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Mechanical Properties of Sandstone at Triaxial Compression Subjected to Coupling Temperature and Pressure

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Abstract

High ground temperature and geo-stress are difficulties encountered in current deep rock mass engineering development. However, research materials on the strength and deformation of rock mass from room temperature to 100 ℃ are limited. Triaxial compression experiments subjected to coupling temperatures at 25 ℃, 50 ℃, and 75 ℃ and confining pressures at 10, 20, and 30 MPa, respectively, were conducted on sandstone from Chongqing Beibei mining area by adopting the rock multi-field coupling triaxial instrument to reveal the mechanical properties of sandstone and its changes and laws of physical parameters under the influence of temperature. The stress strain curve, failure load, average modulus, peak strain, cohesion, and internal friction angle of sandstone were obtained based on the indoor experiment result analysis. Moreover, the influence of temperature and pressure coupling interaction on the physical property and deformation mechanism of sandstone were revealed by analyzing the parameters of mechanical properties. Results show the following: (1) The failure process of sandstone due to coupling temperature and pressure is generally consistent with the stress–strain curve of conventional triaxial compression, and the failure mode is shear failure; (2) When temperature is constant, the failure load increases with confining pressure(a high temperature leads to the rapid increase in confining pressure growth rate); when confining pressure is constant, the failure load influenced by temperature exhibits complex effects related to coupling temperature and pressure; (3) When temperature rises, the average modulus of sandstone first increases then reduces with increasing confining pressure; when the confining pressure is constant, the average modulus reduces along with increasing temperature; (4) The axial peak strain increases with temperature and confining pressure; (5) Cohesion and internal friction angle decrease with increasing temperature, and the weakening effect on cohesion due to temperature increase is larger than that on internal friction angle. This study provides references to explain coupling temperature and pressure issues of rocks in temperature ranging from room temperature to 75 ℃.

Keywords: Coupling temperature and pressure, sandstone, triaxial experiment, mechanical property

1. Introduction

Given that a geological material comprises different mineral substances, the physical parameters and mechanical properties of rocks are not only relevant to their composition of mineral substances but are also closely linked to geological hydrology, ambient temperature, burial depth, and ground stress. With the development of deep mineral resources, the need for the strategic reserve of energy engineering and deep underground disposal of nuclear waste and the influence on rock strength and deformation characteristics from the environment have been increasingly emphasized since $1980s$. Consequently, many studies have emerged. C. David [1] et al. studied the physical characteristics of granite, including porosity, conductivity, acoustic velocity, and attenuation, in thermal and pressure cracking experiments. Jianping Zuo [2] studied the tensile failure mechanism of rocks subjected to coupling temperature and stress in a macroscopic perspective and discovered the transformation of sandstone fracture mechanism under high temperature from brittle to ductile. The tensile strength of sandstone increased and decreased in temperatures below and above $150°C$, respectively. Lianchong Li [3] et al. established the thermal coupling value model by utilizing damage mechanics and thermo-elasticity theory and discussed the evolution mechanism of s microstructure damage and mechanical properties.

However, with the development of deep rock mass engineering, the depth of rock mining also increased. For example, the mining depth of Germany mines increased from $927m$ in 1995 to $762m$ in 1960, and rock temperature reached as high as $43°C$. The Suncun coal mine located in the Tai'an city of Shandong province in China reached a mining depth of approximately $1500m$. In addition, the coal mining depths in Russia and Poland both reached approximately $1500m$. The engineering environment subjected to rock mass at the mining depth had an alarming effect on its mechanical properties. According to research, when digging depth is between $3500-5000m$, the ground stress level is $95-135MPa$. However, in the deep stratum environment, the normal geothermal gradient is from $30°C/km$ to $50°C/km$ in nearby areas, some faults in partial areas with high thermal conductivity have geothermal

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gradient as high as $200°C / km$. High temperature environments not only change the physical and mechanical properties of rock mass but also present serious challenges to construction. Changes in temperature simultaneously act on the rock mass interior. Every $1°C$ of change in temperature may produce $0.4-0.5MPa$ of stress, which would lead to thermal expansion and contraction under temperature stress and cause breakage of the rock mass interior. Therefore, evident changes in engineering rock mass due to rising environmental temperatures cannot be ignored. At present, the construction and repair of underground caverns and deep-buried tunnels in large-scale cities, petroleum engineering drilling and collection, exploration and development of geothermal resources and underground storage of highly radioactive nuclear wastes are all related to the mechanical property issues of rocks at high temperatures. Therefore, the study on rock engineering issues under high temperatures has led to a new direction in rock mechanics research. Researchers have conducted numerous researches works on the physical and mechanical properties of rock mass under high temperatures. Chengdong Su [4] et al. conducted a mechanical effect experiment on coarse sandstone subjected to high temperature at $100°C-900°C$. They discovered that rising temperatures had two different types of influence on the mechanical properties of sandstone: improvement of the bearing capacity of primary fissure closure and inducement of micro cracks due to structural thermal stress, thereby lowering the bearing capacity. Lianying Zhang [5] conducted a uniaxial compression experiment on sandstone at $200°C-800°C$ and discovered that high temperatures evidently lowered peak stress and elastic modulus of sandstones and rapidly increased peak strain. However, most of the currently available research results on rocks were conducted at temperatures above $200°C$. The synchronous loading of temperature and stress cannot be realized due to limitations of experimental instruments and conditions. The currently available results are all conventional triaxial experiments. The rock mass was first heated in a high-temperature furnace and then cooled down to room temperature. The real stress status of rock mass in high temperature cannot be reflected; however, studies on rock mass at temperatures from room temperature to $75°C$ are even rare. Therefore, this study aims to simultaneously find a prompt solution for the verification of changing laws of sandstone mechanical properties at different temperatures through experimentation and clarification of the sandstone coupling status effect from temperature and stress.

