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

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Abstract: *This study aims to investigate the coupled effects of chemical corrosion and temperature on the uniaxial compression mechanical behavior of white sandstone. Specimens were prepared from white sandstone sourced from Zigong, Sichuan Province, and subjected to various coupled chemical and thermal conditioning regimes prior to uniaxial compression testing and COMSOL-based numerical simulation. The results show that, regardless of the coupled conditions, the stress–strain curves consistently exhibit four distinct stages, namely compaction, elasticity, plasticity, and post-peak failure, with a sharp stress drop after the peak, indicative of typical brittle failure. In acidic or alkaline environments, both the uniaxial compressive strength and elastic modulus tend to decrease progressively with increasing temperature. The reductions are relatively modest at 0 °C, 25 °C, and 50 °C, but become substantially more pronounced beyond 75 °C. Under neutral conditions, both parameters decline only slightly with rising temperature and remain essentially stable. At any given temperature, both the uniaxial compressive strength and elastic modulus decrease in the order of neutral > alkaline > acidic. Stress concentrations are observed at the junctions between the specimen end faces and the cylindrical surface, as well as in the central region, with the specimens exhibiting barrel-shaped failure. The numerical predictions are in good agreement with the experimental measurements.*

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

1. Introduction

The uniaxial compression test is one of the fundamental methods for determining the mechanical properties of rock, from which key parameters such as stress–strain curves, uniaxial compressive strength, and elastic modulus can be obtained. These parameters serve as critical bases for stability analysis and support design of surrounding rock in underground engineering.

Sandstone is a widely distributed rock material commonly encountered in geotechnical engineering in southwestern China. White sandstone from the Zigong area of Sichuan Province is characterized by low density, high porosity, and relatively low uniaxial compressive strength, making it highly susceptible to environmental influences. In practical engineering, white sandstone is often subjected to the combined actions of chemical corrosion and temperature: acidic or alkaline ions in groundwater react chemically with rock minerals, altering the internal structure, while temperature variations may accelerate these reaction processes and further affect the mechanical properties of the rock.

Considerable research has been conducted on the uniaxial compression characteristics of rock. With respect to chemical corrosion, Feng et al. [1-3] investigated the mesostructured and macroscopic mechanical properties of sandstone under chemical environments. Han et al. [4] analyzed the effects of chemical solutions on the strength and deformation behavior of sandstone. Regarding temperature effects, Xu et al. [5] studied the strength and deformation characteristics of rock after high-temperature treatment. Mohamadi et al. [6] found that the peak strength of shale decreases with increasing temperature. In terms of coupled chemical corrosion and temperature effects, Wang [7] conducted creep tests on shale under temperature–chemical coupled conditions, while Fang [8] analyzed the influence of thermal–chemical coupling on the physical and mechanical properties of rock. In the field of numerical simulation, Wang et al. [9] performed numerical simulations of creep behavior in tunnel surrounding rock under temperature–stress–chemical coupled fields. In recent years, the combined approach of

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uniaxial compression testing and numerical simulation has been widely adopted in rock mechanics research. Feng et al. [10] established a damage model for freeze–thaw rock and proposed a uniaxial compression simulation method, providing a reference for numerical simulation of rock mechanical properties under thermal effects. Shang et al. [11] investigated multi-scale crack evolution characteristics of coal with different fracture types through real-time CT scanning combined with particle flow simulation. Yang et al. [12] developed a grain-based thermo-mechanical coupled model for heterogeneous granite under thermal shock, offering a methodological reference for numerical simulation of rock failure under temperature–stress coupled conditions. Sun et al. [13] studied the effects of microwave irradiation on thermal damage behavior of granite through uniaxial compression tests combined with the finite-discrete element method. Zhao et al. [14] monitored characteristic stress variations and microcrack evolution in granite under uniaxial compression using acoustic emission techniques, providing an effective means for real-time damage evolution monitoring in uniaxial compression tests.

However, systematic studies on the uniaxial compression characteristics of white sandstone under coupled chemical corrosion and temperature (below 100 °C) remain limited, and comparative analyses between experimental results and numerical simulations are particularly scarce. To address this gap, this study conducts uniaxial compression tests on white sandstone from Zigong, Sichuan Province, after coupled treatment with different chemical solutions and temperatures, and performs numerical simulations using COMSOL Multiphysics. The strength characteristics and deformation behavior of white sandstone under different coupled conditions are systematically analyzed, aiming to provide a reference for geotechnical engineering in similar geological settings.

