Particle Crushing and Energy Dissipation of Saturated Broken Gangue under Compaction

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Abstract. A detailed understanding of particle crushing, which changes particle size distribution and influences the energy dissipation of broken rocks, is extremely important to underground engineering, such as the prevention of dynamic hazards caused by hard roof. We have studied particle crushing and energy dissipation of the saturated broken gangue under variable axial stresses (2, 4, 8, 12 and 16 MPa). Testing results indicate that particle crushing was pervasive and mainly contained fracture, attrition and abrasion. 4 MPa was a critical axial stress for describing particle size distribution, compaction deformation and energy dissipation under compaction. Axial strain was an effective parameter to describe the particle crushing state. In general, both the axial strain and strain energy density were influenced by the initial gradation. A larger Talbot exponent corresponds to a larger axial strain and a smaller strain energy density.

1. Introduction

As underground mining activity rapidly develops to deeper and deeper ground, there have been a number of dynamic hazards caused by hard roof, such as rock burst, coal and gas outburst and shockwaves in goaf [1-3]. Many researches have proved that energy saltation is the main reason for these dynamic hazards and energy saltation is caused by deformation or breaking down of hard roof [4]. In coal mining engineering, hard roof deformation will release energy; in the meantime, the broken rock mass in caved zones will absorb the energy. As a result, the energy dissipation of broken rock mass is an important factor to determine the risk of dynamic hazards. Furthermore, crushing of broken rock mass during compaction is one of the main reasons for energy dissipation. Therefore, it is necessary to take account to the crushing and energy dissipation of broken rock mass in caved zones in mining engineering.

Over the years, many laboratory experiments or numerical simulation have been conducted to study the particle crushing behavior of granular materials [5-14]. The results showed that particle crushing, which may occur during the loading, is mainly affected by the applied stress, the initial grading of the tested materials, the change in particle mixture, the geological framework and the complex shape in physics and geometry. However, few studies have been performed regarding the crushing of the broken rock mass in caved zones.

Broken rock mass in caved zones is a typical inhomogeneous and discontinuous medium, and due to its many fissures, is in weak equilibrium. During the compaction, the fissures and pores between
broken rocks undergo a series of changes, which are accompanied by the absorption and dissipation of energy. Energy dissipation is widely used in analysis of rock failure [3, 15-18].

Overall, the main objective of this study is to further advance the understanding of the particle crushing and energy dissipation of broken rocks, and the main novelty is to quantitatively study the particle size distribution evolution and analyze the relationship between the particle crushing and energy dissipation. The results presented herein provide scientific basis for the prevention of dynamic hazards caused by hard roof in coal mining engineering.

2. Experimental Details

2.1. Preparation for testing samples
The gangue samples used in this test were taken from Xiaojihan Coal Mine in Shanxi province, China. According to the field observation of engineering geological conditions, the broken rock mass in caved zones was in different sizes. In this test, the tested samples consisted of particle size 2.5-5, 5-8, 8-10, 10-12 and 12-15 mm, respectively. In order to study the influence of initial gradation on particle crushing and energy dissipation, the gangue particles within different diameter ranges were proportioned according to Talbot formula[19], and Talbot exponents were 0.2, 0.4, 0.6 and 0.8, respectively. The total mass to each sample was 1500 g, and Table 1 shows the details of the mass percentage of gangue particles in each diameter range to each Talbot exponent. Finally, the samples were placed in a glass container filled with water for seven days to ensure that they were fully saturated [13].

Table 1. The details of the mass percentage of the gangue particles in each diameter range to each Talbot exponent.

| Talbot exponent | Mass percentage in each particle diameter range (%) |
|-----------------|-----------------------------------------------|
|                 | 2.5-5 mm | 5-8 mm | 8-10 mm | 10-12 mm | 12-15 mm |
| 0.2             | 34.5     | 26.3   | 13.3    | 11.4     | 14.5     |
| 0.4             | 30.5     | 26.0   | 14.0    | 12.6     | 16.7     |
| 0.6             | 26.7     | 25.6   | 14.9    | 13.8     | 19.0     |
| 0.8             | 23.2     | 24.9   | 15.5    | 14.9     | 21.5     |

2.2. Experimental equipment and testing procedure
The MTS816.03 system and a self-designed compacting apparatus were the two major parts in the testing system, and the compacting apparatus mainly contained piston, cylinder tube, base and other parts [19]. Due to the movement of overlying strata, the broken rock mass in caved zones support different load at different time, the compaction level from beginning to end increases gradually. Therefore, we should consider the impact of compaction level on particle crushing and energy dissipation of crushed rock. Considering the strata depth (-530 m) and the in-situ strata stress (average bulk density of 0.024 MN/m$^3$), a maximum axial stress of 16 MPa was set for the compacting test. An axial force control mode was applied, and the samples were carried out and separated after the axial stress reached a designed value.

