Research Article
A New Rock Brittleness Evaluation Method Based on the Complete Stress-Strain Curve

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Brittleness is a crucial parameter of rock mass and the key indicator in rock engineering, such as rockburst prediction, tunnelling machine borehole drilling, and hydraulic fracturing. To solve the problem of using present brittleness indexes, the existing rock brittleness indexes were firstly summarised in this paper. Then, a brittleness index (BL), which considers the ratio of stress drop rate and stress increase rate and the peak stress, was proposed. This new index has the advantage of simplifying the acquisition of key parameters and avoiding dimensional problems, as well as taking the complete stress-strain curves into account. While applying the BL, the peak strain is used to describe the difficulty of brittle failure before the peak point, and the ratio of stress drop to strain increase can reflect the stress drop rate without dimension problem. In order to verify the applicability of BL, through the PFC2D, the microparameters and confining pressure were changed to model different types of rock numerical specimens and different stress condition. The results show that the BL can well reflect and classify the brittleness characteristics of different rock types and characterise the constraint of confining pressure on rock brittleness. Moreover, the influence of microparameter on macroparameter was studied. In order to further verify the reliability of the brittleness index (BL), this study conducted uniaxial and triaxial compression tests (30 MPa) on marble, sandstone, limestone, and granite under different confining pressure.

1. Introduction

Brittleness is the key parameter describing the rock failure and is a fundamental parameter in various fields, e.g., mining engineering, rock mechanics, unconventional oil, and hydraulic fracturing [1–10]. Nowadays, the definition for rock brittleness is proposed in different engineering fields. Morely [11] and Hetenyi [12] pointed out that brittleness could be characterised by low strain value or low elongation for lacking ductility or compressibility. Howell [13] thought that brittleness was a performance of rock fracture with low plastic deformations. Ramsay [14] defined brittleness as the loss of cohesion in the elastic range. Similarly, Obert and Duvall [15] investigated the cast iron and rock and then defined brittleness to be a phenomenon of rock breaking or current stress slightly exceeding the yield stress. Tarasov and Potvin [16] pointed out that brittleness was a manifestation of the phenomenon to self-maintain the macroscopic damage after peak point due to the accumulation of elastic energy. Li et al. [17] pointed out the rock brittleness was a property that can well reflect the ability of local damages to develop to space fractures. Kuang et al. [18] proposed that brittle rock mass was easy to suddenly show fractures under external loads with small inelastic deformations. Nowadays, numerous studies [4, 8, 19–32] have shared the view about rock brittleness, and its property can be observed: (1) fracture failures; (2) intensive failure process, crack propagation in a self-sustaining way without external driving; (3) lower strain deformation of grain under loading; (4) higher stress drop rate of postpeak curves; (5) elastic energy abrupt release after peak point; (6) higher resilience; (7) formation of fines and cracks in indentation; and (8) higher angles of internal friction.

During assessing rock brittleness, the brittleness index is crucial for evaluating the risks of rockburst, determining the excavation production of shale gas and oil, assessing the excavation efficiency of the TBM shield tunnelling machines, and so on [33–38]. Nowadays, various rock brittleness
indexes are proposed by different researchers from many perspectives, such as strength, stress-strain, mineral composition, hardness, inner friction angle, Poisson’s ratio, and elastic modulus as shown in Table 1 [1, 3, 7, 16–19, 39–43].

As shown in Table 1, the brittleness indexes $B_1$-$B_4$ are proposed, which is based on uniaxial tensile and UCS strength [3]. Considering the compressive-tensile strength curve, the brittleness indexes $B_3$ and $B_4$ are put out to evaluate the brittleness of rocks quantitatively [1]. The brittleness index $B_5$ is proposed by Qinghui et al. based on three coefficients of postpeak stage, but it is only suitable for a certain rock mass; besides, to obtain accurate value, many experiments are needed [44]. The brittleness indexes $B_6$ and $B_7$ are proposed by Tarasov and Potvin based on elastic modulus and the postpeak modulus [42]. The brittleness indexes $B_8$ and $B_9$ are put forward considering the peak stress-strain and the residual stress-strain [39]. Hucka and Das [19] pointed out brittleness index $B_{10}$ using the ratio of the recoverable strain to the peak strain, while a few parameters are taken into consideration. Meng et al. [41] put forward the brittleness index $B_{11}$ by taking the postpeak stress drop and the relative magnitude into account, and the accuracy of the brittleness index $B_{11}$ is verified through confining pressure experiment. But it cannot reflect the mechanical characteristics of prepeak stress-strain curves.

