

Article

Deformation and Failure Mechanism of Weakly Cemented Mudstone under Tri-Axial Compression: From Laboratory Tests to Numerical Simulation

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Abstract: The success of the water-preserved mining technology is closely related to the stability of the aquiclude and the aquifer, in particular, which is made of weakly cemented rock mas. This paper starts with the tri-axial compression tests on the mudstone specimens obtained from the Ili mining area, followed by the systematic numerical simulation via the Particle Flow Code (PFC) program, aiming at obtaining an in-depth understanding of the response of weakly cemented mudstone under tri-axial compression loading state. The main outcomes obtained from this research indicated that: (1) the behavior of weakly cemented mudstone is closely sensitive to the confining pressure. As the confining pressure increases, both the peak strength and plastic deformation capacity of weakly cemented mudstone will be enhanced; (2) the main feature of weakly cemented mudstone after tests is its centrosymmetric “Z” shape, mainly attributed to the progressive separation of the particle element of mudstone; (3) the behavior of weakly cemented mudstone either in terms of the axial stress-axial strain or the failure mode is sensitive to the confining pressure. If the applied confining pressure is lower than 5 MPa, the micro-cracks are in the form of the single shear band, whereas the tested specimens will tend from brittle shear to plastic shear associated with the “X” shear when the confining pressure is higher than 5 MPa; and (4) The failure of weakly cemented mudstone is mainly attributed to the continuous expansion and penetration of internal microcracks under compression. The brittle failure mode of weakly cemented mudstone tends to ductile failure with the increase of confining pressure. The main contribution of this research is believed to be beneficial in deepening the understanding of the mechanics of weakly cemented mudstone under tri-axial compression and providing the meaningful reference to the practical application of water-preserved mining in the Ili mining area.

Keywords: weakly cemented mudstone; tri-axial compression; acoustic emission; water-preserved mining; PFC; microcrack development; failure mechanism

1. Introduction

The coal resources development strategy of China has been gradually shifted to the western region in recent years. As one of the modern large-scale coal mining areas, the landform, overburden structure, and hydrogeology, as well as the coal seam occurrence conditions of the four coalfields in Xinjiang, are pretty different from that in the eastern mining area [1]. The Ili mining area, being the only one oasis mining area among the four largest coalfields in Xinjiang, is currently developing a chemical industry attributed to its

abundant coal and water resources. During the rapid excavation of coal resources, how to maintain the sustainability of underground water in the Ili mining area has become the biggest concern for coal operators and government managers. Developing the water-preserved mining is thus urgent in the respect of the practical application [1,2].

The critical key to the success of the water-preserved mining technology is to maintain the stability of the aquiclude and the aquifer during the mining process. It has been well noted that the coal seams in the Ili mining area were mainly generated in the late diagenetic Jurassic period, and thus, most aquicludes are made of weakly cemented materials with a high content of clay minerals [3–5]. As indicated by previous research, a large amount of these weakly cemented aquicludes are either the mudstone or the sand stone, which are typical water sensitive rock layers [1–6].

The specific physical-mechanical and hydraulic characteristics of these weakly cemented rocks have an essential influence on disaster prevention and the stability controlling of surrounding rock, limiting the application of conventional water-retaining mining and other advanced mining technologies in the Ili mining area. In addition, how to sustain the stability of surrounding rock for underground mines should also be accounted for [7,8].

During the past several years, many studies have been conducted to explore both the physical and mechanical behavior of weakly cemented rock either at home or abroad. Liu et al. discussed the effects of water content and confining pressure on the failure mode and stress-strain behavior of weakly cemented rocks [6]. Meng et al. carried out the uniaxial and triaxial compression tests on fragile cemented rock, the test results of which revealed the post-peak strain-softening and dilatancy deformation characteristics of tested specimens [9]. Sharma et al. introduced a nonlinear failure envelope to characterize the shear strength of weakly cemented sand [10].

Fan et al. conducted a triaxial compression seepage test on the specimen, which discussed the influence of the mining process on the seepage mechanism of weakly cemented rock [11]. Gonzalo et al., through the application protocol of the inverse problem that is described in detail and illustrated by a series of applications, carried out a study on real laboratory data belonging to two different soils [12]. Acoustic Emission (AE) is a common phenomenon related to brittle fracture, which is produced by the rapid propagation of microcracks [13]. Therefore, acoustic emission technology is widely used in the study of rock failure processes. Nakagawa et al. [14], Yang et al. [15], Song et al. [16], and Zhao et al. [17] analyzed the failure characteristics of rock and the Change law of AE parameters in the course of failure by means of indoor mechanical and acoustic emission tests. The relationship between AE characteristic parameters and rock failure is discussed.

Considering the limitation of laboratory tests in exploring the mechanism response of weakly cemented mudstone under tri-axial compression, the numerical simulation is believed to be the effective method with the development of high-speed computers and mature commercial software. Particularly, it is possible to obtain the in-behind failure progress and corresponding mechanism via the numerical methodology. Compared to finite element modelling (FEM), the discrete element method (DEM) seems to be much more suitable in modelling the weakly cemented rock presented in this research because it can well capture the microstructure and fracture procedure of rock [18–20]. As reported by Potyondy et al., the characteristics of acoustic emission, damage, and strength increase with constraint can be easily reproduced based on a biaxial numerical model [20]. In addition, Manouchehrian et al. proposed a numerical procedure for the analysis of crack propagation in rock-like materials under compressive biaxial loads [21]. Yin et al. presented an investigation of particle flow code in two dimensions (PFC2D) simulation on transversely isotropic rock under different confining pressures based on laboratory experiments [22]. Wu et al. proposed a micro-mechanical based numerical manifold method (NMM) to investigate the micro-mechanisms underlying rock macroscopic response and fracture processes [23]. Zhang et al. adopted a parallel bonding model to investigate the failure of basalt subjected to uniaxial compression; the fracture characteristics and the evolution of an internal crack in basalt is analyzed in detail with the obtained experimental data [24]. Zhou et al. pro-

posed, based on peridynamic theory, a micro-elastoplastic constitutive model considering the post-peak stage of rock mass under compression loading [25]. Yang et al. studied the evolution law of hydraulic fracture propagation and the fracture mode of two holes synchronous hydraulic fracturing under the influence of different factors [26]. Through indoor tests and using PFC software to simulate the deformation and failure process of the rock, the crack development process is reproduced, and the failure mechanism of different rocks is revealed from a microscopic point of view. However, the above research is mostly applied to hard rock, and the research on weakly cemented rock in western mining areas is insufficient at present.

