Experimental Research on Fracture Toughness and Tensile Strength of Red Sandstone under Different Moisture Content

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Abstract: In order to study the variation and correlation of mode I fracture toughness and tensile strength of red sandstone under different moisture content conditions, Brazilian splitting and NSCB tests were carried out on the red sandstone specimens with moisture content of 0%, 1.63% and 3.33% respectively by using the CMT53 test loading system, and the test data obtained were fitted and analyzed. The test results show that: 1. The tensile strength and fracture toughness of red sandstone gradually decrease with the increase of moisture content, and the softening effect of water on red sandstone is obvious, with the reduction coefficients of 0.72 and 0.66, respectively. 2. With the increase of moisture content, the dispersion of tensile strength and fracture toughness of red sandstone increases. 3. The fitting formulas of water content and tensile strength and fracture toughness are obtained by data fitting, and the fitting correlation is relatively high. The piecewise function is used to describe the relationship between tensile strength and fracture toughness. It is convenient to estimate the fracture toughness of red sandstone through its tensile strength and it has a certain reference value for studying the relationship between tensile strength and fracture toughness of red sandstone.

1. Introduction
The destruction and fracture of rocks are inseparable. A large number of practices and studies [1-3] show that the failure of rocks is often related to the microcracks inside the rock and the instability of macroscopic cracks. The ability to resist crack instability and resist brittle fracture is expressed by the fracture toughness $K_I$, which is an inherent property of the material and one of the important mechanical properties of the rock. It plays an important role in evaluating the stability and safety of geotechnical engineering.

M. D. Kuruppu et al [4-5] considered that NSCB samples have more advantages in testing the mode I fracture toughness of rock materials under quasi-static loading conditions. R. J. Fowell et al [6-8] compared the three samples of SR, CB and CCNBD, and considered that the CCNBD sample test method is simple and can be used for the fracture toughness test of various fracture modes. Zhang Sheng et al [9] determined the fracture toughness of marble by using a central circular hole platform disc specimen with a single length of cracks of different lengths, and based on Bazant's scale law theory, the results were fitted according to the results of finite element analysis. A functional expression of the dimensionless energy release rate. Yang Jianfeng et al [10] on the mudstone experimental study, showing that the fracture toughness of mudstone has obvious changes under different soaking effects. Zuo Jianping [11-12] conducted real-time thermal cracking and tensile fracture tests on Beishan granite. It was found that in the range of 25°C ~ 100°C, Beishan granite is dominated by brittle failure, and the temperature is in the range of 100°C. The fracture behavior has
little effect. Zhao Yixin et al. [13] studied the tensile and fracture properties of coal under quasi-static loading conditions, and obtained that the J-integrated fracture toughness is more suitable for evaluating the fracture properties of coal than the plane strain fracture toughness $K_{IC}$.

At present, some researches have been made on the relationship between fracture toughness and strength parameters of rock at home and abroad, but few studies have been conducted on rock mode I fracture toughness and tensile strength under different water content conditions. In view of this, this paper selects red sandstone as the research object for Brazilian splitting and NSCB test, aiming to investigate the influence of water on tensile strength and mode I fracture toughness of red sandstone and the relationship between tensile strength and fracture toughness. Through the research, the fitting formulas of tensile strength, mode I fracture toughness and moisture content of red sandstone and tensile strength and mode I fracture toughness are obtained. It is easy to estimate the mode I fracture toughness by tensile strength of red sandstone. It provides some reference value and experimental data support for the correlation between rock mode I fracture toughness and tensile strength.