Chen et al. [40] put forward a brittleness index $B_{12}$, which is based on the stress growth rate between the prepeak initiation stress and the peak stress and the postpeak stress drop rate. Before the peak point, the brittle is characterised by the stress growth rate from the initiation point to the peak point, while there are two effective ways to obtain the initiation stress, including the inflexion point of the crack volume strain and acoustic emission [45]. In fact, acoustic emission is often affected by noise, which has a great influence on the accuracy at the moment of crack initiation. The other method is depending on the mineral composition and particle size, but the accurate value is often difficult to obtain.

![Figure 1: Simplified stress-strain curve.](image)

Kuang et al. [18] suggested the brittleness index $B_{14}$ considering the postpeak stress decrease rate, peak stress, and stress increase rate from the crack initiation point to the peak point. In this paper, different stress-strain curves were used to obtain the prepeak brittleness index considering the prepeak stress rate and the peak strain; the peak strain and prepeak stress rate were used to characterise the prepeak brittleness. However, the crack initiation strain is hard to be determined as mentioned above, and it is inaccurate to use the peak strain for the brittleness of postpeak stress. In actual engineering, the peak strength of different rock specimens is quite different, which means the unit of the stress is not uniform. Thus, the brittleness index should avoid the influence of dimensional, which is overcome by using the ratio of stress drop to strain increase in this study.

Based on the rock fracture angles, the brittleness indexes $B_{15}$ and $B_{16}$ were proposed by Hucka and Das [19] and Tarasov and Potvin [42]; more attention should be paid to apply it to differentiate rock type. At the same time, the accurate rock fracture angle is often hardly to obtain, limiting the development of the brittleness indexes $B_{15}$ and $B_{16}$. 

### Table 1: Overview of the commonly used brittleness indexes.

| Experiment methods | Formula meaning and explanation |
|--------------------|---------------------------------|
| $B_i = \sigma_i/\sigma_p$, $B_2 = (\sigma_i - \sigma_p)/(\sigma_i + \sigma_p)$, $B_3 = \sigma_i/\sigma_p$, $B_4 = \sqrt{B_3}$ |
| $B_5 = B_1 B_3$, $B_6 = (\epsilon_B - \epsilon_\eta)/(\epsilon_\eta - \epsilon_\eta)$, $B_7 = aCS + \beta CS + \eta c \ CS = \epsilon_p (\sigma_p - \sigma_r)/\sigma_p/\epsilon_p - \epsilon_p$ |
| $B_8 = (\sigma_p - \sigma_r)/\sigma_p$, $B_9 = (\epsilon_p - \epsilon_r)/\epsilon_p$, $B_{10} = \epsilon_r/\epsilon_p$ |
| $B_{11} = B_{11} B_{12}$, $B_{11} = (\sigma_p - \sigma_r)/\sigma_p$, $B_{11} = \log |\mu|/10$ |
| $B_{12} = B_{13} + B_{14}$, $B_{13} = (\sigma_p - \sigma_r)/(\epsilon_p - \epsilon_r)$, $B_{12} = (\sigma_p - \sigma_r)/(\epsilon_r - \epsilon_r)/(\epsilon_p - \epsilon_r)$ |
| $B_{14} = B_{14} B_{15}$, $B_{14} = (\sigma_p - \sigma_r)/(\epsilon_p - \epsilon_r)$, $B_{14} = (\sigma_p - \sigma_r)/(\epsilon_p - \epsilon_r)$ |
| $B_{15} = \sin \theta$, $B_{16} = 45^\circ + \theta/2, \theta$ |
| $B_{17} = 0.5E_{\text{brit}} + 0.5P_{\text{brit}}$, $E_{\text{brit}} = (E - 1)/(8 - 1) \times 100$, $P_{\text{brit}} = (0.4 - 1)/(0.4 - 0.15)$ |
| $B_{18} = (H_p - H_m)/c$, $B_{19} = H_p/K_c$, $B_{20} = H_p E/K_c^2$ |
| $B_{21} = W_{\text{Qz}}/(W_{\text{Qz}} + W_{\text{Carb}} + W_{\text{Clay}})$ |
Rickman et al. [7] proposed the brittleness index \( B_{17} \) to evaluate the shale reservoir, which is located in the Fort-Worth Basin, North America. However, the brittleness index \( B_{17} \) only considers the influence of Poisson’s ratio and the elastic modulus, and more important parameters, such as residual strain, peak strength, and residual strength, are ignored. Besides, many experiments are needed to guarantee the accuracy of parameters.

The brittleness index \( B_{19} \) was proposed by Hucka and Das [19] based on the difference in hardness between the macroindentation and the microindentation. Lawn and Marshall [46] put forward the brittleness index \( B_{19} \) in ceramic engineering. \( H_p \) is the hardness of the ceramic material, representing the quantification of the resistance to deformation. \( K_t \) is the fracture toughness, which is resistant to fracture. Qinghui et al. [44] proposed a method to evaluate rock brittleness considering the influence of postpeak curves stage described by \( B_{20} \). While these indexes just needed to take a few factors into account, their applicability still needs to be considered further.

