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Study on Triaxial Compression Test and Numerical Simulation of White Sandstone under Coupled Chemical Corrosion and Temperature Effects

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Abstract: *This study investigates the influence of coupled chemical corrosion and temperature on the triaxial compression mechanical behavior of white sandstone. Standard cylindrical specimens collected from Zigong, Sichuan Province, were prepared and subjected to coupled conditioning with various chemical solutions and temperatures, followed by triaxial compression tests and COMSOL-based numerical simulations. The results show that under different coupled conditions, the triaxial stress–strain curves of white sandstone generally exhibit four distinct stages: compaction, elasticity, plasticity, and post-peak failure, with a sharp drop after the peak stress, indicative of typical brittle failure. In acidic or alkaline environments, both the triaxial compressive strength and elastic modulus decrease progressively with increasing temperature. The reductions are relatively small at 0 °C, 25 °C, and 50 °C, but become substantially more pronounced beyond 75 °C. Under neutral conditions, by contrast, both parameters decrease only slightly with rising temperature and remain essentially stable. At any given temperature, the triaxial compressive strength and elastic modulus follow the same descending order: neutral > alkaline > acidic. Numerical simulations reveal that high-stress zones are concentrated at the intersections between the circular end faces and the cylindrical surface, as well as in the central region of the specimen. The simulated failure mode is characterized by brittle dilatancy, with cracks developing predominantly parallel to the axial direction. The numerical predictions are in good agreement with the experimental results.*

Keywords: *white sandstone; triaxial compression; chemical corrosion; temperature; numerical simulation*

1. Introduction

During the excavation of underground engineering structures, the surrounding rock is typically subjected to a triaxial compressive stress state. Triaxial compression testing is therefore a crucial method for evaluating the stability of these surrounding rocks. In practical engineering contexts, the surrounding rock is chronically exposed to chemical erosion from groundwater and variations in geothermal temperature, which progressively induce internal structural damage and consequently degrade its strength and deformation characteristics. Consequently, investigating the triaxial compressive mechanical properties of white sandstone under the coupled effects of chemical corrosion and temperature holds significant practical importance.

In recent years, significant progress has been made in triaxial compression tests and numerical simulations. Ewy et al. [1] proposed ISRM-suggested methods for triaxial compression testing of shale and mudstone. Shu et al. [2] investigated the damage mechanisms of rock under high-pressure triaxial compression using the TSID model. Liu et al. [3] developed an elastoplastic constitutive model for expansive rocks under true triaxial compression. Yang et al. [4] combined true triaxial tests with discrete element simulations to study the failure mechanisms of interbedded composite rocks. Ren et al. [5] proposed a DEM-based model to describe stiffness evolution during the crack closure stage. Li and Wang [6] applied a phase-field approach to simulate three-dimensional fracture in heterogeneous rocks. Sarkar and Basu [7] investigated the strength and deformation behavior of layered composite materials under triaxial compression. Regarding chemical corrosion and temperature effects, Feng et al. [8-10] explored the mesostructured and mechanical response of sandstone under various chemical environments. Han et al. [11] analyzed the influence of chemical solutions on the strength and deformation characteristics of sandstone. Xu et al. [12] and Mohamadi et al. [13] examined the post-high-temperature strength and deformation behavior of rock. Wang [14] and Fang [15] conducted experimental studies on creep and physical–mechanical properties of rock subjected to temperature–chemical coupled conditions.

Despite these contributions, systematic investigations addressing the combined effects of chemical corrosion and temperature (below 100 °C) under triaxial compression remain scarce. To fill this research gap, white sandstone collected from Zigong, Sichuan Province, was subjected to coupled treatment with various chemical solutions (H_2SO_4 at pH = 1, distilled water, and NaOH at pH = 13) and at different temperatures (0 °C, 25 °C, 50 °C, 75 °C, and 100 °C). Triaxial compression tests were then conducted under a confining pressure of 1 MPa, in conjunction with COMSOL Multiphysics numerical simulations. The stress–strain curves, strength, elastic modulus, and failure characteristics were systematically analyzed to elucidate the coupled influence mechanism of chemical corrosion and temperature on the triaxial compression mechanical properties of white sandstone.

2. Specimen Preparation and Testing Scheme

The rock material used in this study was white sandstone obtained from Zigong, Sichuan Province. A total of 15 block specimens were selected, all exhibiting good macroscopic homogeneity. Following the specifications outlined in the Standard for Test Methods of Engineering Rock Mass (GB/T 50266-2013) [16], the blocks were machined into standard cylindrical specimens with dimensions of Φ50 mm × 100 mm. The non-parallelism between the two end faces was controlled to within 0.05 mm, and the axial deviation was maintained below 0.25°.

