treated temperature, the more obvious the thermal shock effect, which would show a greater rock strength reduction at the macroscopic manifestation.

Figure 9 gives the stress–strain curves of sandstone specimens at different temperatures under two cooling conditions. It can be seen from Fig.9 that:

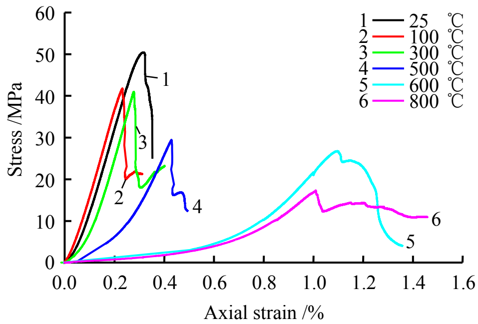
(1) Regardless of the cooling method and the high heat treatment temperature, the sandstone specimens basically present a four-stage stress–strain curve, which is similar to the stress–strain curve of sandstone specimens under normal temperature. The four-stage are summarized as the pore compaction stage, elastic deformation stage, yield stage, and post-peak failure stage.

(2) No matter what type of cooling method is used, it is seen that the peak strain has little difference when the sandstone specimens under low temperature heat treatment. While when the treatment temperature T > 500℃, the peak strain increases rapidly, which is caused by a phase change of quartz once the temperature reaches 573℃. The phase α will transform into phase β[29]. According to Fig.10, it is seen that the content of kaolinite within the rock decreases rapidly at this temperature. A dehydration reaction occurs to the kaolinite and metakaolinite will be formed. It can also be combined with free Ca^{2+} ions within sandstone to form new-phase minerals such as calcium aluminate. Due to these internal changes, the cementation among the microstructure of sandstone is then altered, which causes the weakening of rock brittleness and the increasing of rock ductility. Compared with the natural cooling method, in addition, more obvious increases of the strain and the ductility are found for high-temperature sandstone specimens under the water-cooled method.

(3) When the treatment temperature T > 600℃, the peak strain continues to increase under natural cooling, while the peak strain begins to decrease under water cooling. Because of the use of the water cooling method, the rock specimens are subjected to a rapidly cooled process from a very high temperature of 600–800℃, which will lead to the rapid shrinking of mineral particles that are heated and expanded inside the rock specimen. The internal reactions are then terminated suddenly and the rock specimen will be in a ‘ductility brittleness’ state, which will transform to brittleness.



(a) Stress–axial strain curves under natural cooling



(b) Stress–axial strain curves under water cooling

Fig. 9 Stress–strain curves under different cooling conditions

5 SEM test

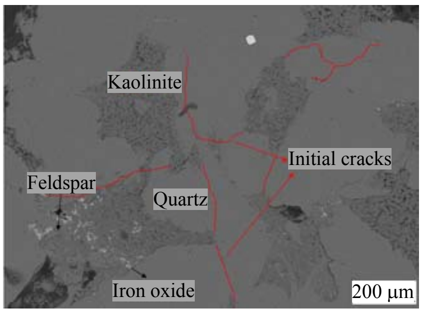
5.1 Test scheme

To further study the microstructure of high-temperature sandstone under different cooling methods, Zeiss Crossbeam 550 electron microscope scanner was used to perform SEM tests on the sandstone specimens. The test specimen was collected from the broken rock specimens after the UCS tests. The collected specimens were cut firstly, then polished and sprayed with charcoal, and finally scanned.

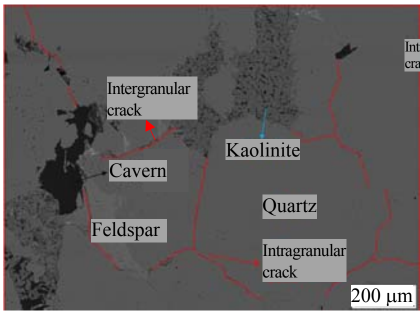
5.2 SEM test result analysis

Figure 10 presents the SEM images of sandstone at different heat treatment temperatures under two cooling methods. It can be seen from Fig.10 that:

