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Softening Damage Analysis of Gypsum Rock With Water Immersion Time Based on Laboratory Experiment

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ABSTRACT In view of the effect of water on the physical and mechanical parameters of natural gypsum rock, in this study, gypsum rock in the goaf of a gypsum mine was selected as the research object, and gypsum rock samples were prepared with different immersion times. In addition, uniaxially tests were performed separately on the gypsum rock samples. Compression and scanning electron microscopy experiments were carried out to analyze the effects of immersion time on the uniaxial compressive strength, elastic modulus, Poisson's ratio, and microstructure of gypsum. The results show that the uniaxial compressive strength and elastic modulus of gypsum are inversely proportional to the water content. However, the Poisson's ratio is direly proportional to the water content, and the failure mode is destroyed by the brittle fracture of a single crack and is transformed into the shear ductile failure of the Y-shaped crack. Microscopically, with increasing immersion time, the bonds in the crystal of the microporous cracks and microcrack tips are weakened by hydrolysis, and the macroscopic structure is complicated by the internal structure of gypsum, and the end of the crack is expanded by the compressive action of water. Based on the damage mechanics, the evolution equation of gypsum soaking softening damage based on time factor was derived. The relationship between the brittleness coefficient and softening damage variable is revealed, providing a theoretical basis for the determination of the softening degree of gypsum in the goaf.

INDEX TERMS Gypsum rock, water immersion, softening damage, brittleness coefficient.

I. INTRODUCTION

With the advancement of urbanization, the construction and the decoration industry have developed rapidly, providing a broad space for the development of the gypsum industry, leading to continuous expansion of the market demand. In recent years, accidents have continued to occur in major gypsum mines due to the rainwater and water inrush [1]. Taking a gypsum mine as an example, due to the poor maintenance of the mined areas in the mining area, a large amount of rainwater is poured into the goaf. Because gypsum rock is highly hydrophilic, it easily absorbs water and softens, and the softening of gypsum rock has a great effect on the stability of goaf. Aiming at this engineering problem, the water immersion softening test of the Zhangzhou gypsum rock was carried out at different times, and the variation in the basic mechanical parameters with immersion time was analyzed to provide a basis for the determination of the softening degree of gypsum rock in the mining area.

In recent years, a lot of experimental research has been carried out on the softening characteristics of the rock after water immersion. In 1974, Louis [2] first proposed the concept of rock hydraulics, which has been widely used in engineering practice. Dyke and Dobereiner [3] believes that the bulk density, initial state, water content, and stress state of rock are the main factors affecting the degree of water

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weakening of rock. For soft rock such as mudstone and coal rock, the water content affects rock compression. The strength index value is the important factor, and it decreases with increasing water content. The reason for the decrease in the compressive strength is that the rock fractures extend and the internal pressure of the crack increases after the rock gets saturated. Auvray *et al.* [4] believes that if the saturated rock mass under stress does not discharge the fissure water and the pore water, it will generate pore water pressure, reducing the rock mass strength. Jingqiang [5] reported that after the rock is saturated, the mechanical properties deteriorate; however, the mechanical inhomogeneity of the medium improves. This phenomenon is characterized by weakened rigidity and enhanced flexibility. Auvray *et al.* [6] believes that after the rock body is immersed in water, the clay mineral fillings in the internal joints, bedding and other structural planes change from solid to plastic. When the water content reaches a certain limit, the filling becomes liquid and the rock mass weakens. Hongpu [7] examined the evolution equation of the rock water damage variable, indicating that the water content has a linear relationship with the elastic modulus and uniaxial compressive strength and is the main factor affecting rock expansion. Colback and Wild [8] proposed that the uniaxial compressive strength of the dry rock after saturation reduced by approximately 50%. Hawkins and Mc Connel [9] studied the effect of water saturation on the strength and modulus of deformation of British sandstones. Priest and Selvakumar [10] studied two sandstones and three limestones and established a relationship between the uniaxial compressive strength and water saturation. Vasarhelyi [11] and Vasarhelyi and Van [12] tested the uniaxial compressive strength and modulus of deformation of limestone under dry and saturated conditions, indicating that the strength and modulus decreased by approximately 34% after saturation. Yilmaz [13] and Yilmazand and Gürkan [14] studied the effect of water content on the peak strength and elastic modulus of gypsum rock. Through analyzing the variations of rock meso-structures using a scanning electron microscope (SEM), Qin *et al.* [15] combined qualitative analysis and quantitative characterization to investigate rock meso-structure damage due to water invasion-water loss cycles. ZHOU *et al.* [16] reported that the influence of water on gypsum goaf, and the mechanical model of goaf stability was established. The conditions of pillar instability under the influence of water were obtained. Sadeghiamirshahidi and Vitton [17] experimentally analyzed the effects of gypsum on the creep properties and the mechanical properties of under water immersion. Li [18] studied the effect of water on the shear creep properties of sandstone and analyzed the corresponding impact mechanism. Meng *et al.* [19] experimentally studied the mechanical properties of shale and pointed out the effect of characteristics of temperature on the mechanical properties of shale. Deng *et al.* [20] conducted an experimental study on the strength degradation of sandstone under the action of saturated water-drying cycle and pointed that the sandstone strength decreases with increasing water saturation.

