Research on strength softening characteristics and microscopic mechanism of sandstone after absorbing water

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Abstract: The deformation of the surrounding rock in roadways occurs because of the coupling effect of water and rock, which decreases the strength of the surrounding rock. The microscopic pore structure in the rock mass develops through and develops into microcracks, which further the rock mass strength. Based on the rock mass strength reduce observation, this article selects Shandong Wanfu coal mine sandstone samples, based on XRD mineral composition and scanning electron microscopy testing, using nuclear magnetic resonance (NMR) and 2,000 kN rock single triaxial rock mechanics experimental equipment to perform NMR experiments and uniaxial compression tests under different water content. Quantitatively study the pore structure and strength change law of water to rock. The experimental results show that with the increase in water absorption time, the water absorption law of sandstone has three stages: accelerated water absorption, decelerated water absorption, and uniform water absorption. The microscopic pore structure of sandstone is gradually filled with water molecules. The water molecules first occupy the micropores, then the mesopores, and finally the macropores. After reaching the saturation state, the micropores account for 51.87%, the mesopores account for 42.76%, and the macropores account for 5.37%. Because sandstone contains hydrophilic iron dolomite and clay minerals, it dissolves and adsorbs hydrophilic minerals after encountering water. The micropores gradually decrease, the mesopores increase, and the macropores do not change. It can be seen from the mechanical strength of rock samples with various water contents that the dry state has the highest mechanical strength, with a strength of 171.58 MPa, a saturated state with the lowest mechanical strength, with a strength of 91.78 MPa, and a softening coefficient of 0.53. The surrounding rock strength is relatively unstable because the pore water pressure increases after the surrounding rock interacts with water. The increased pressure reduces the compressive stress.
between the particles, decreasing the strength of the surrounding rock.

1. Introduction

As the depth of coal mining gradually increases, the difficulty of coal mining is also increasing. In the process of coal mining, it is generally accompanied by the penetration of groundwater on the surrounding rock of the roadway. Due to the coupling of water and rock, the strength of the surrounding rock of the roadway is reduced, causing engineering problems such as roadway deformation, collapse, and shaft wall instability [1-3]. Therefore, scholars at home and abroad have done extensive research on coupling of water and rock under complex geological conditions.

He Manchao et al. [4] used a self-developed, soft rock hydraulic test instrument to study water absorption of deep well mudstone. The research results found that pore size, mineral composition, and clay minerals are the main factors affecting the water absorption characteristics of mudstone. Kang Hongpu [5] studied the geological phenomenon of soft rock expansion from the perspective of damage mechanics, and established the evolution equation of damage mechanics variables under the action of water environment; Rutter [6] studied the influence of interstitial water on calcite in rocks. Hadizadeh [7] studied the softening effect of water on sandstone and quartzite under stress and strain rate. Erguler [8] studied the changes in the mechanical properties of clay-bearing rocks caused by water from the perspective of rock minerals and composition. Guo et al. [9] found that the uniaxial compressive strength of calcareous shale decreases linearly under the actions of various water content.

Microcracks and pores are formed during rock development. The coupling action of water and rock changes the mechanical properties of rocks. In response to this mechanical phenomenon, relevant experts [10-16] performed uniaxial compression experiments, triaxial compression experiments, and uniaxial shear under different water content. Experiments and test results show that due to the influence of water content, the strength of the rock has different degrees of strength softening. Zhou Cuiping [17] performed uniaxial compressive strength experiments, tensile strength experiments, and shear experiments for red-bed soft rocks and mudstones in South China under various water contents. The results showed that the mechanical strength curves of rocks under various water contents have exponents. Guo Hongyun [18] conducted uniaxial compressive strength experiments of pressure and pressure-less water absorption for different lithologies in the depths. The experimental results showed that the strength attenuation rate of soft rock during pressure-less water absorption is larger than that of pressured water absorption.

The above experiments have studied the influencing factors and mechanical properties of rocks in the water absorption process of. However, the study on the microscopic mechanism changes of rocks under the coupling action of water and rock is insufficient. Based on this finding, this article takes Shandong Wanfu coal mine sandstone as the research object, develops the microscopic pore structure and mineral composition change law of rock under the actions of various water content, and reveals the microscopic action mechanism of water on the rock and strength softening mechanism through the uniaxial compressive strength experiment of the rock.
2. Experimental samples and equipment

2.1. Experimental samples

The sample selected in this manuscript is Shandong Wanfu coal mine sandstone, buried at −860 m. The diameter of the sample is 50 mm, and the length of the sample is 1000 mm, drilled on the same core are selected to reduce the amount of rock mass caused by various homogeneities in the experiment, according to the international rock mechanics regulations on the processing accuracy of standard rock samples, the unevenness error of the end surface of the sample does not exceed 0.02 mm and the unevenness of the side surface does not exceed 0.3 mm. All the experimental samples used meet the requirements of the rock mechanics experiment.

