

Research Article

Influence of Water Content on the Mechanical Characteristics of Mudstone with High Smectite Content

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Water content plays an important role in strength of mudstone; many works pay more attention to the strength of dry and saturated rocks. In this study, the water absorption characteristics of mudstone were obtained by a computer-automated WA (water absorption) equipment system experiments. The complete stress–strain curves and UCS (unconfined compressive strength) and E (Young's modulus) of mudstone samples under different water contents were achieved by using the WEP-600 microcomputer-control screen universal testing machine. SEM (scanning electron microscope) test were carried out to study the microstructure characteristics of mudstone samples under different water contents. The results showed that the water absorption process of mudstone consists of three stages. The UCS and E of the mudstone samples markedly decrease with water content increasing. Based on the experimental results and analysis, a porous medium mechanical model of the mudstone was established and a deeper understanding of water-induced strength damage mechanism of the mudstone was achieved.

1. Introduction

Water is one of the factors influencing the mechanical characteristics of rocks [1–8] and also plays a harmful role in engineering [9]. Knowledge and understanding of the mechanisms of the interaction between water and rock and its effects on rock properties are of great importance in engineering [8, 10–12]. However, the mechanism of water-rock interaction and the influence of the water on the mechanical characteristics of rocks are not clear, so it requires further study.

Feng et al. [13] conducted tests to study the water chemistry on microcrack and compressive strength of granite. Vásárhelyi [3] reported that the unconfined compressive strength of saturated sandstone reduced compared with the dry sandstone by analyzing the published data. Vásárhelyi and Ván [3, 14] found that water content is one of the most important factors influencing rock strength. Talesnick and Shehadeh [15] studied the effect of water content on the

stress-strain response and compressive strength of a high-porosity chalk. He et al. [16] conducted experiments to study hydrophilic characteristics of mudstone in deep well. Erguler and Ulusay [17] found that water content has a marked influence on mechanical properties of the clay-bearing rocks studied and with increasing water content reductions in UCS, average modulus of elasticity and tensile strength were up to 90%, 93%, and 90%, respectively. Yilmaz [18] reported that even a very small increase in water content (~1–2%) causes a considerable loss in the strength of gypsum. Zhang et al. [19] found that conglomerate rock strength tended to decrease with increasing water content induced by vapor sorption. Hashiba and Fukui [20] conducted tests to study the effect of water on the deformation and failure of rock and found the water produce a larger effect on the deformation and strength of the rocks. Ciantia et al. [21] carried out experiments to study the water-induced weakening of calcarenites and intended to clarify the process of their mechanical properties degradation. Kim and Changani

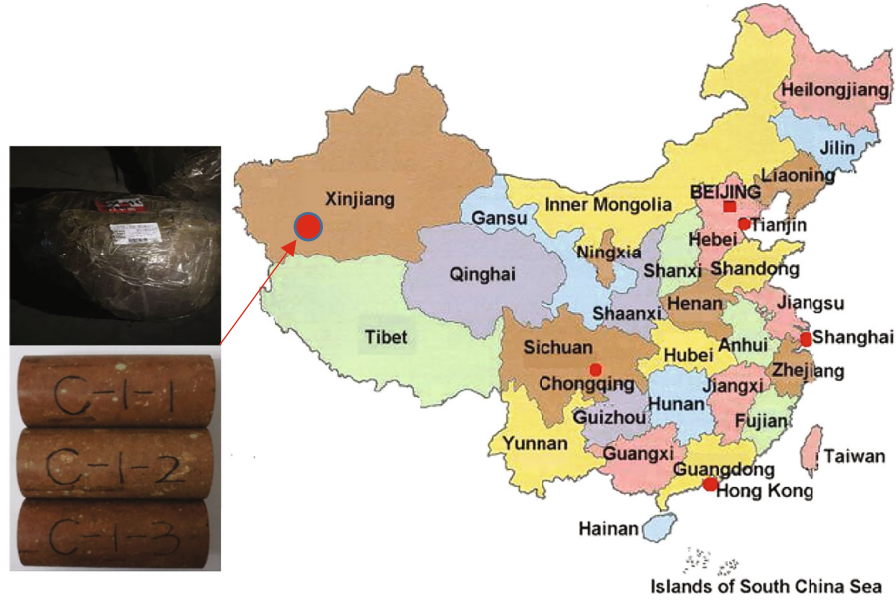


FIGURE 1: Geographical location of mudstone samples in Xinjiang province, China.

TABLE 1: Analytical results of X-ray diffraction for mudstone rocks.