Prior to the coupled treatments, all specimens were oven-dried at 25 °C for 96 hours to eliminate moisture effects. They were then separately immersed in three types of solutions, namely H_2SO_4 solution (pH = 1), distilled water (pH = 7), and NaOH solution (pH = 13), while being simultaneously heated to five target temperature levels: 0 °C, 25 °C, 50 °C, 75 °C, and 100 °C. Throughout the immersion period, the pH values of the solutions were monitored and readjusted daily until the pH remained stable at 100 °C, indicating that chemical equilibrium had been reached. At that point, the specimens were removed from the solutions.

Triaxial compression tests were performed using a TAW-200 testing system, with a constant confining pressure of 1 MPa. Prior to loading, a preload of 200 N was applied to ensure proper contact between the loading platens and the specimen. The confining pressure was then increased at a rate of 0.05 MPa/s until the target value of 1 MPa was achieved. After stabilization of the confining pressure, axial loading was applied under load control at a rate of 50 N/s until specimen failure. The entire loading process and corresponding data were recorded automatically by the testing system.

To complement the experimental program, numerical simulations were conducted using COMSOL Multiphysics. A two-dimensional axisymmetric model with a width of 25 mm and a height of 100 mm was established. The physical and mechanical parameters obtained from white sandstone under various coupled conditions were assigned to the model. The identical confining pressure and axial loading conditions as those used in the laboratory tests were applied in the simulation to predict the stress distribution and deformation characteristics during triaxial compression. The numerical results were then compared with the experimental data to validate the reliability of the model. The detailed grouping scheme for the coupled chemical corrosion and temperature treatment is shown in Table 1.

Table 1 Specific settings of temperature and chemical solutions

Specimen group	Immersion solution	pH value	Solution concentration (mol/L)	Solution volume (L)	Temperature (°C)
A0	H2SO4	1	0.1	20	0
A25	H2SO4	1	0.1	20	25
A50	H2SO4	1	0.1	20	50
A75	H2SO4	1	0.1	20	75
A100	H2SO4	1	0.1	20	100
B0	Distilled water	7	0	20	0
B25	Distilled water	7	0	20	25
B50	Distilled water	7	0	20	50
B75	Distilled water	7	0	20	75
B100	Distilled water	7	0	20	100
C0	NaOH	13	0.1	20	0
C25	NaOH	13	0.1	20	25
C50	NaOH	13	0.1	20	50
C75	NaOH	13	0.1	20	75
C100	NaOH	13	0.1	20	100

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3. Test Results and Analysis

3.1 Stress–Strain Curves

The triaxial compression stress–strain curves of white sandstone subjected to different coupled chemical corrosion and temperature conditions at a confining pressure of 1 MPa are presented in Figs. 1–3.

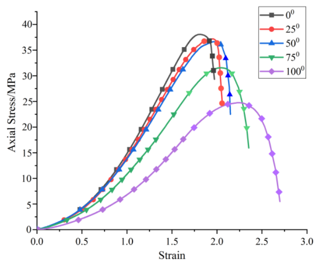

Fig.1 Triaxial stress-strain curve of white sandstone material (pH=1)

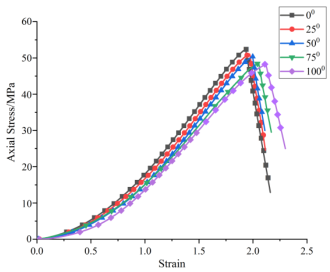

Fig.2 Triaxial stress-strain curve of white sandstone material (pH=7)

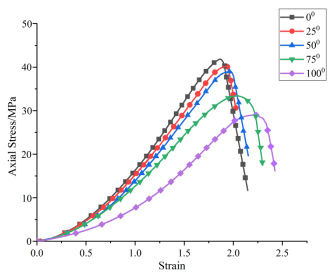

Fig.3 Triaxial stress-strain curve of white sandstone material (pH=13)

Observation from the figures indicates that, after undergoing different coupled treatments, the triaxial stress–strain curves of white sandstone are generally consistent with those observed under uniaxial compression, exhibiting four typical deformation stages: compaction, elasticity, plasticity, and failure. The post-peak curves drop rapidly, indicating distinct brittle failure characteristics.

In acidic or alkaline environments, the pre-peak curves gradually separate with increasing temperature, and the curves corresponding to higher temperatures consistently lie below those corresponding to lower temperatures. At 0 °C, 25 °C, and 50 °C, the curves separate slowly and remain relatively close to one another; however, beyond 75 °C, the curves separate sharply with a notably increased degree of dispersion. In neutral environments, the pre-peak curves at different temperatures separate slowly with little variation, and the curves corresponding to higher temperatures consistently remain below those of lower temperatures.