As the extension of further research on weakly cemented rock in the Ili mining area, this paper presents the concise laboratory tests on another typical weakly cemented rock (i.e., mudstone from the Ili mining area) under tri-axial compression loading with three confining pressures (i.e., 1, 3, and 5 MPa). Differing from previous research [3,6], the acoustic emission (AE) sensors were attached on the tested specimens to capture the micro cracking process during the loading procedure. Taking the tested specimens as the reference, the basic numerical model via the particle flow code (PFC) was established and the input parameters were calibrated. The systematic parametric study was then carried out, covering six typical confining pressures (i.e., 3, 4, 5, 6, 7, and 8 MPa). Based on the combined laboratory tests and numerical modelling, the deformation and failure mechanism of weakly cemented mudstone were well investigated.

2. Laboratory Tests

2.1. Specimen Preparation

The specimens investigated in the present research were all obtained from Ili No. 4 mine, the overburden of which is made of weakly cemented rocks generated during the Jurassic period. The previous research conducted by the authors' research group has demonstrated that the main components of these weakly cemented rocks are hydrophilic mineral and, thus, both the physical and mechanical properties are significantly affected by the moisture content [3,6]. With the consideration of the side-effect of the moisture, the dry processing method was applied to collect rock samples. Note that the shape, size, processing accuracy, and loading speed of rock samples are specified per the International Society of Rock Mechanics (ISRM) [27]. As indicated in Table 1, all tested specimens had a nominal configuration (i.e., Φ 50 mm $\times$ 100 mm).

Table 1. Details of Tested Samples.

Series	Samples	Diameter/mm	Height/mm	Moisture Content/%	Confining Pressure/MPa
Sandy mudstone	NS-N-1	49.5	99.3	6.57	1.0
	NS-N-3	49.6	99.8	6.57	3.0
	NS-N-5	49.9	99.9	6.57	5.0
Mudstone	NY-N-1	49.9	100.3	4.27	1.0
	NY-N-3	49.6	99.8	4.27	3.0
	NY-N-5	49.9	100.1	4.27	5.0

As listed in Table 1, a total of 6 specimens were prepared and tested, which were divided into the sandy mudstone group and mudstone group. Except for the type of rock specimens in these two groups (i.e., sandy mudstone and mudstone), the main feature of these specimens in each group is the confining pressure (i.e., 1 MPa, 3 MPa, and 5 MPa). Note that the values of the moisture content presented herein are all the natural moisture content.

2.2. Experimental Equipment and Process

The MTS-815 mechanical test system and acoustic emission test system are used in the laboratory tests. The MTS-815 rock testing machine can adopt the loading mode

of displacement control and load control. The loading mode of displacement control (0.002 mm/s) was adopted. During the trial tests, the confining pressure was firstly loaded to the predetermined value ($\sigma_2 = \sigma_3 = 1.0$ MPa, 3 MPa, 5 MPa, respectively), and then the axial force was applied until the residual strength was reached. To ensure the reliability of data in the acoustic emission test, two probes were used in the auditory emission test, which was pasted in the middle of the sample and built in the triaxial chamber. To make sure the synchronous acquisition of acoustic emission and mechanical parameters happened synchronously, the acoustic emission and experimental mechanical systems were started at the same time. The preamplifier was set up to 55 dB to collect acoustic emission parameters. All apparatus and testing setting-up can be found in Figure 1 below.

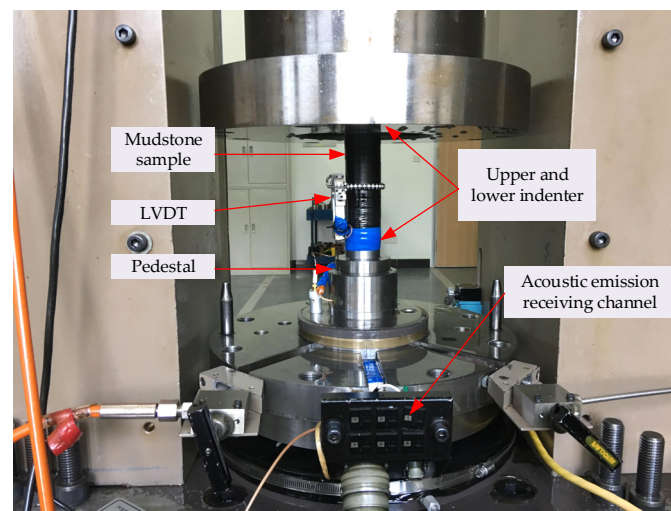


Figure 1. Mechanical and Acoustic Emission Tests.

2.3. Test Results and Discussions

Figure 2 shows the typical failure diagram of weakly cemented sandy mudstone and mudstone rock specimens after tests. It is apparent in Figure 2 that the all tested specimens failed with the single shear surface.

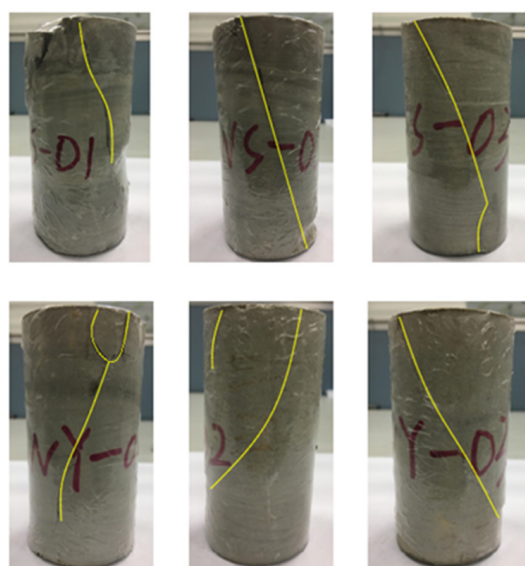
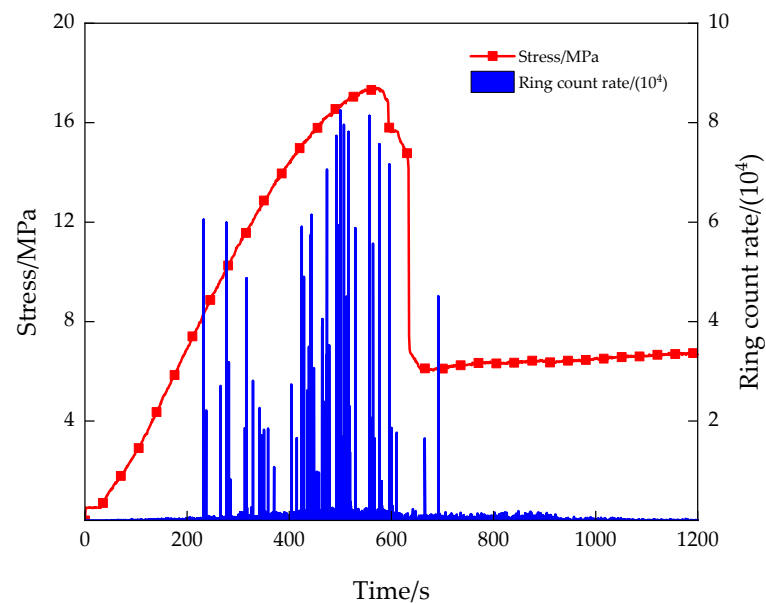