Rock type	All minerals (%)			Clay minerals	Illite	Clay minerals (%)		Chlorite
	Quartz	Potash feldspar	Albite			Kaolinite	Smectite	
Mudstone	25.1	0.8	23.8	50.3	2	3	90	5

[22] found that the static, fast, and dynamic strengths of dry red sandstone and buff sandstone samples were higher than those of saturated samples; on average, water saturation reduced the rock strength by approximately 20%. Cherblanc et al. [23] illustrated that the mechanical characteristics of various sedimentary stones significantly depend on the water content, where 70% loss of their mechanical strengths can be observed when saturated by water. Vásárhelyi [24] discovered that the mechanical parameters of the rock mass similarly depend on the water content than the intact rock. Li et al. [25] proposed an analytical solution of normalized UCS of rock with different degrees of saturation, which provide some new insights to understand the weakening effect of rock strength by the presence of water. Zhang et al. [26] considered that the water content has a significant effect on the cohesive force of coal. Geng and Cao [27] showed that the sandstone deformation mode from brittle to ductile with increasing water content. Zhao et al. [28] found that water content influences the failure pattern of red sandstone.

Although many studies reported that the strength reduction of different types of rocks attributed to an increasing water content, the mechanical strength of rocks under the whole range of water content condition has been less characterized, because many studies pay more attention to the mechanical strength of dry and saturated rocks. Meanwhile, the strength reduction mechanism of rocks that accounts for

the influence of water content has not been very clear; to date, there seems to be not well-proven explanation.

In this paper, we studied the influence of water content on the mechanical characteristics of a special type mudstone with high smectite content. In order to better understand the mechanism of the water content effect on the strength of rock, we obtained the UCS of mudstone rocks under different water contents. Meanwhile, we achieved the microstructure of mudstone under the whole range water content. Based on the gained information, we tried to build a porous medium mechanical model of mudstone to illustrate the strength reduction mechanism that affected by the water content variation.

2. Material and Rock Samples

In this work, rock samples were mudstone, which were taken from Xinjiang province in China. During the transportation, the mudstone rocks were closed by plastic film in order to maintain their original state. The mudstone sample shape was a cylinder of 50 mm in diameter and 100 mm in length. The sample end surfaces were made parallel to within 1/100 mm (as shown in Figure 1). The mineral composition of the mudstone samples were determined by XRD (X-ray diffraction) tests. The results of tests were showed in Table 1.

We can see from the test results that the clay mineral content of this type mudstone is up to 50.3%. Meanwhile,

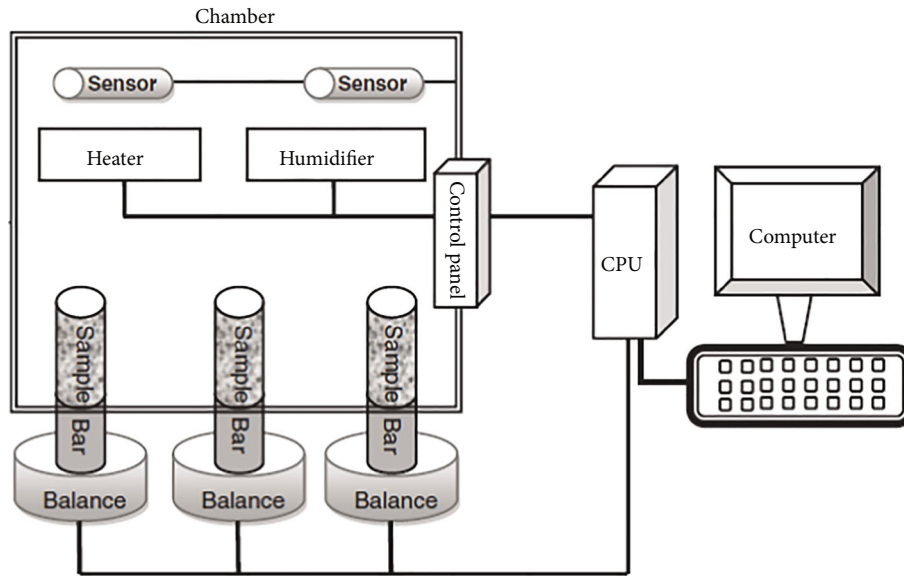


FIGURE 2: Schematic diagram of the experimental system for water vapor sorption of deep soft rocks [13].

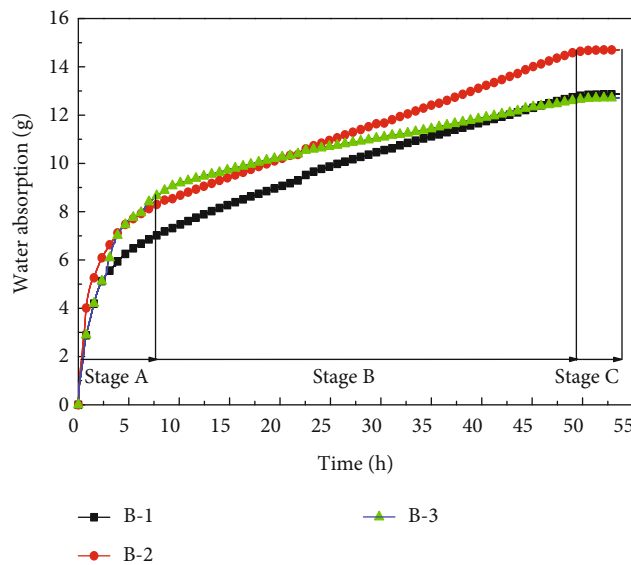


FIGURE 3: Time-water absorption variation curve.

the smectite content accounts for 90% of the whole clay mineral, which has a strong WA (water adsorption) characteristic. Thus, it illustrates that the WA ability of this special mudstone is very strong.

