Research Article

Study on the Static and Dynamic Fracturing Properties of Marble after Being Damaged Dynamically

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A split Hopkinson pressure bar (SHPB) system was first used to perform the cyclic impact loading tests on notched semicircular bend (NSCB) marble specimens. Then, static and dynamic three-point bending tests were conducted on these dynamically damaged specimens, respectively. In the cyclic impact loading tests, the dynamic elastic modulus decreases gradually as the impact number increases, but dynamic cumulative damage exhibits a growing trend. In the static and dynamic three-point bending tests, when dynamic cumulative damage is less than 0.345, the dynamic fracture toughness values are larger than the static fracture toughness values, but the experimental data exhibit the opposite results when dynamic cumulative damage ranges from 0.345 to 0.369. Through the quantitative analysis of fracture surface morphologies, the roughness and area of the fracture surfaces increase with an increasing dynamic cumulative damage. Under the same dynamic cumulative damage of the specimens, both the roughness and area of the surfaces fractured by static three-point bending are larger than those fractured by dynamic three-point bending.

1. Introduction

With the increasing demand for the development of underground engineering, rock dynamics play an increasingly important role [1–4]. In this research field, the effects of environmental factors (freeze-thaw cycles, chemical corrosion, and thermal damage) on the rock dynamic fracture properties have been studied in depth. For example, to study the couple effects of freeze-thaw cycles and dynamic loads on the fracture mechanism of sandstone, Chen et al. [5] conducted the dynamic loading tests on the specimens with different freeze-thaw cycles. Yu et al. [6] carried out the dynamic fracture tests on limestone specimens after chemical corrosion treatment, and they obtained the deterioration laws of fracture mechanical properties. Li et al. [7] explored the dynamic fracturing characteristics of sandstone with different high-temperature damage by using a SHPB apparatus.

In the field of rock statics, many scholars have made great efforts to study the rock static fracture properties and achieved many important results. For example, Han et al. [8, 9] studied the damage evolution law and fracturing properties of sandstone under the couple effects of freeze-thaw cycle and chemical corrosion, and they found that the static fracture toughness deteriorates as the freeze-thaw cycle increases. Hua et al. [10] investigated the effect of dry-wet cycle on the static fracture toughness of CSTBD sandstone specimens by using an electronic universal testing machine. To study the effect of thermal damage on the fracturing properties of granite, Miao et al. [11] carried out the static fracture tests on the specimens with different high temperatures. To clarify the effect of the testing method type and specimen size on fracture toughness, Kataoka et al. [12] performed three types of the static fracture tests on the Kimachi sandstone. To investigate the energy storage and dissipation characteristics during the tension-type failure process of marble, Gong et al. [13] conducted the semicircular bending test by using the MTS322 and MTS landmark-testing systems.

From the above discussion, it can be seen that the current studies mainly focus on the effects of environmental factors
on rock dynamic and static fracture properties. However, few studies have revealed the fracture properties of rocks after being damaged dynamically. In the construction of many underground engineering, Bagde and Petroš [14] found that the surrounding rock was subjected to dynamic loads from machine impact or explosive blasting, which caused different dynamic damages to it. After construction, the reserved surrounding rock bears the static load brought by the redistribution of the in situ rock stress for a long time, and it also encounters dynamic loadings from seismic activity. Once the defect area in the rock breaks, it may induce accidents. Therefore, a comprehensive understanding of the static and dynamic fracture properties of rocks after being damaged dynamically and their differences are of great significance in engineering construction and accident prevention.

In this study, cyclic impact loading tests were first performed to prepare a batch of dynamically damaged NSCB marble specimens. Then, static and dynamic three-point bending tests were performed on these specimens to investigate the variations of the fracturing properties. On the aspect of fracture surface morphologies, the roughness and area of the fracture surfaces were quantitatively analysed. According to the contrast analysis results of static and dynamic fracture properties of the damaged marble, it can provide certain reference meaning for the construction and safety protection of rock engineering.

2. Test Plan

2.1. Preparation of NSCB Marble Specimens. The rock material used in the tests was marble taken from a quarry in Dali, Yunnan Province, China. The marble block is white in colour, and its basic physical and mechanical properties were tested in the laboratory (Table 1).