2. Specimen Preparation and Testing Scheme

The rock material used in this study was white sandstone obtained from Zigong City, Sichuan Province, exhibiting good macroscopic homogeneity. In accordance with the *Standard for Test Methods of Engineering Rock Mass* [15], the rock block was machined into standard cylindrical specimens of 50 mm in diameter and 100 mm in height through cutting, coring, and grinding. The finished specimens were free of visible fractures or joints, with the non-parallelism of the two end faces controlled to within 0.05 mm, and the end faces perpendicular to the specimen axis with a maximum deviation not exceeding 0.25°.

Prior to testing, all specimens were oven-dried at 25 °C for 96 h. They were then immersed in H_2SO_4 solution at pH = 1, distilled water (pH = 7), and NaOH solution at pH = 13, respectively, and simultaneously heated to 0 °C, 25 °C, 50 °C, 75 °C, and 100 °C. During the immersion period, the pH values were monitored and adjusted daily until no further change was observed at 100 °C, at which point the specimens were removed from the solutions. 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

Uniaxial compression tests were carried out on a TAW-200 testing machine. Each specimen was positioned at the center of the machine base, with its axis carefully aligned with the loading platen.

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After a preload of 200 N was applied, axial loading was performed under load control at a rate of 50 N/s until specimen failure occurred, and the entire loading process was recorded.

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 of white sandstone under different coupled conditions were assigned to the model to simulate the stress and deformation distribution during uniaxial compression, and the numerical results were subsequently compared with the experimental data.

3. Test Results and Analysis

3.1 Stress–Strain Curves

The uniaxial compressive stress–strain curves of white sandstone under different coupled chemical corrosion and temperature conditions are presented in Figs. 1–3.

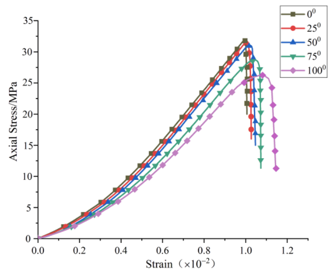

Fig.1 Uniaxial stress-strain curve of white sandstone materials (pH=1)

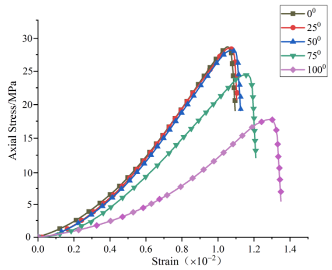

Fig.2 Uniaxial stress-strain curve of white sandstone materials (pH=7)

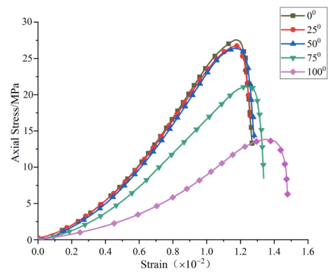

Fig.3 Uniaxial stress-strain curve of white sandstone materials (pH=13)

From the figures, it can be observed that the stress–strain curves of white sandstone under different coupled conditions consistently exhibit four distinct deformation stages: compaction, elasticity, plasticity, and post-peak failure. The post-peak portions drop sharply, indicating pronounced brittle failure characteristics.

In acidic or alkaline environments, the pre-peak curves gradually diverge with increasing temperature, and those corresponding to higher temperatures consistently remain below those at lower temperatures. At 0 °C, 25 °C, and 50 °C, the curves stay relatively close to one another; however, a marked separation occurs beyond 75 °C. In neutral environments, the pre-peak curves at different temperatures separate slowly, with only minor variations throughout the temperature range.

3.2 Uniaxial Compressive Strength and Elastic Modulus

The uniaxial compressive strength and elastic modulus of white sandstone under different coupled chemical corrosion and temperature conditions are presented in Table 2.