\( B_{21} \) is proposed to evaluate the shale brittleness in the shale gas drilling industry [6], which only takes the effect of mineral content into account but ignores the effect of the stress state and diagenesis. With the development of stress, the rock changes from a state of brittleness to ductility; then, different porosity, compactness, and porosity will be formed in the rock, which has a large impact on the brittleness. Thus, these conditions limit the development of the brittleness index \( B_{21} \).

Previous studies have demonstrated that the accurate evaluation of rock brittleness requires many parameters and achieve well application in different areas. Compared with other brittleness indexes, the brittleness index based on the stress-strain curves, which is easier to be obtained and quantified, is adopted in this study. In addition, these existing brittleness indexes are put forward for their own engineering backgrounds, which means high pertinence and poor application. In actual engineering project, the accuracy obtained of rock brittleness is important to determine the construction design, which has great significance for reducing the risk of rockburst and spalling hazards. Therefore, the characteristics of prepeak and postpeak in stress-strain curves, as well as full stress-strain curves, are considered in this study. Based on this, by considering the difficulty of prepeak brittle failure and the stress drop rate, a new brittleness index \( B_{1} \) was proposed; it has the advantage of innovatively simplifying the acquisition of key parameters and considering the complete stress-strain curves and avoiding the dimensional problems. During application of the \( B_{1} \), the peak stress is used to describe the different degree of brittle failure before the peak points, and the ratio of stress drop to strain increase describes the stress drop rate with dimension problem. In fact, the mechanical properties of rock specimens are different, even those rock specimens taken from the same location. Besides, the brittleness difference based on the stress-strain curves is hard to be determined.

Due to these limitations, the control variable method was used to construct numerical models with different microparameters in PFC2D, in which the brittleness differences are easy to be confirmed. The results are used to verify the accuracy and applicability of the brittleness index \( B_{1} \). Due to the complexity of rock specimens, uniaxial and triaxial compression tests were performed on marble, sandstone, limestone, and granite samples. The change law of rock brittleness was also analysed based on the rock fracture feature.

2. Rock Evaluation Method Based on the Complete Stress-Strain Curve

Based on the above analyses, the stress-strain curves are used to propose a new method. The simplified stress-strain curves are shown as Figure 1 [43].

In Figure 1, the stress-strain curve is simplified as the polyline, which the point \( A (\sigma', \varepsilon') \) is the peak point, and the point \( B (\sigma, \varepsilon) \) is the residual point. As shown in Figure 1, the polyline \( OABC \) can be divided by the points \( A \) and \( B \), respectively, and the corresponding mechanical parameters can be easily obtained.

According to Kuang et al., the peak strain and the increase rate from initiation point to peak point are the key factors of prepeak brittle characteristics [18]. And the peak strain is regarded as the relative magnitude of inelastic
deformations. Moreover, peak strain can represent the difficulty of brittle failure [17]. Due to the limitation of determining the initiation point, the peak strain was used to reflect the change of the prepeak brittle degree. Therefore, the prepeak brittleness index $B_{L_1}$ should be inversely proportional to the peak strain.

Firstly, the brittleness index of prepeak stage could be defined as

$$B_{L_1} = \frac{1}{\varepsilon_p}.$$  \hspace{1cm} (1)

The brittle characteristics of postpeak stages are important for evaluating the rock mass brittleness, and various brittleness indexes are proposed based on the postpeak stage of stress-strain curves. Among them, the brittleness indexes $B_8$ and $B_9$ are commonly used, which consider the stress drop and the strain increase, respectively, while it has the limitation, shown as Figure 2.

As shown in Figure 2(a), the OAB, OAC, and OAD represent different rock specimens. Due to the brittleness characteristics of postpeak stage, the brittleness of OAB is higher than the brittleness of OAC and OAD. But, the brittleness values of OAB, OAC, and OAD, which are calculated by the brittleness index $B_8$, are the same. It is mainly because the influence of strain changes is ignored. Similarly, in Figure 2(b), the brittleness of OAB should be higher than the OAC and OAD. But the calculated results of the brittleness for the OAB, OAC, and OAD are the same, because the influence of stress change is not considered. Therefore, due to the limitation of the brittleness indexes $B_8$ and $B_9$, $B_{L_2}$ was proposed in this study to reflect the change of the brittle degree, which considers the stress drop rate $B_8$ and the strain increase rate $B_9$. It is worth noting that the interference of dimension is avoided. And the brittleness index $B_{L_2}$ should be proportional to the stress drop rate and inversely proportional to the strain increase rate. Secondly, the postpeak brittleness index $B_{L_2}$ can be expressed as follows:

$$B_{L_2} = \frac{\sigma_p - \sigma_f}{\varepsilon_r - \varepsilon_p}.$$  \hspace{1cm} (2)