The underlying mechanisms can be explained as follows. In acidic or alkaline environments, chemical reactions take place between the mineral components of the sandstone and the H^+ or OH^- ions present in the solutions, resulting in internal damage to the rock. This process causes a transition from elastic to elastoplastic deformation behavior, accompanied by enhanced plasticity, which in turn induces the observed morphological changes in the stress–strain curves. Temperature below 100 °C has

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a limited direct deteriorating effect on the rock; it primarily accelerates the rates of chemical reactions, thereby exacerbating the aforementioned damage process. Under identical conditions, the extent of reaction between the sandstone components and H^+ ions is greater than that with OH^- ions, which explains why the curves in acidic environments exhibit more pronounced variations than those in alkaline environments.

3.2 Triaxial Compressive Strength and Elastic Modulus

The triaxial compressive strength and elastic modulus of white sandstone under different coupled conditions are listed in Table 2. From the tabulated data, the following observations can be made:

(1) At a given temperature, the triaxial compressive strength and elastic modulus of white sandstone exhibit considerable variations across different chemical environments: the highest values are obtained under neutral immersion, followed by alkaline immersion, and the lowest under acidic immersion.

(2) In acidic or alkaline environments, both the triaxial compressive strength and elastic modulus tend to decrease progressively with increasing temperature. At 0 °C, 25 °C, and 50 °C, the reductions are relatively limited and remain essentially stable; however, beyond 75 °C, the reductions become substantially more pronounced. Taking the acidic environment as an example, the triaxial compressive strength decreases from 38.1 MPa at 0 °C to 24.7 MPa at 100 °C, corresponding to a reduction of 35.2 %; the elastic modulus decreases from 3.1×10^3 MPa to 1.8×10^3 MPa, representing a reduction of 41.9 %.

(3) In neutral environments, both the triaxial compressive strength and elastic modulus decrease slowly with rising temperature, with only minor variations. From 0 °C to 100 °C, the triaxial compressive strength decreases modestly from 52.2 MPa to 47.6 MPa, corresponding to a reduction of 8.8 %; the elastic modulus decreases from 4.0×10^3 MPa to 3.4×10^3 MPa, representing a reduction of 15.0 %.

Table 2 Triaxial compressive strength and elastic modulus of white sandstone under different coupling conditions

Group	pH	Temperature (°C)	Triaxial compressive strength (MPa)	Elastic modulus ($\times10^3$ MPa)
A0	1	0	38.1	3.1
A25	1	25	37.1	2.9
A50	1	50	36.6	2.8
A75	1	75	31.6	2.4
A100	1	100	24.7	1.8
B0	7	0	52.2	4.0
B25	7	25	50.9	3.9
B50	7	50	50.0	3.8
B75	7	75	48.2	3.5
B100	7	100	47.6	3.4
C0	13	0	41.8	3.3
C25	13	25	40.3	3.1
C50	13	50	39.1	2.9
C75	13	75	33.4	2.6
C100	13	100	28.9	2.2

The above results indicate that in neutral environments, temperature (below 100 °C) exerts only a minor direct influence on the triaxial compressive strength and elastic modulus of white sandstone. In acidic or alkaline environments, however, temperature significantly aggravates rock deterioration primarily through accelerating the rates of chemical reactions, and the two factors act in a mutually reinforcing and superimposed manner.

3.3 Numerical Simulation Results

Numerical simulations of the triaxial compression process were carried out using COMSOL Multiphysics under a confining pressure of 1 MPa. In view of the axisymmetric geometry of the specimens, a two-dimensional axisymmetric model with dimensions of 25 mm in width and 100 mm in height was constructed.

The stress distribution contours of white sandstone specimens subjected to various coupled conditions during triaxial compression are displayed in Fig. 4.