The marble block was made into 36 NSCB specimens by coring, cutting, and polishing, and their geometric dimensions are shown in Figure 1. Based on the testing requirements of the International Society for Rock Mechanics (ISRM), two surfaces of the specimens were polished to the smoothness of less than 0.05 mm and parallelism of less than 0.02 mm.

2.2. Cyclic Impact Loading Tests. Cyclic impact loading tests were performed by using a SHPB system located at the mechanics laboratory of China University of Mining and Technology. The SHPB system is composed of a gas gun, a striker, an incident bar, a transmission bar, and an absorbing bar (Figure 2). The bars and striker are made of 50 mm diameter maraging steel with 7800 kg/m³ density, 210 GPa elastic modulus, and 5170 m/s P-wave velocity. The strain gauges are affixed to the incident, and transmission bars are used to measure the stress wave propagation. To obtain better waveform and achieve constant strain-rate loading, the rubber discs were used as the pulse shapers in the tests [15–18].

In the cyclic impact loading tests, the air pressure was selected as 0.10 MPa, which can meet the requirement of causing dynamic damage to the specimens without breaking them (Figure 3). This part was detailed in the previous study [19]. 36 NSCB specimens were divided into 6 groups according to the test conditions, and their corresponding numbers are listed in Table 2.

Based on one-dimensional stress wave theory, the stress \( \sigma_s \), strain \( \varepsilon_s \), and strain rate \( \dot{\varepsilon} \) of the specimen are obtained as

\[
\begin{align*}
\sigma_s &= \frac{E_b A_b}{2 A_s} \left[ \varepsilon_i(t) + \varepsilon_r(t) + \varepsilon_i(t) \right], \\
\varepsilon_s &= \frac{C_{pb}}{I_s} \int_0^t \left[ \varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_i(t) \right] dt, \\
\dot{\varepsilon} &= \frac{C_{pb}}{I_s} \left[ \varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_i(t) \right],
\end{align*}
\]

where \( \varepsilon_i(t) \), \( \varepsilon_r(t) \), and \( \varepsilon_i(t) \) respectively, represent the incident, transmission, and reflection strain waves; \( A_b \), \( C_{pb} \), and \( E_b \) respectively, represent the cross-sectional area, P-wave velocity, and elastic modulus of the bar; and \( I_s \) and \( A_s \) respectively, represent the initial length and cross-sectional area of the specimen.

Figure 4(a) presents the typical waveforms recorded in the 3rd impact loading of the CJ5-Sa specimen. It can be observed that \( V_i + V_r = V_s \); that is, the dynamic forces on both ends of the specimen are approximately equal, and the specimen reaches the dynamic force equilibrium state.

2.3. Static Three-Point Bending Test. The static three-point bending test of the dynamically damaged specimens was performed by using a DNS100 electronic universal testing machine (Figure 5(a)). The loading rate was selected as 0.06 mm/min, which can satisfy the requirement (loading rate is not higher than 0.20 mm/min) of static crack propagation [20].

2.4. Dynamic Three-Point Bending Test. The dynamic three-point bending test of the dynamically damaged specimens was performed by using a SHPB apparatus (Figure 5(b)). To ensure that the specimens obtained a stable loading rate, the air pressure used in this test was also 0.10 MPa. Figure 4(b) shows the measured waveforms of the CJ4-Db specimen in the dynamic three-point bending test, and it can be found that the specimen reaches the dynamic force equilibrium state.

3. Experimental Results of the Cyclic Impact Loading Tests

3.1. Dynamic Mechanical Characteristic Curves. Figure 6 presents the dynamic stress-strain curves of the CJ5-Db specimen under 5 cycles of impact. As the impact number increases, dynamic peak stress and dynamic elastic modulus all decrease gradually. The increasing dynamic damage caused by the continuous development of microcracks in the
Table 1: The basic physical and mechanical properties of the marble.

| Property                     | Value       |
|------------------------------|-------------|
| Density (g/cm³)              | 2.70        |
| P-wave velocity (m/s)        | 4584.52     |
| Compressive strength (MPa)   | 126.05      |
| Tensile strength (MPa)       | 8.60        |
| Young’s modulus (GPa)        | 25.18       |
| Poisson’s ratio              | 0.24        |

Note: R is the radius of the specimen, R = 25 mm; B is the thickness of the specimen, B = 25 mm; a is the length of artificial prefabricated crack, a = 5 mm; and S is the distance between two supporting points, S = 25 mm.