Thus, the new rock brittleness index $B_L$ can consider the brittle characteristics of the complete stress-strain curves. Finally, the brittleness index $B_L$ is shown as follows:

$$B_L = B_{L_1} \times B_{L_2} = \frac{(\sigma_p - \sigma_f)}{\sigma_p (\varepsilon_r - \varepsilon_p)}.$$  \hspace{1cm} (3)

![Figure 3: The stress-strain curves obtained by experiment and by numerical simulation.](image)

![Figure 4: Unconfined compressive test (cracks described by red lines).](image)

![Figure 5: Stress-strain curves under different parallel bond modulus.](image)
Due to the complexity and diversity of rock specimens, this study takes the control variable method to obtain different numerical specimens; the stress-strain and rock fracture feature will be similar, making it easier to determine the brittleness difference of different numerical specimens. In this way, the application and accuracy of the brittleness index can be well verified.

3. Numerical Modeling with PFC

3.1. The Determination of Microparameters. The appropriate microparameters are critical to achieving a good simulation result. It is worth noted that the microparameters of PFC are not the same as the macromechanical parameters of rock materials; there is no specific corresponding relation between microparameters and macromechanical. Then, the “trial and error” process was adopted. Figure 3 shows the comparison of stress-strain curves of experiment results and simulation results through the “trial and error” method.

Similarly, the final failure modes of the numerical specimens and that of indoor tests are shown in Figure 4.

As shown in Figures 3 and 4, the final failure models of the numerical specimen and experimental specimen were both splitting failure, whose shape and length were relatively close. This furtherly proves that the orthogonal experiment is correct. The elastic modulus, Poisson’s ratio, and the peak strength of numerical specimen and experiment specimen were 20.45 GPa (20.34 GPa), 0.16 (0.17), and 70.68 MPa (71.05 MPa), respectively.

During application of PFC, the size of the model and the particle contact parameters are involved. In this paper, the method of controlling variable was used to simulate different types of rock specimens. In order to guarantee the numerical model consistent with the physical test, the specimen with the size of 50 mm × 100 mm was made, and the porosity (n) was set as 0.16, the bulk density was 2800 kg/m³, the minimum particle size was set as 0.4 mm, and the ratio of the maximum particle size to the minimum particle size (Rmax/Rmin) was set as 2. Moreover, the parallel bond modulus (pb_emod) was set as 40 GPa, the particle stiffness ratio was 2.0, the parallel bond strength and parallel shear strength were both set as 6.0 MPa, and the friction coefficient was set as 0.4. Considering the mechanical characteristics of rock is affected by the confining pressure, the confining pressure in the simulation was set as 5 MPa to fit the actual stress state.

Considering the influence of mesoscopic parameters, the parallel bond modulus (pb_emod), the parallel bond (pb_coh), and the friction coefficient were all calibrated in this manuscript. Because the rock brittleness is affected by the confining pressure, different confining pressure was applied to simulate the different stress conditions of rock specimens.
3.2. The Influence of Mesoparameters on Mechanical Macroparameter

3.2.1. Parallel Bond Modulus. The parallel bond modulus (pb_emod) is set as 20 GPa, 30 GPa, 40 GPa, and 50 GPa while keeping other mesoscopic parameters and the confining pressure (5 MPa) unchanged. The stress-strain curves obtained from simulation are shown in Figure 5.

It can be seen that the peak strain and the peak stress increase as the parallel bond modulus increases. As mentioned before, the peak strain can reflect the difficulty of brittle failure, which means in the prepeak stage of stress-strain curves, the brittleness decreased as the parallel bond modulus increases [17]. In the postpeak stage, the residual stress and residual strain decrease as the parallel bond modulus increases, as well as the stress drop rate increases. Therefore, in the postpeak stage, the brittleness of the numerical specimen will decrease as the parallel bond modulus increases. For the numerical core (d), its yield stage was longer than other numerical cores with strong ductility. As for the numerical specimens (b) and (c), they were in the stage of transition from ductility to brittleness, and its brittleness was lower than the brittleness of numerical core (a). Therefore, considering the prepeak and postpeak brittleness characteristics of the numerical specimens, the brittleness degree of numerical specimens increases as the parallel bond modulus increases.