There are relatively a few experimental studies on gypsum rock. Yu *et al.* [21] studied the meso-structure evolution of gypsum at different salt concentrations at normal temperature, indicating significant changes in the meso-structure of gypsum crystals in different salt concentrations, affecting the physical and mechanical properties, especially permeability, extreme strength, and deformation characteristics. Bouzit *et al.* [22] studied the conventional triaxial compression properties of anhydrite. Studies have shown that with increasing confining pressure, the deformation characteristics of anhydrite show a gradual transition from brittle to ductile nature, with peak and residual strength and confining pressure. The residual strength is significantly more sensitive to confining pressure than the peak intensity. Liang *et al*. [23] and Adams *et al*. [24] studied the mechanical properties of gypsum under soaking in high temperature salt solution soaking at high temperature and found that the mechanical strength of gypsum rock deteriorated with increasing temperature, increasing salt solution concentration, and prolonging immersion time.

However, the abovementioned experimental studies did not establish a constitutive model of gypsum water immersion softening, thus this paper analyzed the failure form of gypsum from macroscopic and microscopic aspects, and established the constitutive model of gypsum water immersion softening, which supplements the gap of current research. Based on the gypsum rock freshwater immersion softening test, the effect of different immersion times on the mechanical properties of gypsum rock was analyzed, discriminating the lithology of gypsum rock. The brittleness coefficient is used to visually judge the softening degree of the test piece and can be applied to the determination of the softening range and softening degree of the surrounding rock passing through the gypsum layer tunnel. It can effectively remedy the vacancy of current research.

II. SAMPLE PREPARATION AND INSTRUMENTATION

Rock samples were collected from a gypsum mine in northern Jiangsu at a sampling depth of approximately 300 m below the surface. Test piece processing technology is as follows: Select a large piece of intact, non-destructive and regular cubic rock block at the construction site in the gypsum mine. After transporting to the laboratory, the test piece was processed in the laboratory. According to the method recommended by the international rock mechanics test, it is processed into a cylindrical standard test piece with a diameter of 50 mm and a height of 100 mm, and the unevenness of the end face of the test piece is controlled within 0.3 mm; the uniaxial compressive strength and tensile strength test of gypsum rock were measured using a CSS-44100 electronic universal testing machine with a maximum axial pressure of 100 kN (Figure 1).

III. TEST PLAN

1) In order to study the effect of different immersion times on the mechanical parameters of gypsum rock,

(a) Standard sample (b) Testing machine

FIGURE 1. Test sample and test platform.

the experimental scheme was designed to test the water content of gypsum rock under natural conditions for 1 day, 7 days, 15 days, and 30 days of water immersion. According to different water immersion times, the samples were divided into five groups for water immersion tests. In order to decrease the error, three samples were selected for each group. The sample was dried first, and then weighed and recorded. After each set of immersion sample reaches the predetermined immersion time, the surface moisture is wiped dry and then weighed and recorded. After weighing, the rock sample is placed in a sealed bag to prevent the rock sample from being exposed to the air, causing water loss. The difference between the two weights was calculated, and the moisture content of the sample was calculated by the Eq. (1).

$$\omega = \frac{M_2 - M_1}{M_2} = \frac{\Delta M}{M_2} \times 100\% \tag{1}$$

where M_1 is the weight after drying, M_2 is the natural weight, and M is the difference between them.

2) In order to study the strength and deformation characteristics of gypsum rock under different immersion times under uniaxial compression conditions, the variation in the mechanical parameters such as uniaxial compressive strength, elastic modulus, and Poisson's ratio of gypsum rock with immersion time is discussed. The gypsum samples of 1 day, 7 days, 15 days, and 30 days of water immersion were subjected to uniaxial compression test and loaded by the equal displacement loading method until the test piece was broken with a loading rate of 0.1 mm/min.
3) In order to study the degradation mechanism of water on the gypsum rock microscopically, images of the gypsum rock samples in the natural state and after water immersion for 1 day, 7 days, 15 days, and 30 days for 2000 times were scanned using an FEG-SEM scanning electron microscope. The scanned images were analyzed.