Figure 1: Schematic of the NSCB marble specimen.

Figure 2: Schematic of the SHPB experimental system.

Figure 3: Photograph of cyclic impact loading tests.

Table 2: Specimen numbers and test conditions.

| Group | CJ0  | CJ1  | CJ2  | CJ3  | CJ4  | CJ5  |
|-------|------|------|------|------|------|------|
| Impact number | 0   | 1    | 2    | 3    | 4    | 5    |
| Specimen no.   | CJ0-Sa | CJ1-Sa | CJ2-Sa | CJ3-Sa | CJ4-Sa | CJ5-Sa |
|                 | CJ0-Sb | CJ1-Sb | CJ2-Sb | CJ3-Sb | CJ4-Sb | CJ5-Sb |
|                 | CJ0-Sc | CJ1-Sc | CJ2-Sc | CJ3-Sc | CJ4-Sc | CJ5-Sc |
|                 | CJ0-Da | CJ1-Da | CJ2-Da | CJ3-Da | CJ4-Da | CJ5-Da |
|                 | CJ0-Db | CJ1-Db | CJ2-Db | CJ3-Db | CJ4-Db | CJ5-Db |
|                 | CJ0-Dc | CJ1-Dc | CJ2-Dc | CJ3-Dc | CJ4-Dc | CJ5-Dc |

Note: specimens with “S” and “D” in the numbers indicate that they need to be subjected to the static and dynamic three-point bending tests, respectively.
Figure 4: Dynamic force equilibrium check. (a) Cyclic impact loading tests. (b) Dynamic three-point bending test.

Figure 5: Static and dynamic three-point bending tests. (a) Loading system of the static three-point bending test. (b) Photograph of the dynamic three-point bending test.
specimen under the action of stress waves is the main degradation mechanism.

3.2. Dynamic Cumulative Damage. The elastic modulus method is a recommended method to assess the damage degree of rock in damage mechanics. Hence, the dynamic cumulative damage DE of the specimens can be expressed as follows [21]:

\[
DE = 1 - \frac{E_{dn}}{E_{d1}}
\]  

(2)

where \(E_{d1}\) and \(E_{dn}\) respectively, represent the dynamic elastic modulus of the specimen under the 1st and \(n\)-th impact loading and \(n\) represents the total impact number. \(E_{dn}\) in equation (2) can be calculated via the following formula [22]:

\[
E_{dn} = \frac{\dot{\varepsilon}_d n}{\dot{\varepsilon}_n}
\]  

(3)

where \(\dot{\varepsilon}_n\) and \(\dot{\varepsilon}_n\) are the average strain rate and loading rate of the specimen under the \(n\)-th impact loading, respectively.

The evolution law of \(E_{dn}\) and DE with impact number is shown in Figure 7. It can be observed that \(E_{dn}\) exhibits a decreasing trend from 42.63 (group CJ1) to 26.91 MPa (group CJ5), while DE exhibits a growing trend from 0 (group CJ1) to 0.369 (group CJ5).

4. Experimental Results of the Static Three-Point Bending Test

4.1. Load-Displacement Curves. In the static three-point bending test, the typical load-displacement curves of the specimens are presented in Figure 8(a), and the curves can be divided into three stages. (1) The compaction stage: the curves are concave and the slope increases gradually. The duration of this stage is closely related to the dynamic cumulative damage of the specimen. Compared with the CJ2-Sa specimen (\(DE = 0.097\)), the number of the micro-cracks in the CJ5-Sc specimen (\(DE = 0.376\)) increases significantly (Figure 8(b)), which results in a substantial increase in the duration of the compaction stage. (2) The line elastic stage: the slopes of the curves remain unchanged, but this stage tends to be insignificant with the increase of impact number of the specimens. (3) The brittle failure stage: the bearing capacity is lost rapidly and the specimens are brittle fractured.

