Numerical Study of Brittle Characteristics of Deep Buried Conglomerate Based on Discrete Element Method

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ABSTRACT: Hydraulic fracture has become one of the technical means for efficient development of oil and gas reservoirs, and the brittle rock damage characteristics are the key mechanical indicators for fracturing to form complex fracture networks. The current research on brittle rock characteristics is mainly focused on shale reservoirs, and there is a lack of systematic and in-depth understanding of the characteristics of anisotropic, strongly inhomogeneous conglomerates and their fine-scale damage mechanisms. Through drilling cores and indoor rock mechanics experiments, discrete particle simulation techniques are introduced to reproduce the microfracture expansion mechanism of deeply buried conglomerates, and the study shows that conglomerate brittleness is more sensitive to the surrounding pressure, particle size and volumetric block proportion. Based on the simulation results, the brittleness evaluation index of conglomerate formation is established, which has certain reference significance for understanding the brittle characteristics of deep conglomerate and field fracture design.

Keywords: Conglomerate, Brittleness, Particle flow code (PFC), Microscopic, Evaluation method.

1 INTRODUCTION

The geological conditions of MH block in Xinjiang oilfield in western China are extremely complex. The Permian Upper Urho Formation is a typical low-porosity and low-permeability reservoir. The formation of a large-scale complex artificial seam network around the well perimeter by volume fracturing technology is the key to the efficient development of this type of reservoir, and the brittle characteristics of the formation are the key mechanical indicators for the formation of a complex seam network by fracturing. It is generally believed that the stronger the brittleness of the rock, the better the effect of reservoir modification under fracturing. Most of the current research related to rock brittleness characteristics revolves around shale formations, so focusing on the brittleness characteristics of gravel formations is crucial to the evaluation of fracturing engineering desserts and the optimal design of fracturing schemes.

Brittleness is the property of a rock to fail when it undergoes very small deformation under stress. Many scholars have studied the mechanical properties, deformation laws and damage mechanisms of brittle rocks. Martin & Chandler (1994) summarized the failure characteristics within brittle rocks and classified four stages of the stress-strain curve during compressional rupture of rocks (see Figure 1). Hoek E. (2005) improved the study of the mechanical properties of brittle rocks by suggesting that the basic mechanical properties of brittle rocks depend mainly on the state of crack extension within the rock. Qin et al. (2020) suggested that conglomerates exhibit more significant heterogeneous properties than conventional brittle rocks due to poor particle sorting and large particle size differences. In order to gain a deeper understanding of the fine-scale mechanism of brittle rock damage, scholars have proposed and developed a variety of numerical simulation tools in recent years. The Particle Flow Code (PFC) method proposed by P. A. Cundall & O. D. L. Strack (1979) is particularly suitable for the failure of brittle rocks due to micro-cracks, since it takes into account the contact state between multiple types of particles and their changing characteristics. It has been applied to fundamental research fields such as particle dynamics and failure of different media.

Laboratory uniaxial and triaxial rock mechanical compression experiments were carried out to study the brittle damage characteristics of deeply buried conglomerates. Afterwards, the fine fracture characteristics of the conglomerate were simulated using PFC, and finally a quantitative evaluation of the conglomerate brittleness was completed based on the simulation results.

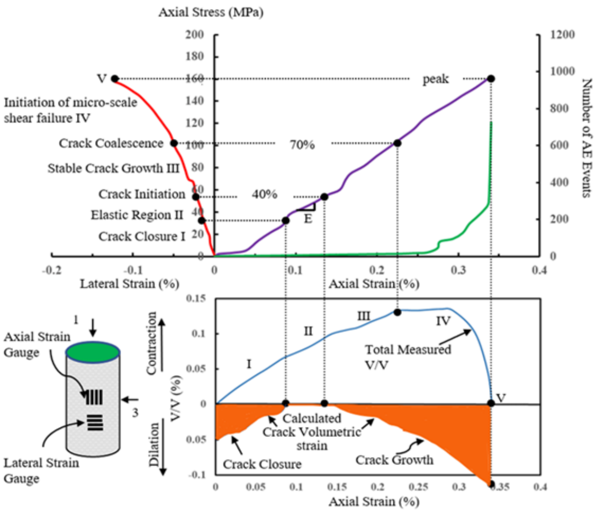


Figure 1. Four stages of compression failure process of brittle rocks.