Based on the stress-strain curves in Figure 5, the mechanical parameters and the brittleness index $B_L$ were calibrated and calculated in Table 2, and the variations of the brittleness index $B_L$ with parallel bond modulus are plotted in Figure 6. As for the postpeak stage, when the parallel bond modulus is 20 GPa, the brittleness of numerical specimen (d) is significantly lower than other numerical specimens. And the calculated results of brittleness index $B_L$ should reflect the brittle characteristics of numerical specimen (d).

As shown in Figure 6, it can be obtained that the value of $B_L$ increases as the parallel bond modulus increases, and when the parallel bond modulus was set as 20 GPa, the value of $B_L$ was apparently lower than other numerical specimens, which verifies the accuracy and application of brittleness index $B_L$. It is mainly because that particles become more and more incompressible as the parallel bond modulus increases, and they are more likely to slide rather than compress each other, resulting in more macroscopic fracture surfaces.

3.2.2. Parallel Bond Strength. The parallel bond strength (pb_coh) was set as 12 MPa, 9 MPa, 6 MPa, and 3 MPa, while keeping other mesoscopic parameters and confining pressure unchanged. The stress-strain curves were obtained and shown in Figure 7.

As the parallel bond strength increases, the elastic modulus is the same. The peak stress and peak strain of specimens (a)–(c) were the same but differ from the specimen

Table 3: The mechanical parameters and the brittleness index of different parallel bond strength.

| Parallel bond strength/MPa | Elastic modulus (GPa) | Poisson’s ratio | Peak stress/MPa | Peak strain/10$^{-3}$ | Residual stress/MPa | Residual strain/10$^{-3}$ | $B_L$ |
|---------------------------|----------------------|----------------|-----------------|-----------------------|-----------------------|--------------------------|------|
| 3                         | 20.42                | 0.144          | 35.86           | 1.76                  | 11.42                 | 3.94                     | 0.428 |
| 6                         | 20.42                | 0.173          | 56.48           | 2.14                  | 23.4                  | 4.26                     | 0.330 |
| 9                         | 20.42                | 0.173          | 77.04           | 2.35                  | 32.31                 | 4.8                      | 0.243 |
| 12                        | 20.42                | 0.204          | 96.16           | 2.56                  | 43.49                 | 5.34                     | 0.195 |

Figure 8: Variations of the brittleness index $B_L$ with parallel bond modulus.

Figure 9: Variations of the brittleness index $B_L$ with the friction coefficient.
(d), because the parallel shear strength \( (p_{b_{-ten}}) \) is set as 6 MPa. Thus, when \( p_{b_{coh}}/p_{b_{ten}} > 1 \), the changes of the parallel bond strength \( (p_{b_{coh}}) \) mainly led to change of postpeak stage stress-strain curves. By contrast, when the \( p_{b_{coh}}/p_{b_{ten}} < 1 \) \( (p_{b_{coh}} = 3 \text{ MPa}) \), the changes of parallel bond strength \( (p_{b_{coh}}) \) led to peak stress and peak strain reduction. Keeping the value of \( (p_{b_{ten}}) \) remained unchanged, and the changes of parallel bond strength \( (p_{b_{coh}}) \) did not lead to the change of elastic modulus.

According to stress-strain curves in the prepeak stage, the brittle degree of numerical specimens (a)–(c) are the same and lower than the numerical specimen (d). In the postpeak stage, the residual stress and residual strain of the numerical specimens (a) to (d) are gradually decreasing, and the order of the stress drop rate of the specimens (a)–(c) was \( c > b > a \). As for specimens (c) and (d), the stress drop rates are 0.579 and 0.612, respectively. Referring to the complete stress-strain curves, the order of numerical specimens’ brittle degree was determined to be \( d > c > b > a \).

Based on the stress-strain curves in Figure 7, the brittleness index \( B_L \) and the mechanical parameters were determined and calculated in Table 3 and Figure 8.

It can be obtained from Figure 8 that the brittleness index \( B_L \) decreases as the parallel bond modulus increases, which well reflect the brittle degree of different numerical specimens.

As for the constitutive model, the cohesive force between the particles increases with the parallel bond strength, as well as the interaction force between the particle and the duration of the yield stage during loading. Therefore, the degree of brittle decreases with the parallel bond strength.

3.2.3. Friction Coefficient. While keeping other mesoscopic parameters and confining pressure unchanged, the friction coefficients \( (f) \) were set as 0.8, 0.6, 0.4, and 0.2. The stress-strain curves are shown in Figure 9.