IV. TEST RESULTS AND ANALYSIS

A. ANALYSIS OF WATER ABSORPTION PERFORMANCE

The test data are listed in Table 1. The average moisture content of gypsum rocks in the natural state and water immersion for 1 day, 7 days, 15 days, and 30 days was calculated to be 0.2467%, and 0.3001%, 0.4320%, 0.7051%, and 0.8755%, respectively.

The relationship between different water immersion times and water content of gypsum rock was established. Figure 2 shows that the gypsum rock has strong hydrophilicity, and its water content increases with increasing immersion time, however, the growth rate decreases with increasing immersion time. In the initial stage of immersing gypsum rock in water, the micropores and fissures in the rock mass increase with increasing immersion time, and the air in the pores is gradually discharged and filled with water, thereby rapidly increasing the water content in the initial immersion stage. Later, because the pores in the rock mass are gradually filled with water, the ability of the pores to absorb water decreases, thus gradually decreasing the absorption rate of the water. The fitting equation of the water content and water immersion time is shown by Eq. (2) with the correlation coefficient $R^2 = 0.8499$.

$$\omega_t = 0.16 \ln(t) + 0.258 \tag{2}$$

B. ANALYSIS OF UNIAXIAL COMPRESSIVE TEST RESULTS

Under the action of water, the internal microstructure will change, and the connection between the rock particles will also be destroyed, leading to less compact microstructure, which in turn deteriorates the mechanical properties with

TABLE 1. Change law of water content of gypsum rock in different water immersion times.

Sample	t/d	M_1/g	M_2/g	$\Delta M/g$	$\omega/\%$	$\bar{\omega}/\%$
dz0-1		441.91	441.15	0.76	0.1723	
dz0-2	Natural	444.01	442.71	1.30	0.2936	0.2467
dz0-3		442.58	441.37	1.21	0.2741	
dz1-1		447.37	446.11	1.26	0.2824	
dz1-2	1	445.35	443.85	1.50	0.3379	0.3001
dz1-3		451.22	449.96	1.26	0.2800	
dz7-1		444.28	442.12	2.16	0.4886	
dz7-2	7	448.60	446.32	2.28	0.5108	0.4824
dz7-3		449.62	447.48	2.14	0.4479	
dz15-1		447.84	444.68	3.16	0.7106	
dz15-2	15	449.35	446.00	3.35	0.7511	0.7051
dz15-3		451.18	448.25	2.93	0.6537	
dz30-1		446.01	441.35	4.66	1.1056	
dz30-2	30	444.35	440.88	3.47	0.7870	0.8755
dz30-3		446.17	442.92	3.25	0.7338	

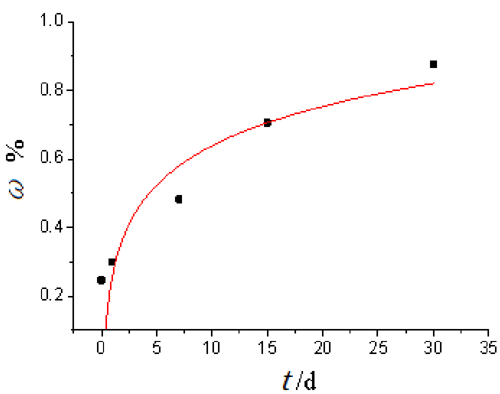


FIGURE 2. Curve of moisture content of gypsum rock in different immersion times.

continuous increase in the immersion time. The softening degree of gypsum rock also increases. The full stress–strain relationship curve of gypsum rock under uniaxial compression reflects the stress–strain properties of the rock sample under stress (Figure 3). The mechanical parameters of the sample are listed in Table 2.

1) UNIAXIAL COMPRESSIVE STRENGTH ANALYSIS

The corresponding relationship between the uniaxial average compressive strength and the average water content of the gypsum rock samples with different immersion times is shown in Table 3.

Figure 4 shows the relationship between the uniaxial compressive strength and water content is generally linear, and the two characteristics are negatively correlated. The uniaxial compressive strength decreases with increasing water content, and the trend of decline is larger, indicating that water has an obvious softening effect on gypsum rock, and the uniaxial compressive strength will greatly reduce after long-term water immersion. The compressive strength of gypsum rock with a water content of 0.8755% in 30 days of water immersion decreased by 35.61% compared to the natural state. Immersing gypsum rock in water shows an obvious softening effect of water on the uniaxial compressive strength of gypsum rock. At the initial stage of water immersion, the uniaxial compressive strength of gypsum rock decreased greatly. With increasing immersion time to 15 days, the decline in the compressive strength slowed down, and the relationship between the uniaxial compressive strength and immersion time became approximately exponential. The fitting function is shown by Eq. (3) with the correlation coefficient $R^2 = 0.94654$.