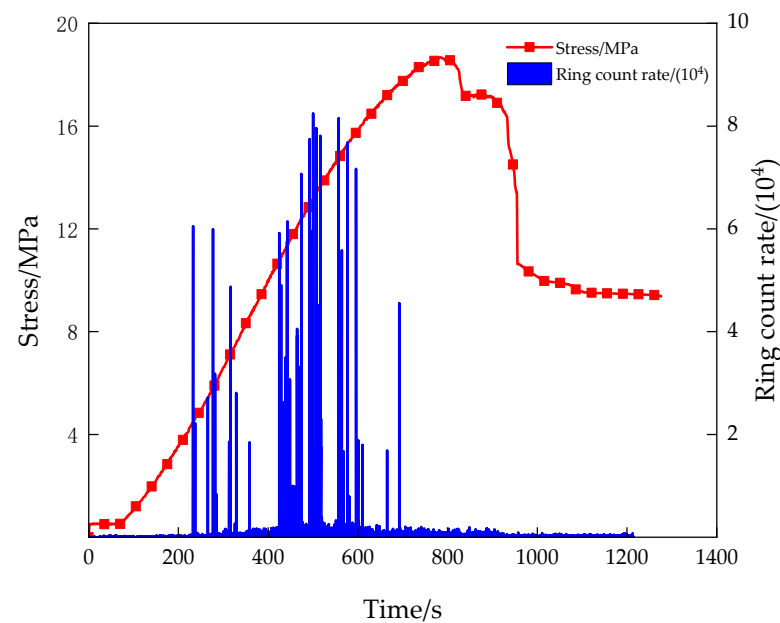
Figure 2. Failure Diagram of Weakly Cemented Sandy Mudstone and Mudstone Samples.

There are lots of parameters recorded by the acoustic emission (AE) system. Among them, the ringing count is believed to be one of the typical characteristic parameters [15].

When the material properties of tested specimens changed, there must be the release of strain energy, mainly attributed to the dislocation movement fracture and crack propagation. Therefore, the acoustic emission characteristics of sandy mudstone and mudstone are studied by using the ringing count as a characterization parameter. Figure 3 shows the relationship of the acoustic emission ringing count-stress-time of weakly cemented mudstone under different stress states (a, b, and c correspond to confining pressures of 1 MPa, 3 MPa, and 5 MPa, respectively).

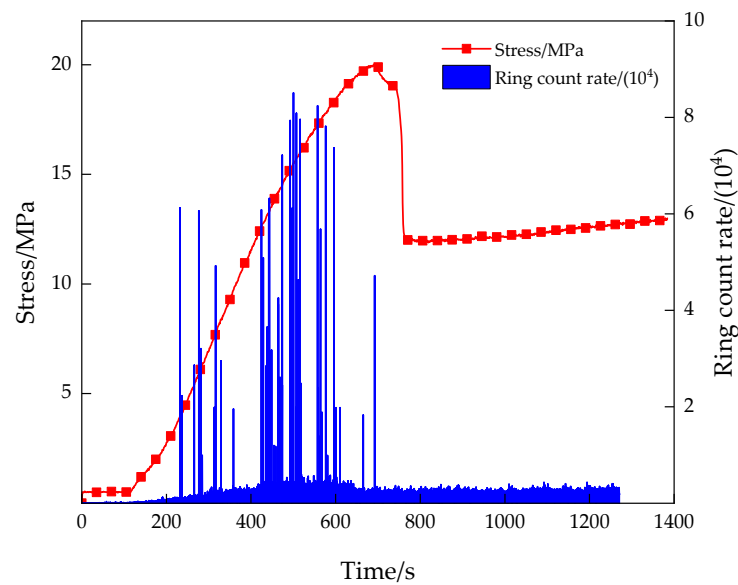


(a)



(b)

Figure 3. Cont.

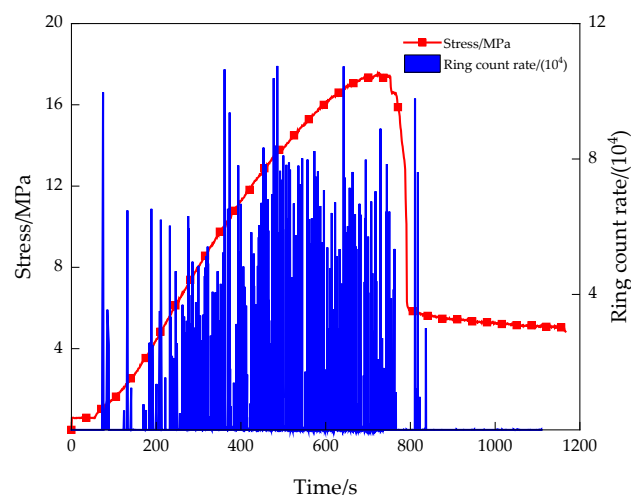


(c)

Figure 3. Relationship of Stress-time-ring Count of Weakly Cemented Mudstone. (a–c correspond to confining pressures of 1 MPa, 3 Mpa, and 5 MPa, respectively).