Therefore, this study adopts the method of realizing loading and recording of stress–strain curves at high temperature by utilizing the rock triaxial coupling instrument. The coupling experiment of temperature and pressure at a temperature range from room temperature to $75°C$ was conducted on the sandstone samples to reflect the mechanical properties and coupling relationship between high temperatures and confining pressure accurately. Thus, this research provides a reference for the study on deep rock mass engineering at high temperatures.

2. State of the art

In recent years, many domestic and international researchers have conducted many experiments and theoretical research works on the mechanical properties and deformation characteristics of rock masses at high temperature and obtained certain achievements. G. Wu [6] conducted studies on sandstone mechanical properties and physical parameters at high temperatures ranging from $20\,°C$ to $1200\,°C$. He concluded that environmental temperature changes influenced the mechanical properties of the rock, but certain deviations in the mechanical properties were observed during high temperatures. This observation excludes the mechanical experiment conducted on rocks that were cooled down to room temperature. Hong Tian [7] concluded the changing law of sandstone physical properties after being subjected to high temperatures, which were distributed in international publications in the past decade. However, his conclusions were lacking. Biao Kong [8] conducted a uniaxial compression experiment on sandstone subjected to high temperatures and studied its fracture mechanics behavior and acoustic emission law. The AE event count of sandstone treated through high temperatures more rapidly grew during the initial loading phase than that at room temperature. Its fracture and deformation behaviors were notable, but no discussion on the acoustic emission law at high temperatures was provided. Weiqiang Zhang [9] conducted physical and mechanical property change experiments on marble and sandstone at high temperature range from $25\,°C$ to $500\,°C$ to classify rock changes in terms of different temperature gradients, but monitoring and classification during high temperature process had not been realized. Chao Lü [10] studied changing laws of sandstone tensile strength at temperature range from room temperature to $900\,°C$. He concluded that the tensile strength rapidly decreased in $300\,°C$ –$600\,°C$ and $800\,°C$ –$900\,°C$ but lacked real-time data of tensile strength change during high-temperature process. Xiaoli Xu [11] conducted triaxial compression on granite after undergoing high temperature from $25\,°C$ to $1000\,°C$. He proposed that the temperature had considerable influences on rock mechanical properties but was inapplicable for tensile strength change during high-temperature process. Chongbang Xu [12] conducted triaxial compression tensile strength experiment on sandstone subjected to high temperature from $400\,°C$ to $1000\,°C$ and established the post-high-temperature sandstone triaxial tensile strength formula, including temperature and temperature threshold parameters, but lacked research during the high-temperature process. Xingfen Ming [13] conducted experiments on sandstone subjected to high temperature at $50\,°C$–$1000\,°C$ and analyzed its mechanical properties and thermal damage characteristics; however, the changes in mechanical properties during the high-temperature process are still not reflected. P. K. Gautam [14] conducted experiments and studies on sandstone which went through fire in the Indian region; he only concluded the sandstone thermal damage formula in the simulated fire and only reflected the sandstone mechanical properties after high temperature. Xiangxi Meng [15] conducted triaxial compression experiment by utilizing granite with different initial damages at high temperature from $100\,°C$ to $650\,°C$; he concluded the interaction relations amongst granite permeability, initial damage status, and thermal cracking critical temperature, but experiment research for the temperature range under $100\,°C$ was lacking. Guenther Glatz [16] utilized the new type of computed tomography technology into rock triaxial high temperature and pressure experiments, which can endure high-temperature scan at high temperature above $400\,°C$; this method compensates for the deficiency of the conventional computed tomography computer, which can only work in a designed temperature range below 180 $°C$. Hui Deng [17] conducted triaxial compression experiment on the tight quartz sandstone of oil and gas reservoir at temperature range from $15\,°C$ –$150\,°C$ and under confining pressure range of $0-100MPa$. He discovered that the combined actions by temperature and confining pressure may lead to different failure types, and confining pressure influence on rock strength was higher than that of the temperature. However, mineral compositions of the tight quartz sandstone of gas reservoir had their special characteristics, which cannot reflect the characteristic of engineering rock mass. Zhanguo Ma [18] studied changing laws of sandstone thermal expansion coefficient on sandstone heated from 400 $°C$ –800 $°C$, but other mechanical property parameters were lacking. Guanglei Zhou [19] conducted the simulation analysis of aging creep damage model value by utilizing multi physics coupling analysis software on brittle rocks subjected to coupling temperature and stress, but evidence of a large quantity laboratory experiment data were lacking. Qiangyong Zhang [20] conducted the high-temperature triaxial creep experiment on diversion tunnel granite under different temperatures and loaded stress routes. He also analyzed creep deformation characteristics, strength, and failure mode due to temperature, confining pressure and axial pressure but emphasized on the creep effect influenced by temperature, thus lacking in high-temperature conventional triaxial experiment data.