3. Particle crushing and particle size distribution evolution

3.1. Particle crushing
Particle crushing resulted from continuous damage, which was caused by the mutual extrusion and shear fractures between rock particles, and resulted in an increase in small particles. Based on the X-ray CT images, there were mainly three types of particle crushing, including fracture, attrition and abrasion, as shown in Figure 1. Fracture was caused by the formation of tensile fractures or shear fractures in particles, which easily occurred in the slender particles and separated a particle into two main parts accompanied by smaller particles formed along the fracture zone, as shown in Figure 1(a). Attrition was pervasive under compaction and resulted from the stress concentration in the vicinity of
contact points (e.g., corner-corner or corner-surface contact) between the angular particles. Attrition often occurred in the particles with sharp corners and resulted in the particle corners falling off, as shown in Figure 1(b). Abrasion, which made the shape of particles more circular, was caused by the formation of reciprocal shear fractures between gangue particles whose shapes were relatively regular, as shown in Figure 1(c).

![Figure 1. Particle crushing. (a) fracture, (b) attrition and (c) abrasion.](image)

### 3.2. Particle size distribution evolution

In order to study particle size distribution evolution quantitatively, the average particle size is defined and given by the following equation

\[ d_a = \sum_{i=1}^{6} d_{ai} P_i \]  \hspace{1cm} (1)

where \( d_a \) is the average size of the rock particles, \( d_{ai} \) is the median of each particle size range, and \( P_i \) is mass percentage of gangue particles in each size range.

Figure 2 illustrates the average particle size-axial stress curves. In Figure 2, it was observed that the average particle size decreased with an increase in the axial stress. When axial stress was less than 4 MPa, the average particle size decreased rapidly by 23.3\%-26.0\%, compared with the values in initial state. That indicated that gangue particles were crushed in large numbers. When the axial stress exceeded 4 MPa, the average particle size decreased slowly, which indicated that particle crushing occurs slightly. That was mainly because that in the initial stage of compaction, gangue particles contained many flaws and sharp corners, and particle crushing easily occurred. In the later stage, the samples were dense, the particles were in close contact (surface-surface contact) with each other, and particle crushing was difficult to occur. As a result, the average particle size decreased slowly.
4. Energy dissipation

4.1. Deformation of samples
Figure 3 illustrates the axial strain-stress curves. In Figure 3, axial strain increased with an increase in axial stress. The increase process consisted of two stages, a rapid increase (0-4 MPa), during which the axial strain was 70.4%-74.3% of the total strain, and a slow increase (4-16 MPa). That was mainly because in the initial stage of compaction, the particles contained many flaws and corners and the samples were in a loose state. Particles were easy to be crushed and rearranged, and pores were compressed and closed rapidly. In comparison, at the later stage, most of the pores disappeared, and the particles were in close contact with each other, thus the axial strain increasing slowly. Furthermore, we found that the relationship between the axial strain and axial stress could be described by the logarithmic function.

Figure 3. Relationship between axial strain-axial stress.

In addition, the axial strain was influenced by the initial gradation, and a larger Talbot exponent indicated a larger axial strain. That was because a larger Talbot exponent corresponded to a larger mass percentage of the large particles, which were more likely to cause pores.

Figure 4 shows the axial strain-average particle size curves. In Figure 4, it was found that the relation between the axial strain and average particle size could be described by the linear function. As
shown in section 3.1 and 3.2, particle crushing was one of the main factors which cause the compaction deformation of the samples. The larger the axial strain, the more the particle crushing, thus corresponding a small average particle size value. Therefore, axial strain can be used as an effective parameter to describe the particle crushing state of the saturated broken gangue.

Figure 4. Relationship between axial strain-average particle size.