4.2. Static Fracture Toughness. In 1984, Chong and Kuruppu [23] first proposed the calculating method of mode I static fracture toughness KICS of the NSCB specimen, and this method is recommended by ISRM. The calculating formula is as follows:

\[
K^S_{IC} = \frac{P_{\text{max}} \sqrt{\alpha a}}{2RB} Y,
\]  

(4)

where \(P_{\text{max}}\) is the peak load of the specimen during static three-point bending and \(Y\) is a dimensionless function, which depends on the length \(a\) and the distance \(S\). \(Y\) can be expressed as [20]

\[
Y = -1.297 + 9.516 \left(\frac{S}{2R}\right) - 0.47 + 16.457 \left(\frac{S}{2R}\right)(\alpha_a)
+ \left[1.071 + 34.401 \left(\frac{S}{2R}\right)\right] \alpha_a^2,
\]  

(5)

where \(\alpha_a\) denotes the dimensionless crack length, \(\alpha_a = a/R = 0.20\).

As presented in Figure 9, there is an obvious negative linear correlation between KICS and DE. KICS decreases from 1.08 (DE = 0) to 0.59 MPa-m0.5 (DE = 0.368), which indicates a decrease in the ability of marble to resist fracture failure. The main reason is that the damage area or weak interface inside the specimen increases with the increase of...
Based on the least energy principle of rock failure, the main crack will choose the path with the least energy consumption to propagate forward when the specimen is fractured. Therefore, the greater the DE of the specimen is, the smaller the KICS is.

5. Experimental Results of the Dynamic Three-Point Bending Test

Because the specimen reached the dynamic force equilibrium state during the dynamic loading period (Figure 4), the history of mode I stress intensity factor \( K_I(t) \) can be expressed as [24]

\[
K_I(t) = \frac{P_d(t)S}{BR^{3/2}} Y(\alpha_s),
\]

where \( P_d(t) \) is the dynamic force applied on the specimen and \( Y(\alpha_s) \) is a dimensionless function. For \( aS = S/2R = 0.50 \), \( Y(\alpha_s) \) can be calculated as follows [24]:

\[
Y(\alpha_s) = 0.5037 + 3.4409\alpha_s - 8.0792\alpha_s^2 + 16.489\alpha_s^3.
\]

The peak value of \( K_I(t) \) curve is defined as the dynamic fracture toughness KICD of the specimen. It can be seen from Figure 9 that KICD exhibits a decreasing trend from 1.46 (DE = 0) to 0.58 MPa·m\(^{0.5}\) (DE = 0.370). Compared with the KICD of group CJ0 (KICD = 1.67 MPa·m\(^{0.5}\)) (Table 3), the KICD of group CJ5 decreases by 65.27%.

**Figure 8:** Load-displacement curves and impacted surfaces of the specimens. (a) The typical load-displacement curves. (b) Comparison of the impacted surfaces.

**Figure 9:** Relationship between the fracture toughness and DE. Note: In Figure 9, when DE is 0, it corresponds to the experimental data of group CJ1. The meaning represented in Figures 13 and 14 are the same.
6. Analysis of the Failure Patterns

6.1. Failure Patterns. Figure 10 displays the typical failure patterns of NSCB specimens after being subjected to static and dynamic three-point bending tests. Although the fracture processes of the specimens all extend from the crack tip to the loaded end, the failure patterns of the specimens with different impact numbers and loading rates are significantly different.

In terms of impact number, the crack paths of the specimens subjected to either static or dynamic three-point bending tests all behave more and more tortuous as the impact number increases. The main reason is that the greater the impact number, the more the damage area or weak interface inside the specimen and the greater the probability of the main crack encountering them. Based on the least energy principle of rock failure, the main crack will propagate forward by continuously changing the direction. Eventually, the crack paths behave more and more tortuous in the failure pattern.

In terms of loading rate, in the case of the same impact number, the crack paths of the specimens fractured by static three-point bending are more tortuous than those fractured by dynamic three-point bending. This is because the loading rate of the static three-point bending test is very small, the microcracks inside the specimen obtain the sufficient development, and the main crack has more time to choose the path that is easier to propagate.

6.2. Fracture Roughness Measurement. There are close relationships between the fracture roughness and the rock mechanical characteristics. Therefore, the quantitative characterization of the roughness of fracture surface is very necessary. In this study, the fracture surface morphologies of the specimens were detected by using a three-dimensional (3D) laser scanner. Based on the scanned data, the fracture surface morphologies can be reconstructed (Figure 11).