1.1. Sample preparation and test plan

According to the Brazilian disc preparation method recommended by ISRM [14], $36\phi50$mm×25mm disc specimens were processed, and 27 Brazilian discs were cut to form 27 SCB specimens, which were divided into A, B and C. Then three groups of NSCB specimens with groove width of 1 mm and depth of 4, 7 and 10 mm were prepared by slitting at the bottom center of group A, B and C, three samples in each group. Group A specimens were dried (water content: 0%), which was placed in an oven at a temperature of 105° for 24h. Group C was subjected to saturation treatment (water content: 3.33%), which was immersed in water for 48 hours. Group B was first dried, and then immersed in water until the water content was about 1/2 of C group (water content: 1.63%). The test piece parameters are detailed in Table 1. In the same way, the remaining 9 Brazilian discs were finally divided into three groups of D, E and F, which were respectively dried, semi-saturated and saturated for the Brazilian splitting test. The parameters of the test pieces are shown in Table 2.

| Number | $D$ (mm) | $t$ (mm) | $m$ (g) | Cutting depth $a$ (mm) | $a/R$ | Moisture content $w$ (%) |
|--------|----------|----------|--------|------------------------|-------|-----------------------|
| A      |          |          |        |                        |       |                       |
| A4-1   | 50.12    | 25.36    | 60.82  | 3.9                    | 0.16  | 0                     |
| A4-2   | 50.05    | 25.14    | 60.02  | 3.94                   | 0.16  | 0                     |
| A4-3   | 49.94    | 25.02    | 58.21  | 3.92                   | 0.16  | 0                     |
| A7-1   | 49.92    | 26.07    | 60.71  | 6.87                   | 0.28  | 0                     |
| A7-2   | 50.05    | 25.81    | 60.44  | 6.98                   | 0.28  | 0                     |
| A7-3   | 49.96    | 26.15    | 61.18  | 7.04                   | 0.28  | 0                     |
| A10-1  | 50.08    | 25.56    | 60.04  | 9.88                   | 0.40  | 0                     |
| A10-2  | 50.15    | 25.59    | 60.32  | 9.9                   | 0.40  | 0                     |
| A10-3  | 50.07    | 25.49    | 59.91  | 9.95                   | 0.40  | 0                     |
| B      |          |          |        |                        |       |                       |
| B4-1   | 49.95    | 25.24    | 59.17  | 3.94                   | 0.16  | 1.80                  |
| B4-2   | 50.08    | 25.57    | 60.24  | 3.97                   | 0.16  | 1.63                  |
| B4-3   | 50.06    | 24.94    | 58.98  | 3.93                   | 0.16  | 1.67                  |
| B7-1   | 50.03    | 25.14    | 59.94  | 7.05                   | 0.28  | 1.65                  |
| B7-2   | 50.12    | 24.83    | 60.25  | 7.03                   | 0.28  | 1.60                  |
| B7-3   | 50.17    | 25.52    | 59.93  | 7.01                   | 0.28  | 1.41                  |
| B10-1  | 50.06    | 25.59    | 59.91  | 9.99                   | 0.40  | 1.54                  |
| B10-2  | 50.07    | 25.73    | 61.42  | 10.00                  | 0.40  | 1.73                  |
| B10-3  | 50.10    | 25.42    | 60.07  | 9.92                   | 0.40  | 1.66                  |
| C      |          |          |        |                        |       |                       |
| C4-1   | 50.03    | 24.86    | 58.26  | 3.94                   | 0.16  | 3.50                  |
| C4-2   | 50.08    | 24.96    | 59.69  | 3.98                   | 0.16  | 3.39                  |
| C4-3   | 49.95    | 25.25    | 59.32  | 4.00                   | 0.16  | 3.29                  |
| C7-1   | 49.98    | 25.12    | 58.04  | 6.96                   | 0.28  | 3.37                  |
| C7-2   | 49.90    | 24.68    | 56.72  | 7.02                   | 0.28  | 3.27                  |
| C7-3   | 50.12    | 25.61    | 60.39  | 7.06                   | 0.28  | 3.30                  |
| C10-1  | 50.04    | 25.44    | 59.64  | 10.04                  | 0.40  | 3.51                  |
| C10-2  | 50.14    | 25.41    | 60.76  | 10.00                  | 0.40  | 3.10                  |
| C10-3  | 50.03    | 25.12    | 58.27  | 10.02                  | 0.40  | 3.23                  |
Table 2. Parameters of Brazilian disc specimens.