The study results mainly engage in experiments and theoretical analysis conducted in mechanical properties and physical parameters after high temperature of sandstone. Owing to limitations of current experimental instruments and conditions, studies on sandstone mechanical properties during high-temperature process are limited. Most research works on high-temperature sandstone are concentrated on high temperature above 200 $°C$, but studies from room temperature to 80 $°C$ are even rare. According to data statistics, with the development of petroleum engineering exploration, rock mass in deep oil and gas reservoir exploitation, geothermal exploitation of high-temperature rock mass, underground space excavation, and deep burial and disposal of high radioactive and nuclear waste, complicated occurrence condition has stronger mechanical influences than those of shallow rock mass. Moreover, the mechanical problems of deep rock mass under actions of low temperature and pressure cannot be ignored, thus becoming urgent engineering problems that require solutions. This study conducts the triaxial compression experiment under coupling temperatures and confining pressures on sandstone from Chongqing Beibei mining areas by utilizing the rock multi-field coupling instrument. During the high-temperature and high-pressure process, the sandstone stress–strain curve, failure load, average modulus, peak strain, cohesion, and internal friction angle are obtained. Sandstone failure mode, strength and deformation properties, and changing law of sandstone mechanical properties subjected to coupling temperature and pressure are obtained via analysis, and experimental basis for solving similar engineering problems and conducting subsequent researches are provided.

The remainder of this study is organized as follows: Section 3 describes the experiment instruments and methodology. Section 4 presents the changing laws of sandstone mechanical properties through analysis and calculation on the failure load, average modulus, peak strain, cohesion, and internal friction angle. The sandstone stress–strain curve is obtained from the experiment. Conclusions are summarized in Section 5.

3. Methodology

3.1 Experimental Instrument

This experiment adopts the rock full stress multi-field coupling triaxial instrument manufactured by the Top Industry Co., Ltd. from French, as shown in Fig. 1. This instrument independently controls confining pressure, axial pressure, and seepage field pressure via the high-precision servo high-pressure pump set, which can adapt to rock stratification characteristic. The instrument can also accurately measure index parameter and improve stability and reliability of long-time multi-field coupling experiment. This instrument can be used to conduct conventional rock mechanical, rock theology, multi-phase medium rock mechanical permeability, rock THMC coupling experiment, multi-phase seepage multi-field coupling, hydro fracture, supercritical CO_2 fracture experiments. This instrument can apply $1000kN$ of axial maximum load, $60MPa$ of maximum confining pressure, temperature range from $0\,°C$ to $90\,°C$, $60MPa$ of maximum pore pressure, $20mm$ of axial maximum deformation, and $5mm$ of radial maximum deformation. Axial displacement is measured by the linear variable differential transformer, and hoop strain is measured by the hoop strain gauge fixed at the middle section of the test piece. The instrument provides four types of loading methods, including displacement, strain, stress, and pumping capacity.

This experiment adopts sandstone from a certain mine located in Beibei, Chongqing, with average density of $2374kg/m^3$. According to the requirement of the *Regulation for Testing Physical and Mechanical Properties of Rock* item, rock samples are processed into column-shaped standard test pieces measuring $50mm$ in diameter and $100mm$ in height. Longitudinal wave velocity of each test piece is measured by the acoustic detector to ensure homogeneity of test pieces, and samples with large dispersion are rejected, as shown in Fig. 2. The measured longitudinal wave velocity is $2.273-2.632km/s$, average wave velocity is $2.482km/s$, and dispersion coefficient is 4.29%, thereby satisfying the experiment requirements.

3.2 Experimental method

Standard rock test pieces with a dimension of $50mm\times100mm$ were prepared according to the *Engineering Rock Mass Experiment Method Standard* and *Water Resource and Hydropower Engineering Rock Mass Experiment Protocol* to research sandstone seepage law under water saturation conditions. The confining pressure of the experiment is set at 10, 20, and 30 MPa, and temperature is set at three gradients of $25\,°C$, $50\,°C$, and $75\,°C$. Each confining pressure and temperature comprises one group of experiment, and each group has three test pieces. Hence, the conventional triaxial experiments are conducted at different temperatures and confining pressures on a total of 27 sandstone test pieces. Detailed experiment steps are as follows:

Fig. 1. Rock Multi-field Coupling Triaxial Instrument

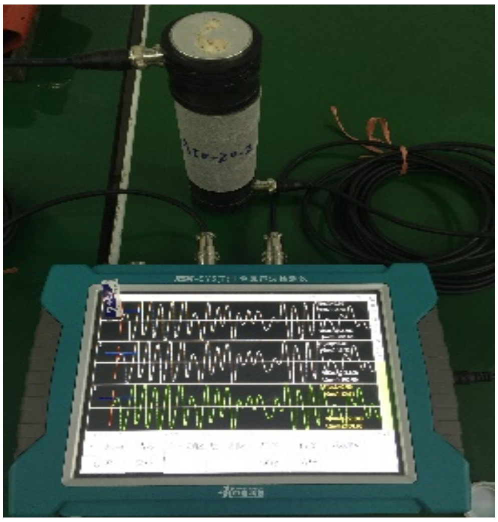


Fig. 2. Longitudinal Wave Velocity

(1) Standard sandstone test piece is placed into instrument accessory of the custom-made fluorine rubber sleeve to be tightly wrapped to insulate from oil, rock core on steel joint is placed flatly and evenly, and cushion pad is arranged on top of the rock core. Axial and hoop strain gauges are installed and adjusted, data cables of the strain gauges are connected to the base port, and the initial value is set.