Tab.2 Uniaxial compressive strength and elastic modulus of white sandstone under different coupling conditions

Group	pH value	Temperature (°C)	Uniaxial compressive strength (MPa)	Elastic modulus ($\times 10^3$ MPa)
A0	1	0	27.5	3.17
A25	1	25	26.5	3.06
A50	1	50	26.0	2.98
A75	1	75	21.0	2.40
A100	1	100	13.5	1.65
B0	7	0	30.5	4.05
B25	7	25	30.1	3.98
B50	7	50	29.9	3.90
B75	7	75	29.2	3.69
B100	7	100	27.1	3.41
C0	13	0	28.8	3.39
C25	13	25	28.6	3.21
C50	13	50	28.5	3.11
C75	13	75	25.0	2.72
C100	13	100	18.7	2.12

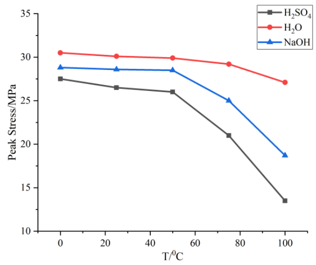

Fig.4 Uniaxial compressive strength degradation curve under different coupling conditions

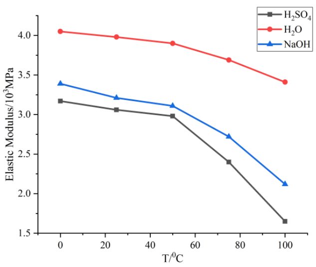

Fig.5 Elastic modulus degradation curve under different coupling conditions

Table 2 presents the uniaxial compressive strength and elastic modulus of white sandstone under different coupled chemical corrosion and temperature conditions. Figs.4 and 5 illustrate the deterioration of uniaxial compressive strength and elastic modulus with temperature under the same coupled conditions, respectively. From the table and figures, the following observations can be made:

(1) In acidic or alkaline environments, the uniaxial compressive strength of the specimens gradually decreases with increasing temperature (below 100 °C). At 0 °C, 25 °C, and 50 °C, the strength decreases slowly and remains essentially stable; however, beyond 75 °C, the strength drops sharply. In neutral environments, the uniaxial compressive strength decreases slowly with increasing temperature

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and remains essentially unchanged.

At a given temperature (below 100 °C), the uniaxial compressive strength of white sandstone varies across different chemical environments: the highest value is obtained under neutral immersion, followed by alkaline immersion, and the lowest under acidic immersion.

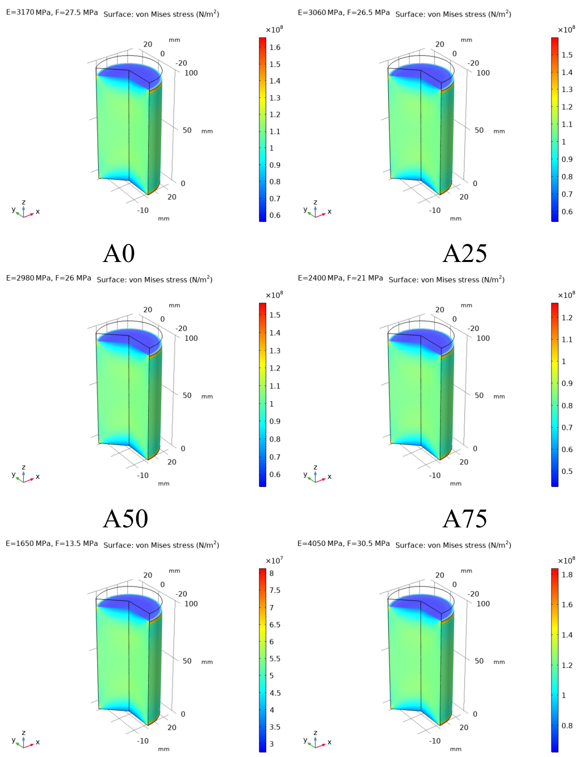
The underlying mechanisms can be explained as follows. Temperature below 100 °C primarily affects the strength of the rock by accelerating the rates of chemical reactions, thereby inducing damage and reducing the strength. Chemical corrosion alone has a certain influence on the uniaxial compressive strength, but its effect becomes more significant when combined with temperature. The influences of chemical corrosion and temperature on the strength of white sandstone are mutually reinforcing and superimposed.

(2) After different coupled chemical corrosion and temperature treatments, the overall decreasing rate of the elastic modulus of white sandstone exhibits a trend of initially slow and then rapid decline with increasing temperature. The decreasing rate is the slowest under neutral immersion, the fastest under acidic immersion, with a substantial difference between the two, and the decreasing rate under alkaline immersion falls between that under acidic and neutral conditions.