It can be found from some previous studies [25-27] that the average value of joint roughness coefficients (JRCs) of some unidirectional parallel 2D profiles selected from the fracture surface is regarded as the fracture roughness. However, the real fracture surface morphologies are 3D. To study the geometry of 3D fracture surface in depth, the spatial distribution characteristics of the fracture surfaces were quantitatively analysed [28]. Each 0.1 × 0.1 mm square area in Figure 11 is considered as an element, and each element has specific 3D spatial distribution parameters, which include asperity height, slope angle, and aspect direction.

Through statistical induction of the results, the frequency distributions of 3D spatial distribution parameters of the fracture surface mesh elements of the CJ0-Da specimen and CJ5-Sc specimen are shown in Figure 12. Figure 12(a) shows the histogram of the asperity height-frequency distribution, and the standard deviations (StDev) of CJ0-Da and CJ5-Sc are 0.4136 and 0.7746 mm, respectively. Figure 12(b) shows a histogram of the slope angle-frequency distribution, and the StDev of CJ0-Da and CJ5-Sc are 9.6119° and 12.1031°, respectively. Figure 12(c) shows a polar plot of the aspect direction-frequency distribution, and the StDev of CJ0-Da and CJ5-Sc are 102.492° and 105.752°, respectively.

Figure 13 presents the variations in StDev of 3D spatial distribution parameters with DE. As the DE increases, the StDev of all parameters show a two-stage growth trend, which indicates that the roughness of fracture surfaces increases gradually. In the range of DE from 0 to 0.369, the StDev of the asperity height shows an increase of 56.03% (static) and 39.87% (dynamic), and the StDev of the slope angle shows an increase of 26.57% (static) and 24.69% (dynamic), and the StDev of the aspect direction shows an increase of 2.68% (static) and 2.22% (dynamic). The StDev of 3D spatial distribution parameters of the surfaces fractured by static three-point bending are larger than those fractured by dynamic three-point bending; namely, the roughness of the surfaces fractured by static three-point bending is greater than that fractured by dynamic three-point bending.

Assuming that the fracture surface is continuous and differentiable, the area of the fracture surfaces is calculated via the following formula [26]:

\[ S_a = \frac{\int_{\text{surface}} \left( 1 + \left( \frac{\partial z}{\partial x}(x, y) \right)^2 + \left( \frac{\partial z}{\partial y}(x, y) \right)^2 \right)^{1/2} \, dx \, dy}{d^2} \]

\[ S_a \approx d^2 \sum_{i=1}^{N_x-1} \sum_{j=1}^{N_y-1} \left[ \left( \frac{z_{i+1,j} - z_{i,j}}{d} \right)^2 + \left( \frac{z_{i,j+1} - z_{i,j}}{d} \right)^2 \right] \]

(8)
where $S_{a}^{S}$ and $S_{a}^{D}$, respectively, denote the area of the surfaces fractured by static and dynamic three-point bending; $N_{x}$ and $N_{y}$, respectively, denote the number of points along the $x$ and $y$ axes; $d$ denotes the side length of mesh element planes; and $Z_{i,j}$ is the height of the point $(x_{i}, y_{j})$.

As shown in Figure 14, $S_{a}^{S}$ and $S_{a}^{D}$ all show a growing trend as DE increases. On the whole, the $S_{a}^{S}$ values are larger than the $S_{a}^{D}$ values, and the difference between them increases from 0.92% (DE = 0) to 2.36% (DE = 0.369). By fitting the experimental data, it is found that there are also good linear correlations between DE and $S_{a}^{S}$ and $S_{a}^{D}$ ($R^2 = 0.90$ and $R^2 = 0.87$).
Figure 11: Continued.
Figure 11: Reconstruction of the fracture surface morphologies. (a) CJ0-Sa. (b) CJ0-Da. (c) CJ1-Sb. (d) CJ1-Dc. (e) CJ3-Sc. (f) CJ3-Da. (g) CJ4-Sb. (h) CJ4-Da. (i) CJ5-Sc. (j) CJ5-Da.

Figure 12: Continued.
Figure 12: The frequency distributions of 3D spatial distribution parameters of fracture surface mesh elements of CJ0-Da and CJ5-Sc. (a) Asperity height. (b) Slope angle. (c) Aspect direction.