The basic information of the sample is shown in Table 1. X-ray diffraction experiments on sandstone show that its mineral composition is quartz, clay minerals, plagioclase, and iron dolomite, of which quartz accounts for 62.3%, clay minerals accounts for 24.9%, plagioclase accounts for 9.4%, and iron dolomite accounts for 3.4% (Table 2).

| Numbering | Lithology | Hydrated state, % | Diameter, mm | Height, mm | Quality, g | Density, g/cm³ |
|-----------|-----------|-------------------|--------------|------------|------------|---------------|
| A1        | sandstone | 0                 | 50.16        | 100.01     | 502.75     | 2.55          |
| A2        | sandstone | 28                | 50.12        | 100        | 516.09     | 2.62          |
| A3        | sandstone | 53                | 50.09        | 99.99      | 509.81     | 2.59          |
| A4        | sandstone | 76                | 50.20        | 99.98      | 513.45     | 2.60          |
| A5        | sandstone | 100               | 50.06        | 100        | 510.35     | 2.59          |

Table 1 Basic information about samples

| Clay,% | Quartz,% | Feldspar,% | Dolomite,% |
|--------|----------|------------|------------|
| 24.9   | 62.3     | 9.4        | 3.4        |

Table 2 Mineral composition information

2.2. Experimental equipment

(a) Uniaxial compression experiment  (b) Nuclear magnetic resonance core analyzer

Figure 1. Experimental equipment

The uniaxial compression experiment equipment is the 2,000 kN rock single triaxial experimen
system of the State Key Laboratory of Deep Rock Mechanics and Underground Engineering of China, University of Mining and Technology (Beijing). The computer operation and data processing system consists of a host, a servo-loading system, a servo-confining pressure-loading system, and a measurement control system, as shown in Figure 1(a). The sandstone water absorption microscopic pore structure experiment uses the MicroMR-nuclear magnetic resonance (NMR) core analyzer produced by Shanghai Niumai Company. The test temperature is 20°, the minimum relaxation time is 0.01 ms, and the maximum relaxation time is 1,0000 ms, as shown in Figure 1(b).

2.3. Experimental step

(1) Make number markings and size measurement on the rock sample, carry out drying treatment, and dry the rock sample in a 110° oven for 24 h.

(2) Take the rock sample out of the oven and weigh the dried mass $m_0$ on an electronic balance. Select the sample that needs to be immersed to reach saturation for the first NMR experiment.

(3) Choose a beaker with a capacity of 500 mL, place the selected core in the center of the beaker, and weigh 300 mL of distilled water into the beaker, so that the sample is completely immersed in distilled water.

(4) After immersion for 1 min, take out the sample and wipe its surface dry, weigh its mass on an electronic balance as $m_1$, and conduct the second NMR experiment.

(5) Soak for 5 min, 20 min, and 120 min. Repeat the operation of step (4) to make the sample reach a saturated state, calculate water saturation of the sample, and require 28%, 53%, and 76% of the sample for uniaxial compression mechanics experiment. Perform immersion experiments until the requirements of the experimental design are met.

3. Experimental results

3.1. Sandstone water absorption experiment

Figure 2(a) shows the T2 spectrum of sandstone water absorption, where the abscissa represents the relaxation time and the relaxation time is proportional to the pore radius. The relaxation time can be approximately used to represent the pore radius distribution of the rock. The ordinate represents the amplitude, and the amplitude is related to the number of hydrogen atoms in this range. It can be seen from the figure that the peak appears in the range 1–10 ms, and the peak is the largest. The three relaxation mechanisms for fluids in rock pores are diffusion relaxation, volume relaxation, and surface relaxation. The lateral relaxation time is expressed as

$$\frac{1}{T_2} = \frac{1}{T_{2b}} + \frac{1}{T_{2s}} + \frac{1}{T_{2d}}$$  \hspace{1cm} (1)

During the water absorption process of sandstone, with the increase in the water absorption time, the T2 spectrum area and mass of sandstone gradually increase, as shown in Figure 2(b). The abscissa represents the logarithm of time, the left ordinate represents the T2 spectrum area of sandstone, and the right ordinate represents the quality of sandstone. The red line represents the quality change curve of sandstone, the blue line represents the spectral area change curve, and there is a proportional relationship between the two. The water absorption process of sandstone has three sections: accelerated water absorption section, decelerated water absorption section, and the uniform water absorption section.
3.2. Uniaxial compression experiment

Figure 3(a) shows the uniaxial compression mechanics experimental curve of sandstone under the actions of various water content. The abscissa represents the strain, and the ordinate represents the uniaxial compression strength. When water saturation is 0%, the uniaxial compressive strength value is the largest and the strength value is 171.58 MPa. When water saturation is 28%, the uniaxial compressive strength is 157.09 MPa and the compressive strength value is reduced by 8.45%. When water saturation is 53%, the uniaxial compressive strength value is 132.36 MPa, and the compressive strength value is reduced by 22.86%. When water saturation is 76%, the uniaxial compressive strength value is 125.25 MPa, and the compressive strength value decreases. When the moisture content reaches the saturated state, the uniaxial compressive strength value is the smallest and the strength value is 91.78 MPa; the compressive strength value decreases. The strength softening factor is 0.53.