$$\sigma_c = 17.804\omega_t^2 - 37.26\omega_t + 40.129 \tag{3}$$

2) ANALYSIS OF ELASTIC MODULUS CHANGE

Figure 5 shows the relationship between the elastic modulus of the gypsum rock and the water content, indicating that the elastic modulus of gypsum rock decreases with increasing water content, showing an obvious weakening effect of water

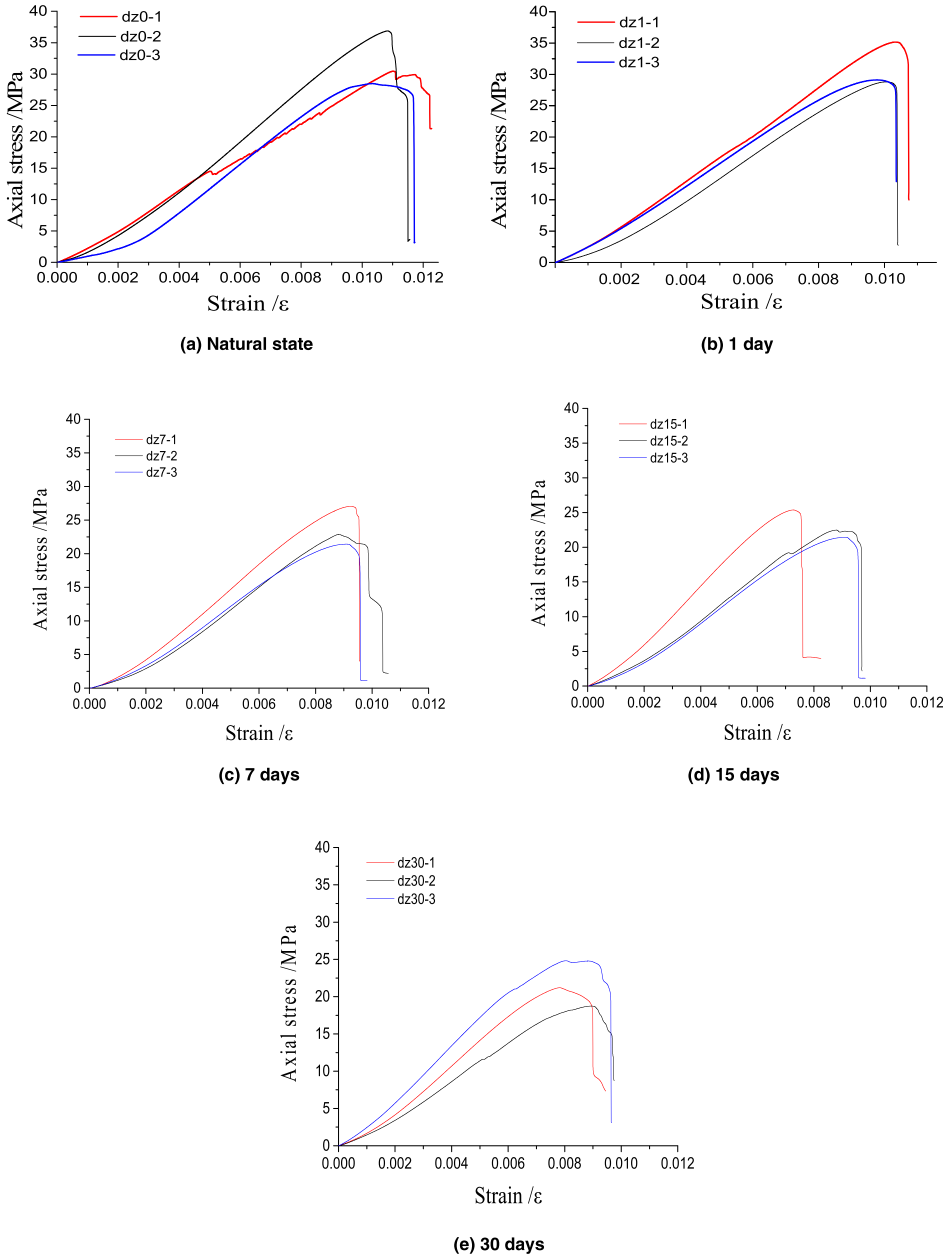


FIGURE 3. The stress–strain relationship of gypsum rock under uniaxial compression.

on the gypsum rock deformation. At the initial stage of water immersion, the elastic modulus decreases rapidly, and later slows down gradually. The elastic modulus of gypsum rock is approximately exponential with water immersion time. The fitting function is shown in Eq. (4) with the correlation coefficient $R^2 = 0.9823$.

$$E_\omega = 4.9e^{-0.7\omega} \tag{4}$$

3) POISSON'S RATIO CHANGE ANALYSIS

The relationship between Poisson's ratio of gypsum rock and the immersion time is shown in Figure 6, indicating that Poisson's ratio of gypsum rock increases with immersion time; and the linear fitting function is shown by Eq. (5), and the correlation coefficient $R^2 = 0.91041$.

$$\mu_t = 0.162 + 0.005t \tag{5}$$

4) ANALYSIS OF DAMAGE CHARACTERISTICS

Figure 7 shows that the failure characteristics of natural gypsum rock under uniaxial compression are mainly splitting and tensile failure, and the fracture surface runs through the whole sample. With increasing immersion time, the brittleness of the rock decreases and shear slip begins to appear. The damage

TABLE 2. Mechanical properties under uniaxial compression test of gypsum rock with different immersion times.