(2) Temperature of the temperature-controlled area is increased to the experiment temperature and maintained for 2h to facilitate even heating of test pieces. Confining pressure value is then set and increased up to the set value at velocity of $0.1MPa/s$. Axial load is applied after confining pressure is stabilized.

(3) Axial displacement control method is adopted, and axial load at $0.02mm/\min$ loading velocity is applied until test piece fails. During this process, the experiment instrument automatically records full stress–strain curve of rocks: axial and hoop displacement values at each time point are recorded during the experiment process. Thus, the axial and hoop strains are calculated, and the stress–strain curve is then formed based on stress value of the test.

(4) After peak stress is loaded, test piece fails. After failure is stabilized, confining pressure is unloaded, temperature is lowered to room temperature, the test piece is taken out, and experiment data are arranged and analyzed.

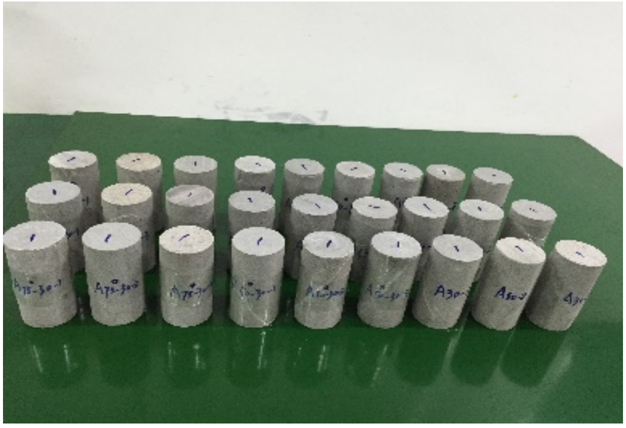


Fig. 3. Sandstone Test Pieces

4 Result Analysis and Discussion
I
4.1 Failure Mode Analysis
Fig. 4 shows the failure mode of the partial test piece. The figure indicates that the failure mode and fracture pattern of the sandstone subjected to coupling temperature and confining pressure are still mainly in the form of shear failure. A penetrated main fracture surface is exhibited by the test piece, and the main fracture surface and the direction of the maximum main stress form an included angle. With increasing temperature, multiple cracks in parallel near the main fracture surface would occur, and fracture pattern would change from smooth to coarse. Moreover, failure cracks would increase with rising temperature and confining pressure.

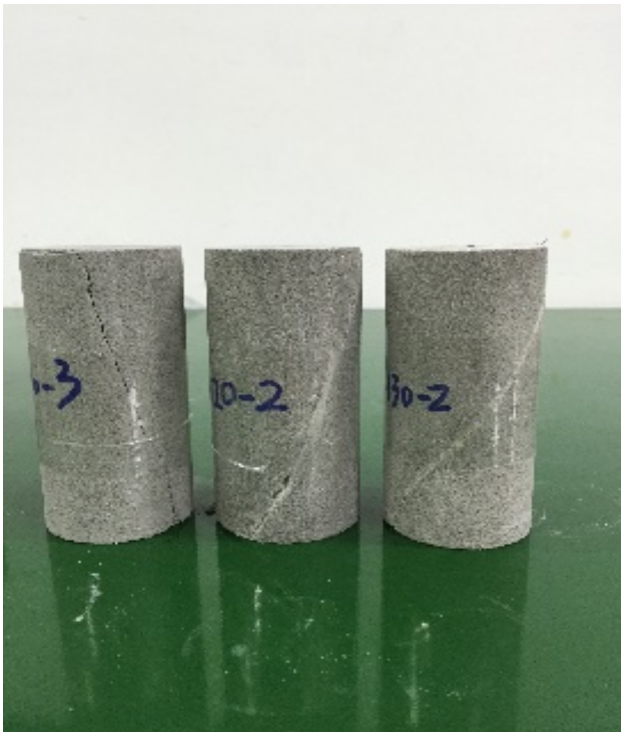
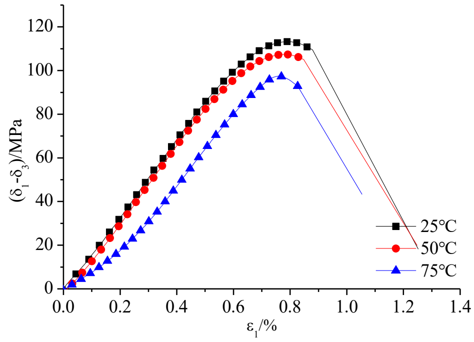