| Number | D (mm) | H (mm) | Moisture content w (%) |
|--------|--------|--------|------------------------|
| D1     | 50.02  | 25.02  | 0                      |
| D2     | 50     | 25.7   | 0                      |
| D3     | 49.98  | 25.68  | 0                      |
| E1     | 50.08  | 25.8   | 1.71                   |
| E2     | 50.02  | 25.2   | 1.68                   |
| E3     | 50.04  | 26.12  | 1.73                   |
| F1     | 50.06  | 25.26  | 3.38                   |
| F2     | 50.06  | 26.08  | 3.40                   |
| F3     | 50.08  | 26.02  | 3.47                   |

ISRM recommends that when using the NSCB method to test the mode I quasi-static fracture toughness of rock materials, the distance S between the support points and the diameter D of the sample should satisfy $0.5 \leq S/D \leq 0.8$ [4]. In this paper, $S/D=0.8$ is selected for testing. The geometry of the sample required for the test is shown in figure 1.

**Figure 1. Geometric figure of NSCB and Brazilian disc specimens.**

1.2. Experimental scheme

The Brazilian splitting and NSCB tests were carried out with the CMT53 electronic universal test loading device in Shandong key laboratory of Shandong university of science and technology. All tests were displacement control loading with a loading rate of 0.1mm/min, which was in line with the requirements of static crack growth (the loading rate was no more than 0.2mm/min) [4]. The system automatically recorded the load and displacement data when the testing machine was loaded. The red sandstone NSCB sample and the Brazilian disc sample are placed as shown in figure 2.

**Figure 2. Placement of red sandstone NSCB and Brazilian disc specimens.**

2. Red sandstone-like BD splitting test

Table 3 gives the parameters such as the diameter, height and failure load of the red sandstone Brazilian disc specimen.
Table 3. BD splitting test results.

| Number | D (mm) | H (mm) | P (N)    | σ (MPa) | σa (MPa) |
|--------|--------|--------|----------|---------|----------|
|        |        |        |          |         |          |
| D      |        |        |          |         |          |
| 1      | 50.02  | 25.02  | 11029.01 | 5.61    | 5.5      |
| 2      | 50.08  | 25.8   | 9214.24  | 4.54    | 4.48     |
| 3      | 49.98  | 25.68  | 11366.74 | 5.64    |          |
| E      |        |        |          |         |          |
| 1      | 50.08  | 25.2   | 8195     | 4       | 3.95     |
| 2      | 50.06  | 26.12  | 8400.11  | 4.2     |          |
| 3      | 50.04  | 26.08  | 8195     | 4.23    |          |
| F      |        |        |          |         |          |
| 1      | 50.06  | 25.26  | 8400.11  | 4.2     |          |
| 2      | 50.06  | 26.08  | 8195     | 4       | 3.95     |
| 3      | 50.08  | 26.02  | 7410.87  | 3.62    |          |

The tensile strength of red sandstone can be calculated according to equation [15]:

\[
\sigma_t = \frac{2P}{\pi DH}
\]  \hspace{1cm} (1)

Where, \(\sigma_t\) is the tensile strength of the rock; \(P\) is the maximum load when the specimen is destroyed; \(D\) is the sample diameter; \(H\) is sample thickness. According to equation (1), the tensile strength of red sandstone can be calculated, and the specific results are shown in table 3.

According to the tensile strength of red sandstone under different water content, a scatter diagram with water content as the horizontal axis and tensile strength as the vertical axis was drawn, and a quadratic polynomial fitting was carried out, as shown in figure 3.

