NMR-based investigation on deterioration characterization of gypsum breccia in surrounding rock undergoing flow-by wetting-drying cycles

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Abstract. In underground engineering, many geological hazards caused by the cyclic actions of wetting and drying occur under flowing water conditions. Understanding the evolution of the strength and pore structure characteristics of some environmentally sensitive surrounding rocks under these conditions is critical for maintaining the long-term stability of tunnels. In this study, the deterioration characteristics of gypsum breccia in the surrounding rock of an anonymous tunnel in Shanxi under the flow-by wetting-drying cycles were investigated. After being treated by wetting-drying cycles with different flow conditions (0 and 10 l/h), the evolution characteristics of the pore structure of gypsum breccia were characterized using the nuclear magnetic resonance (NMR) technique. The relationship between the P-wave velocities and the pore characteristics of gypsum breccia was studied. The results showed that the water flow would accelerate the deterioration process of gypsum breccia in the wetting-drying process. The microstructure damage of gypsum breccia was induced by the combined action of the wetting-drying cycles and water flow. There was a significant correlation between the attenuation of P-wave velocity and the development of the pore structure of gypsum breccia. The study can provide references for the engineering design of tunnels in gypsum breccia.

Keywords: Gypsum breccia, Water flow, Wetting-drying cycles, NMR.

1 Introduction

Cyclic wetting-drying is one of the most destructive actions that induce damage to in situ rock in many engineering fields [1]. The influence of cyclic wetting-drying on rock materials has been investigated by many researchers in physical and mechanical studies [2–4]. However, the cyclic wetting-drying process remains a poorly understood component of the rock weathering process [5]. More importantly, previous studies on the deterioration characteristics of rocks are mostly based on stagnant water conditions, ignoring the fact that many geological hazards caused by the cyclic actions of wetting and drying occur under flowing water conditions. In fact, when the wetting process of cyclic action is formed in a flowing water environment, its destructiveness would be further enhanced. Especially for sulfate rocks, due to their strong karstification in flowing water, they will soon lose the engineering properties required by the geotechnical structures. Gypsum breccia is a typical sulfate rock with large amounts of gypsum minerals, which is easily dissolved with hydraulic, mechanical, and chemical changes, causing a series of engineering problems [6, 7]. A typical example can be found in an anonymous tunnel in Shanxi Province, China. It is a rail tunnel located in a gypsiferous stratum with a low groundwater table and dense fissures, and rainwater is the primary supply source of groundwater. In the rainy season, the groundwater can continue to flow through the surrounding along the seepage channels. In this process, the types of fissures (interpenetrated fissure and closed fissure), the excavation of tunneling, the design of waterproofing-
drainage for the tunnel, and cracking of lining can cause the change of the flow state of groundwater. Under these engineering geology conditions, a series of tunnel disasters, such as lining cracking, falling blocks, water seepage, corrosion, and mud pumping, have appeared in successions for only one and a half years after completing the tunnel. Although the tunnel design phase, engineers have evaluated the influence of wetting-drying cycles on the gypsiferous surrounding rock. The influence of this cyclic degradation on the gypsiferous surrounding rock, however, is still underestimated. Many factors lead to this underestimation, but the water flow rate could be one of the most important factors, which cannot be ignored. Sadeghiamirshahidi and Vitton pointed out that water flow would significantly accelerate gypsum rock's dissolution [8]. Thus, flow rates cannot be ignored in the cyclic wetting-drying process on gypsiferous rocks. According to the statistical results of 53 water leakage points in the tunnel, the water at more than 12 leakage points was flowing, and one of them was even gushing. It indicated that the surrounding rocks at these locations were experiencing wetting-drying cycles as well as erosion by water flow at the same time. There is, however, still a poor understanding of the additional effect of water flow on the cyclic wetting-drying process. The role of flow rate in the deterioration of gypsiferous rock also needs to be evaluated.

In recent years, with the development of testing technology, many studies have focused on investigating the relationship between rocks' micro characteristics (e.g., pores and cracks) and their macroscopic properties [9, 10]. As a non-intrusive technique for characterizing porous materials, the NMR obtained widespread applications. The NMR technology has shown good performance in the research that the development of rocks' pore characteristics under cyclic actions that existed in natural (such as wetting-drying cycles and freezing-thawing cycles) [11, 12].

