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Fractal characteristics of crushed particles of coal gangue under compaction

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ABSTRACT

The surface morphology of compacted and crushed gangue presents self-similarity and other fractal characteristics. This research constructed a fractal model for the particle size of compacted and crushed gangue based on fractal theory and particle size distribution information. To investigate the fractal characteristics of compacted gangue, compaction experiments were carried out under varied stresses and with different particle sizes. Results showed that the particle size distributions of crushed gangue specimens with two distinct lithology exhibited fractal characteristics. Fractal dimension of each crushed specimen ranged from 0.352 to 2.654, with increase of stress, the particle size of each specimen tended to be distributed in a more dispersed fashion. Meanwhile, the fractal dimension increased with increased content of small particles, and tended to be a definite value. While the fractal dimension decreased with increased rock strength for the same initial particle size gradation and stress.

1. Introduction

In coal mining, gangues which are piled up on the surface after discharge pose a threat to the environment around mining areas [1–4]. Coal mining by solid backfill mining technology, as a green mining method was proposed to solve problems such as pressed coal and gangue deposition presented by traditional mining technologies [5–7]. Using this method, solid wastes such as gangues can be used to backfill mined-out areas directly to replace the coal removed, protect surface construction from subsidence, and reduce environmental harm [8,9]. However, gangues backfilled in mined-out areas are likely to crush due to the overburden pressure. Then the crushed particles result in changes in their gradation which affect the strength and deformation of such gangue backfills [10,11]. Thus, research into the relationship between particle breakage and pressure for compacted gangues will provide useful guidance for mining practitioners using solid backfill mining technology.

Scholars have carried out a series of studies on gangue particle breakage. Zhang et al. [12] performed compaction experiments on loose gangues, and obtained a relationship between strain, expansion coefficient, and compactness, as well as some relevant characteristics relating to compaction time.

Shi and Cheng [13] established the fractal model of rockfill material based on four groups of triaxial test with high confining pressure. Jiang et al. [14] discussed the relationship between the compactness and breakage of coal gangues using compaction experiments by dividing the compaction into two stages: crushed and consolidation. Su et al. [15] obtained compaction characteristics for crushed gangues with three distinct lithologies and showed that the expansion coefficients increased with increasing particle size. Moreover, the rest of the measured expansion coefficients were little influenced by lithology or particle size. Liu et al. [11,16] performed experimental research to investigate the basic mechanical properties of gangues for road-use in Northern Xuzhou city, China and refined current thinking on the issue of particle breakage. Zhou et al. [17] studied the compressive deformation and energy dissipation of gangue in the loading process under conditions of different particle sizes, loading rates and first-time stress loads. Most existing studies investigated the breakage phenomenon and factors influencing gangue particle breakage. Few studies have been made on the variation of fractal dimension of crushed particles with different compaction stresses and gradations.

This research established a model for the crushed particle size of compacted gangue based on fractal theory and particle size distribution information. In addition, the authors explored the fractal characteristics of particle breakage for compacted gangue by conducting compaction experiments under varied stresses and with different particle sizes.

2. Fractal model for crushed particles of coal gangue

The compaction and breakage of particle packs may be considered as an energy dissipation process, characterised by self-similarity. Therefore, the authors applied a fractal model to describe the particle size distribution of gangue after compaction. Based on the association of