The underlying mechanisms can be explained as follows. Temperature below 100 °C has a limited direct effect on the elastic modulus, but its influence becomes significant when combined with chemical corrosion. Chemical corrosion alone has a certain influence on the elastic modulus, but its effect becomes more significant when combined with temperature. The influences of chemical corrosion and temperature on the elastic modulus of white sandstone are mutually reinforcing and superimposed.

3.3 Numerical Simulation Results

Numerical simulations of uniaxial compression were performed on white sandstone specimens under different coupled chemical corrosion and temperature conditions. The stress contours of the specimens under these conditions during uniaxial compression are presented in Fig. 6.



A0 A25

A50 A75

A100 B0

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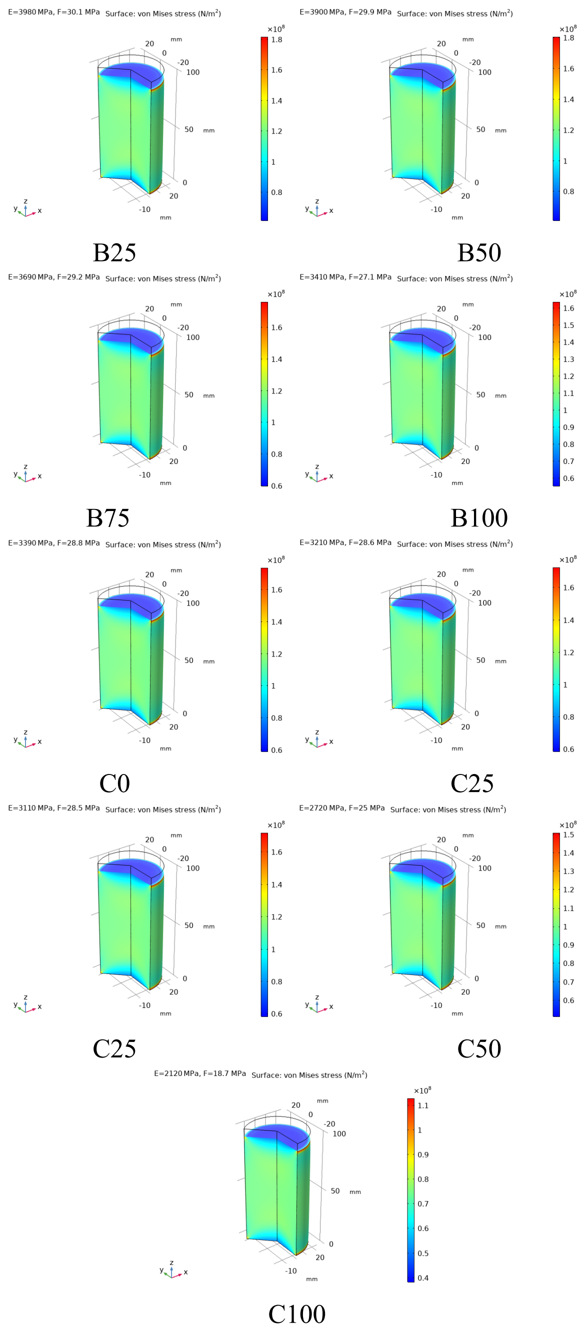

Fig.6 Stress cloud diagrams of white sandstone specimens under uniaxial compression under different coupling conditions

From the stress contours in Fig. 6, it can be observed that the stress distribution patterns of white sandstone specimens under uniaxial compression are generally similar across different coupled conditions. Regions with relatively high stress are primarily 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 occurs at the junction between the circular end faces and the cylindrical surface.

The deformation contours (both axial and radial) of white sandstone specimens under uniaxial compression for different coupled conditions are presented in Fig. 7.

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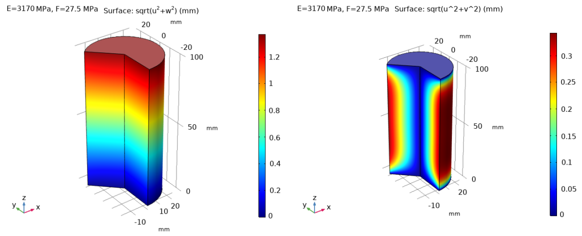
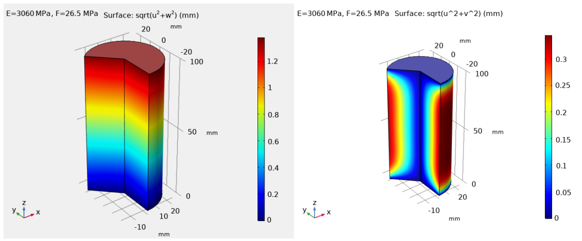