Figure 13: Variations in StDev of 3D spatial distribution parameters with DE. (a) Asperity height (b) Slope angle. (c) Aspect direction.
7. Conclusions

In this paper, cyclic impact loading tests were first performed to prepare a batch of dynamically damaged NSCB marble specimens. Then, static and dynamic three-point bending tests were performed on these specimens to study the variations of the fracturing properties. The main conclusions are as follows:

1. In the cyclic impact loading tests, Ed decreases gradually as the impact number increases, but DE exhibits a growing trend. In the static and dynamic three-point bending tests, when DE < 0.345, the KICD values are larger than the KICS values, and the difference between them decreases gradually with the increase of DE. But the experimental data exhibit the opposite results when DE ranges from 0.345 to 0.369. By fitting the experimental data, it is found that there are good linear correlations between DE and KICS and KICD.

2. Through the quantitative analysis of the fracture surface morphologies, the roughness and area of the fracture surfaces of the specimens increase as the DE increases. Under the same DE of the specimens, both the roughness and area of the surfaces fractured by static three-point bending are larger than those fractured by dynamic three-point bending.

Data Availability

Data supporting this research article are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] S. H. Li, W. C. Zhu, L. L. Niu, M. Yu, and C. F. Chen, "Dynamic characteristics of green sandstone subjected to repetitive impact loading: phenomena and mechanisms," Rock Mechanics and Rock Engineering, vol. 51, no. 6, pp. 1921–1936, 2018.
[2] F.-Q. Gong, X.-F. Si, X.-B. Li, and S.-Y. Wang, "Dynamic triaxial compression tests on sandstone at high strain rates and low confining pressures with split Hopkinson pressure bar," International Journal of Rock Mechanics and Mining Sciences, vol. 113, pp. 211–219, 2019.
[3] S. M. Yang, Y. S. Liu, K. Du, and J. Zhou, "Dynamic failure properties of sandstone under radial gradient stress and cyclical impact loading," Frontiers in Earth Science, vol. 7, pp. 1–10, 2019.
[4] N. Wu, Z. Zhu, C. Zhang, and Z. Luo, "Dynamic behavior of rock joint under different impact loads," KSCE Journal of Civil Engineering, vol. 23, no. 2, pp. 541–548, 2019.
[5] L. Chen, X. B. Mao, S. L. Yang, C. An, and P. Wu, "Experimental investigation on dynamic fracture mechanism and energy evolution of saturated yellow sandstone under different freeze-thaw temperatures," Advances in Civil Engineering, vol. 2019, Article ID 2375276, 16 pages, 2019.
[6] L. Y. Yu, Z. Q. Zhang, J. Y. Wu, R. C. Liu, H. Qin, and P. X. Fan, "Experimental study on the dynamic fracture mechanical properties of limestone after chemical corrosion," Theoretical and Applied Fracture Mechanics, vol. 108, Article ID 102620, 15 pages, 2020.
[7] M. Li, X. Mao, L. Cao, H. Pu, R. Mao, and A. Lu, "Effects of thermal treatment on the dynamic mechanical properties of coal measures sandstone," Rock Mechanics and Rock Engineering, vol. 49, no. 9, pp. 3525–3539, 2016.
[8] T. Han, J. Shi, and X. Cao, "Fracturing and damage to sandstone under coupling effects of chemical corrosion and freeze-thaw cycles," Rock Mechanics and Rock Engineering, vol. 49, no. 11, pp. 4245–4255, 2016.
[9] T. L. Han, J. P. Shi, Y. S. Chen, and X. S. Cao, "Salt solution attack-induced freeze-thaw mechanical degradation and its correlation with strength characteristic of mode-I fracture sandstone," International Journal of Geomechanics, vol. 20, no. 5, p. 21, Article ID 04020039, 2020.
[10] W. Hua, S. Dong, Y. Li, and Q. Wang, "Effect of cyclic wetting and drying on the pure mode II fracture toughness of sandstone," Engineering Fracture Mechanics, vol. 153, pp. 143–150, 2016.
[11] S. T. Miao, P. Z. Pan, P. Y. Yu, S. K. Zhao, and C. Y. Shao, "Fracture analysis of Beishan granite after high-temperature treatment using digital image correlation," Engineering Fracture Mechanics, vol. 225, Article ID 106847, 2020.
[12] M. Kataoka, Y. Obara, L. Vavro, K. Sourcek, S.-H. Cho, and S.-J. Jeong, "Effect of testing method type and specimen size on mode I fracture toughness of Kimachi sandstone," Journal of MMIF, vol. 135, no. 5, pp. 33–41, 2019.
[13] F.-Q. Gong, S. Luo, and J.-Y. Yan, "Energy storage and dissipation evolution process and characteristics of marble in three tension-type failure tests," Rock Mechanics and Rock Engineering, vol. 51, no. 11, pp. 3613–3624, 2018.
[14] M. N. Bagde and V. Petroi, "Fatigue properties of intact sandstone samples subjected to dynamic uniaxial cyclical loading," International Journal of Rock Mechanics and Mining Sciences, vol. 42, no. 2, pp. 237–250, 2005.
[15] D. J. Frew, M. J. Forrestal, and W. Chen, "Pulse shaping techniques for testing brittle materials with a split Hopkinson
pressure bar,” *Experimental Mechanics*, vol. 42, no. 1, pp. 93–106, 2002.

