Damage Evolution Characteristics of Non-fractured Regions during the Rock Fracture Process of Cracked Chevron Notched Brazilian Disc Specimens with Different Water Contents

Kui Zhao; Daoxue Yang*; Peng Zeng; Lin Song; Jinjian Wang;
School of Resources and Environmental Engineering, Jiangxi University of Science and Technology, Jiangxi, Ganzhou 341000, China.
*Corresponding author: Yang Daoxue (daoxuey@126.com)

Abstract: To investigate the influence of water content on crack evolution during the fracture process of the red sandstone rock material, the damage and mechanical properties of cracked chevron notched Brazilian disc red sandstone specimens, with different water contents, were experimentally investigated. Using a P-wave velocity meter, the damage information of red sandstone specimens with different water contents, in the non-fractured region, during the pure mode I and II fracture processes, was quantitatively analyzed. The experimental results show that the damage amount of the non-fractured region, during the pure mode I and II fracture processes, increases linearly with an increase in the internal water content of the red sandstone specimens. Thus, the results from this study can provide certain theoretical basis for studying the evolution mechanism of microcracks in the fracture process of CCNBD specimens with the disparate water contents.

1. Introduction
Recently, extensive experimental, theoretical, and numerical studies have been performed to understand the fracture behavior of different rock materials [1]. Presently, the International Society for Rock Mechanics (ISRM) recommends four test methods to experimentally determine the versatile and reliable values for mode I fracture toughness of rocks [2-4]. Such methods include chevron notch cylindrical specimen subjected to symmetric three-point bend loading, chevron notch short rod (CNSR) specimen, cracked chevron notched Brazilian disc (CCNBD) specimen subjected to diametral compression, and edge cracked semi-circular bend specimen under three-point bend. CNSR and CCNBD specimens are used to experimentally determine versatile and reliable values for mode II fracture toughness of rocks [1, 5-8]. However, the CCNBD method is more popular in quantifying the rock fracture toughness because of its many favorable properties such as easy specimen preparation, simple testing procedure, wide-ranging specimen geometries, and simple loading fixture [1, 9-11]. Water is an important factor that weakens the mechanical properties of rock materials [12-14]. In rock engineering, an increase in the water content of rock materials may lead to a significant decrease in strength and deformation performance [15-17]. Rock failures can lead to various engineering failures and geological disasters such as landslides [18, 19], dam foundation deformation [20], karst collapse [21, 22], and mine water inrush [23, 24], all of which can cause casualties and serious financial loss. Consequently, the influence of water content on the mechanical properties of rock materials has gleaned significant research attention in recent years [25]. Various studies on the mechanical properties and fracture toughness characteristics of rocks with varying water contents have been carried out. For example, Erguler et al. found a
negative exponential correlation between the compressive strength and water content of clay-containing rocks [26]. Chen et al. [27, 28] conducted a large number of tests to explore the influence of water content on the sub-crack growth rate and stress corrosion of shale. The results revealed the relationship between the stress intensity factor and the rate of sub-crack growth with different water contents. Zhou et al. [29, 30] investigated the relationship between water content and fracture toughness during the mode I fracture process of sandstone and the evolution mechanism of microcracks. The results show that the mode I fracture toughness of sandstone decreases non-linearly with increasing internal water content.

The current research on the mechanical properties of water-weakened rocks mainly focuses on the strength and mode I fracture toughness. However, not much research activity has been directed to the damage characteristics of non-fractured regions during the fracture process of water-weakened CCNBD specimens. Thus, this study aims to conduct both the mode I and II fracture tests of water-weakened CCNBD specimens to study the evolution of the physical properties of non-fractured regions during the fracture process. The damage information of the non-fractured area during the fracture process of the CCNBD specimen was analyzed via the P-wave velocity approach, which was used to define the damage. The findings provide a theoretical basis for analyzing the influence of water on the evolution mechanism of microcracks.