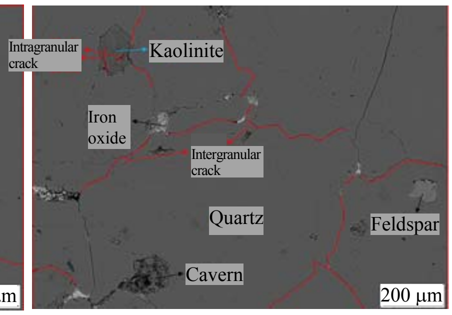
(1) When the sandstone is at a temperature of 25℃, it is observed that the internal structure is relatively complicated. It is cemented by various sand grains, with a relatively high content of quartz, as well as other mineral components such as kaolinite, feldspar, and iron oxide. In addition, a small amount of micro-cracks is observed inside the rock specimen, which mainly consists of the initial cracks that propagate at the boundaries of mineral particles, as shown in Fig.10(a).



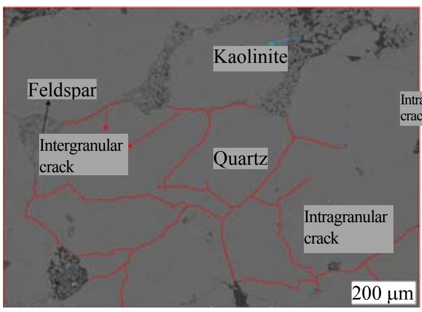
(a) 25℃



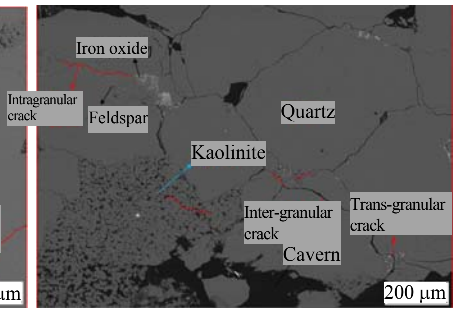
(b) 300℃ under natural cooling



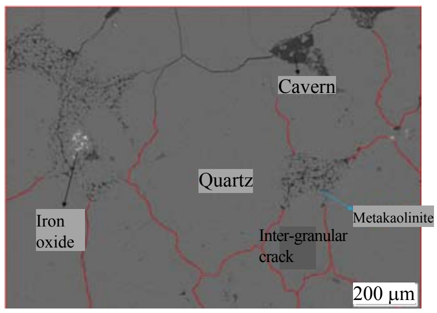
(c) 300℃ under water cooling



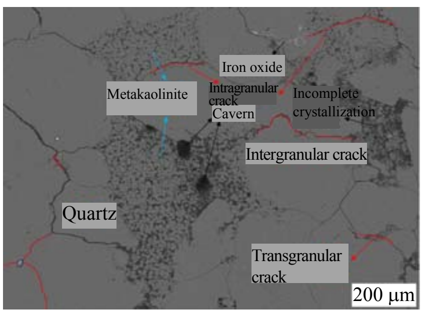
(d) 500℃ under natural cooling



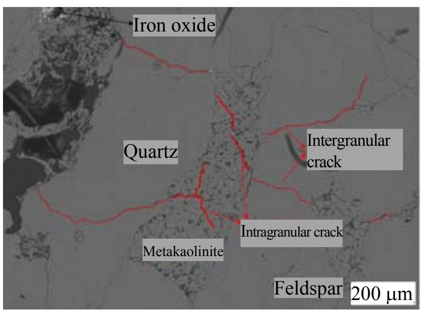
(e) 500℃ under water cooling



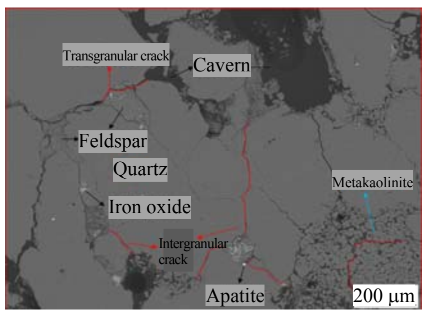
(f) 600℃ under natural cooling



(g) 600℃ under water cooling



(h) 800℃ under natural cooling



(i) 800℃ under water cooling

Fig. 10 SEM images of heat-treated sandstone under different cooling conditions

(2) Compared with the sandstone case at 25℃, when the heat treatment temperature T reaches 300℃, a few intra-granular cracks and inter-granular cracks begin to occur inside the rock specimen, but the cracks are not fully developed at this time. The width of the cracks is small and the cracks are not fully connected. By comparing Fig.10(b) with Fig.10(c), it is seen that the two cooling methods have non-significant effect on the growth of sandstone microscopic cracks in this temperature range. From the macroscopic point of view, it is shown that the pore change trends are consistent and the change extents are similar at this temperature under the two cooling methods.