[16] K. Xia and W. Yao, “Dynamic rock tests using split Hopkinson (Kolsky) bar system - a review,” *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 7, no. 1, pp. 27–59, 2015.

[17] S. Luo and F. Q. Gong, “Experimental and numerical analyses of the rational loading waveform in SHPB test for rock materials,” *Advances in Civil Engineering*, vol. 2018, Article ID 3967643, 13 pages, 2018.

[18] Q. Ping, C. L. Zhang, H. P. Su, and H. Zhang, “Experimental study on dynamic mechanical properties and energy evolution characteristics of limestone specimens subjected to high temperature,” *Advances in Civil Engineering*, vol. 2020, Article ID 8875568, 12 pages, 2020.

[19] L. Y. Yu, A. Q. Fu, Q. Yin, H. W. Jing, T. Zhang, and H. Qin, “Dynamic fracturing properties of marble after being subjected to multiple impact loadings,” *Engineering Fracture Mechanics*, vol. 230, Article ID 106988, 22 pages, 2020.

[20] M. D. Kuruppu, Y. Obara, M. R. Ayatollahi, K. P. Chong, and T. Funatsu, “ISRM-suggested method for determining the mode I static fracture toughness using semi-circular bend specimen,” *Rock Mechanics and Rock Engineering*, vol. 47, no. 1, pp. 267–274, 2014.

[21] Z. L. Wang, H. H. Zhu, and J. G. Wang, “Repeated-impact response of ultrashort steel fiber reinforced concrete,” *Experimental Techniques*, vol. 37, no. 4, pp. 6–13, 2013.

[22] R. Ulusay, *The ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 2007-2014*, Springer International Publishing, Switzerland, 2015.

[23] K. P. Chong and M. D. Kuruppu, “New specimen for fracture toughness determination for rock and other materials,” *International Journal of Fracture*, vol. 26, no. 2, pp. R59–R62, 1984.

[24] Y. X. Zhou, K. Xia, X. B. Li et al., “Suggested methods for determining the dynamic strength parameters and mode-I fracture toughness of rock materials,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 49, pp. 105–112, 2012.

[25] N. Barton and V. Choubey, “The shear strength of rock joints in theory and practice,” *Rock Mechanics*, vol. 10, no. 1-2, pp. 1-54, 1977.

[26] T. Belem, F. Homand-Etienne, and M. Souley, “Quantitative parameters for rock joint surface roughness,” *Rock Mechanics and Rock Engineering*, vol. 33, no. 4, pp. 217–242, 2000.

[27] G. Rong, J. Yang, L. Cheng, and C. Zhou, “Laboratory investigation of nonlinear flow characteristics in rough fractures during shear process,” *Journal of Hydrology*, vol. 541, pp. 1385–1394, 2016.

[28] Q. Yin, R. Liu, H. Jing, H. Su, L. Yu, and L. He, “Experimental study of nonlinear flow behaviors through fractured rock samples after high-temperature exposure,” *Rock Mechanics and Rock Engineering*, vol. 52, no. 9, pp. 2963–2983, 2019.