2. Materials and Methods

2.1. Preparation of the CCNBD specimens

Red sandstone is the most common widely distributed sedimentary rock in the southern area of Jiangxi Province, China. The water sensitivity of red sandstone is the main cause of engineering geological disasters during and after rainfall. Therefore, it is important to study the effect of water content on the damage evolution characteristics of non-fractured regions during mode I and II fracture processes of red sandstone. Red-colored sandstone rock samples gotten from the Ganzhou area in southern Jiangxi Province were used in this study. 32 Brazilian disc specimens (Φ100 mm × 30 mm) were prepared following the mode I and II fracture mechanics test procedures recommended by the ISRM. A rotary saw blade was used to perform a prefabricated crack treatment at the center of each disc specimen to make a 2-mm-wide crack. A schematic representation of the process is shown in Fig. 1.

2.2 Preparation of the CCNBD specimens with varying moisture contents

The prepared CCNBD specimens were divided into four groups with different water contents. Each group had eight CCNBD specimens, four of which were tested for pure mode I fracture mechanics and the other four were tested for pure mode II fracture mechanics. The processing procedure for each group of CCNBD specimens is as follows:

First group (dry group): The first group of specimens was placed in an oven at a temperature of 105 °C for 24 h to dehydrate the rock specimens and were cooled to room temperature afterward. Afterward, the mass and P-wave velocity of each specimen was measured and recorded. CCNBD specimens were successively numbered from T1–T4 (Mode I Fracture) and S1–S4 (Mode II Fracture), as shown in Table 1. After waxing and sealing all the specimens, pure mode I and II fracture mechanics experiments were carried out.

Second group (immersion for 1 h): The second group of specimens was dried, and the
relevant parameters were measured and recorded. The dried CCNBD specimens were immersed in distilled water for 1 h, and the mass of each CCNBD specimen after soaking was measured and recorded. CCNBD specimens were successively numbered from T5–T8 (Mode I Fracture) and S5–S8 (Mode II Fracture), as shown in Table 1. After waxing and sealing all the specimens, pure mode I and II fracture mechanics experiments were carried out.

Third group (immersion for 4 h): The third group of specimens was dried, and the relevant parameters were measured and recorded. The dried CCNBD specimens were immersed in distilled water for 4 h, and the mass of each CCNBD specimen after soaking was measured and recorded. CCNBD specimens were successively numbered from T9–T12 (Mode I Fracture) and S9–S12 (Mode II Fracture), as shown in Table 1. After waxing and sealing all the specimens, pure mode I and II fracture mechanics experiments were carried out.

Fourth group (saturated group): The fourth group of specimens was dried, and the relevant parameters were measured and recorded. The dried CCNBD specimens were immersed in distilled water, and the increasing percentage of mass was regularly measured during the water saturation process until a constant water content was attained for each CCNBD specimen. CCNBD specimens were successively numbered from T13–T16 (Mode I Fracture) and S13–S16 (Mode II Fracture), as shown in Table 1. After waxing and sealing all the specimens, pure mode I and II fracture mechanics experiments were carried out.

Table 1. Status and experiment types of CCNBD specimens.

| Specimen number | Status               | Experiment type     |
|-----------------|----------------------|---------------------|
| T1–T4           | Dry                  | Pure Mode I fracture|
| S1–S4           | Dry                  | Pure Mode II fracture|
| T5–T8           | Immersion for 1 h    | Pure Mode I fracture|
| S5–S8           | Immersion for 1 h    | Pure Mode II fracture|
| T9–T12          | Immersion for 4 h    | Pure Mode I fracture|
| S9–S12          | Immersion for 4 h    | Pure Mode II fracture|
| T13–T16         | Saturated            | Pure Mode I fracture|
| S13–S16         | Saturated            | Pure Mode II fracture|

The water content of rock refers to the ratio of the quality of the rock suction water and the drying quality at normal temperature and pressure:

\[
W_i = \frac{m_i - m_s}{m_s}
\]

where \(W_i\) (%) is the water content present in the rock sample, \(m_i\) (g) is the mass of the dry rock specimen, and \(m_s\) (g) is the mass of the rock specimen in the immersed state. Using equation (1), the water contents of the second to fourth groups of CCNBD specimens were calculated. The average water content of each group of CCNBD specimens is shown in Fig. 2, and the water absorption processes of all CCNBD specimens in the fourth group are shown in Fig. 3.