4.2. Energy dissipation
Strain energy density is used to express the energy consumed by the deformation of saturated broken gangue per unit volume under compaction [4]. In this test, the elastic deformation of testing equipment (e.g., dowel bar, compacting head, piston, cylinder tube and pedestal) played a negligible role, and the work done by MTS816.03 system was mainly consumed by the deformation of samples and friction between the gangue particles and cylinder tube inner wall. The work done by compaction of per unit volume of samples \( W \) could be calculated by

\[
W = \int_0^\varepsilon \sigma d\varepsilon
\]  

(2)

Substituting the logarithmic function in Figure 3 into Eq. (2), we could obtain

\[
W = \frac{1}{b_1} [a_1 \exp(\varepsilon / a_1) - a_1 - \varepsilon]
\]  

(3)

The unit energy dissipation of the friction between the particles and cylinder tube inner wall \( W_m \) could be calculated by

\[
W_m = \int_0^\varepsilon \left[ \mu \lambda \sigma 2\pi rh_0 (1 - \varepsilon) \right] \frac{h_0}{2} d\varepsilon = \frac{\lambda \mu h_0 W}{r}
\]  

(4)

where \( \mu, \lambda, r \) and \( h_0 \) are the friction coefficient, lateral pressure coefficient, radius of the cylinder tube inner wall and initial height of sample, respectively. Zhou et al. [3] set \( \mu = 0.25 \) and \( \lambda = 0.43 \). Therefore, the strain energy density \( \nu_\varepsilon \) of the samples could be expressed as

\[
\nu_\varepsilon = W - W_m = (1 - 0.1075 \frac{h_0}{r})W
\]  

(5)
Figure 5 shows the strain energy density-axial strain curves. In Figure 5, the strain energy density increased with an increase in axial strain. The increase process could be divided into two stages which were consistent with the two stages of compaction deformation. In this test, we did not observe obvious elastic deformation of the samples after unloading. Therefore, the energy consumed by deformation of samples mainly consisted of two parts, including the energy consumed by particles arrangement, and the energy consumed by particle crushing. In rapid increase stage of deformation, samples were loose, the friction between particles was small, and particle crushing was easy to occur, thus a small amount of energy consumed. As a result, the strain increased rapidly, and the strain energy density increased slowly. The deformation in this stage accounted for 70.4%-74.3% of the total deformation but the energy dissipation accounted for only 27.3%-30.2% of the total energy. In comparison, in slow increase stage of deformation, samples were dense, the friction between particles was large, and particle crushing was difficult to occur, thus a large amount of energy consumed. Therefore, the strain increased slowly, and the strain energy density increased rapidly. The deformation in this stage accounted for only 25.7%-29.6% of the total deformation but the energy dissipation accounted for 69.8%-72.7% of the total energy.

![Strain energy density vs. Axial strain](image)

**Figure 5.** The relationship between strain energy and axial strain.

In addition, the strain energy density was influenced by the initial gradation. To same axial strain, a larger Talbot exponent indicated a smaller strain energy density. In other words, sample with small Talbot exponent consumed more energy to reach the same strain than samples with large Talbot exponent. That was mainly because that the sample with a large Talbot power exponent had larger mass percent of large particles, which caused more pores and were easier to be crushed, thus, the same amount of deformation consumed less energy.

Figure 6 shows the strain energy density-average particle size curves. In Figure 6, during compaction, with the decrease of the average particle size, the strain energy density increased at an accelerated rate. In the initial stage of the increase process, corresponding to the rapid decrease of average particle size, particles were easily to be crushed and a small amount of energy was consumed, thus the strain energy density increasing slowly. In comparison, in the later stage, corresponding to the slow decrease of average particle size, particle crushing was difficult to occur, and a large amount of energy was consumed, thus the strain energy density increasing rapidly.
5. Conclusions
(1) The compaction process of the saturated broken gangue mainly included particle rearrangement and particle crushing. Particle crushing was pervasive under compaction and mainly contained three types, e.g., fracture, attrition and abrasion.

(2) Both the particle size distribution and compaction deformation changed with the increase of axial stress. The two changed processes could be divided into two stages, respectively, a rapid change (0-4 MPa) and a slow increase (4-16 MPa). Analysis of the differences in the saturated broken gangue under compaction indicated that 4 MPa was a critical axial stress for describing the particle crushing and compaction deformation. The relationship between the axial strain and average particle size could be described by the linear function. Axial strain could be used as an effective parameter to describe the particle crushing state of saturated broken gangue.

(3) The strain energy density increased with an increase in the axial strain. The increase process could be divided into two stages, which were consistent with the two stages of compaction deformation. In rapid increase stage of deformation, the strain energy density increased slowly. In comparison, in slow increase stage of deformation, the strain energy density increased rapidly.

(4) In general, both the axial strain and the strain energy density were influenced by the initial gradation. To same axial stress, a larger Talbot exponent corresponded to a larger axial strain. To same axial strain, a larger Talbot exponent corresponded to a smaller strain energy density.

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