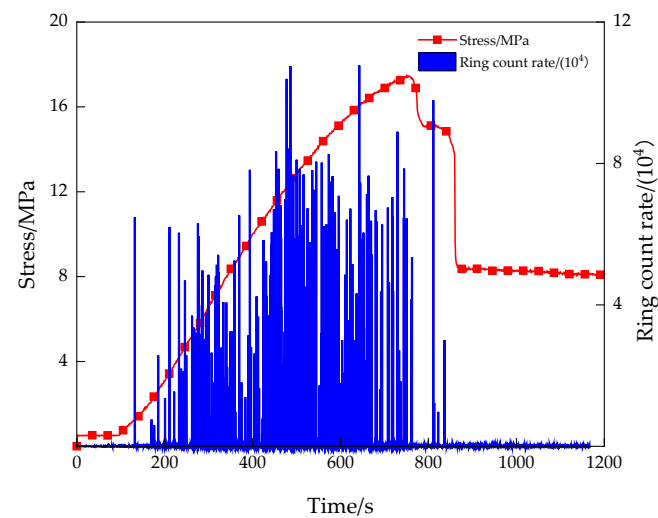
The acoustic emission signals agree well with the five-stage axial stress-time curve shown in Figure 3. With the increase of confining pressure, the peak strength, residual strength, and pre-peak plasticity of the weakly cemented sandy mudstone increase as well. The ringing count at the residual stage tends to increase, but the duration of the elastic stage is short. Meanwhile, the period of the stress softening stage increases.

Figure 4 shows the acoustic emission ringing count-stress-time of weakly cemented sandy mudstone (a, b, and c correspond to confining pressures of 1 MPa, 3 MPa, and 5 MPa, respectively). Different from that shown in Figure 3, both the number and values of ringing numbers at the initial fracture compaction stage increase, indicating the occurrence of original fractures. With the increase of axial stress, the linear elastic stage of fracture formation and expansion indicates that the sandy mudstone has no practical significance, which has also been observed by Zhao et al. [28]. The sandy mudstone has a large ring count before and after entering the residual strength stage.

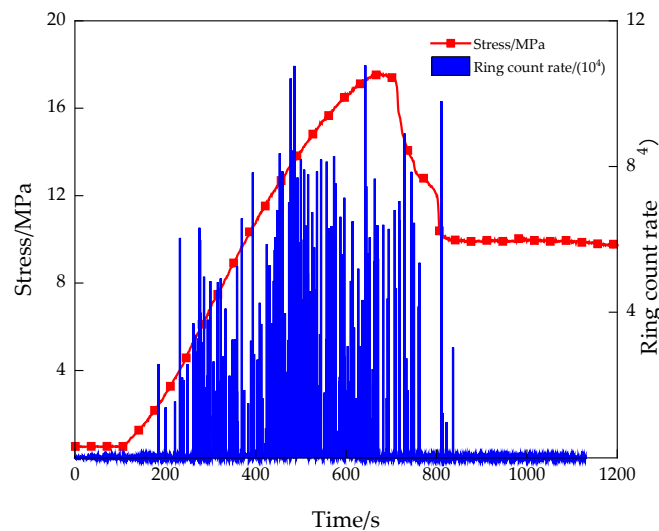


(a)

Figure 4. Cont.



(b)



(c)

Figure 4. Relationship of Stress-time-ring Count of Weakly Cemented Sandy Mudstone. (a–c correspond to confining pressures of 1 MPa, 3 MPa, and 5 MPa, respectively).

It can also be seen from Figures 3 and 4 that: (1) at the initial stage of compaction, the ringing number recorded by AE sensors exhibited a continuous increase, associated with the increase of axial stress; (2) at the elastic deformation stage, the stress-strain curve looks like a straight line. During this period, the axial deformation is mainly due to the closing of micro-cracks. Correspondingly, the slip of cemented particles and the compression of the solid skeleton result in the elastic deformation. Moreover, the acoustic emission characteristics are relatively quiet; (3) at the plastic deformation stage, the original cracks will be open and expanded again. During this period, the new cracks will be developed and accumulated rapidly.

The acoustic emission (AE) characteristics ranged from relatively quiet in the elastic phase to continuous large acoustic emission ringing counts, and then reached the peak of the ringing counts. Therefore, if acoustic emission is taken as the precursory information of rock failure, it should be noted when the peak value of ringing count is reached. Rock failure does not occur but is caused by the rapid expansion of internal cracks and accelerated

damage. When the rock goes peak strength, the acoustic emission characteristics are not prominent, and the ringing count is not apparent.

The rapid expansion of cracks generally occurred through the strain softening stage, associated with a sharp decline in load-bearing capacity, and the rock specimen has a macro-fracture surface. However, rock specimens had a specific bearing capacity after failure at the residual strength stage. During this stage, lots of secondary cracks were formed and expanded.

As presented above, these weakly cemented rock specimens have heterogeneity and, thus, the deformation and failure mechanics in-behind are not clear when the number of tested specimens is not large enough. To fill up this research gap, the numerical simulation on weakly cemented rock specimens will be presented in subsequent chapters.

3. Numerical Simulation

Different from the finite element modelling (FEM) with the continuum model, the constitutive properties of material cannot be automatically written into the PFC program and, thus, the determination of the micro-parameters will be significantly important in rebuilding the numerical model. In addition to the determination of the input parameters, how to assign the interface properties, such as the bond between different particles, is also the critical concern. In general, the interface bond between different particles will be destroyed if the maximum force applied on the model exceeded its bond strength [20,29]. Because the basic element in PFC is the circular discs bonded together, it is suitable to represent the progressive damage of mudstone, which is directly related to the mechanics analysis.

3.1. Establishment of Basic Model

In this research, the basic numerical model is reproduced in accordance with the same configuration of the specimens tested in the laboratory. The PFC 2D program was applied and the rectangular model with a length of 100 mm and a width 50 mm was determined as the basic model (see Figure 5).

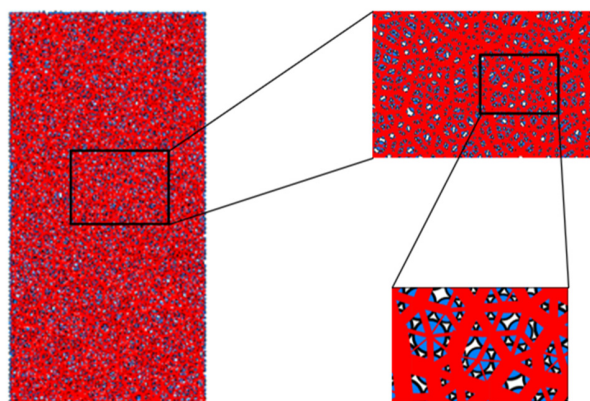


Figure 5. Numerical Model.

It has been well noted that the selection of micromechanics parameters is the key to the numerical simulation and the reasonable microscopic parameters are the foundation of the simulation results. The fact is, however, that no direct relationship between the micro-mechanical parameters in PFC and the macro-parameters measured in the laboratory is available currently [20,29]. To solve this technical problem, the calibration process of the micro-parameters shown in Figure 6 is adopted. In detail, the stress-strain curves of the typical specimen under uniaxial compression were selected as the reference and then the key micro-mechanical parameters were calibrated until both the stress-strain response and the failure mode of the numerical model matched up with their counterparts presented in the laboratory test. The meaning of the short form used in Figure 6 will be explained in detail in Table 2.