3. Experimental Investigation

3.1. Water Adsorption Test

3.1.1. *Test Equipment.* A computer-automated WA equipment system was used to study the water absorption performance of rock samples. As shown in Figure 2, the equipment system is composed of the main test chamber, weighing sub-

system, and data acquisition subsystem. During the experiments, the laboratory environment is relatively closed and stable. The indoor temperature of the laboratory is 20°C, and the humidity of the laboratory is 55%.

3.1.2. Water Absorption Curves of Mudstone Samples.

As shown in Figure 3, the WA curves of mudstone samples consist of three stages, stages A, B, and C. During stage A, WA rate decreases with time in a nonlinear pattern, and the average water absorption weight of rock samples was 8.01 g; during stage B, WA rate decreases with time in a linear pattern, and the average water absorption weight of rock samples reached 13.45 g; during stage C, WA rate is near

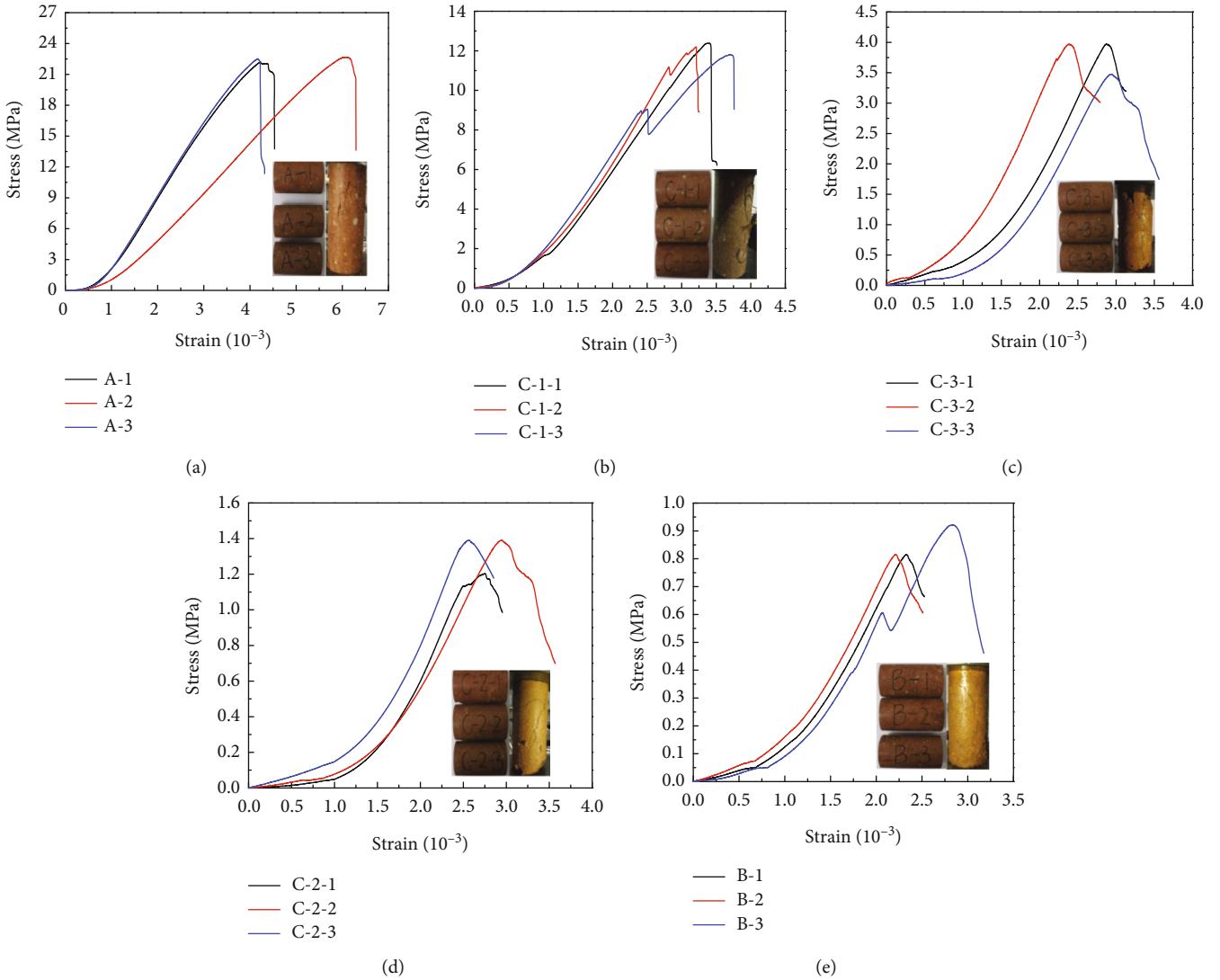


FIGURE 4: Stress–strain curves of mudstone samples under different water contents ((a) dry state, (b) 7% water content, (c) 8% water content, (d) 9% water content, and (e) 10% water content (saturated state)).