Through data fitting, the composite formula of tensile strength and water content of red sandstone is obtained. Correlation coefficient \(R^2=1\), and the fitting formula is:

\[
\sigma_t = 0.0842w^2 - 0.7412x + 5.5
\]  \hspace{1cm} (2)

By observing figure 3 and table 3, it can be found that the softening effect of water on the tensile strength of red sandstone is relatively obvious, and the reduction coefficient of the tensile strength is 0.72. With the increase of water content, the tensile strength gradually decreases. Secondly, the slope of the fitting curve decreases with the increase of water content, indicating that the change rate of tensile strength decreases with the increase of water content. In addition, the dispersion of tensile strength is also significantly correlated with water content. Dry red sandstone has the highest tensile strength, with the average tensile strength of 5.5MPa and the dispersion coefficient of 0.031. The tensile strength was 4.48MPa and the dispersion coefficient was 0.047. The saturated tensile strength is the lowest, 3.95MPa, and the discrete coefficient is 0.064. It shows that the higher the water content is, the greater the discreteness of the tensile strength of red sandstone is, which indicates that the measured data deviate from the stable value.
3. Fracture toughness test of red sandstone NSCB

The test results of 25 specimens (A4-3 and A7-2 specimens were not obtained) were measured. According to the test results, it was found that: the prefabricated slit depth and water weakened the peak strength of the red sandstone sample significantly, and the average peak load of the specimen gradually decreased with the increase of slit depth and water content.

The fracture toughness of specimens depends on peak load, incision length and specimen thickness. At present, the commonly used calculation formula of $K_{IC}$ of plane strain fracture toughness of NSCB samples of rock materials is as follows [16]:

$$
K_{IC} = Y^' P_{\text{max}} \sqrt{\pi a} / (2Rt)
$$

$Y' = -1.297 + 9.516 \left[ s/(2R) \right] - \left\{ 0.47 + 16.457 \left[ s/(2R) \right] \right\} \beta + \left\{ 1.071 + 34.401 \left[ s/(2R) \right] \right\} \beta^2$

Where, $\beta$ is the slit depth of dimension one, $\beta = a / R$; $R$ is the specimen radius (mm); $a$ is slit depth (mm); $t$ is the thickness of the sample (mm); $Y'$ is a dimensionless stress intensity factor. According to the formula (3) and (4) available red sandstone mode I fracture toughness values, the specific measured parameters and the calculation results are shown in table 4.

### Table 4. Calculations of NSCB Fracture Toughness Test for Red Sandstone.

| Number | $a/R$ | Peak load (N) | $Y'$ | Plane strain fracture toughness value (MPa·mm^{1/2}) | Average value of plane strain fracture toughness (MPa·mm^{1/2}) |
|--------|-------|---------------|------|-----------------------------------------------------|--------------------------------------------------------|
| A A4-1~4-3 | 0.16 | 1526±11 | 4.88 | 20.65±0.03 |
| A A7-1~7-3 | 0.28 | 1277±83 | 4.74 | 21.7±1.3 | 21.46±0.59 |
| A A10-1~10-3 | 0.40 | 952±24 | 5.31 | 22.03±0.29 |
| B B4-1~4-3 | 0.16 | 1491±72 | 4.87 | 20.40±0.97 |
| B B7-1~7-3 | 0.28 | 999±98 | 4.73 | 17.62±1.92 | 19.29±1.2 |
| B B10-1~10-3 | 0.40 | 840±62 | 5.41 | 19.85±1.49 |
| C C4-1~4-3 | 0.16 | 964±105 | 4.87 | 13.25±1.42 |
| C C7-1~7-3 | 0.28 | 651±16 | 4.74 | 11.52±0.22 | 13.35±1.55 |
| C C10-1~10-3 | 0.40 | 637±37 | 5.43 | 15.30±0.99 |