Fig. 4. Partial Test Piece Failure Mode

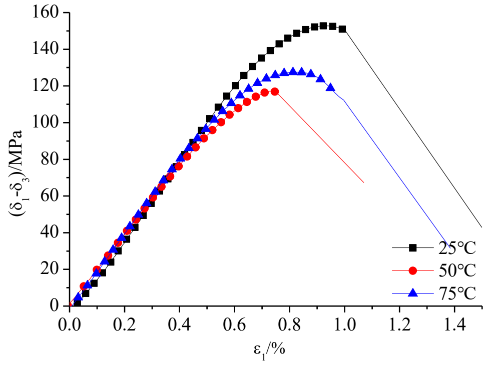
4.2 Stress–Strain Curve Analysis

Based on collected triaxial experiment data, the triaxial full stress–strain curve diagrams of sandstone at temperatures of $25\,°C$, $50\,°C$, and $75\,°C$ and confining pressures at 10, 20, and 30 MPa, respectively are established. As shown in Fig.5 and Fig.6, the failure process of sandstone subjected to coupling temperature and pressure and the stress–strain curve of the conventional triaxial compression, which has both undergone four phases [21] of compact, elastic, yield, and failure are generally the same. After initial stress, rock interior mineral substance contact and connection become closely connected; micro fissures become close under external force and rock is compacted. The strength curve presents an upper concave shape; when the confining pressure is high, the compacted effect is notable, and deformation development is rapid. After rock enters the elastic deformation phase, the material presents elastic deformation characteristics, and the stress–strain curve presents the linear growth of the linear segment in a positive proportional relation. When the confining pressure is high, the linear slope is also high. Rapid stress–strain growth velocity leads to high temperature; when the linear elastic deformation phase is short, the test piece rapidly enters the yield phase. With continuously increasing stress and temperature, stress concentrates on the micro cracks of rock interior and expands forward, micro fissures reopen after closure during the compacted phase, closure and expansion of fissures are unevenly distributed in space and time, the stress–strain curve no longer remains linear but in the form of curve, and the test piece enters the yield phase. When load reaches 80%–90% of peak strength, the micro fissures rapidly expand and form the main crack. With continuously increasing stress, the rock interior crack penetrations form a macroscopic crack zone, and crack expansion reaches an unstable status. When load reaches bearing limitations of the test piece, bearing capacity of the test piece will be lost, thus leading to failure.

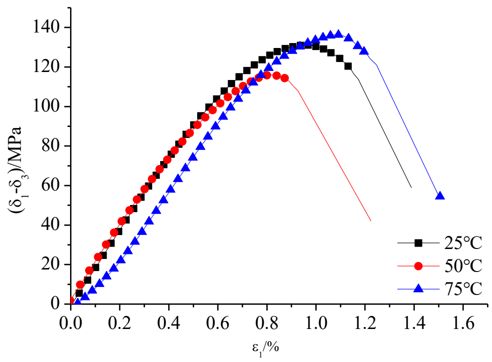
Fig. 5 (a) and (b) show that when the confining pressure is constant, rock sample strength decreased with increasing temperature due to thermal stress produced by inflation of interior mineral particles of rock sample after heating, and connection between particles are weakened to the decreasing strength. It can be seen from the fig. 5 (c) shows that rock sample strength is $136.33MPa$ at $30MPa$ and $75\,°C$, which is higher than that at $30MPa$ and $50\,°C$. If rock sample interior demonstrates enough pores and fissure spaces, then the thermal stress could close the original fissure, thus increasing rock sample compressive strength. Mechanical effects due to increasing temperature, including weakening and strengthening effects, are diversified, and these effects are relevant to rock mass interior mineral compositions and fissure structure. Fig. 6 shows that when temperature is constant, the effect of the confining pressure limits rock sample cracking development and lateral deformation and increases bearing capacity. Thus, rock sample strength is considerably increased with confining pressure.



$(a)\ \delta_3 = 10MPa$

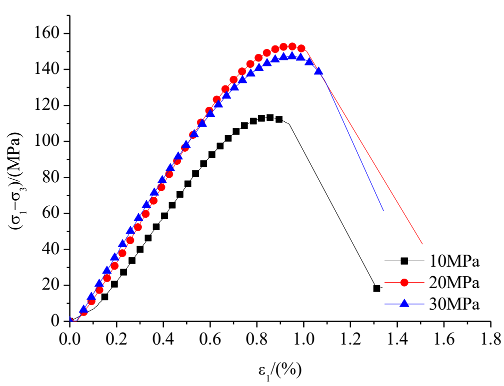


$(b)\ \delta_3 = 20MPa$

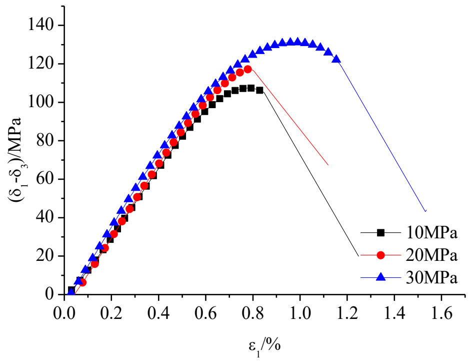


$(c)\ \delta_3 = 30MPa$

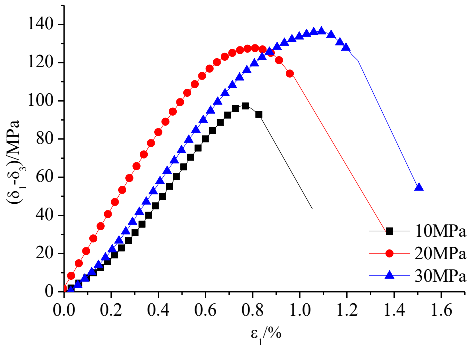
Fig. 5. Sandstone triaxial full stress–strain curve at different temperatures when confining pressure is constant