TABLE 2: Mechanical parameters of mudstone under different water contents.

Water content (%)	Number	Density (g/cm^3)	UCS (MPa)	Average UCS (MPa)	E (GPa)
0 (dry)	A-1	2.22	22.19	22.45	4.61
	A-2	2.21	22.65		
	A-3	2.21	22.50		
7 (nature)	C-1-1	2.25	12.38	12.12	2.94
	C-1-2	2.26	12.19		
	C-1-3	2.25	11.80		
8	C-3-1	2.29	3.95	3.79	0.84
	C-3-2	2.30	3.96		
	C-3-3	2.30	3.47		
9	C-2-1	2.33	1.22	1.33	0.22
	C-2-2	2.33	1.39		
	C-2-3	2.29	1.38		
10 (saturated)	B-1	2.39	0.82	0.86	0.19
	B-2	2.36	0.83		
	B-3	2.37	0.92		

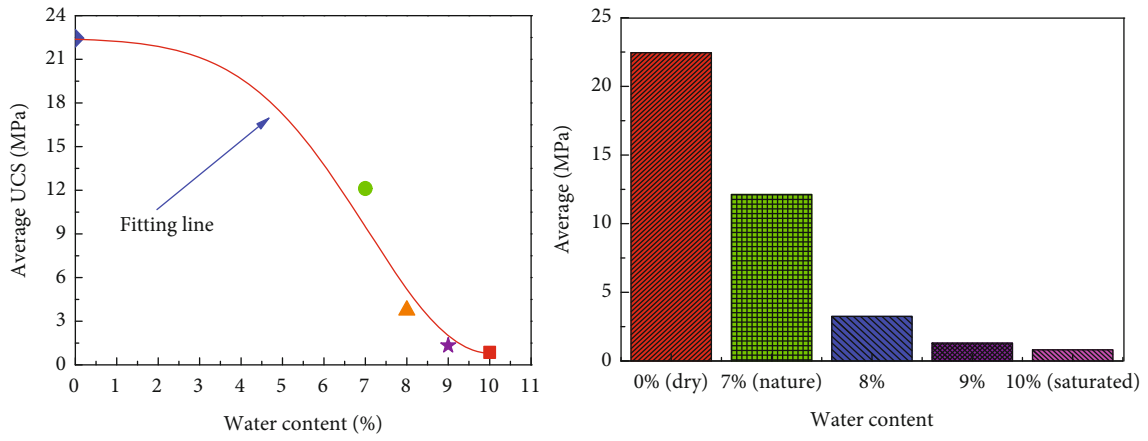


FIGURE 5: Average UCS of mudstone samples under different water contents.