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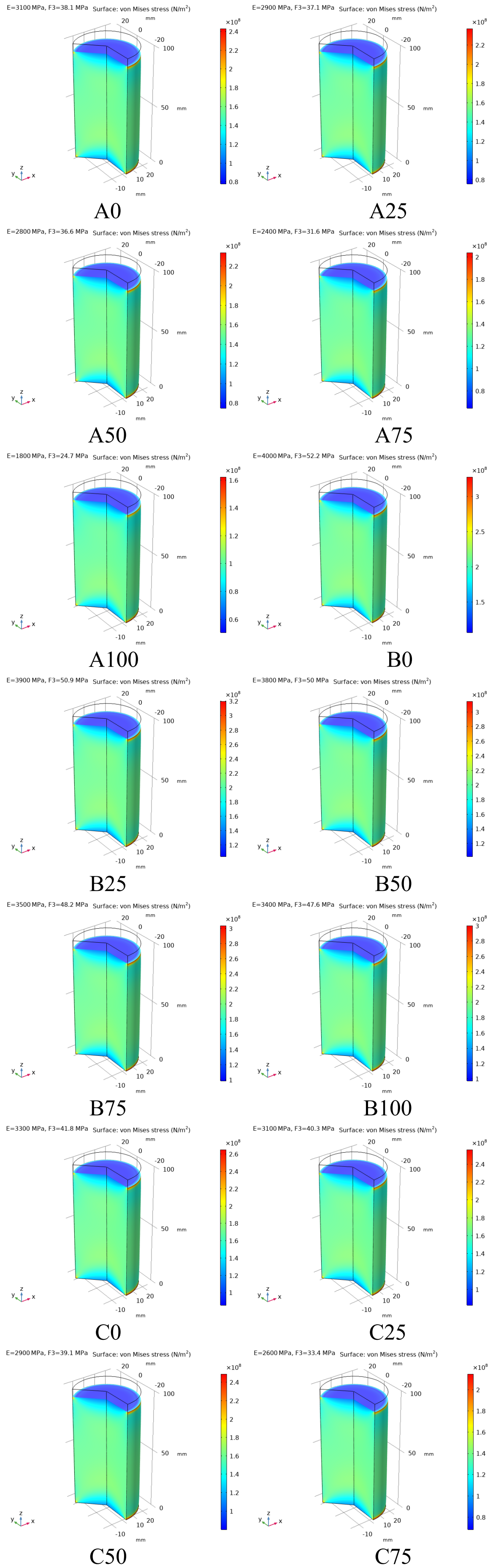

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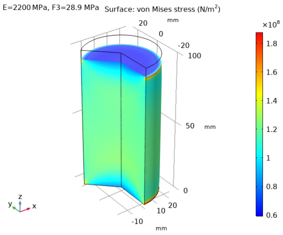

C100

Fig.4 Stress cloud diagrams of white sandstone specimens under triaxial compression under different coupling conditions

From Fig. 4, it can be observed that the stress distribution patterns in white sandstone specimens under triaxial compression are generally consistent across different coupled conditions. Regions with relatively high stress are concentrated at the junctions between the circular end faces and the cylindrical surface, as well as in the central portion of the specimen. The maximum stress is identified at the junction of the circular end face and the cylindrical surface, where localized minor fragmentation is first observed during testing.

Fig.5 Experimental Phenomena of Triaxial Compression of White Sandstone Specimen

From Fig. 5, it can be observed that, since the confining pressure (1 MPa) is substantially lower than the axial failure load, the axial force dominates the loading process. As the axial pressure progressively increases, the stress within the central region of the specimen rises continuously. Once it reaches a critical threshold, splitting failure occurs from the middle portion of the specimen, with cracks propagating essentially parallel to the cylindrical axis. The overall failure mode is characterized as brittle fracture.

The numerical results are in good agreement with the experimental data obtained from triaxial compression tests, which confirms the validity of the established numerical model and the reliability of the test results.

4. Conclusions

(1) Chemical corrosion and temperature exert a significant coupled influence on the triaxial compressive mechanical properties of white sandstone. At a given temperature, both the triaxial compressive strength and elastic modulus decrease in the order of neutral > alkaline > acidic environments, with the most severe deterioration observed under acidic conditions.

(2) Temperature below 100 °C has a limited direct effect on white sandstone; it primarily accelerates the rates of chemical reactions, thereby promoting mineral dissolution and pore enlargement, which indirectly reduces the strength and stiffness of the rock. The temperature of 75 °C is identified as the critical threshold beyond which the mechanical properties deteriorate sharply.

(3) The deterioration of triaxial compressive strength and elastic modulus induced by chemical corrosion and temperature exhibits a mutually reinforcing and superimposed effect. When each factor acts individually, the changes in mechanical properties are relatively moderate; however, when the two

factors act together, the damage is significantly exacerbated, with the combination of acidic environment and elevated temperature producing the most pronounced degradation.

(4) Under triaxial compression, the failure mode of white sandstone is characterized as brittle fracture, with the specimen splitting from the middle portion and cracks propagating essentially parallel to the cylindrical axis. Stress concentration is observed at the junctions between the circular end faces and the cylindrical surface, as well as in the central region of the specimen. The numerical simulation results are in good agreement with the experimental data, validating the reliability of the established model.

(5) The findings of this study provide an experimental basis and theoretical reference for the stability assessment of surrounding rock in underground engineering under complex environmental conditions, and offer guidance for the support design of tunnels and roadways in similar geological settings.

Acknowledgement

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Data Availability Statement

The data used to support the findings of this study are available from the corresponding author upon request.

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