Sample	t / d	σ_c/MPa		E/GPa		μ	
		Test value	Average value	Test value	Average value	Test value	Average value
dz0-1		30.47		3.94		0.177	
dz0-2	Natural	36.86	31.95	4.11	4.10	0.164	0.171
dz0-3		28.51		4.25		0.172	
dz1-1		35.15		3.95		0.168	
dz1-2	1d	28.79	31.02	4.23	4.07	0.184	0.178
dz1-3		29.11		4.03		0.182	
dz7-1		27.01		3.70		0.189	
dz7-2	7d	25.94	25.28	3.66	3.49	0.202	0.196
dz7-3		22.88		3.12		0.213	
dz15-1		21.43		3.05		0.198	
dz15-2	15d	24.41	23.73	2.98	3.07	0.243	0.214
dz15-3		25.36		3.18		0.201	
dz30-1		18.72		2.48		0.358	
dz30-2	30d	21.20	20.75	2.57	2.55	0.312	0.339
dz30-3		22.32		2.61		0.346	

TABLE 3. The relationship between the average uniaxial compressive strength and the average water content of gypsum rock.

t/d	σ_c/MPa	ω / %
Natural	31.95	0.2467
1	31.02	0.3001
7	25.28	0.4824
15	23.73	0.7051
30	20.75	0.8755

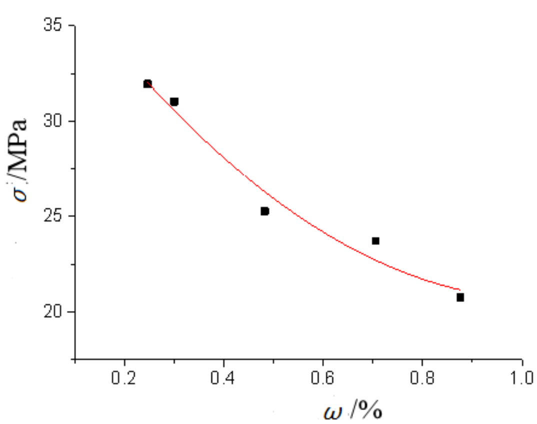


FIGURE 4. Relationship between the compressive strength and water content of gypsum rock under uniaxial compression.

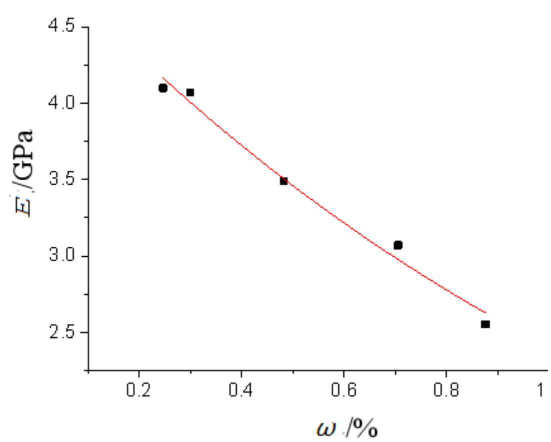


FIGURE 5. Relationship between the modulus of elasticity and moisture content of gypsum rock under uniaxial compression.

is removed, and the longer the immersion time, the more obvious the shear failure of the rock sample. In addition, more cracks lead to the formation of Y-type fracture cracks.

Figure 7 shows that the failure characteristics of natural gypsum rock under uniaxial compression are mainly splitting and tensile failure, and the fracture surface runs through the

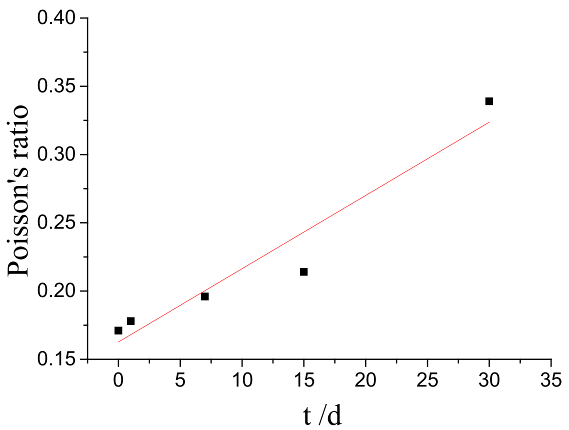


FIGURE 6. Relationship between Poisson's ratio of gypsum rock and water immersion time.