As shown in figure 4, the mode I fracture toughness $K_{IC}$ along with the change of moisture content of quadratic polynomial fitting, the correlation coefficient $R^2=1$, the fitting formula is:

$$K_{IC} = -0.6523w^2 - 0.2647w + 21.46$$

Figure 4. The relationship curve between mode I fracture toughness $K_{IC}$ and moisture content of red sandstone.
Type can be found: the mode I fracture toughness $K_{IC}$ decreases with increasing moisture content and slope increases gradually. Water content has a certain influence on the discreteness of plane strain fracture toughness of red sandstone. The average of mode I fracture toughness under dry condition is 21.46 MPa mm$^{-1/2}$ and the dispersion coefficient is 0.027; the second under semi-saturated condition is 19.29 MPa mm$^{-1/2}$ and the dispersion coefficient is 0.062; while the lowest under saturated condition is 13.35 MPa mm$^{-1/2}$ and the dispersion coefficient is 0.116. Second, the water is obtained by calculation of red sandstone fracture toughness of softening coefficient is 0.66, showing that water in I red sandstone mode fracture toughness $K_{IC}$ softening effect is obvious.

4. Correlation analysis between mode I fracture toughness and tensile strength of red sandstone

The linear fitting and polynomial fitting of the obtained experimental data show that the linear fitting correlation coefficient is less than 0.82, and the polynomial fitting does not satisfy the general rule that the fracture toughness increases with the increase of moisture content, and cannot accurately describe the relationship. Therefore, a piecewise straight line is used to describe the relationship between mode I fracture toughness $K_{IC}$ and tensile strength (as shown in figure 5.). The broken line diagram is divided into two straight lines. The formulas for each straight line are as follows:

$$K_{IC} = 0.6345w + 1.1035 \quad (3.95 \leq w \leq 4.48), \quad K_{IC} = 0.927w - 0.6237 \quad (4.48 < w \leq 5.5)$$ (6)

Figure 5. The line chart of relationship between mode Ⅰ fracture toughness $K_{IC}$ and tensile strength.

It can be found from the line chart that the $K_{IC}$ of red sandstone increases with the increase of tensile strength, that is, the tensile strength and fracture toughness of red sandstone reach the highest under dry conditions, and reach the lowest under saturated conditions. Secondly, the slope of the line in the interval [3.95, 4.48] is significantly larger than the slope of the line in the interval (4.48, 5.5), indicating that the rate of change of the mode I fracture toughness $K_{IC}$ increases with the increase of the tensile strength. The segmental straight line is used to describe the correlation between the $K_{IC}$ of the red sandstone mode I fracture toughness and the tensile strength under different moisture content conditions, which is more suitable for the data obtained from the test. When the moisture content of red sandstone is known, it will be more convenient to calculate the mode I fracture toughness $K_{IC}$ by the tensile strength obtained from Brazilian splitting test.

5. Conclusion

(1) Brazilian disc splitting and NSCB tests were performed on dry, semi-saturated and saturated sandstone samples. The test results show that the tensile strength and mode I fracture toughness of red sandstone decrease with the increase of water content, and the softening effect of water on the tensile strength and mode I fracture toughness of red sandstone is obvious, and the reduction factor is 0.72 and 0.66.

(2) The fitting formulas of tensile strength and mode I fracture toughness of red sandstone with water content are obtained. The correlation coefficients are $R^2=1$. According to the fitting formulas, the tensile strength and mode I fracture toughness of red sandstone under different moisture content can be calculated.
(3) With the increase of moisture content, the tensile strength and fracture toughness of red sandstone are more and more discrete.

(4) Based on the experimental data, the break-line diagrams of mode I fracture toughness $K_{IC}$ and tensile strength of red sandstone under different moisture content are obtained, and the formula of piecewise straight line is obtained. Through the formula, it can be found that the mode I fracture toughness of red sandstone increases with the increase of tensile strength, and the linear slope in the interval $[3.95, 4.48]$ is obviously larger than that in the interval $(4.48, 5.5)$. Therefore, the piecewise function is more suitable for describing $K_{IC}$ and tensile strength of mode I fracture toughness of red sandstone.

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