A0



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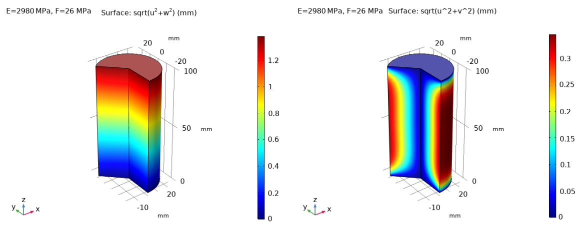
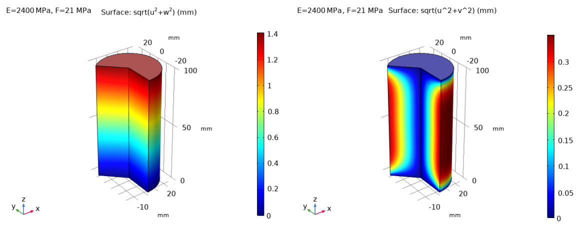


A50



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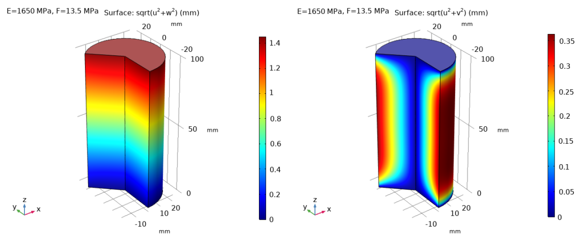
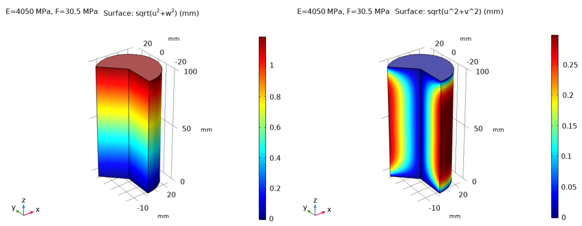


A100



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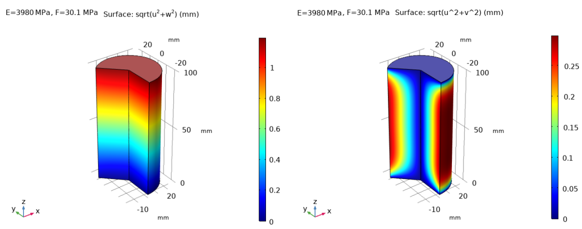

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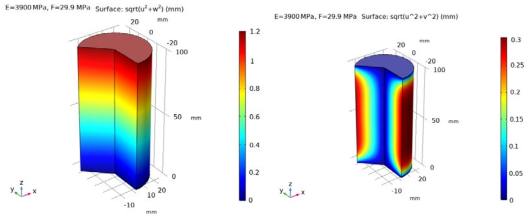

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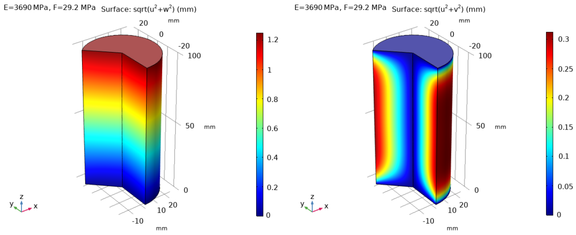

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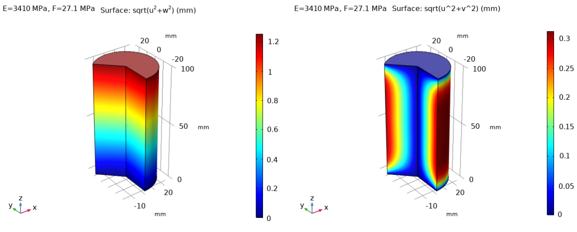