2 LABORATORY EXPERIMENT

2.1 Experimental scheme

Two sets of standard cylindrical specimens of 50 mm length were tested in uniaxial compression and triaxial compression at an effective confining pressure of 20 MPa with the aid of the RTR-1500 rock mechanics testing system (see Figure 2). The experimental conditions meet the relevant standards of the International Society of Rock Mechanics (ISRM) (Fairhurst & Hudson, 1999).

Figure 2. RTR-1500 Rock Mechanics Testing System.

2.2 Brittle characteristics of conglomerates

The compression-deformation damage process of brittle rocks can be divided into two stages. Before the failure, the total strain of the rock is small, while the damage of the specimen occurs when the stress reaches the peak strength, as shown by the rapid drop of the stress and the slope of the stress-strain curve becomes large.

Figure 3 shows the representative stress-strain curves and specimen failure characteristics of conglomerate specimens under two loading conditions. The conglomerate sample produces an axial strain of approximately 0.5% at the peak stress. After the stress reaches the peak strength, the stress falls quickly and the stress-strain curve shows a large slope. Figure 3b shows that multiple distinct fracture planes (red lines) appear on the surface of the rock samples after the experiment.

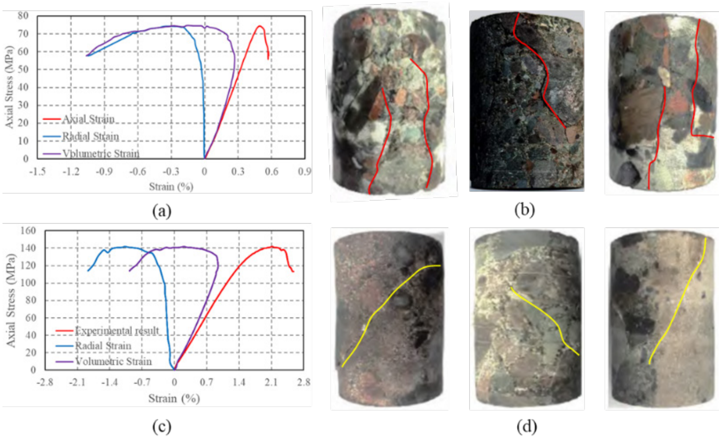


Figure 3. Stress-strain curves and post-experimental gravel rock samples.

The specimens undergo three stages of elastic deformation, plastic yield deformation, and post-peak stress drop under triaxial compression at an confining pressure of 20 MPa. With the increase of strain, the increment of stress is smaller, showing a significant plastic deformation characteristic. Axial strain exceeding 2.1% when loaded to peak strength. After unloading, no rapid drop in stress was observed for each specimen (see Figure 3c). Figure 3d shows that only one shear failure face appears in the post-experimental rock sample (yellow lines). On the whole, under the circumferential pressure of 20 MPa, the test rock samples are mainly plastic deformation, and the brittle failure feature is not significant.

3 DISCRETE ELEMENT NUMERICAL MODEL

Due to the anisotropy of the cementation strength of the downhole conglomerate, secondary cracks may occur when coring (D.A. Jiménez & S.A.B. da Fontoura 2016). In order to reproduce the original state of the conglomerate as much as possible, a numerical method of particle flow is introduced in this paper to describe the macroscopic conglomerate mechanical properties from the microscopic perspective of particle cementation (see Figure 4).

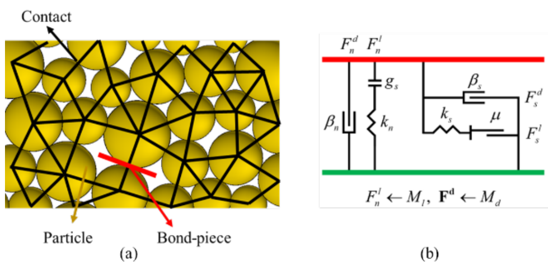


Figure 4. Full grain-cement system in PFC.