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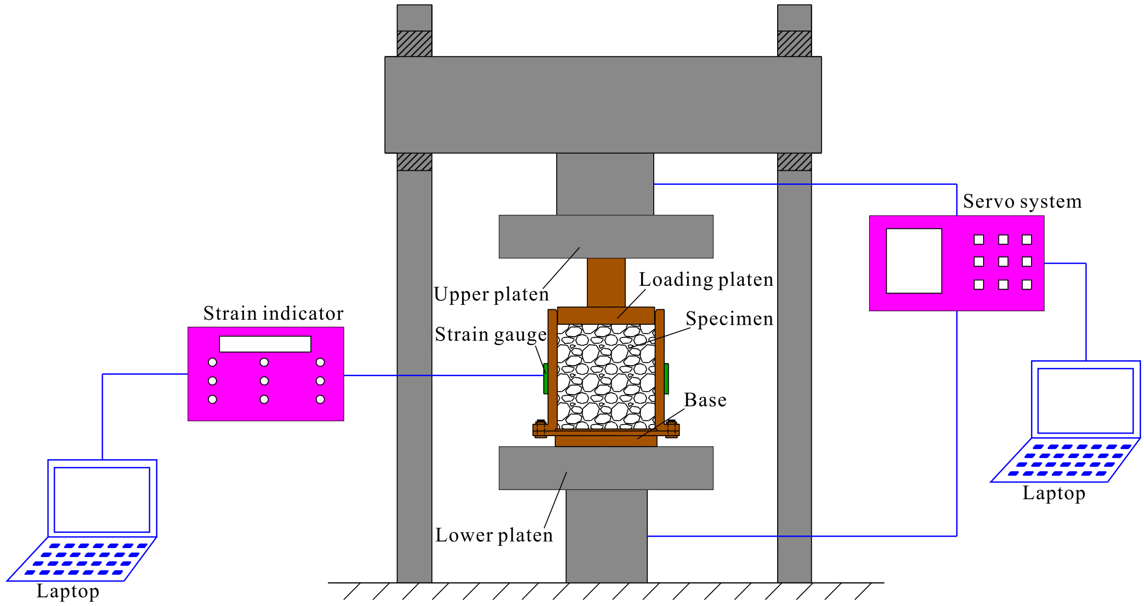

Fig. 1. Schematic illustration of experiment system.

particle numbers and characteristic scale, the basic fractal definition is:

$$N \propto r^{-D} \quad (1)$$

where N refers to the number of particles with characteristic scale (particle radius) bigger than r, D is the fractal dimension, $r_{m.}$ denotes the minimum radius, N_m is the number of particles with radius bigger than $r_{m.,}$ also called the total number. According to Eq. (1):

$$\frac{N}{N_m} = \left(\frac{r}{r_m}\right)^{-D} \quad (2)$$

Based on the particle size and quantitative frequency distribution of corresponding particles, the fractal dimension D can be obtained. However, screen testing usually calculates particle size gradation according to mass proportion. It is inconvenient here to derive statistics for particle numbers corresponding to each particle size. Therefore, the association of particle size and mass has to be found. Turcotte [18] assumed that mass is subject to a Weibull distribution:

$$\frac{M(r)}{M_T} = 1 - \exp\left(-\left(\frac{r}{\sigma}\right)^{\alpha}\right) \quad (3)$$

where $M(r)$ is the particle mass with radius smaller than r, M_T is the total mass, and σ is associated with the average size. Suppose that $\sigma << 1$, after series expansion, Eq. (3) may be simplified to:

$$\frac{M(r)}{M_T} = \left(\frac{r}{\sigma}\right)^{\alpha} \quad (4)$$

Differentiating Eq. (4):

$$dM \propto r^{\alpha-1} dr \quad (5)$$

Similarly, after differentiation of Eq. (1):

$$dN \propto r^{-D-1} dr \quad (6)$$

The relationship between particle numbers and mass is:

$$dN \propto r^{-3} dM \quad (7)$$

According to Eq. (5) and Eq. (6):

$$\alpha = 3 - D \quad (8)$$

The fractal dimension D is then calculated. The derivation above, suggested by Turcotte, includes the assumption of $r/\sigma \ll 1$, which possibly limits its feasibility. To exclude this assumption, Eq. (1) is rewritten based on the fractal relationship of particle numbers to particle size. Therefore, the number of particles with size larger than d become:

$$N(x>d) = Cd^{-D} \quad (9)$$

where C is a coefficient of proportionality, the mass of particles with size less than d is:

$$M_d(x<d) = \int_{d_m}^{d} s\rho x^3 dN(x) \quad (10)$$

where s is the shape factor of the particles; ρ is their density; and d_m is the minimum particle size. Since there is:

$$dN(x) = CDx^{-D-1} dx \quad (11)$$

Table 1
Mechanical properties of coal gangue.

Lithology	Density ρ (kg/m^3)	Elastic modulus E/GPa	Poisson μ	Compressive strength σ_c/MPa	Tensile strength σ_t/MPa	Cohesion c/MPa	Internal friction angle φ/°
Sandstone	2940	75.68	0.19	135.85	18.89	12.86	37.55
Sandy mudstone	2800	17.98	0.32	67.61	6.73	10.61	35.49