(3) When the treated temperature $T \geqslant 500$℃, the internal thermal stress is caused by the un-uniform expansion of the internal mineral particles, which leads to an increasing in the extent of the initial crack propagation at the boundaries of different mineral particles. More new cracks are formed and the crack density is significantly increased. In addition, when comparing SEM results of Fig.10(d), 10(e), 10(f), 10(g), 10(h), and 10(i), it is found that the crack density is higher under water cooling method and the cracks are more interconnected with each other. Besides, the crack width is also increased significantly and more caverns are formed in the server opening of cracks. Therefore, the macroscopic performance of sandstone is the continued increasing of the porosity after this temperature under the water cooling method, while the porosity relatively keeps the same under the natural cooling condition. This observation is mainly caused by the rapid cooling of the sandstone when water cooling is used at such high temperatures. The large temperature gradient will cause the expanded mineral particles to shrink rapidly in a short time, which may result in greater thermal stress and uncoordinated shrinkage to cause the porosity to increase.

(4) When the temperature is further increased from 600℃ to 800℃, it is observed that the content of kaolinite decreases, and the metakaolinite increases greatly inside the rock specimen. This is caused by the dehydration reaction of kaolinite at high temperature [27], resulting in metakaolinite. In the meantime, the degree of crack development is also increased significantly and a fracture network has been formed within the water-cooled sandstone specimen. A large number of intra-granular cracks and trans-granular cracks are spread within the water-cooled sandstone specimen. In addition, the caverns are also further expanded. All these changes will lead to water conducting channels, leading to a substantial increase in water permeability, which is also one of the reasons why the sandstone strength is greatly reduced caused by the water cooling at this temperature.

6 Conclusions

(1) Compared with the natural cooling method, the water cooling method has a large influence on the sandstone strength. As the heat treatment temperature increases, the sandstone strength continues to decrease, with a maximum decrease extent of 65.6%. When the $T>500$℃, phase change has occurred for the quartz in the high-temperature sandstone under the two cooling methods. The kaolinite transforms into the metakaolinite, which causes the weakening of sandstone brittleness, the increasing of the sandstone ductility, and the rapidly increasing of the peak strain. More obvious strain increment and stronger ductility are observed in the water-cooled high-temperature treated sandstone.

(2) 500℃ can be considered as the critical temperature value of the influence on the sandstone porosity for the two cooling methods. When the heat treatment temperature $T<500$℃, the two cooling methods have little effect on the total porosity of sandstone. When the $T>500$℃, the pore change rate of sandstone basically remains the same under the natural cooling method, while the porosity of sandstone continues to increase from 13.86% to 17.48% under the water cooling method. The maximum increase rate can reach up to 26.19%. Besides, the proportion of pores with large size (>10 μm) has also increased significantly. This is mainly caused by the rapid cooling of the expanded mineral particles due to the rapid cooling of the sandstone at high temperatures, which causes larger thermal stress and uncoordinated shrinkage. The thermal stress and uncoordinated shrinkage will cause the crack density and width to increase significantly, and the degree of interconnection among each other is even heavier, resulting in many new and further enlarged pores.

(3) The SEM images show that when the temperature $T>500$℃, an increase in the extent of initial cracks at the boundaries of different mineral particles and more new cracks are formed due to the un-uniform expansion of mineral particles inside the rock specimens. In addition, when the temperature further increases to 800℃, the degree of crack propagation and development is increased largely, and a fracture network has been formed, which results in a large number of intra-granular and trans-granular fractures in the water-cooled sandstone specimens. The caverns are further expanded at high temperature. This observation explains the phenomenon of strength significantly decrease from the perspective of fracture propagation during high-temperature cooling process.

(4) When water is used to cool high-temperature sandstone, many factors are unfavorable for seepage prevention such as the porosity, the proportion of large pore, and the development and interconnection of the internal fracture network. Therefore, when water cooling in a similar high temperature environment (such as fire extinguishing using water after a tunnel is on fire), the possible engineering hazards caused by the cooling method should be fully considered.

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