3.1 Parameter calibration

To reproduce the fine-scale brittle damage characteristics of conglomerates, a particle mineral component modeling technique was used to describe conglomerates in this study. Mineral modeling follows four steps. First, high-resolution photographs of the conglomerate were obtained (see Figure 5a). Next, the rock surface image is segmented using digital processing techniques to obtain two mineral components, gravel and matrix (see Figure 5b). Afterwards, the segmented image is vectorized (see Figure 5c). Finally, the pre-generated particles in the PFC are divided into mineral assemblies based on vectorized mineral boundaries (see Figure 5d).

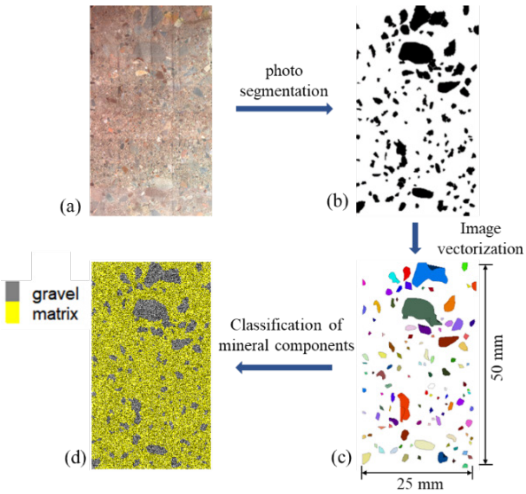


Figure 5. Particle flow model of conglomerate mineral components.

Based on the results of triaxial compression experiments, a linear parallel bonding model was chosen to complete the calibration of the fine-scale cementation parameters between the particles by trial-and-error method (see Figure 6). Some of the bond parameters are shown in Table 1.

Table 1. Meso-mechanical parameters of the parallel bond in the minerals.

Parallel-bond model		Parameters for minerals		
Meso-parameters	Symbol(unit)	Gravel	Matrix	Bond surface
Particle density	P(kg/m^3)	2650	2400	
Normal to shear stiffness ratio	$\bar{k}_n/\bar{k}_s$	1.3	1.2	1.2
Tensile strength	σ_c(MPa)	72	60	54
Cohesion	c(MPa)	60	45	40

The numerical model matches well with the results of the laboratory experiments until the specimen reaches its peak strength(see Figure 6a). Figure 6b shows the specimens under confining pressure conditions with mainly tensile damage.

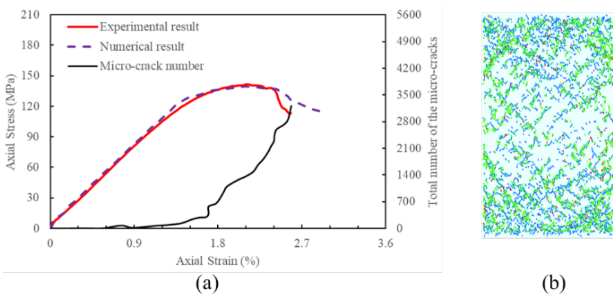


Figure 6. Triaxial compression calibration result.

3.2 *Evaluation of conglomerate brittleness*

The current brittleness index evaluation models can be broadly classified into two categories. The first method is based on mineral fractions, but it does not effectively consider the internal structure and sedimentary properties of the rock (Kivi et al. 2018; Lawal et al. 2021). The second type of evaluation method is based on the mechanical properties of the rock(Li et al. 2022; Chen et al. 2018). The numerical model proposed in this study can well combine these two methods and solve the problem of inconsistent brittleness evaluation due to characteristics such as complex conglomerate structure and strong heterogeneity.

The quantitative evaluation of conglomerate brittleness was carried out using the cut-line modulus of peak strength method. The method integrates the peak strength and peak strain during rock failure.

$$B_P = \alpha \frac{\sigma_P}{\varepsilon_P} \tag{1}$$

Where σ_P is the peak strength, MPa. ε_P is the peak strain, %. α is the model coefficient, taking the value of 0.1. B_P indicates the brittleness index based on the cut-line modulus, dimensionless.