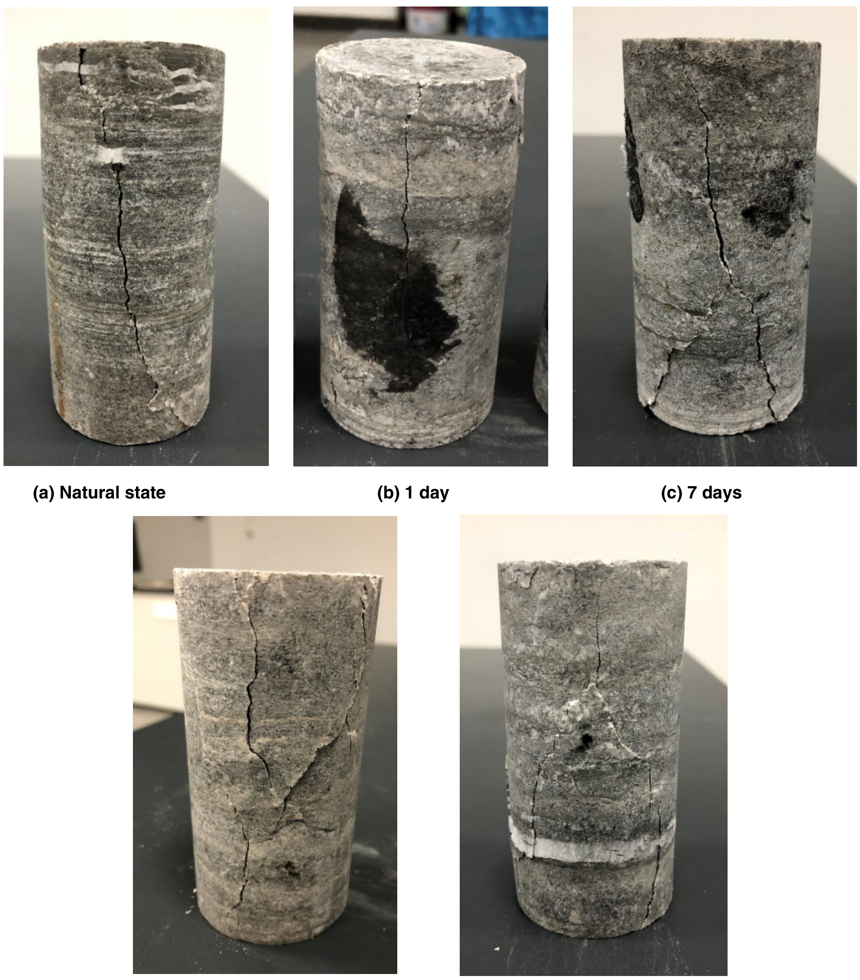
whole sample. With increasing of immersion time, the brittleness of the rock decreases and shear slip begins to appear, and the longer the immersion time, the more obvious the shear failure of the rock sample. In addition, cracks gradually convert to the Y-type fracture cracks.

C. SEM ANALYSIS OF GYPSUM ROCK

Water has a certain degrading effect on the physical and mechanical properties of gypsum rock. In order to reveal the deterioration mechanism of water to gypsum rock from the microscopic view, the GEG gypsum rock with different water immersion days was scanned using FEG-SEM equipment. Figure 8 shows the scanned image; the left side is the scan of the original image, and the right size corresponds to the grayscale image.

Figure 8 shows that the micropores and microcracks of the gypsum rock in the natural state are in a closed state, making the surface relatively flat; however, the structural layering of the rock is more obvious, and the bedding is closely connected to maintain a good compact and hard state.

Figure 9 shows that after 7 days of immersing in water, the gypsum rock is infiltrated because of the micro-cracks inside the gypsum and the gap between the micro-pores.



(a) Natural state (b) 1 day (c) 7 days

(d) 15 days (e) 30 days

FIGURE 7. Uniaxial compression failure characteristics of gypsum rock in different immersion time.