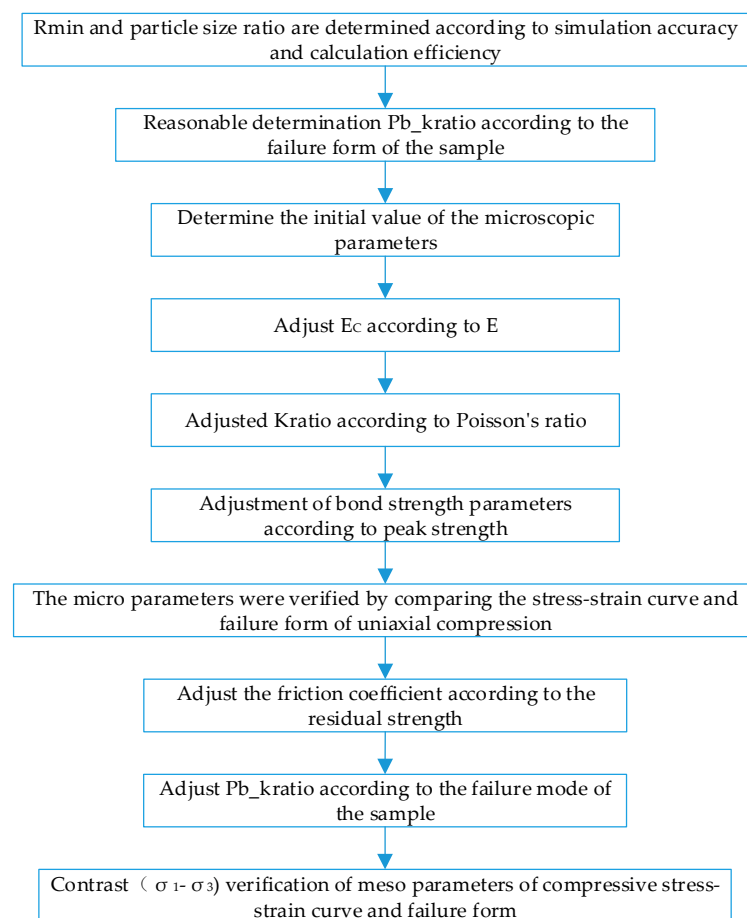


Figure 6. Calibration Process of Micromechanical Parameters.

Table 2. The Meaning of the Short Form Used in Figure 6.

Short Form	Description
Kratio	Normal-to-shear stiffness ratio
Pb_kratio	Bond normal-to-shear stiffness ratio
Ec	Particle contact modulus
E	Elastic modulus

In accordance with the calibration process depicted in Figure 6, the set of microscopic parameters used to reproduce the weakly cemented mudstone under uniaxial compression are listed in Table 3 for reference.

Table 3. Micromechanical Parameters Selected for the Uniaxial Numerical Model.

Properties	Input Parameter	Numerical Value
Ball Properties	Rmin/mm	0.45
	Rmax/Rmin	1.67
	Bulk density [$\text{kg}\cdot\text{m}^{-3}$]	1650
	Particle friction coefficient	0
Parallel Bond Model Properties	Parallel-bond normal-to-shear stiffness ratio	1.33
	Parallel-bond modulus [GPa]	2
	Parallel-bond cohesion [MPa]	5
	Parallel-bond tensile strength [MPa]	5
	Parallel-bond friction angle/(°)	19

3.2. Verification of Basic Model

Figure 7 compares the axial stress-axial strain curves of the numerical model and tested specimen in the laboratory. It is apparent that the mechanical response of the numerical model agrees well with its counterparts obtained from the laboratory test, indicating the feasibility of the calibration procedure shown in Figure 7. In addition to the stress-strain response, the failure mode of the numerical model is very similar to that of the tested specimen, which can be found from Figure 7.

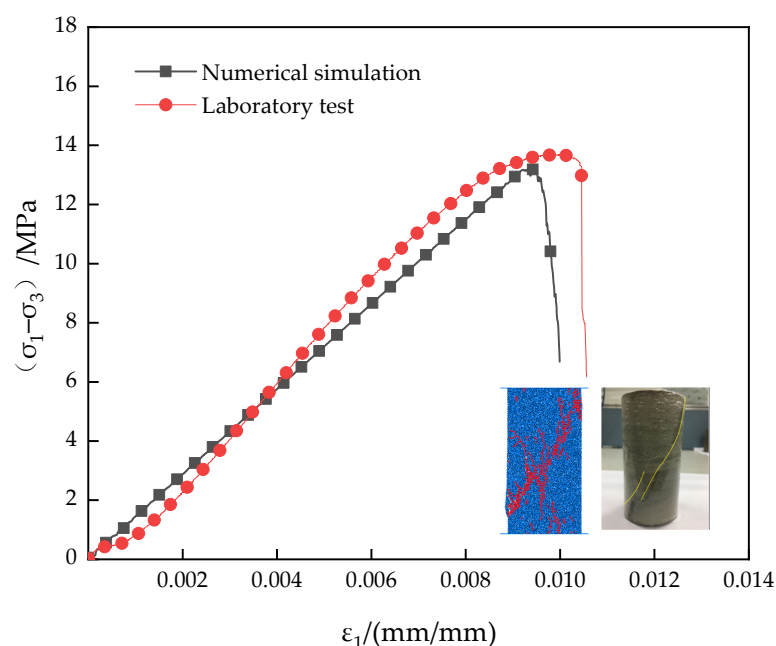


Figure 7. Comparison of Stress-strain and Failure Modes between Indoor Uniaxial and Numerical Simulation.