Based on the numerical model, the effect of different confining pressure, gravel particle size and gravel volume block proportion(VBP) on the brittleness of conglomerate was investigated. Due to the limitation of page, Figure 7 only shows the microcrack extension results of conglomerate specimens under partial confining pressure. The specimens are dominated by randomly distributed tensile microcracks below 10 MPa payload, and the percentage of shear cracks and mixed tensile-shear cracks is close. The specimen gradually transitions from tensile damage to shear damage mode as the confining pressure increases, and the percentage of mixed tensile-shear cracks increases.

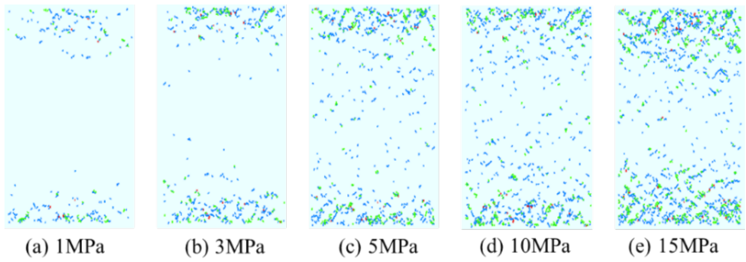


Figure 7. Micro-crack propagation results under different confining pressures.

The brittleness index of the conglomerate of the Upper Urho Formation was calculated under different surrounding pressures based on above results (see Figure 8)。The results show that the conglomerate undergoes a change from brittle to plastic failure mode as the confining pressure increases.

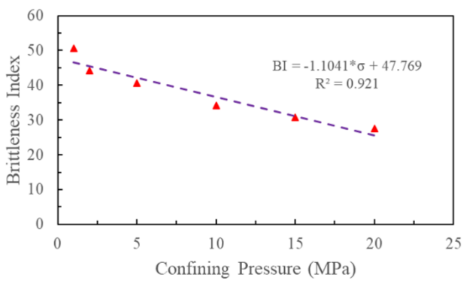
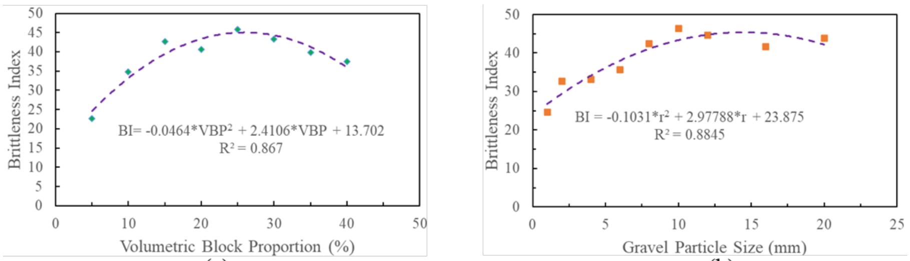


Figure 8. Relationship between brittleness index and confining pressure of conglomerate.

The effects of gravel grain size (1-20 mm) and VBP (0-40%) on the conglomerate brittleness index were also simulated (see Figure 9). Conglomerate brittleness first rises and then shows a slow decreasing trend as the gravel particle size grows. The number of contacts between gravel and matrix particles increases with lager gravel particle size. However, constrained by VBP, the weak contact surfaces of the model decrease. Similarly the effect of VBP on conglomerate brittleness can be limited by the gravel grain size. The gravel is more likely to slide along weak contact surfaces of the particles as the cement amount reduces, resulting in increased plastic deformation of the specimen.



(a) (b)

Figure 9. Relationship between brittleness index and VBP and particle size.

4 CONCLUSIONS

A numerical model of conglomerate was established based on indoor experiments and PFC, and the characteristics of conglomerate brittleness under different conditions were studied,which reproduce the tensile, shear and mixed tensile-shear micro-crack extension mechanisms. Experiments and numerical simulations show that the deformation damage of conglomerates of the Upper Urho Formation exhibits certain brittle characteristics. The results of the brittleness index show that the brittleness of the conglomerate decreases with the increase of the confining pressure, and increases first and then decreases with the rise of the conglomerate grain size and VBP. The results of this study can be used to evaluate the brittle nature of gravel strata.

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