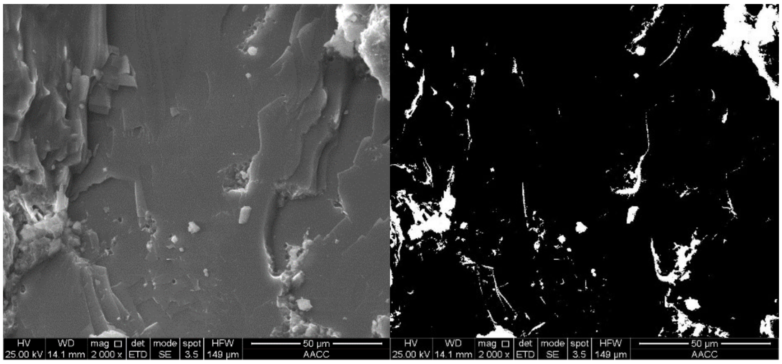


FIGURE 8. SEM images of natural gypsum rock.

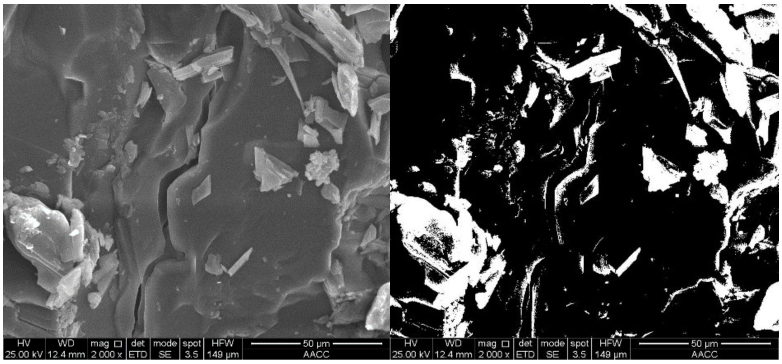


FIGURE 9. SEM images of gypsum rock soaked for 7 days.

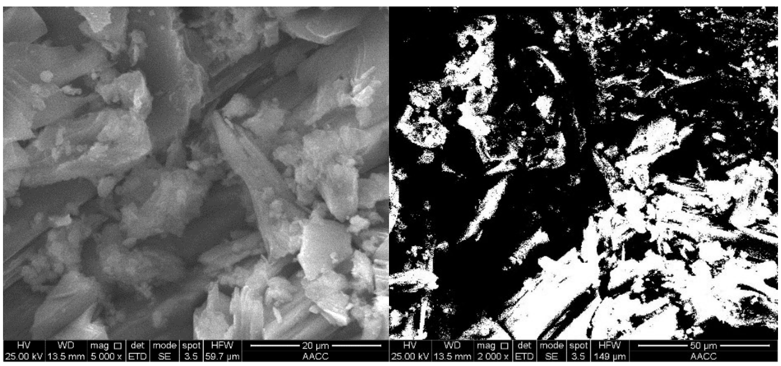


FIGURE 10. SEM images of gypsum rock soaked for 15 days.

Besides, the infiltration is due to the fact that the crystal grains and the bond in the crystal at the tip of the micro-crack are hydrolyzed and weakened. The internal structure shows micro-crushing phenomenon to some extent, indicating that the pore structure tends to be complex. This observation confirms that water has a certain weakening effect on gypsum rock, but the number of cracks is small.

Figure 10 shows that after 15 days of immersing the rock in water, the microstructure of the gypsum rock changes greatly, showing an obvious fracture phenomenon and many cracks. The internal layering has a certain breaking phenomenon, making the pore structure more complicated. Thus, water significantly weakens gypsum rock.

Figure 11 shows that after 30 days of immersing gypsum rock in water leads to a large number of cracks, and its internal structure is obviously damaged, with the sever breaking of the internal layering. After immersing gypsum rock for a long time, water enters its internal structure, causing significant damages to the internal structure of gypsum rock, resulting in significantly increased porosity, complex pore structure, cracks filled with water, and reduced friction between the cracks.

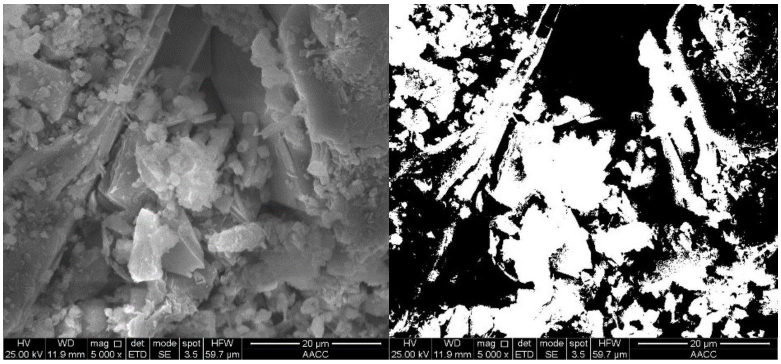


FIGURE 11. SEM images of gypsum rock soaked for 30 days.