![Fig. 2. Average water contents of the second, third, and fourth groups of CCNBD specimens.](image-url)
2.3. Experimental scheme

The different fracture patterns of the CCNBD specimens are determined by the angle (α) between the rotating crank and the load direction. In this study, the ratio of the angle between the load and the crack direction and that between the load and the crack length-diameter were determined numerically and theoretically. Afterward, studies of the pure mode I and II fracture processes of the CCNBD specimens were performed. Fig. 4 shows a schematic of pure mode I and II fracture loading methods. Ayatollahi et al. used the finite element analysis method to study the relationship between the crack inclination angle and the crack length diameter in pure Mode II fracture process [5] and obtained a relationship as shown in Fig. 5.

Fig. 3 Variation of water content with immersion time for the eight CCNBD specimens in the fourth group.

where \( R \) is the radius of the CCNBD specimen, \( R_1 \) is the radius of the rotating saw blade, \( a \) is the effective crack length of the CCNBD specimen, \( a_0 \) is the crack penetration length of the CCNBD specimen, \( a_s \) is the surface crack length of the CCNBD specimen, and \( h \) is the thickness of the CCNBD specimen.
Pure mode I and II fracture mechanics experiments of the CCNBD specimens with different water contents were performed using an RMT-150C precision electronic servo press (Jiangxi University of Science and Technology). The displacement control was used as the loading method. A loading rate of 0.3 mm/min was used for all specimens as reported in the literature [29]. During the experiment, the load–displacement data of each CCNBD specimen was measured and recorded until a macro fracture was formed in the specimen.

3. Damage Evolution Characteristics of Non-fractured Regions during Rock Fracture Process with Different Water Contents

The P-wave velocity of red sandstone is mainly related to its particles, cement, and microstructure (such as microcracks, pores, and joints). In this study, the difference in the chemical composition of the internal constituent particles and the cement of the red sandstone specimens is relatively small because the red sandstone specimens were acquired from the same red sandstone mass. The changing P-wave velocity characteristics of the red sandstone specimen and its internal microstructure (microcracks and pores) evolution characteristics are intrinsically related. Thus, the P-wave velocity variation of the red sandstone specimens can be used to characterize the rock damage information.

To explore the evolution characteristics of the damage information of the non-fractured regions of each CCNBD specimen during pure mode I and II fracture processes, the P-wave velocities of two areas dried before and after the experiment were measured and recorded. The two areas of the CCNBD specimen were marked and numbered according to the different P-wave velocities on both sides. The smaller P-wave velocity was marked as the S1 area, while the other side was marked as the S2 area. A schematic of the S1 and S2 areas is shown in Fig. 6.

![Fig. 6. Schematic of the S1 and S2 areas.](image)

To study the damage evolution of the non-fractured regions during the experiment, the damage variable is defined by the change in the P-wave velocity of the rock before and after the external load [30]:

$$D = 1 - \left( \frac{V_p}{V_{op}} \right)^2$$

where, $D$ is the damage amount, $V_p$ (m/s) is the P-wave velocities of the two areas dried after the experiment and $V_{op}$ is the P-wave velocities of the two areas dried before the experiment. In this study, the variation of the P-wave velocity was used to quantitatively analyze the damage information of the non-fractured regions during pure mode I and II fracture processes of the CCNBD specimens with varying water contents. The damage variations during the experiment were statistically analyzed, as shown in Fig. 7.
Fig. 7 shows that during the pure mode I and II fracture experiments, the damage amounts in the S1 and S2 non-fractured regions increased with increasing water content in the CCNBD specimens. The average damage amounts of non-fractured regions with varying water contents are shown in Table 2.

| State                | $D_{I-S1}$ (%) | $D_{I-S2}$ (%) | $D_{II-S1}$ (%) | $D_{II-S2}$ (%) |
|----------------------|----------------|---------------|-----------------|-----------------|
| Dry                  | 5.03           | 4.47          | 5.77            | 4.64            |
| Immersion 1 h        | 8.98           | 8.22          | 9.74            | 8.69            |
| Immersion 4 h        | 11.47          | 10.02         | 11.43           | 10.92           |
| Saturated            | 13.38          | 11.89         | 13.36           | 12.80           |