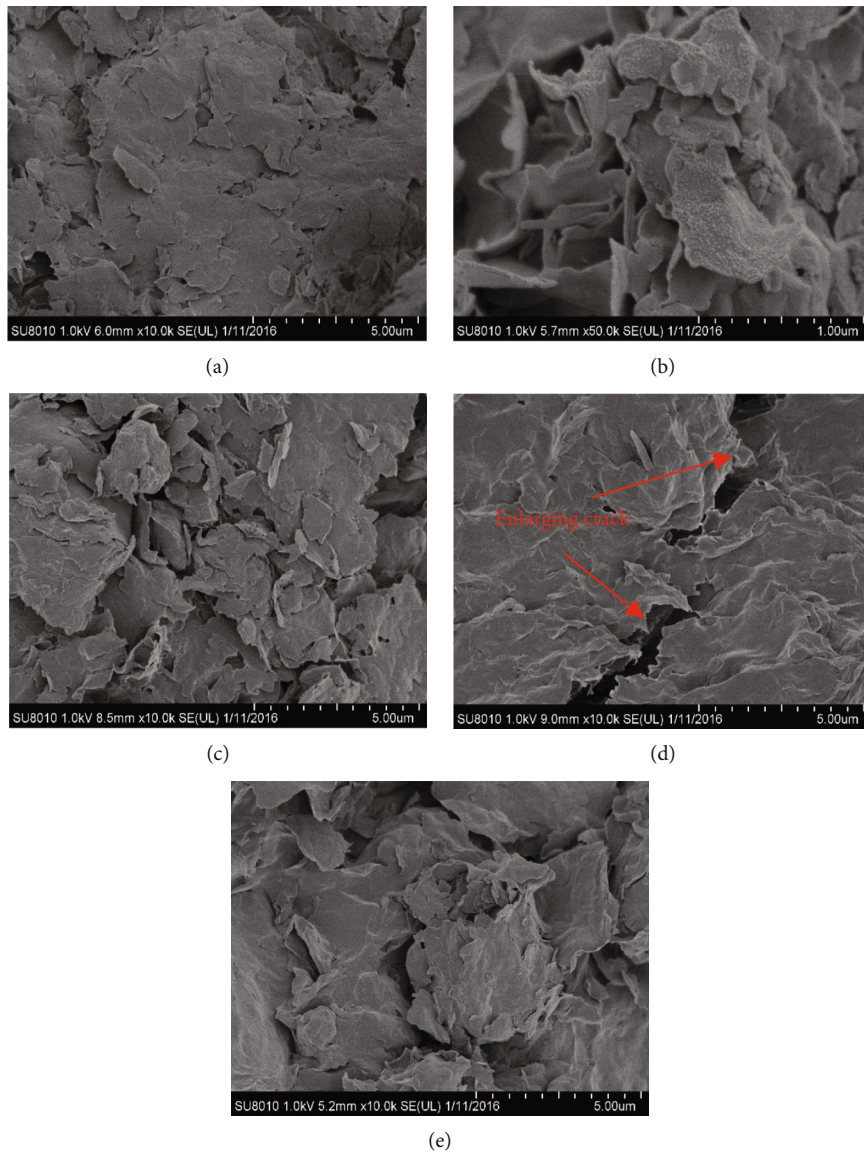


FIGURE 6: SEM pictures of rock samples under different water contents ((a) dry state, (b) 7% water content, (c) 8% water content, (d) 9% water content, and (e) 10% water content (saturated state)).

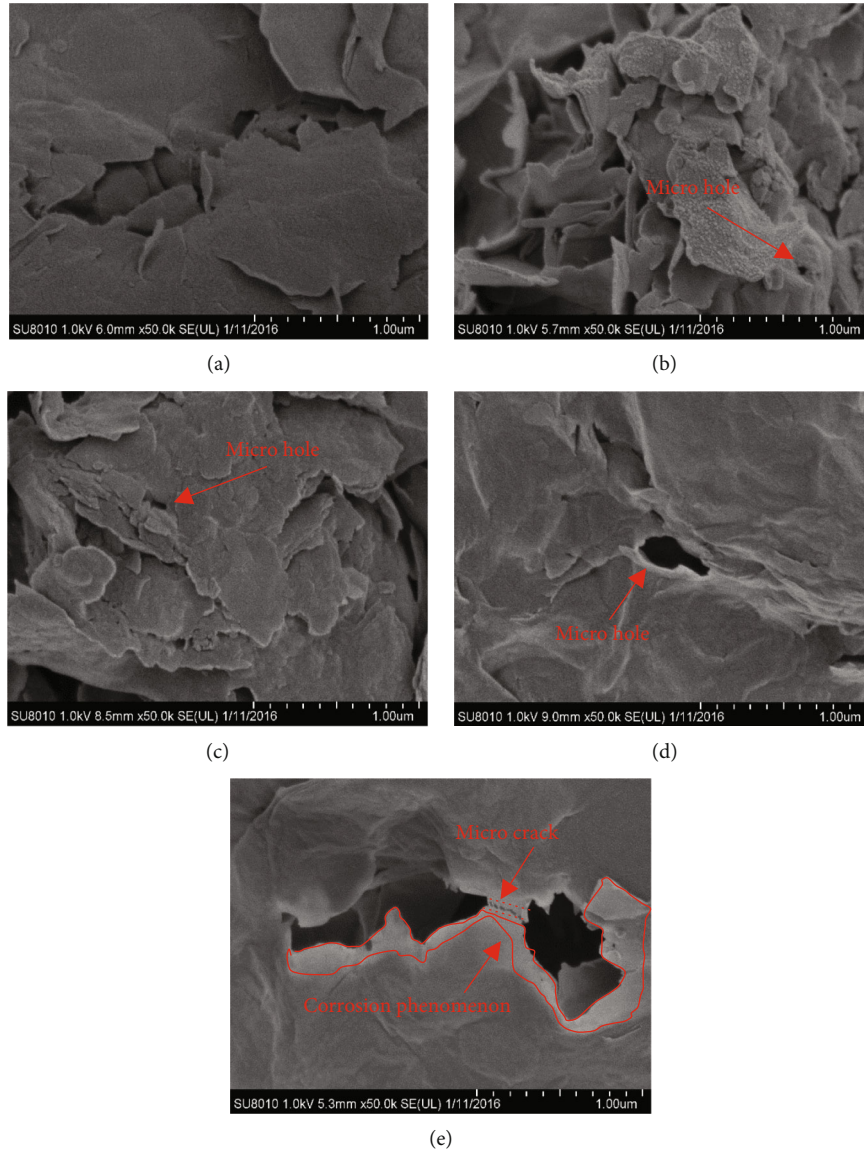


FIGURE 7: SEM pictures of rock samples under different water contents under ((a) dry state, (b) 7% water content, (c) 8% water content, (d) 9% water content, and (e) 10% water content (saturated state)).

zero, and the average water absorption weight of rock samples was zero.