In this paper, a series of flow-by wetting-drying cycles tests for the gypsum breccia collected from the surrounding rock of an anonymous tunnel in Shanxi was carried out. After being treated by wetting-drying cycles with different flow conditions (0 and 10 l/h), the evolution characteristics of the pore structure of gypsum breccia were characterized using the nuclear magnetic resonance (NMR) technique. The relationship between the P-wave velocities and the pore characteristics of gypsum breccia was studied.

2 Experimental materials and methods

The gypsum breccia, which was obtained from intact gypsum breccia rock blocks in an anonymous tunnel in Shanxi, were used in this study. Specimen preparation followed the testing guidelines of the ISRM (International Society for Rock Mechanics) [13]. All gypsum breccia specimens were cylindrical with a diameter of 50 mm and a height of 100 mm, and the ends of the specimens were smooth to within ± 0.02 mm (see Fig. 1a). The main mineral components of the gypsum breccia specimens were determined by X-ray diffraction and included gypsum (89%), dolomite (7.6%), and Silica (3.4%).

The experimental scheme for the flow-by wetting-drying cycles tests was designed as follows. The gypsum breccia specimens were put in the specimen bottles of the homemade equipment of stagnant-flowing water environment simulation and saturated by tap water with a temperature of 23 °C at different flow rates for 48 h [14]. The detail of this homemade equipment is shown in Fig. 1b. This equipment can simultaneously set four different flow rates. After the wetting process, the gypsum breccia specimens were dried in a drying oven for 48 h (at a temperature of 40 °C) until mass constancy. One wetting-drying cycle is equivalent to the combination of one wetting process and one drying process. In these experiments, the number of wetting-drying cycles $n$ was designed to be $n = 10$, the flow rates $v$ was designed to be $v=0$, and 10 l/h.
The NMR tests were conducted using the MesoMR23-060H-I analysis system (Suzhou Niumag Analytical Instrument, China). After the specimens were treated by the wetting treatment (after 0, 2, 5, 7, and 9 cycles), the saturated specimens were covered with a layer of plastic wrap to avoid moisture loss before the NMR test. NMR $T_2$ relaxation time was measured using the CPMG (Carr–Purcell–Meiboom–Gill) pulse-sequence [15]. The experimental parameters were as follows: spectrometer frequency $SF = 12$ MHz; Frequency offset $O1 = 154976.57$ Hz; Scanning number $NS = 32$; Radiofrequency delay $RFD = 0.010$ ms; Number of echoes $NECH = 16000$; $90^\circ$ pulse length $P1 = 11.00$ μs; $180^\circ$ pulse length $P2 = 22.00$ μs; Waiting time $TW = 6000$ ms; Echo time $TE = 0.200$ ms.

3 Experimental results and analyses

3.1 Pore size distribution characteristics

Large pores have large $T_2$ values, while small pores have small $T_2$ values [16]. As per Zhou et al., the pores corresponding to $T_2$ peaks less than 10 ms were considered as the micropores pores, and those larger than 10 ms were considered as the macropores [17].

Fig. 2 shows the $T_2$ spectrum of gypsum breccia specimens after undergoing wetting-drying cycles with different flow rates. It can be seen that there were 3 peaks at each $T_2$ spectrum, and the left peaks were higher than the others, revealing that the pores of the gypsum breccia specimens were mainly micropores. It can be seen from Fig. 2a and b that there was similar development of pores in the gypsum breccia specimens after undergoing wetting-drying cycles with different flow conditions. With increasing $n$, all peaks gradually shifted to the right, i.e., the $T_2$ value corresponding to the peaks gradually increased. However, the area of the peaks corresponding to the $T_2$ value is less than 10 ms increased first (before $n = 5$) and then decreased (after $n = 5$), while the area of the peaks corresponding to the $T_2$ value is larger than 10 ms increased gradually. It indicates that the number of pores in the gypsum breccia specimen was in a period of rapid growth within $n = 5$. With increasing $n$, this growth rate gradually decreased, and more and more micropores pores grew into the macropores.
Fig. 2. $T_2$ spectrum of gypsum breccia specimens after undergoing wetting-drying cycles with different flow conditions: (a) under the condition of stagnant water, (b) under the condition of flowing water.