From Table 2, $D_{I-S1}$ and $D_{I-S2}$ represent the average damage amounts of S1 and S2 non-fractured regions during pure mode I fracture process, respectively, while $D_{II-S1}$ and $D_{II-S2}$ represent the average damage amounts of S1 and S2 non-fractured region during pure mode II fracture process, respectively. Table 1 shows that during the pure mode I and II fracture experiments, with the same immersion time, the average damage amount of the S1 area is greater than that of the S2 area. Thus, the experimental results show that as the initial damage of the red sandstone increases, the weakening capacity of water also gradually increases. The relationship between the amount of damage in the non-fractured region and the different water contents is shown in Fig. 8.
As evident in Fig. 8, the relationship between the damage amount of the non-fractured region and the water contents is linear.

4 Conclusion

Through pure mode I and mode II fracture mechanics experiments conducted on red sandstone rock samples with different water contents, the following conclusions were drawn:

1. During the pure mode I and II fracture experiments, the damage amounts in the non-fractured region of S1 and S2 areas increased as the water content present in the CCNBD specimen increased.

2. The weakening capacity of water increases with increasing initial damage to the red sandstone.

References

[1] Aliha, M.R.A., 2014. Rock fracture toughness study using cracked chevron notched Brazilian disc specimen under pure modes I and II loading-A statistical approach. Theor. Appl. Fract. Mec. 69, 17-25.

[2] Ouchterlony, F., 1988. ISRM suggested methods for determining fracture toughness of rocks, Int. J. Rock Mech. Min. Sci. Geomech. Abstr. 25, 71-96.

[3] Fowell, R.J., 1995. Suggested method for determining mode I fracture toughness using cracked chevron notched Brazilian disc (CCNBD) specimens, Inter. J. Rock Mech. Min. Sci. Geomech. Abs. 321,57-64.