3.3. Biaxial Modeling

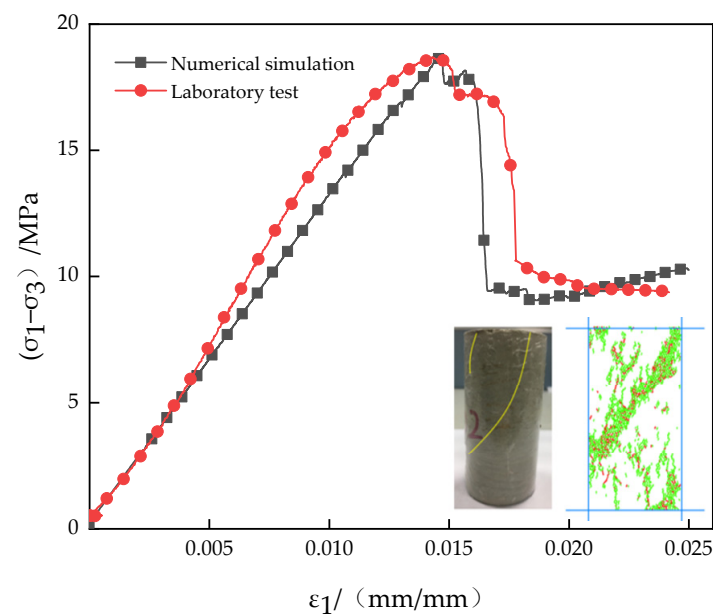
The verification of the basic model presented above has successfully demonstrated the feasibility of the PFC modeling. Thus, the biaxial compression test was consequently carried out in this section. Note that the only difference between the biaxial modelling and the uniaxial modelling is that the latter is imposed with a specific boundary condition to apply the confining pressure. In addition, the inherent wall in the PFC program is rigid and both the wall and the rigid particles will move to overlap. To successfully apply the confining pressure onto the numerical model, the user defined function (UDF) should be therefore adopted, aiming at providing the constant confining pressure during the simulation procedure. Herein, the gradual expansion method was adopted to generate the model and the loading method was applied to control the wall with the constant speed of 0.1 m/s [30].

Once the biaxial model was set up, the following step was to apply the confining pressure. Table 4 demonstrates all parameters input into the biaxial model, which was adopted in accordance with the calibration procedure depicted in Figure 6. The failure process of weakly cemented mudstone under different confining pressures was investigated on the basis of the microscopic mechanical parameters listed in Table 4.

Figure 8 compares both the axial stress-axial strain curves and the failure mode of the mudstone specimens confined by the 3 MPa lateral confining pressure. Herein, the numerical simulation represents the biaxial model discussed above. It is apparent that these two curves are approximately same and, thus, it is the other evidence to verify the feasibility of PFC model presented in this research.

Table 4. Micromechanical Parameters Selected for Biaxial Numerical Model.

Properties	Input Parameter	Numerical Value
Ball Properties	$R_{\min}/\text{mm}$	0.45
	$R_{\max}/R_{\min}$	1.67
	Bulk density [$\text{kg}\cdot\text{m}^{-3}$]	1650
	Particle friction coefficient	0.53
Parallel Bond Model Properties	Parallel-bond normal-to-shear stiffness ratio	1.95
	Parallel-bond modulus [GPa]	2
	Parallel-bond cohesion [MPa]	5
	Parallel-bond tensile strength [MPa]	5
	Parallel-bond friction angle/(°)	19

**Figure 8.** Comparison of Stress-strain and Failure Modes between Indoor Tri-axial and Numerical Simulation ($\sigma_3 = 3$ MPa).

4. Deformation and Failure Mechanism of Weakly Cemented Mudstone

4.1. Failure Modes

It is apparent that the microcracks of weakly cemented mudstone specimens are sensitive to the confining pressure. When the confining pressure is relatively small (3 MPa, 4 MPa, and 5 MPa), the main feature of these microcracks concentrated nearby the shear zone. Once these microcracks developed and the visible shear crack developed and connected together, the main failure mode of the weakly cemented rock specimens was then completed. It can also be found that the failure mode of rock specimens with the single shear crack under the low confining pressure (3 MPa and 5 MPa) was very similar to that observed from the laboratory test.

Moreover, once the confining pressure exceeded to threshold point (i.e., 6 MPa, 7 MPa, and 8 MPa), the “X” band failure mode occurred, which can be found from the failure modes shown in Figure 9. This observation indicates that the tested specimens trended from brittle to plastic in some content. Moreover, lots of microcracks can be seen from the lower right corner of the sample.

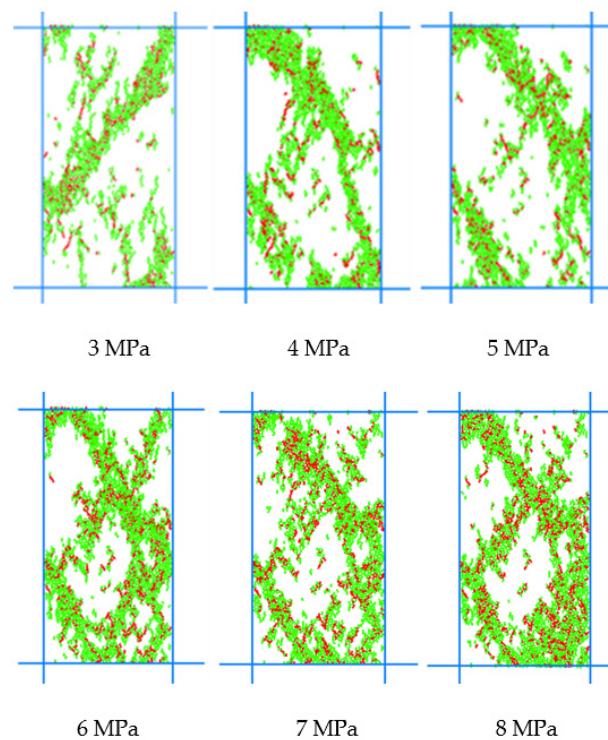


Figure 9. Final Failure Diagram of Rock Sample under Different Confining Pressures.

4.2. Stress-Strain Relationship

Figure 10 presents the stress-strain curves of the numerical modelling results, in which the only difference is the confining pressure ranging from 3 MPa to 8 MPa. It is obvious that both the peak strength and residual strength of weakly cemented mudstone specimens increase with the confining pressure. In addition, the elastic modulus also exhibited an increase when the applied confining pressures increased. In particular, the growth of the confining pressure led to the transition of weakly cemented mudstone specimens from brittleness to the ductility with sufficient axial deformation ability. This is a very important observation because the ductility of the strata directly affect the stability of overburdened strata when the water-preserved mining is adopted.

4.3. Analysis of the Failure Mechanism

As stated earlier, the progressive failure of rock specimens under biaxial compression is the effective method to analyze the failure mechanism of weakly cemented rock specimens. Herein, the cracking procedure of specimens confined with variable pressures are plotted together in Figure 11 for further discussion. The tensile cracks are marked in green, while the shear crack is represented by the red line. In general, the crack is caused by the unbalance force at different positions of the rock specimens under compression. If the unbalance force exceeds either the shear or the compressive strength of the specimens, shear or tensile cracks will occur at these specific positions. Correspondingly, multiple cracks will propagate through the cracks and result in the final failure. It can be seen from Figure 11 that the pre-peak failure process of weakly cemented mudstone is roughly the same when they are under different confining pressures. That is, the main fracture surface is generally formed when the peak strength is reached. However, these cracks will rapidly develop during the post-peak stage until the macro fracture surface is generated.