3.2. UCS Tests of Mudstone under Different Water Contents.

In order to better understanding the mechanical properties of mudstone samples under different water contents, the WEP-600 microcomputer-control screen universal testing machine was used to evaluate the unconfined compression strength (UCS) and Young's modulus (E) of the mudstone samples. The loading rate of UCS tests is 0.2 mm/min.

Stress-strain curves and mechanical parameters of mudstone samples in UCS test are shown in Figure 4 and Table 2, respectively. Obviously, the UCS and Young's modulus (E) of mudstone samples markedly decrease with

the water content increasing. In Figure 5, we found that the relationship between mudstone average UCS and the water content meet the following exponential law as described by

$$\sigma(w) = A \exp(B(w - 10)) + C, \quad (1)$$

where $\sigma(w)$ is the average UCS of mudstone samples; A , B , and C are -21.64, -0.005 and 22.45, respectively; and w is the water content.

3.3. SEM Tests. In order to better understanding the water-induced strength damage property of mudstone, the SEM tests were carried out to obtain the microstructure characteristics of mudstone samples under different

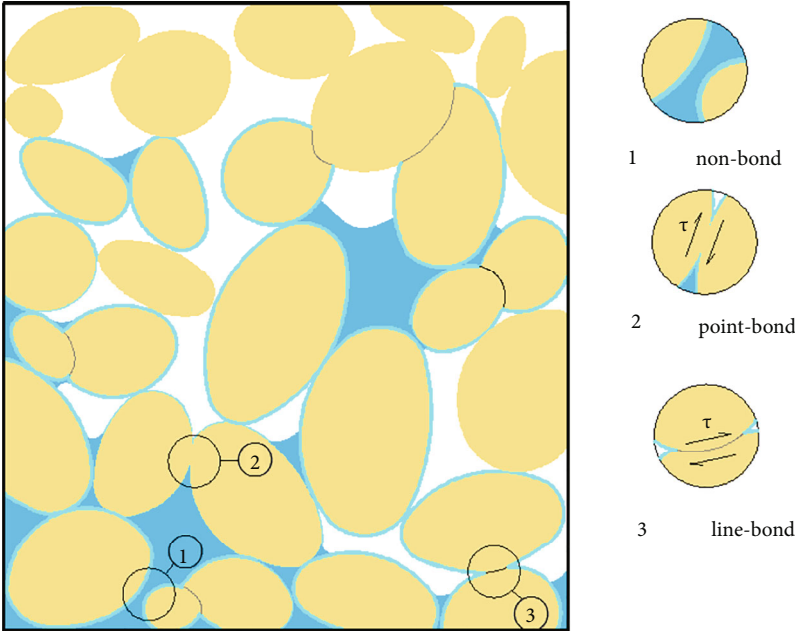


FIGURE 8: Porous medium mechanical model of mudstone.