It can be obtained that as the friction coefficient increased, the slope of the stress-strain curve in the prepeak stage increased significantly, so did the elastic modulus (Figure 9). At the same time, the peak stress increases while the peak strain showed a decreasing trend. As for the mechanical characteristics in the postpeak stage, with the increase of the friction coefficient, the stress drop rate increases, reflecting the transition from ductility to brittleness. Referring to the complete stress-strain curves, the brittle degree of specimens increased with the friction coefficient. Compared with numerical specimens (a)–(c), the yield stage and peak strain of numerical specimen (d) were significantly increased. Thus, the brittleness index of specimen (d) should be lower than other specimens. It needs to be noticed that the stress-strain curves of different specimens become similar as the friction coefficient increases, indicating the brittle characteristics are becoming closer. Therefore, it can be inferred that as the friction coefficient increases, the brittleness index of different numerical specimens decreases.

Table 4: The mechanical parameters and the brittleness index of different friction coefficient.

| Friction coefficient | Elastic modulus (GPa) | Poisson’s ratio | Peak stress/MPa | Peak strain/10^{-3} | Residual stress/MPa | Residual strain/10^{-3} | \( B_L \) |
|----------------------|----------------------|----------------|-----------------|---------------------|----------------------|-----------------------|--------|
| 0.2                  | 14.27                | 0.14           | 28.23           | 1.98                | 11.41                | 4.14                  | 0.232  |
| 0.4                  | 20.42                | 0.16           | 35.86           | 1.76                | 11.93                | 3.37                  | 0.414  |
| 0.6                  | 25.56                | 0.17           | 39.62           | 1.55                | 14.85                | 2.82                  | 0.492  |
| 0.8                  | 29.67                | 0.20           | 43.52           | 1.47                | 13.12                | 2.75                  | 0.546  |

Figure 10: Variations of the brittleness index \( B_L \) with the friction coefficient.

Figure 11: Stress-strain curve of numerical specimens under different confining pressure.
specimens should increase more and more slowly. Based on Figure 9, the brittleness index $B_L$ and the mechanical parameters were determined and calculated in Table 4 and Figure 10.

It could be obtained from Figure 10 that the brittleness index $B_L$ increases as the friction coefficient increases, which is highly consistent with the brittle differences among different numerical specimens mentioned before. Meanwhile, as the friction coefficient increased, the increase rate of $B_L$ became slow, verifying the application and accuracy of $B_L$.

3.3. The Influence of Confining Pressure on Mechanical Macroparameter. The confining pressure was set as 20 MPa, 15 MPa, 10 MPa, and 5 MPa while keeping mesoscopic parameters unchanged. The stress-strain curves of simulation are shown in Figure 11.

It can be easily obtained that the brittleness decreases as the confining pressure increases, which is consistent with the actual situation. Based on the stress-strain curves in Figure 11, the mechanical parameters and the brittleness index $B_L$ were determined and calculated in Table 5 and Figure 12.

As shown in Figure 13, the elastic modulus, peak stress, and peak strain all increased as the confining pressure increases. In the postpeak stage, as the confining pressure increases, the residual stress and the residual strain increase while the stress drop rate decreases, which means the brittle degree of numerical specimens decreases as the confining pressure increases. The variation of brittleness index $B_L$ can well reflect the fluctuation of rock brittle. And the results show a linear relationship between the brittleness index $B_L$ and the confining pressure.

4. The Performance of the Evaluation Method under Uniaxial Compression and Triaxial Compression

4.1. Uniaxial Compression. In order to further verify the scope of application of the brittleness index $B_L$ in this study,
Table 6: Uniaxial compression test data of rock samples with different lithologies.

| Rock specimens | $\sigma_p$/MPa | $\epsilon_p/10^{-3}$ | $\sigma_r$/MPa | $\epsilon_r/10^{-3}$ | $B_8$ | $B_9$ | $B_{11}$ | $B_{12}$ | $B_L$ |
|----------------|----------------|----------------------|----------------|----------------------|-------|-------|-------|-------|-------|
| Marble         | 57.892         | 3.839                | 7.83           | 5.47                 | 0.865 | 0.425 | 0.042 | 0.674 | 0.530 |
| Sandstone      | 108.631        | 5.34                 | 0.795          | 5.763                | 0.993 | 0.079 | 0.140 | 2.628 | 2.347 |
| Limestone      | 168.32         | 2.436                | 6.033          | 2.734                | 0.964 | 0.122 | 0.167 | 5.564 | 3.235 |
| Granite        | 214.496        | 3.389                | 0.736          | 3.478                | 0.997 | 0.026 | 0.237 | 24.04 | 11.197 |

Figure 15: Changes in brittleness index of four rock samples under uniaxial compression.
four different lithologies, including marble, sandstone, limestone, and granite, were selected to conduct uniaxial compression experiments. These rocks were processed into a standard specimen, which the height and the diameter are set as 100 mm and 50 mm, respectively. The stress-strain curves and results of four kinds of rocks under uniaxial compression are shown as Figures 13 and 14.