3.2 Spatial distribution characteristics of pores

The analysis of the variation of the porosity of gypsum breccia specimens could be further confirmed by the MRI results. The signal strength of an MRI represents the density of hydrogen protons in a material. MRI can distinguish rock from water because the water contains many more hydrogen protons than the skeleton of rock. Since the cracks and pores are filled with water, the signals from the water can be used to locate the cracks. The color bar in this paper provides a relative scale for the moisture content.

Fig. 3 shows typical proton density-weighted images of the cross-section of gypsum breccia specimens subjected to wetting-drying cycles. In the color bar, colors from black, blue, red, to gold represent the proton density from low to high, and high proton density denotes relatively high moisture content. With increasing $n$, the aggregation of high proton densities distributed in the shallow layer of the specimen under the flowing water condition was earlier and more significant than that of the specimen under the stagnant water. It was mainly due to a more broken specimen surface of the former caused by water flow erosion. However, there were similar development
characteristics of high proton density areas in their internal structure. After undergoing wetting-drying cycles, some clusters of proton densities appeared in the shallow layer of the specimen when \( n = 2 \). As the number of wetting-drying cycles continued to increase, these clusters of proton densities gradually grew and spread to the deeper layer of specimens. When the number of wetting-drying cycles was increased to 5, tiny areas of high proton density merged to form larger zones and some strip clusters of high density appeared, which indicates the formation of cracks. When the number of wetting-drying cycles increased to 7 and 9, with the cracks developed, the length and width of strip clusters of high density gradually grew and interconnected. When \( n = 9 \), some areas with high proton density disappeared due to the collapse of breccia grains of the specimens.

### 3.3 Relationship between the porosity and P-wave velocity

The porosity of gypsum breccia specimens can be obtained from the intensity of NMR signals using the following equation [18]:

\[
\phi = \frac{\sum m_i \cdot S_i \cdot G_b \cdot V_b}{M_b \cdot s \cdot g \cdot V} \cdot 100\%
\]

where \( \phi \) is the porosity of the gypsum breccia specimen (%), \( m_i \) is the amplitude of the \( T_2 \) spectrum of the \( i^{th} \) \( T_2 \) component of the gypsum breccia specimen, \( M_b \) is the total amplitude of the \( T_2 \) spectrum of the standard specimen, \( S_b \) is the number of scanning times for the standard specimen during the NMR data acquisition, \( s \) is the number of scanning times for the gypsum breccia specimen, \( G_b \) is the receiving gain of the standard specimen in NMR data acquisition, \( g \) is the receiving gain of the gypsum breccia specimen in NMR data acquisition, \( V_b \) is the total water content of the standard specimen (cm\(^3\)), and \( V \) is the volume of the gypsum breccia specimen (cm\(^3\)).

The relationship between the porosity and P-wave velocity of the specimens was established, as shown in Fig. 4. It can be seen that under nine times wetting-drying cycles, the P-wave velocity of gypsum breccia specimens decreased exponentially with increasing the porosity. With the dissolution of soluble cement, the internal pore structure tended to be stable gradually. Under different flow conditions, the same porosity corresponded to different wave velocities. This phenomenon may be caused by the difference in the structure of specimens, but it is mainly due to the different spatial distribution of pores under different flow conditions.

![Fig. 4. Relationship between the P-wave velocity and porosity of gypsum breccia specimens after undergoing W-D cycles with different flow rates.](image)

### 4 Conclusions

The conclusions can be summarized as follows:

The dissolution behavior of rocks in water is the main reason for the deterioration of gypsiferous rocks in the wetting-drying process. The water flow would accelerate the deterioration process of gypsiferous rocks in the wetting-drying process, and cause a more broken specimen surface than that under the condition of stagnant water.

The \( T_2 \) spectrum indicated that microstructure damage was induced by the combined action of the wetting-drying cycles and water flow. The pores of the gypsum breccia specimens were mainly micropores, the proportion of the pores with sizes 0.1~1μm was largest. Moreover, the MRI work showed that the original internal
structure of gypsum breccia specimens was homogeneous and compact. After several wetting-drying cycles, the pores and cracks increased and grew, and the deterioration depth and degree increased gradually. Due to the different spatial distribution of pores under different flow conditions, the same porosity under different flow conditions corresponding to different wave velocities. The P-wave velocity of gypsum breccia specimens decreased exponentially with increasing the porosity. With the dissolution of soluble cement, the internal pore structure tended to be stable gradually. There was a significant correlation between the attenuation of P-wave velocity and the development of the pore structure of gypsum breccia specimens.

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