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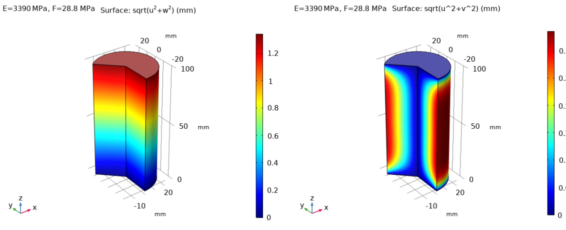
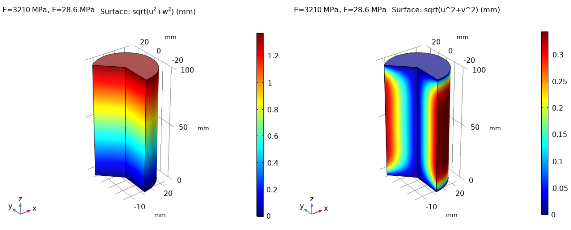
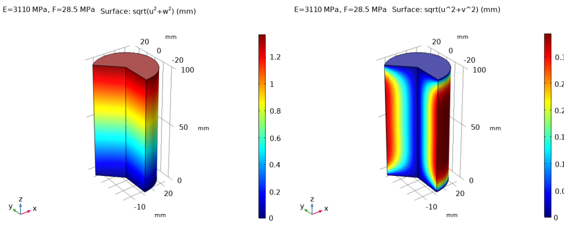


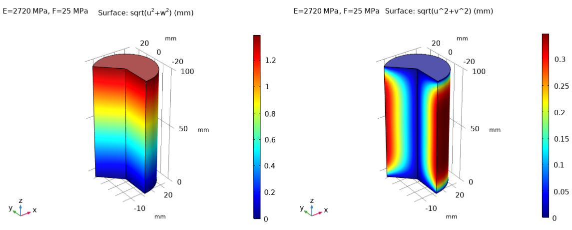
C0



C25



C50



C75

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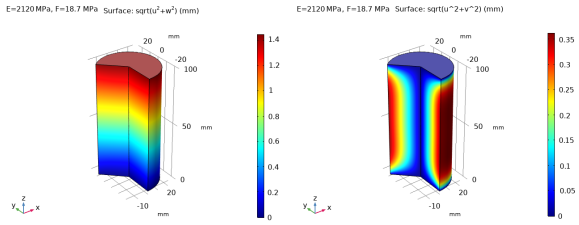

C100

Fig.7 Deformation cloud diagrams of white sandstone specimens under uniaxial compression under different coupling conditions

From the deformation contours in Fig. 7, it can be observed that the maximum axial deformation occurs at the upper end face of the white sandstone specimen, while the maximum radial deformation is located at the outer edge of the central cross-section through the specimen center. This manifests as a significant bulging phenomenon in the middle portion of the cylindrical specimen, exhibiting a barrel-shaped deformation pattern. The numerical simulation results are consistent with the uniaxial compression test results.

4. Conclusions

(1) After being subjected to different coupled chemical corrosion and temperature conditions, the uniaxial compressive stress–strain curves of white sandstone consistently exhibit four distinct stages: compaction, elasticity, plasticity, and post-peak failure. The post-peak portions drop sharply, indicating typical brittle failure characteristics.

(2) In acidic or alkaline environments, the pre-peak curves gradually diverge with increasing temperature, and those corresponding to higher temperatures consistently remain below those at lower temperatures. At 0 °C, 25 °C, and 50 °C, the curves remain relatively close to one another; however, a marked separation occurs beyond 75 °C. In neutral environments, the pre-peak curves at different temperatures separate slowly, with only minor variations throughout the temperature range.

(3) In acidic or alkaline environments, both the uniaxial compressive strength and elastic modulus tend to decrease progressively with increasing temperature. The reductions are relatively modest at 0 °C, 25 °C, and 50 °C, but become substantially more pronounced beyond 75 °C. Under neutral conditions, both parameters decline only slightly with rising temperature and remain essentially stable.

(4) At a given temperature, the uniaxial compressive strength and elastic modulus vary considerably across different chemical environments: the highest values are obtained under neutral immersion, followed by alkaline immersion, and the lowest under acidic immersion.

(5) Numerical simulation results reveal that, under uniaxial compression, high-stress regions are primarily 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 axial deformation occurs at the upper end face, while the maximum radial deformation is located at the outer edge of the middle section, resulting in a barrel-shaped failure pattern. The numerical predictions are in good agreement with the experimental measurements.

(6) Temperature below 100 °C exerts a limited direct deteriorating effect on white sandstone; it primarily promotes rock damage and the degradation of strength and elastic modulus by accelerating chemical reaction rates. The influences of chemical corrosion and temperature on the strength of white sandstone are mutually reinforcing and superimposed.

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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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