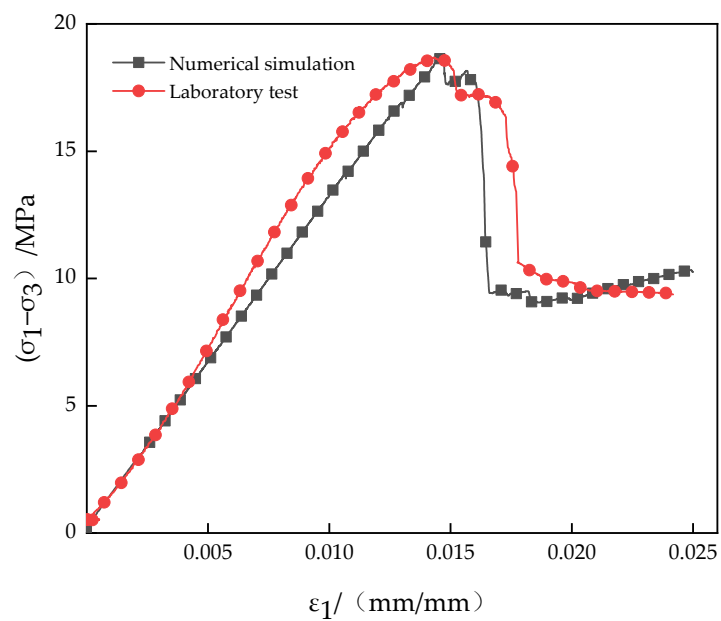


Figure 10. Numerical Simulation of Stress-strain Curve under Different Confining Pressures.

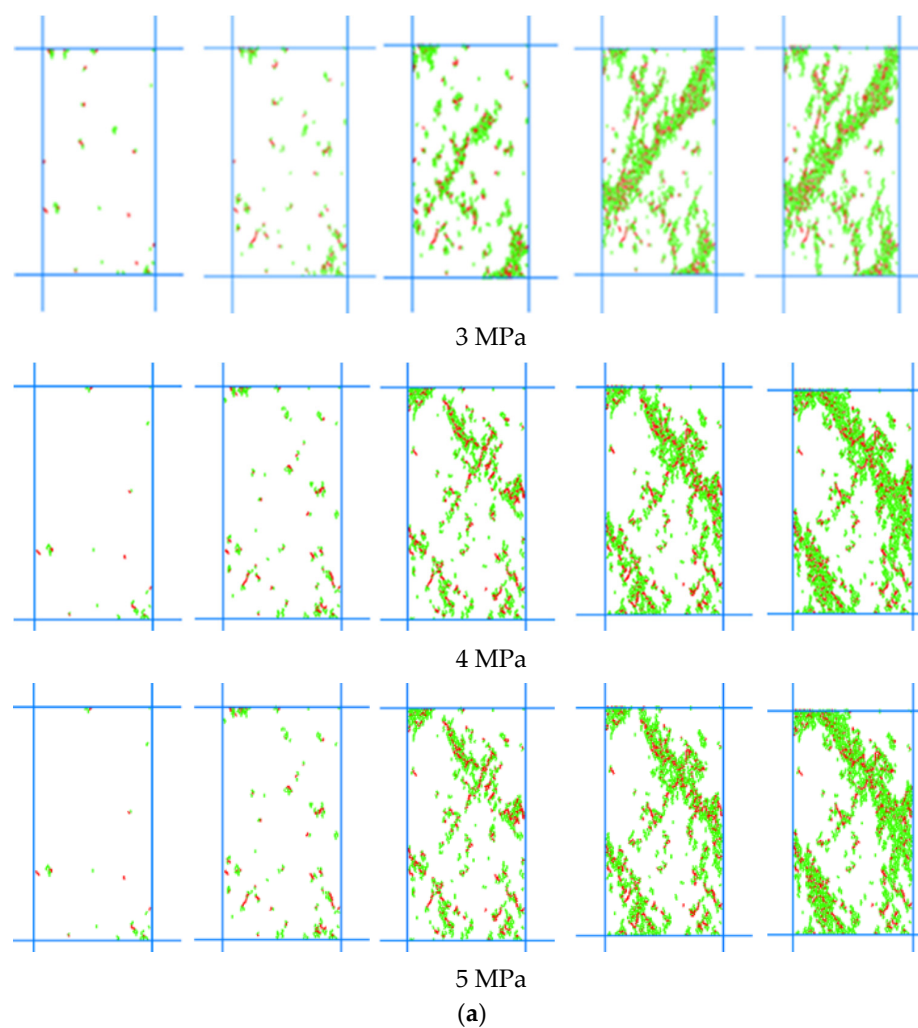


Figure 11. Cont.