$(a)\ T=25°C$



$(b)\ T=50°C$



$(c)\ T=75°C$

Fig. 6. Sandstone triaxial full stress–strain curve at different pressures when temperature is constant

Sandstone strength is considerably influenced by confining pressure and temperature. Although when test piece is subjected to different confining pressures at the same temperature, stress–strain relations have the same characteristics prior to peak, but the difference in peak stresses is relatively large. Fig.7 shows the relation between axial failure load and confining pressure at different temperatures. When confining pressure is increased from $10MPa$ to $20-30MPa$ at $25\ °C$, its average strength increases from 112.94 to 126.72 and 133.41 MPa; when confining pressure increases from 10 MPa to 20–30 MPa at $50\ °C$, its average strength increases from 100.23 to 120.57 and 130.97 MPa; when confining pressure increases from 10 MPa to 20–30 MPa at $75\ °C$, its average strength increases from 97.19 to 122.80 and 136.39 MPa. Therefore, when temperature is constant, the axial failure load increases with confining pressure, and its growth velocity is related to coupling temperature and confining pressure. Coefficient of k is introduced to present growth velocity of the axial failure load, and the calculation formula of coefficient k is shown as follows:

$$k=\frac{\Delta(\delta_1-\delta_3)}{\Delta\delta_3} \tag{1}$$

Where k is growth velocity of the axial failure load. By calculating, the value of k is shown as follows:

$$\begin{cases} k_{25°C}=1.024 \\ k_{50°C}=1.537 \\ k_{75°C}=1.960 \\ \dfrac{k_{25°C}}{k_{75°C}}=1.914 \end{cases} \tag{2}$$

Thus, the influence introduced by joint action of temperature and confining pressure cannot be ignored. High temperature and confining pressure lead to the rapid growth velocity of test piece axial failure load. This condition is relevant to rock interior partial micro fissure closure due to temperature and lateral deformation limited by the increasing confining pressure, rock compactness, and bearing capacity.

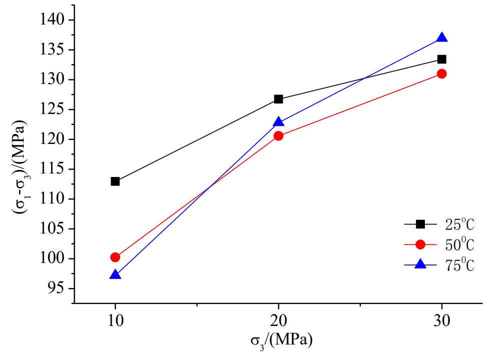


Fig. 7. Axial failure load and confining pressure relation at different temperatures

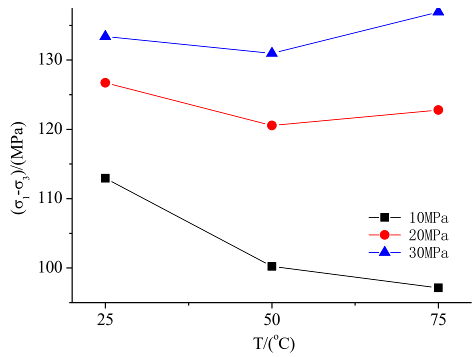


Fig. 8. Axial failure load and temperature relation at different confining pressures

Fig. 8 shows the relation between axial failure load and temperature at different confining pressures. Rock strength is reduced with increasing temperature when $T\le 50°C$ and continuously reduced when $T\ge 50°C$ and low confining pressure is $\delta_3=10MPa$. The axial average compressive strength of sandstone is 13.95% lower at $75\ °C$ than its value at $25\ °C$. When high confining pressure is $\delta_3=20$ and $30MPa$, rock strength increased (a high temperature leads to rapid rock strength growth velocity). When $\delta_3=20MPa$, the axial average compressive strength of rock is 4.55% higher at $75\ °C$ than that at $50\ °C$. This finding is different from the reduction of rock strength due to increasing temperature. Owing to the existence of rock interior fissure, when rock interior cracking is absent due to the insufficient temperature increase range, thermal stress is generated to realize fissure closure and improve compressive strength. Therefore, the influences of temperature and confining pressure on strength are not simply overlapping but are presented in a complex relation [22] that needs further research. Fig. 9 presents the 3D stress diagram among axial failure load, confining pressure, and temperature.