As shown in Figure 14, limestone, granite, and sandstone mainly occurred tensile failure, and their failure nearly penetrates; this is a kind of strong brittle characteristics. As for the marble, the failure form is mainly the shear failure with weak brittleness. Among the four groups of rocks, granite happened to be the complete test destruction, its fracture angle was close to 90°, and the fracture surface was relatively rough. Moreover, this fracture surface penetrates the entire rock mass, and the top is nearly fractured, which is more severe than the other three. Therefore, the brittleness of granite should be higher than other three specimens. As for limestone, the fracture surface also penetrates the entire rock sample, and the slag after the failure can be seen at the bottom. However, the fracture surface of the limestone is not as rough as granite, and the degree of damage is also slightly lower, as well as the fracture angle, indicating the brittleness of limestone is lower than that of granite. For sandstone, the damage degree and roughness of the fracture surface is obviously lower than that of limestone. The fracture surface of sandstone does not penetrate the entire rock mass, but there exists obvious cracking on the top. For marble, its brittleness is lower than that of the other three groups of rock samples, its damage degree is the lowest, only local spalling damage occurred, and its fracture surface does not penetrate the entire rock mass. Compared with sandstone, the roughness of the fracture surface and fracture angle of the marble was lower. After the failure, the marble shows good integrity without serious damage. Therefore, it can be concluded that the order of the brittleness of the rock samples should be the following: granite > limestone > sandstone > marble.

In this paper, several groups of commonly used methods based on stress-strain curves were selected to further compare the difference between the brittleness index \( B_L \) and other brittleness indexes. Based on the stress-strain curves (Figure 13), the detailed data and calculation results are shown in Table 6 and Figure 15.

It could be seen from Figure 15 that the brittleness indexes \( B_{13}, B_{11}, \) and \( B_{12} \) can all reflect the difference in brittleness of the four different rock specimens. In this study, the order of brittleness of the rock specimens is marble < sandstone < limestone < granite. However, the brittleness index \( B_8 \) cannot reflect the brittle degree changes. It is because that the brittleness index \( B_8 \) only considers the influence of stress change, and this makes the result not accurate enough. As for the brittleness index \( B_9 \), it can basically reflect the brittleness changes among different rock specimens but fails to quantify the difference in brittleness of different rock specimens. This may because the brittleness index \( B_9 \) only considers the influence of the peak stress and residual stress rather than the postpeak stress drop rate. The brittleness index \( B_{11} \) can reflect the difference in brittle degree of different rock specimens very well, but its value only varies within a small range, so it cannot measure the brittle degree changes of different rocks accurately. The brittleness indexes \( B_{13} \) and \( B_{12} \) can reflect the brittle degree changes of different rock specimens more accurately.

4.2 Conventional Triaxial Compression. In order to further evaluate the accuracy of the brittleness index \( B_1 \) of different rocks under the impact of confining pressure, a series of conventional triaxial compression tests were performed on granite, sandstone, limestone, and marble under the confining pressure of 30 MPa. Figure 16 shows the stress-strain curves of 4 different lithologies under the confining pressure of 30 MPa, and it can be seen that compared with the rock specimens under uniaxial compression, the brittle degree and the postpeak stress drop rate of granite, limestone, and sandstone were significantly reduced. And the experiment results of different rock specimens under confining pressure are shown as Figure 17.

Previous studies found that as the brittleness of the rock increases, the more complete the destruction, the rougher the fracture surface, and the greater the fracture angle. As
shown in Figure 17, the damage of granite was the most serious, and the fracture surface was very rough, which penetrates the entire rock mass with the fracture angle of 90°, and the upper part of the rock mass is cracked and uplifted. Therefore, brittleness of granite is the highest compared to the other three groups of rocks.

Figure 18: Comparison of the brittleness indexes under confining pressure.

The damage of limestone is mainly in the form of shearing failure and splitting failure, and there are obvious splitting cracks in the middle of the rock sample. From Figure 17, it can be clearly seen that the fracture surface of the limestone also penetrated the entire rock mass with a fracture angle of around 90°. At the same time, the bottom
of the rock sample is uplifted. Therefore, the brittleness of limestone and granite should be higher than that of sandstone and marble. For sandstone and granite, the fracture surface of granite is rougher, and the fracture width is larger, so the brittleness of granite is higher than that of limestone.

The damage of sandstone is mainly induced by the partial cracks of the rock sample; the fracture surface with the small width of fissure does not penetrate the entire rock mass, and only a small amount of rock on the top of the rock specimens is broken. For marble, after the triaxial compression test, the marble rock sample exhibited bulging as a whole without obvious cracks, which is considered to be a relatively obvious ductile failure. In summary, the order of brittleness of the rock sample should be granite>limestone>sandstone>marble.