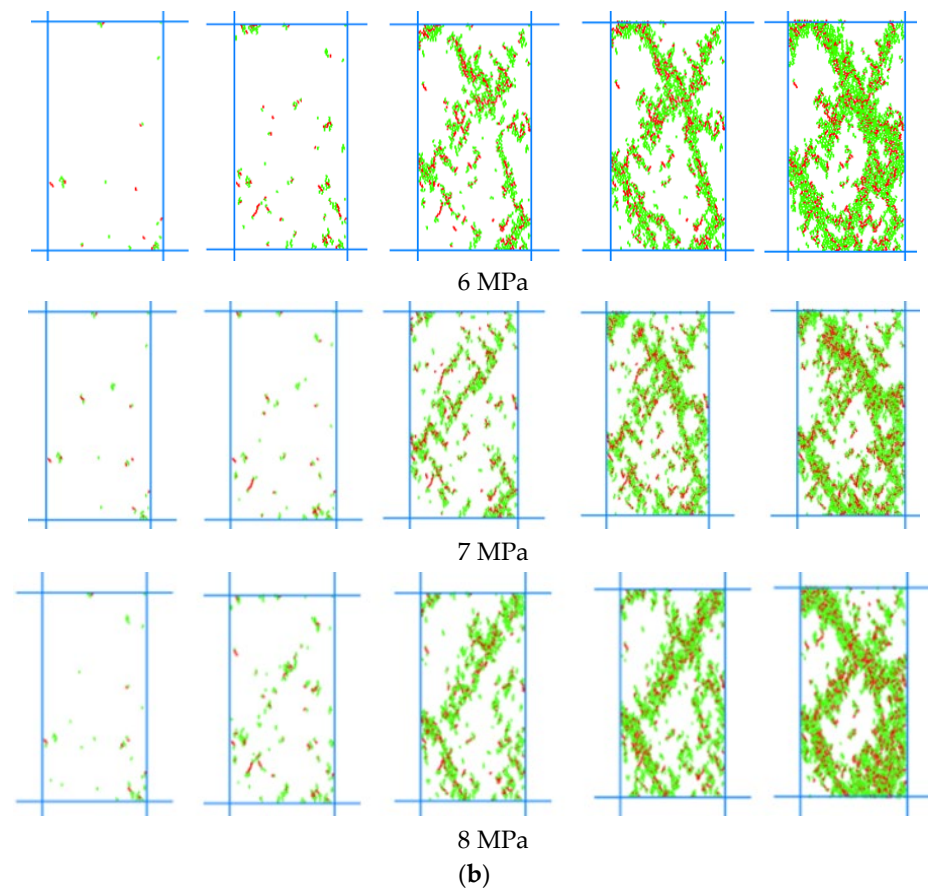


Figure 11. Development Diagram of Rock Cracks at Different Stages (five diagrams correspond to five stages of the stress-strain curve: initial compaction stage, elastic stage, plastic deformation stage, strain-softening stage, and residual strength stage). (a) Failure Process of Rock under Low Confining Pressure. (b) Failure Process of Rock under High Confining Pressure.

As can be seen from Figures 11 and 12, no crack was observed at the initial stage. The microcracks grow gradually at the elastic stage, starting with the tensile cracks and then the occurrence of these shear and tensile cracks. When these cracks are compared, it is apparent that most of them are in the form of tensile cracks, even though the development cracks will not last a long time. This observation is also in accordance with the results of laboratory tests.

It is interesting in Figure 12 that these microcracks expanded rapidly nearby the peak strength. When the peak strength was reached, the number of micro-cracks exhibited were quickly increasing, the evidence of which is the approximately 90° growth curve depicted in Figure 12. Consequently, these microcracks will develop to the macro cracks. It is also indicated that the damage process of weakly cemented mudstone is concentrated around the peak strength. Different from that at other stages, the shear crack no longer develops and the tensile crack increases slowly at the residual strength stage.

The other interesting observation shown in Figure 12 is the symmetric “Z” type curves of the cumulative number of microcracks, exhibiting the nonlinear growth during compression. The “Z” curve shown in Figure 12 consists of five portions, including the no crack initiation portion at the initial compaction stage, slow growth portion at the elastic stage, fast growth portion at the plastic deformation stage, fast growth portion at the stress softening stage, and the smooth growth portion corresponding to the residual strength stage. At the beginning of the crack initiation, two kinds of cracks such as the shear and tensile were observed, the majority of which are in the form of tensile cracks. During the subsequent crack development, the number of tensile cracks experienced a quick increase. This situation is not observed in the pre-peak stage and the stress softening stage, during

which the growth trend of two kinds of cracks is approximately similar. At the residual strength stage, the shear crack kept stable while the tensile crack grew steadily.

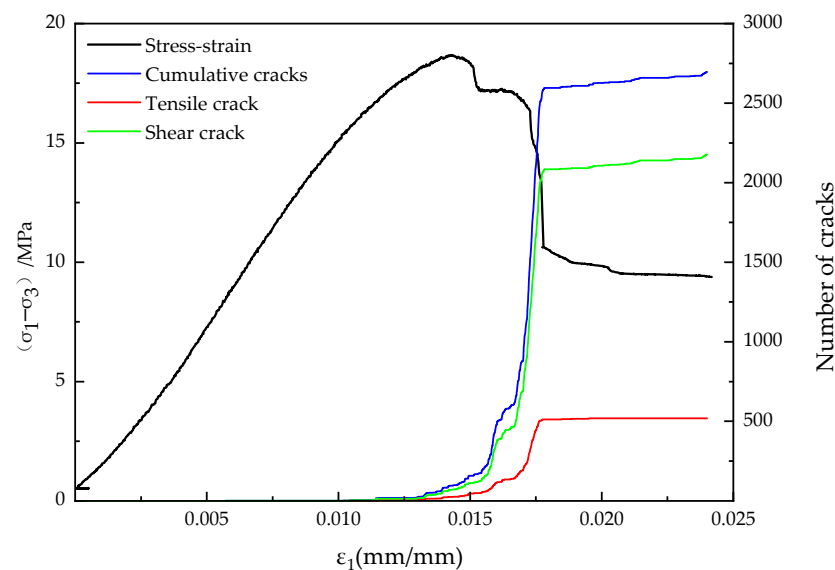


Figure 12. Stress-strain and Microcrack Development Diagram of Weakly Cemented Mudstone ($\sigma_3 = 3$ MPa).

When the laboratory tests and numerical modelling results are compared and discussed together, it is not difficult to find out that the micro-cracks in weakly cemented mudstone develop rapidly in the pre-peak plastic deformation stage and the post-peak strain softening stage. The progressive failure procedure has revealed that the deformation and failure of weakly cemented rock specimens are mainly concentrated in the pre-peak plastic deformation stage and the post-peak strain softening stage.

5. Conclusions

This paper has presented the laboratory tests firstly, followed by the discrete element modelling (DEM) on the weakly cemented mudstone collected from the Ili mining area, for which the application of the water-preserved mining technology is urgent. On the basis of the experimental tests and numerical analysis, the following conclusions can be drawn:

- (1) The behavior of weakly cemented mudstone is closely sensitive to the confining pressure. As the confining pressure increases, both the peak strength and plastic deformation capacity of weakly cemented mudstone will be enhanced.
- (2) The typical failure mode of the weakly cemented mudstone is featured with the symmetrical “Z” type nonlinear growth. The stress-strain curve can be classified into five portions: no cracks, slow growth, rapid growth, nearly 90° linear growth, and stable growth, in accordance with the progressive development of micro-cracks;
- (3) If the applied confining pressure is lower than 5 MPa, the micro-cracks are in the form of the single shear, whereas the tested specimens will tend from brittle shear to plastic shear associated with the “X” shear if the confining pressure is higher than 5 MPa;
- (4) The failure of weakly cemented mudstone is mainly attributed to the continuous expansion and penetration of internal microcracks under compression. The brittle failure mode of weakly cemented mudstone tends to ductile failure with the increase of confining pressure.

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