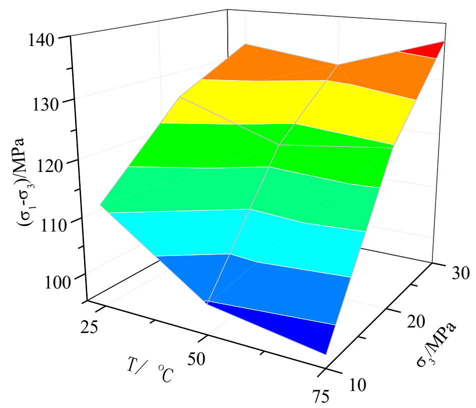


Fig. 9. 3D stress diagram showing axial failure load, confining pressure, and temperature

4.3 Relation between average modulus, confining pressure and temperature

Based on the stress–strain curve of rock triaxial experiment, average modulus E_{av} of sandstone sample and $\varepsilon_{\max}$ of axial peak strain are obtained through analysis, the Mohr's stress circle is drawn, and the relation between cohesion C and internal friction angle φ is derived. Considering the relation between average modulus at different temperatures and confining pressure in Fig. 10, confining pressure increases from $10\ MPa$ to 20–30 MPa, and all E_{av} increases and then later decreases; when rock experiences changes in confining pressure at $25\,°C$, E_{av} increases from $19.303\ GPa$ to $19.787\ GPa$, demonstrating an increase range of 2.45%; at $50\ °C$ E_{av} increases from $16.093\ GPa$ to $18.916\ GPa$, which shows an increase range of 17.54%; at $75\ °C$ E_{av} increases from $16.047\ GPa$ to $19.103\ GPa$, showing an increase range of 19.04%. Thus, increasing confining pressure suppresses sandstone interior fissure development and lateral deformation, and stress on fissure surface is positively increased. Overall deformation rigidity also shows an increase. Thus, the average modulus increases with confining pressure. Under the condition of room temperature at $25\,°C$, the changes in average modulus are few. However, when temperature increases, sandstone average modulus rises and then decreases with increasing confining pressure. These results explain that fluctuation of the average modulus is due to temperature. As shown in Fig. 11, when $\delta_3 = 10MPa$ and rock experiences high-temperature changes, E_{av} decreases from $19.303\ GPa$ to $16.047\ GPa$, showing a decrease range of 16.87%; when $\delta_3 = 20MPa$, temperature at $75\,°C$ E_{av} is $19.910\ GPa$ and $25\,°C$ E_{av} is $20.067\ GPa$, exhibiting a decrease range of 0.78%; when $\delta_3 = 30MPa$, temperature at $75\,°C$ E_{av} is $19.103\ GPa$ and $25\,°C$ E_{av} is $19.787\ GPa$, showing a decrease range of 3.45%. These results indicate that when confining pressure is constant, sandstone average modulus decreases with increasing temperature, and the average modulus decrease range at low confining pressure is higher than that at high confining pressure. Temperature increase causes expansion of the sandstone interior fissure, and elastic modulus is weakened under actions of temperature and then decreases. When confining pressure is low, the lateral restriction is low, and the elastic modulus decrease range is high.

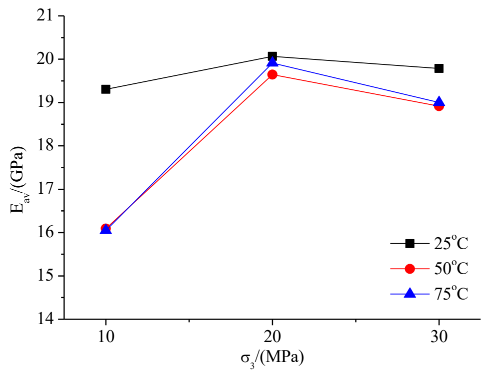


Fig. 10. Average modulus and confining pressure relation at different temperatures

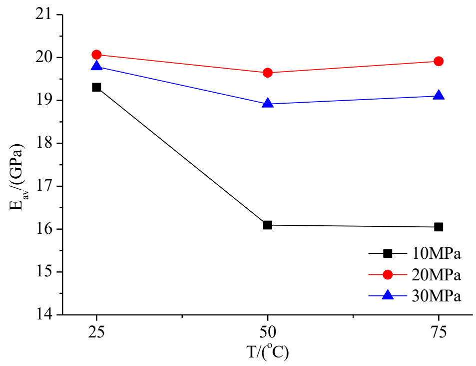


Fig. 11. Average modulus and temperature relation at different confining pressures

4.4 Relation between the axial peak strain and confining pressure and temperature

Fig. 12 and Fig. 13 show the following results: when the confining pressure is constant, the axial peak strain slowly grows with the increasing temperature; when the confining pressure is high, the increase in axial peak strain range is also high; when the temperature is constant, the axial peak strain considerably increases with confining pressure; when the temperature is high, the increase in the axial peak strain range is also high. The axial peak strain of rock evidently increases under confining pressure and temperature. Thus, the ductility of the rock can be improved when the temperature and confining pressure increase within a certain range.