Based on the stress-strain curve in Figure 16, the relevant mechanical indicators are determined, and the brittleness indexes $B_8$, $B_9$, $B_{11}$, $B_{12}$, and $B_{1}$ are calculated. The detailed mechanical parameters and brittleness index are shown in Table 7 and Figure 18.

As shown in Figure 18, the brittleness indexes of $B_8$, $B_9$, $B_{11}$, $B_{12}$, and $B_{1}$ can basically reflect the brittle degree changes, which is consistent with the above analysis. As for $B_9$, it cannot reflect the actual situation due to the limitation of only considering the effect of the peak strain and residual strain. Meanwhile, according to experiment results above, the brittleness of sandstone should be higher than that of marble, which is not consistent with the brittleness index $B_{12}$. While the values of brittleness index $B_9$ are similar, this is inconsistent with the actual experimental results. In a word, the brittleness indexes $B_{11}$ and $B_{12}$ can well evaluate the change of the brittleness degree for different lithology under triaxial compression, but the value of brittleness index $B_{11}$ for the marble is lower than 0, and it is not in line with consensus. In particular, the units of stress and strain are MPa and %, respectively, which may limit the application of brittleness index $B_{11}$. But the brittleness index $B_{12}$ can well avoid the influence of unit inconsistency; this also verifies the application and accuracy of $B_{12}$.

5. Conclusion and Suggestion

In rock engineering, the accurate result of rock brittleness has great significance in hydraulic fracturing and rockburst prediction fields. In this study, firstly, some commonly used brittleness indexes were analysed and summarised in detail. Then, a brittleness evaluation method $B_1$ based on the complete stress-strain curve was proposed. Due to the complexity and variety of rock specimens, the PFC2D was adopted to build different numerical specimens to obtain the brittle difference of different numerical specimens by using the method of variable control. The numerical simulation results well verified the accuracy and application of the brittleness index $B_1$. Finally, conventional triaxial tests and uniaxial tests were performed on marble, sandstone, limestone, and granite specimens to reflect the advantage of the new proposed brittleness index. The main conclusions can be drawn as follows:

(1) This study proposed a new brittleness index $B_1$ based on peak strain and the ratio of the stress drop rate to the strain increase rate; it can be easily obtained and well avoided the influence of dimensional. The feasibility of the brittleness index is well proven by theoretical analysis.

(2) The brittleness index $B_1$ can well reflect the phenomenon of brittleness degree decreasing with the confining pressure. Besides, using the method of variable, controlling to construct different numerical specimens can help judge the brittleness difference between different numerical specimens, verifying the accuracy and consistency of brittleness index $B_1$.

(3) As the parallel bond modulus increases, the brittleness of numerical specimens decreases, while the decrease rate becomes low. It may be because that the particle becomes more incompressible as the parallel bond modulus increases; thus, the specimens more easily occur failure. Particles are more likely to slide rather than compress each other, resulting in more macroscopic fracture surfaces and increases brittle degree. The brittleness of numerical specimens decreases as the parallel bond strength (pb_coh) increases. When the $\text{pb_coh}/\text{pb_ten}$ (parallel shear strength) $> 1$, the change of parallel bond strength (pb_coh) mainly influences the postpeak brittle characteristic. When the $\text{pb_coh}/\text{pb_ten} < 1$, the change of pb_coh will lead to the change of prepeak characteristics.

(4) The brittleness indexes $B_{11}$, $B_{12}$, and $B_{1}$ can well reflect the actual experimental results. However, the brittleness $B_8$ can basically reflect the trend of brittleness change but fails in quantifying the brittleness difference among different rock specimens. Moreover, the brittleness $B_9$ has lower consistency with the experimental results, and it cannot reflect the change of brittleness. The brittleness indexes $B_{11}$ and $B_{12}$ can well reflect the change of brittleness of rock specimens in different lithology. The brittleness index $B_{12}$ can basically reflect the change of brittleness.

**Symbols**

- $\sigma_i$: The tensile strength
- $\sigma_p$: The peak strength
- $\sigma_r$: The residual strength
- $\sigma_c$: The crack initiation stress
- $\varepsilon_i$: The crack initiation strain
- $\varepsilon_m$: Reference value of the minimum peak strain
- $\varepsilon_m$: Reference value of the maximum peak strain
- $\alpha, \beta, \gamma$: Are all the standardised coefficients
- $E$: The elastic modulus
- $\theta$: The inner friction angle

Symbols
Data Availability

The data, which is used to support the findings of this study, are all included within this article.

Conflicts of Interest

There are no conflicts of interest of this paper.

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