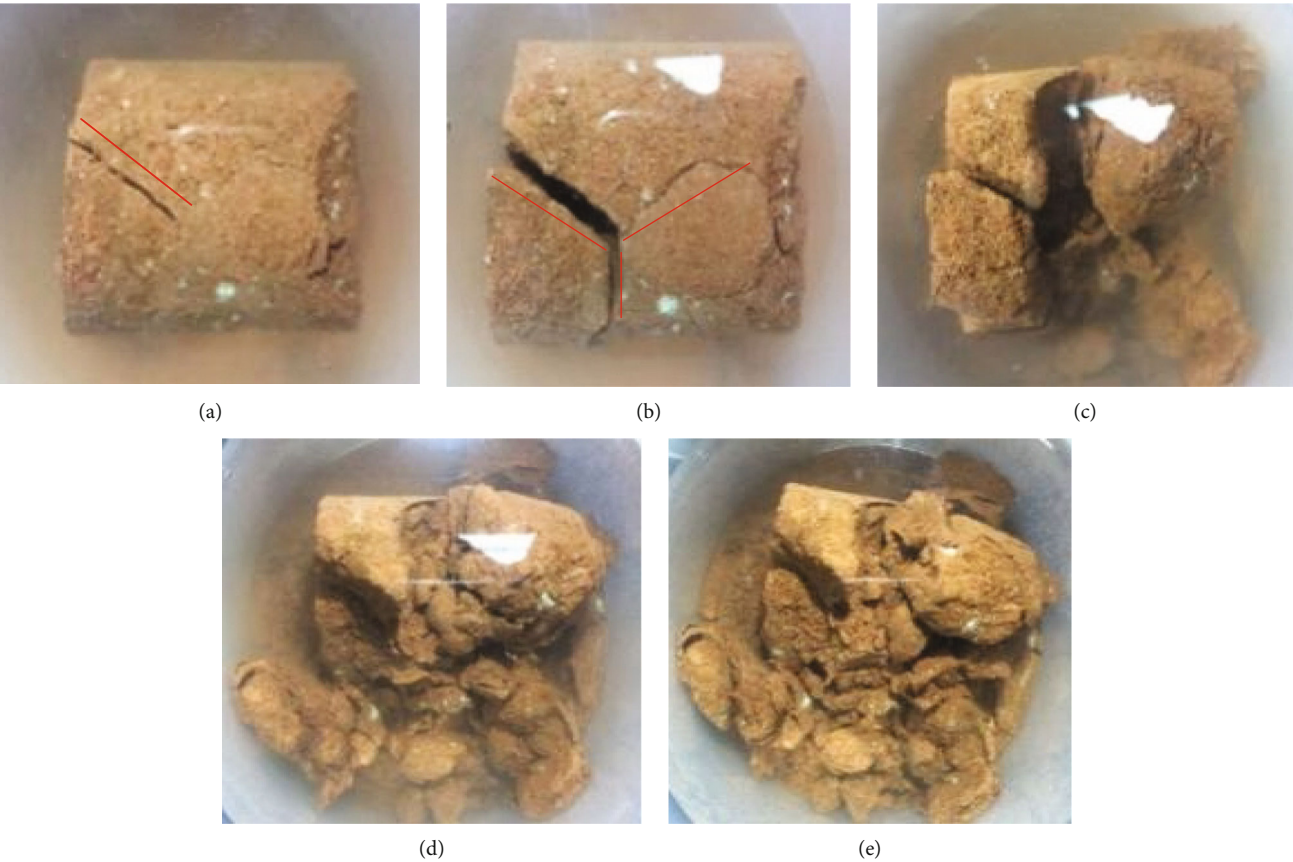


FIGURE 9: Disintegration of the mudstone ((a) after 1 minute in water, (b) after 10 minutes, (c) after 20 minutes, (d) after 60 minutes, and (e) after 26 hours).