Figure 3(b) shows the fitting curve of strength softening of sandstone under various water saturation. Origin9 is used to fit the uniaxial compression test data. After fitting, $R^2 = 0.97786$, the fitting effect is excellent. The fitting equation formula is

$$\sigma = -53.9077 \times e^{-0.6 \omega} + 224.9762$$

Here, $\omega$ represents the water saturation and $\sigma$ represents the uniaxial compressive strength value.
Sandstone exhibits a decrease in strength after encountering water, which causes deformation and collapse of the surrounding rocks in tunnels or roadways, resulting in unnecessary engineering accidents. In other words, when water and rock are coupled, the microscopic pores and mineral composition of sandstone change. Therefore, research on these influencing factors will help further understand the micro-mechanical changes in the process of water absorption.

4. Influencing factors

4.1. Microscopic pore structure

Figure 4(a) is a normalized cumulative curve obtained by accumulating the amplitude values of the T2 spectrum of the sandstone under various water absorption times, and then dividing the accumulated amplitude points by the sum of the amplitudes for each water absorption state. The normalized cumulative curve can be expressed as the cumulative distribution curve of the sandstone pore radius. It can be seen from the figure that as the water absorption time increases, the normalized curve first moves to the left and then to the right.

Figure 4(b) shows the change curve of the microscopic pore structure under different water-containing conditions. According to the definition of micropores by the International Society for Theoretical and Applied Chemistry (IUPAC), pores with a diameter less than 2 nm are called micropores, those with a pore diameter between 2–50 nm are called mesopores, and those with a pore diameter greater than 50 nm are called macropores. Based on this classification, green means micropores, red means mesopores, and blue means macropores. In the process of water absorption, water molecules occupy three pores at the same time. When the pores are filled with water molecules, the proportion of macropores does not change. Therefore, the water absorption process is divided into two stages. In the first stage, the number of micropores first increased and then decreased, mesopores first decreased and then increased, and macropores continued to decrease. After reaching the saturation state, micropores accounted for 51.87%, mesopores accounted for 42.76%, and macropores accounted for 5.37%. In the second stage, as the soluble matter in the rock gradually dissolves as the immersion time increases, the
micropores intersect each other to form mesopores and the loss of mineral particles in the rock decreases the strength of the rock.

![Normalized T2 Spectrum](image)

(a) normalized T2 spectrum  
(b) pore distribution

**Figure 4.** The microscopic pore change curve of sandstone

4.2. **Scanning electron microscopy**

In the analysis of the mineral composition when encountering water, it is found that the relative content of clay minerals and iron dolomite decreases after encountering water; however, the mechanism of action is unclear enough. Based on this observation, we conducted scanning electron microscopy (SEM) tests under various hydrated conditions, as shown in the figure, to analyze the change and migration of mineral components. As shown in Figure 5(a), in the dry state of sandstone, the intergranular pore structure develops and the microcrystalline quartz particles exist in the flocculent illite, making the quartz particles cement each other. Figure 5(b) shows an SEM view of sandstone in a saturated state. When clay meets water, it swells and some clay minerals are dissolved, which reduces the cementing ability between quartz particles. As the clay minerals increase with the immersion time, the clay minerals cemented between the quartz particles gradually swell and dissolve and the cementation between the particles decreases.

![SEM Images](image)

(a) before water absorption  
(b) after water absorption

**Figure 5.** Microscopic mineral changes before and after water absorption
5 Conclusion

(1) While immersing sandstone in water, the microscopic pore structure is gradually filled with water molecules. The water molecules first occupy the micropores, then the mesopores, and finally the macropores. After reaching the saturation state, micropores account for 51.87%, mesopores account for 42.76%, and macropores account for 5.37%. The proportion of pores among the three is because of the hydrophilic iron dolomite and clay minerals in the sandstone, which cause dissolution and adsorption of hydrophilic minerals when exposed to water. The micropores gradually decrease and the mesopores increase.

(2) With the gradual increase in water content, the uniaxial compressive strength of sandstone gradually decreases and the strength softening coefficient is 0.53. Fitting the uniaxial compressive strength of different water content, the fitting equation formula is

\[ \sigma = -53.9077 \times e^{\frac{60}{312.34}} + 224.9762 \]  

(3)

The fitting effect is excellent.

(3) Sandstone is mainly composed of quartz, plagioclase, iron dolomite, and clay minerals, among which clay minerals are composed of illite. Quartz and plagioclase are hard to dissolve in water; however, iron dolomite undergoes physical and chemical reactions when it meets water and partially dissolves in it. The illite and illite-mixed layers in clay minerals interact with water. The swelling and dissolution of the illite-mixed layers in water, leads to changes in the microscopic pore structure of the sandstone, which reduces cementation between rock particles and further reduces the uniaxial compressive strength.

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