[4] Kuruppu, M.D., Obara, Y., Ayatollahi, M.R., Chong, K.P., Funatsu, T., 2013. ISRM suggested method for determining the mode I static fracture toughness using semi-circular
bend specimen. Rock Mech. Rock Eng. 47(1), 267-274.
[5] Ayatollahi, M.R. and Aliha, M.R.M., 2007. Wide range data for crack tip parameters in two disc-type specimens under mixed mode loading. Comput. Mater. Sci. 38(4), 660-670.
[6] Aliha, M.R.M. and Saghafi, H., 2013. The effects of thickness and Poisson’s ratio on 3D mixed-mode fracture. Eng. Frac. Mech. 98, 15-28.
[7] Kotousov, A., 2012. Three-dimensional finite element mixed fracture mode under anti-plane loading of a crack. Theor. Appl. Fract. Mech. 62, 26-33.
[8] Dai, F., Wei, M. D., Xu, N. W., 2014. Numerical Assessment of the Progressive Rock Fracture Mechanism of Cracked Chevron Notched Brazilian Disc Specimens. Rock Mech. Rock Eng. 48(2), 463-479.
[9] Wang, Q. Z., Fan, H., Gou, X. P., Zhang, S., 2013 Recalibration and clarification of the formula applied to the ISRM-suggested CCNBD specimens for testing rock fracture toughness. Rock Mech. Rock Eng. 46(2), 303-313.
[10] Wang, Q. Z., Jia, X. M., Wu, L.Z., 2004. Wide-range stress intensity factors for the ISRM suggested method using CCNBD specimens for rock fracture toughness tests. Int J Rock Mech Min Sci. 41, 709-716.
[11] Fowell, R. J., Xu, C., Dowd, P.A., 2006. An update on the fracture toughness testing methods related to the cracked chevron notched Brazilian disk (CCNBD) specimen. Pure Appl. Geophys.163(5-6), 1047-1057.
[12] Zhou, Z., Cai, X., Cao, W., Li, X., Xiong, C., 2016. Influence of water content on mechanical properties of rock in both saturation and drying processes. Rock Mech. Rock Eng. 49(8), 3009-3025.
[13] Hu, Q., Wang, S., Qu, T., Xu, T., Huang, S., Wang, H., 2020. Effect of hydraulic gradient on the permeability characteristics of foam-conditioned sand for mechanized tunneling. Tunn. Undergr. Space Technol. 99, 10377.
[14] Xu, Q., Chen, J., Xiao, M., 2020. Analysis of unsteady seepage field and surrounding rock stability of underground cavern excavation. Tunn. Undergr. Space Technol. 97, 103239.
[15] Kim, E., Changani, H., 2016. Effect of water saturation and loading rate on the mechanical properties of Red and Buff Sandstones. Inter. J. Rock Mech. Min. Sci. 88, 23-28.
[16] Zhou, Z. L., Cai, X., Ma, D., Du, X. M., Chen, L., Wang, H. Q., Zang, H. Z., 2019. Water saturation effects on dynamic fracture behavior of sandstone. Int. J. Rock Mech. Min. Sci. 114, 46-61.
[17] Zhou, Z. L., Cai, X., Ma, D., Cao, W. Z., Chen, L., Zhou, J., 2018. Effects of water content on fracture and mechanical behavior of sandstone with a low clay mineral content. Eng. Fract. Mech. 193, 47-65.
[18] Iverson, R. M., 2000 Landslide triggering by rain infiltration. Water Resour. Res. 36(7), 1897-1910.
[19] Brunetti, M. T., Peruccacci, S., Rossi, M., Luciani, S., Valigi, D., Guzzetti, F., 2010. Rainfall thresholds for the possible occurrence of landslides in Italy. Nat. Hazard. Earth Sys. 10(3), 447-458.
[20] Wu, F., Qi, S., Lan, H., 2005. Mechanism of uplift deformation of the dam foundation of Jiangya water power station, Hunan Province, P.R. China. Hydrogeol J. 13(1), 451-466.
[21] Bai, H., Ma, D., Chen, Z., 2013. Mechanical behavior of groundwater seepage in karst collapse pillars. Eng. Geol. 164, 101-106.
[22] Shi, S., Bu, L., Li, S., Xiong, Z., Xie, X., Li, L., Ma, D., 2017. Application of comprehensive prediction method of water inrush hazards induced by unfavorable geological body in high risk karst tunnel: a case study. Geomat. Nat. Haza. Risk 8(2), 1407-1423.
[23] Huang, Z., Zeng, W., Zhao, K., 2019. Experimental investigation of the variations in hydraulic properties of a fault zone in Western Shandong, China. Hydrology J. 574, 822-835.
[24] Ma, D., Cai, X., Li, Q., Duan, H., 2018. In-situ and numerical investigation of groundwater inrush hazard from grouted karst collapse pillar in Longwall mining. Water. 10(9), 1187.
[25] Xie, K., Jiang, D., Sun, Z., Chen, J., Zhang, W., Jiang, X., 2018. NMR, MRI and AE Statistical Study of Damage due to a Low Number of Wetting–Drying Cycles in Sandstone from the Three Gorges Reservoir Area. Rock Mech. Rock Eng. 51(11), 3625-3634.
[26] Erguler, Z. A., Ulusay, R., 2009. Water-induced variations in mechanical properties of clay-bearing rocks. Int. J. Rock Mech. Min. Sci. 46(2):355-370.
[27] Chen, X. F., Eichhubl, P., Olson, J. E., 2017. Effect of water on critical and subcritical fracture properties of Woodford Shale. J. Geophys. Res-Sol. Ea. 122, 2736-2750.
[28] Chen, X. F., Eichhubl, P., Olson, J. E., Dewers, T. A., 2019. Effect of Water on Fracture Mechanical Properties of Shales. J. Geophys. Res-Sol. Ea. 124(3), 2428-2444.
[29] Xu, Y., Dai, F., Zhao, T., Xu, N. W., & Liu, Y., (2016). Fracture toughness determination of cracked chevron notched Brazilian disc rock specimen via Griffith energy criterion incorporating realistic fracture profiles. Rock Mech. Rock Eng. 49(8), 3083-3093.
[30] Zhao, M. J., Xu, R., 2000. The rock damage and strength study based on ultrasonic velocity. Chin. J. Geotech. Eng. 22(6), 720-722.