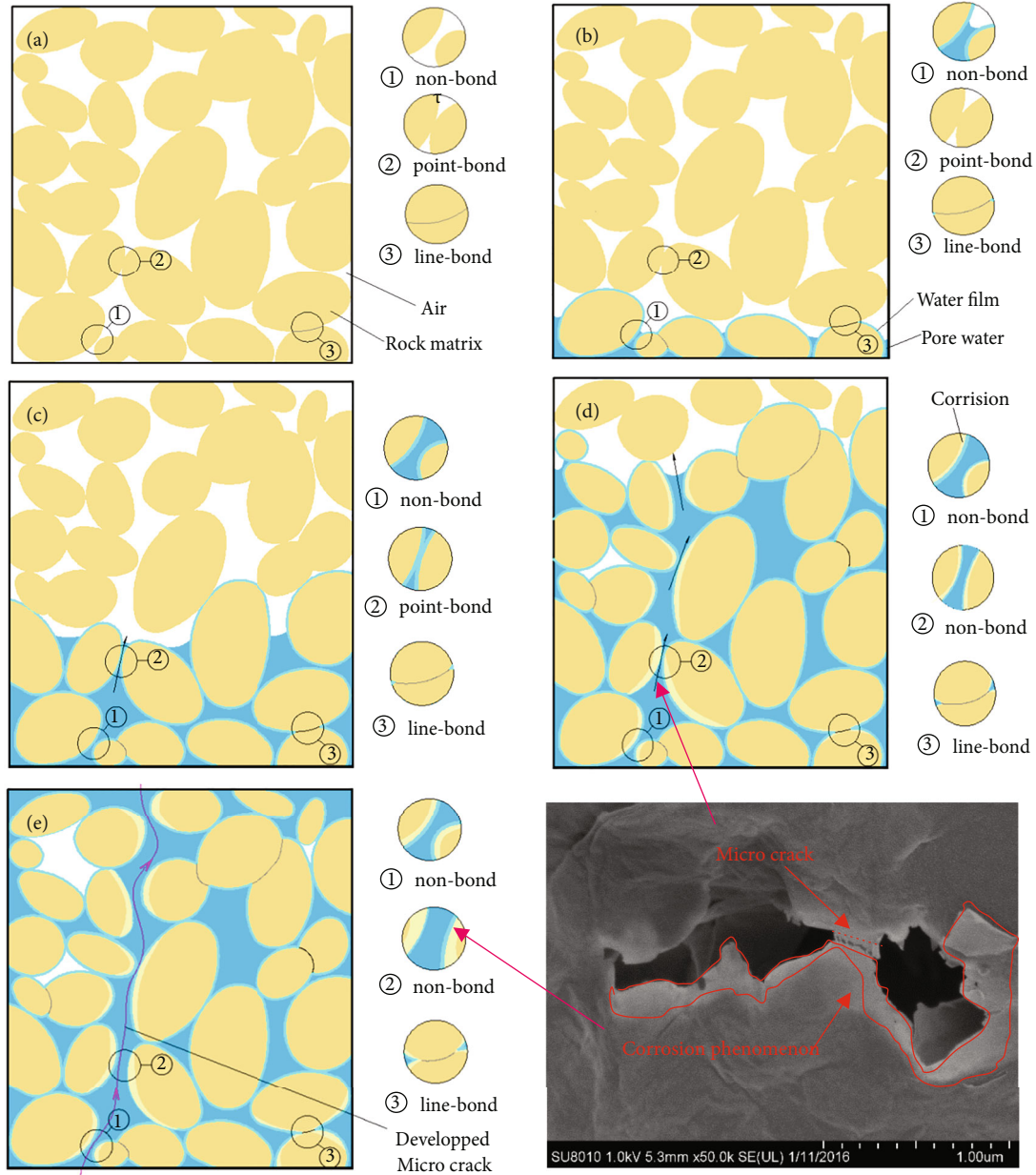


FIGURE 10: Water absorption-induced strength damage process of the mudstone.

water contents. As shown in Figure 6(a) compared with the natural state, the dry rock sample had compact structure and small porosity. As shown in Figure 6(b), the surface of the rock sample in the natural state is “crimped” and has many microholes. As shown in Figure 6(c), the surface connections of mudstone under 8% water content may became weak. As shown in Figure 6(d), when the water content reaches 9%, the pore is enlarged and connected. As shown in Figure 6(e), when the water content was up to 10% (saturated state), the surface of mudstone sample appeared loose “mud” shape. Thus, we can obtain that with the water content increasing, the microstructure of mudstone became loose, the pores were enlarged, and the connection bonds became weak.

As shown in Figure 7, it can be seen more clearly that the microholes in the rock samples gradually develop with the water content increasing. When the water content reaches 10% (in Figure 7(e)), the corrosion phenomenon appeared and the microcrack was connected. It indicates that with the water content increasing, water flow behavior in the gap increase, which produces serious corrosion effect on the rock.

4. Mechanism of Water-Induced Strength Damage

4.1. Porous Medium Mechanical Model. Based on the above experimental results and analysis, a porous medium

mechanical model was established (as showed in Figure 8). The rock matrix is surrounded by a thin water film. There are three bond pattern types between the rock matrices: non-bond, point-bond, and line-bond. The failure mode of bond is shear failure.

4.2. Water Absorption-Induced Strength Damage Process of the Mudstone. Water can produce serious influence on the strength of the mudstone. As shown in Figure 9(a) a “\” shape crack appeared on the rock sample only after 1 min in the water. After 10 minutes, the crack developed to be a “Y” shape crack (Figure 9(b)). After 20 minutes, the mudstone started to peel off (Figure 9(c)). After 60 minutes, the mudstone appeared to disintegrate (Figure 9(d)). After 26 hours, the mudstone were completely disintegrated (Figure 9(e)). From the phenomenon above, it can draw a conclusion that water can produce serious influence on the strength of the mudstone.

Based on the all results and analysis above, the mechanism and process of mudstone’s water absorption-induced strength damage were predicted. As shown in Figure 10(a), the mudstone was in dry state. As shown in Figure 10(b), when the mudstone started to absorb water, water entered into the pore of rock, and the water film around the rock matrix became thick under the action of smectite strong adsorption. As shown in Figure 10(c), with the increasing of water adsorption, a part of rock matrix dissolved in the water and some point-bonds between the rock matrices were destroyed. As shown in Figure 10(d), the shear dislocation between the rock matrices occurred because of the damage of the bond between the rock matrices and some pores were connected which resulted to the developing of the crack; meanwhile, the effect of erosion make the mechanical properties mudstone further decreasing during the process that water flow through the rock pore. As shown in Figure 10(e), when the water absorption of the rock sample is close to saturation, the more mineral composition of rock matrix dissolved in the water, the structure of mudstone became more loose, and some microcracks were produced.

5. Conclusions

The special mudstone has strong water absorption characteristics, and its WA curves consist of three stages, nonlinear stage, linear stage, and horizontal stage.

The UCS and E of mudstone markedly decrease with the water content increasing, and the relationship between UCS of mudstone and the water content meet the exponential law.

With the water content increasing, the microstructure of mudstone become loose, the pores are enlarged, the corrosion phenomenon appeared, and the microcrack were connected.

The mechanism and process of mudstone’s water absorption-induced strength damage is that with the water absorption increasing; first, the water film around the rock matrix becomes thick under the action of smectite strong adsorption; then, some parts of the rock matrix dissolve in the water and some bonds between the rock matrix were

destroyed; the shear dislocation between the rock matrices occurs, some pores are connected which resulted to the developing of the crack, and the erosion influence makes the mechanical properties of mudstone to further decrease.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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