TABLE 4. Relationship between the brittleness coefficient of gypsum rock and water immersion time.

t/d	Natural	1	7	15	30
n	5.052	5.052	2.042	1.607	1.327

V. GYPSUM ROCK SOFTENING DAMAGE AND BRITTLENESS COEFFICIENT

In this section, the damage constitutive model of gypsum rock under water immersion conditions is theoretically established, and the variation in the mechanical properties of gypsum rock after water contact is described.

Incorporating Eq. (2) into Eq. (5), the relationship between the uniaxial compression elastic modulus and the immersion time is obtained, as expressed by Eq. (6):

$$E_t = 4.9e^{-0.112\ln(t)+0.258} \tag{6}$$

The damage variables defined based on the elastic modulus are:

$$D = 1 - \frac{E_t}{E'} \tag{7}$$

where E' is the initial elastic modulus and E_t is the elastic modulus of the damage

Substituting Eq. (6) into Eq. (7), the softening damage equation of the damage variable of the gypsum rock with the immersion time is obtained as follows:

$$D(t) = 1 - e^{-0.112\ln(t)-0.1806} \tag{8}$$

According to Lemaitre's strain-based impairment variables:

$$D = \left(\frac{\varepsilon}{\varepsilon_s}\right)^n \tag{9}$$

where ε is the axial strain; ε_s is constant; and n is the brittleness coefficient.

According to the strain equivalent hypothesis, the uniaxial constitutive model of gypsum rock considering damage is expressed by Eq. (10):

$$\sigma = E'\varepsilon(1-D) = E'\varepsilon\left[1-\left(\frac{\varepsilon}{\varepsilon_s}\right)^n\right] \tag{10}$$

At the peak of stress:

$$\frac{d\sigma_c}{d\varepsilon_c} = 0 \tag{11}$$

The following Eqs. are obtained.

$$\varepsilon_s = \varepsilon_c\sqrt[n]{n+1} \tag{12}$$

$$n = \frac{\sigma_c}{E'\varepsilon_c - \sigma_c} = \frac{\sigma_c/E_t}{E'\varepsilon_c/E_t - \sigma_c/E_t} = \frac{E_t}{E'-E_t} \tag{13}$$

The methods expressed by Eq. (7) and Eq. (13) lead to the following equation.

$$n = \frac{1}{D} - 1 \tag{14}$$

Substituting Eq. (8) into Eq. (14) leads to the following equation.

$$n = \frac{e^{-0.112\ln(t)-0.1806}}{1-e^{-0.112\ln(t)-0.1806}} \tag{15}$$

According to Eq. (15), the relationship between the brittleness coefficient of gypsum rock and the immersion time was established, as shown in Table 4 (the natural state moisture content is 0.258).

Table 4 indicates that the brittleness coefficient of gypsum rock decreases with increasing water immersion time, i.e., the brittleness coefficient of gypsum rock is negatively correlated with the damage variable. With increasing damage variable, the brittleness coefficient decreases. The continuous reduction in the brittleness coefficient of gypsum rock indicates the transition from brittleness to ductility.

VI. CONCLUSION

Through the experimental study on softening damage of gypsum rock caused by immersion time, some conclusions are drawn as follows:

(1) The water absorption rate in the initial stage of gypsum immersion is high and gradually decreases with increasing immersion time; the uniaxial compressive strength and elastic modulus of gypsum are negatively correlated with the water content, and the uniaxial compressive strength and elastic modulus decrease with increasing water content; Poisson's ratio of gypsum rock increases with immersion time; the failure characteristics of natural gypsum rock under uniaxial compression are mainly splitting and tensile failure. With increasing water immersion time, the brittleness of rock decreases, and shear-slip damage begins to occur, forming a Y-shaped fracture.
(2) The SEM electron microscopy image analysis indicates that with increasing immersion time, the aqueous solution gradually fills the microporous cracks in the test piece, and the crystal bond at the tip of the microcrack is hydrolyzed and weakened, complicating the macroscopic internal structure of the gypsum. In addition, the end of the crack is subjected to the compressive action of water; therefore, the microcracks easily squeezed and expanded, and simultaneously the originally opened microcrack is difficult to close, and the lubrication of the aqueous solution reduces the friction between the two walls of the microcrack.
(3) Based on the principle of elastic modulus damage, the softening damage equation of gypsum rock damage variable with water immersion time was established, and the brittleness coefficient of gypsum was introduced by the strain–strain equivalent principle. The brittleness coefficient and water immersion time of gypsum rock were obtained. The relationship between the changes shows that the brittleness coefficient of gypsum rock is negatively correlated with the damage variable. With increasing water immersion time, the brittleness coefficient of gypsum rock decreases continuously, and the gypsum lithology changes from brittle to ductile characteristic.

DATA AVAILABILITY STATEMENT

The data are all available and has been explained in this article, readers can access the data supporting the conclusions of the study.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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