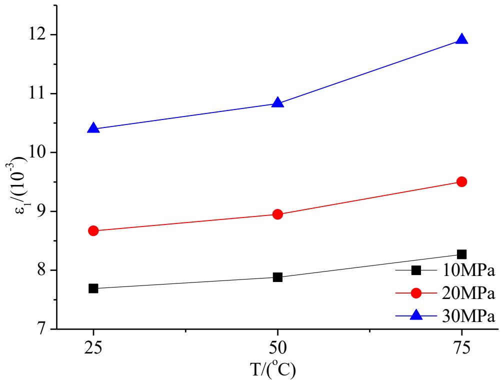


Fig. 12. Axial peak strain and temperature relation at different confining pressures

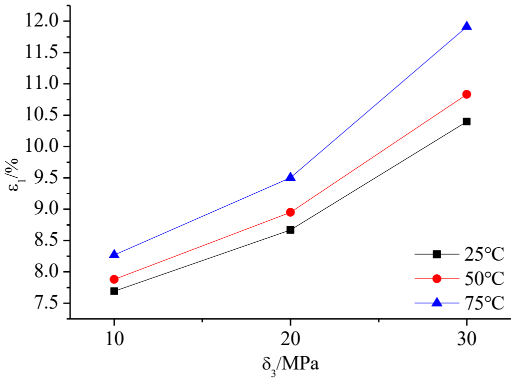


Fig. 13. Axial peak strain and confining pressure at different at different temperature

4.5 Relation between the cohesion and internal friction angle and temperature

Based on the triaxial experiment data, Mohr's circles at different temperatures and failure envelopes are drawn, and the shear strength index of rocks in different temperatures is derived.

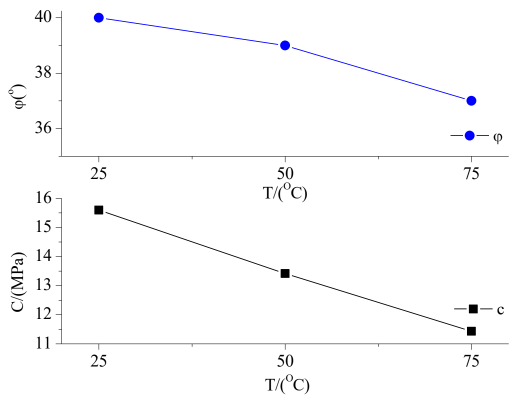


Fig. 14. Relation between cohesion, internal friction angle and temperature

At $25\,°C$ the sandstone cohesion C and internal friction angle φ are 15.6 MPa and $40°$, respectively. At $50\,°C$, the cohesion C and internal friction angle φ are 13.42 MPa and $39°$, respectively. At $75\,°C$, the cohesion C and internal friction angle φ are 11.43 MPa and $37°$, respectively. Thus, cohesion decreases with increasing temperature, and the internal friction angle shows a downward trend with rising temperature. Overall, the decrease in cohesion and its weakening effect due to rising temperatures have more influence than that of only the internal friction angle.

5. Conclusions

This study analyzed the stress–strain curve, failure load, average modulus, peak strain, cohesion, and internal friction angle of sandstone by adopting the experimental research method to explore the mechanical properties of sandstone (which had been subjected to coupling temperature and stress) and reveal its changing laws and physical parameters at ambient temperature from $25\,°C$ to $75\,°C$. The following conclusions could finally be drawn:

(1) The failure process of sandstone subjected to coupling temperature and pressure is generally consistent with the stress–strain curve of conventional triaxial compression, and failure mode is shear failure. When temperature is constant under coupling temperature and pressure, axial failure load increases with confining pressure; when the temperature and confining pressure are both high, the axial failure load of the test subject increases and the velocity accelerates. When confining pressure is constant, the axial failure load influenced by temperature is shown as follow:

(a) When $T \le 50°C$, the temperature increases as rock strength decreases.

(b) When $T \ge 50°C$, rock strength continuously decreases at low confining pressure $\delta_3 = 10MPa$.

(c) However, rock strength presents an increasing trend at high confining pressure $\delta_3 = 20MPa$ and $\delta_3 = 30MPa$. When the temperature is high, the rock strength increasing velocity is fast.

(2) Temperature action would cause fluctuations on the average modulus. The sandstone average modulus increases then reduces with increasing confining pressure and rising temperature. The average modulus decreases with increasing temperature when the confining pressure is constant. The decrease range at low confining pressure is larger than that at high confining pressure.

(3) When confining pressure is constant, the axial peak strain increases with temperature; when the confining pressure is high, the increase range is large; when temperature is constant, the axial peak strain increases with confining pressure; when the temperature is high, the increase range is also high.

(4) Cohesion and internal friction angle decrease with increasing temperature. The decrease range of the internal friction angle is small, and the cohesion weakening effect due to rising temperature is more than that on internal friction angle.

This study conducted a rock triaxial compression experiment subjected to the simultaneous coupling of high temperature and confining pressure. Experiment data reflected the changing law of sandstone mechanical properties subjected to coupling temperature and pressure, which compensated for the experiment data deficiency in this temperature range and provided certain references for solving similar deep rock mass engineering problems and subsequent research works. Given that the experiment instrument was restricted by controls of the temperature heating loading device, the current experiment data at high temperatures subjected to coupling temperature and pressure could not be tested. In future research, the development of temperature-control device and the analytic demonstration of the integration of experiment data with actual deep rock mass monitored data would be synchronously promoted. This approach would allow an improved understanding of mechanical property of rocks subjected to coupling temperature and pressure and provide accurate data.

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