Breakage law and fractal characteristics of broken coal and rock masses with different mixing ratios during compaction

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Abstract
Broken coal and rock masses are the major part of the goaf. The compaction characteristics of coal and rock masses and the breakage law of whose particles during compaction exert an important influence on various aspects including control of strata motion, prediction of surface subsidence, and backfill mining. In this paper, the triaxial compaction experiment on broken coal-rock masses with different mixing ratios was carried out. The test results showed that with the increase of stresses, the strain of coal-rock masses gradually rose while the porosity, bulking factor, and degree of compaction gradually declined. During the compaction of coal-rock masses, the fitting curves of the strain, porosity, bulking factor, and degree of compaction with stresses of coal samples all appeared as a cubic function of stresses. The breakage behavior of coal particles underwent three stages: structure re-arrangement and breakage of particles, particle breakage, and compression-induced deformation of particles. With increasing stress, the crushing amount of particles gradually grew while the increase rate of the crushed particles gradually decreased and the larger the particle strength was, the lower the increase rate of the crushing amount. Additionally, in the compaction process of samples, particle breakage mainly appeared before the stress reached to 8 MPa while the coal and rock particles were hardly crushed after the stress was larger than 8 MPa. With increasing stresses, the particle size gradation of samples gradually became reasonable and the lower the particle strength of samples was, the more reasonable the particle size gradation of compacted samples. The particle size gradation of various compacted and crushed samples showed a favorable fractal characteristic. In the stage with a low stress, the value of fractal dimension $D$ rapidly grew and the fractal dimensions $D$ of various samples tended to be stabilized after the stress reached to a high level.

KEYWORDS
broken coal-rock masses, compaction test, fractal characteristic, particle breakage, particle size gradation

1 INTRODUCTION

After the coal mining, friable immediate roof and immediate roof are fractured and caved into the goaf, which forms a caving zone in goaf together with left-over coal in the goaf. The caving zone in goaf is mainly composed of broken coal and rock masses, whose vertical height can be 4-11 times of the mining height, showing a high porosity. As the constant mining of
the working face, on the condition that the goaf is not filled, the broken coal and rock masses in goaf are gradually compacted under the pressure of overlying strata and their own deadweight to thus result in large-area surface subsidence.6-10 probably causing various problems including ground cracks, building damage, and water and soil loss,11,12 as shown in Figure 1. On the condition that the goaf is filled with solid wastes, the aforementioned problems are solved.13-15 However, during the goaf backfill using the solid wastes, the backfill materials (mixture of broken coal and rock masses) are also gradually compacted owing to being influenced by the pressure of overlying strata and their own deadweight. Moreover, the backfill materials with different mixing ratios exhibited different degrees of breakage and deformation during the compaction, leading to different effects of backfill mining on the control over the surface subsidence.16-18 Overall, investigating the compaction characteristics and the law of particle breakage of coal and rock masses during the compaction exerts guidance significance on various aspects including analyzing the prediction of surface subsidence, effect of backfill mining, and mixing proportion optimization of backfill materials.

Numerous scholars have investigated the compaction characteristics of broken rock masses and acquired some achievements. Salamon19 theoretically explored the stress-strain relation of broken rock masses during the compaction. Ma et al20 experimentally showed that stress-strain characteristics of broken rocks in the compaction process appear as an exponential relationship and they analyzed the influence of particle size and strength on the stress-strain characteristics of broken rocks. By conducting the compaction test on broken rocks, Zhang et al21 suggested that rocks show a high breakage rate under a low relative pressure and the breakage rate of rocks is low after the compaction stress on rock masses is higher than a certain value. The gradation curve of broken rocks can be described by using a quadratic polynomial. Su et al22 revealed the stress-strain relation during the compaction of the three gravels (sandstone, sandy mudstone, and mudstone) and analyzed the influences of rock strength, rock size, and compaction stress on the compaction characteristics of gravels. Scholars also carried out a series of researches on the breakage of coal gangue in the compaction process. By carrying out the compaction test on coal gangue, Zhang et al23 suggested the relationship of the strain, bulking factor, and degree of compaction of coal gangue in the compaction process. Zhou et al24 investigated the compression-induced deformation and energy dissipation during compaction of coal gangue on the condition of different particle sizes, loading rates, and initial stresses. Zhang

![Figure 1](image_url)
et al.\textsuperscript{25} explored the fractal characteristics of broken particles in coal gangues under different compaction stresses and particle size gradations. By experimentally investigating the deformation characteristics of backfill bodies (gangue and coal ash) during compaction, Xu et al.\textsuperscript{26} found the optimal mixing ratio of gangue and coal ash (backfill bodies). It can be seen that majorities of current researches mainly investigate the compression-induced breakage of rocks and coal gangue and analyze various factors influencing particle breakage. However, few researches are reported about the breakage law and fractal characteristics of broken coal and rock masses in the compaction process. Owing to the mixture of broken coal and rock masses is the main backfill materials of goaf, it is necessary to investigate the compaction characteristics and breakage law of broken coal and rock masses with different mixing ratios, which has great significance on predicting and controlling mining-induced surface subsidence.

By using the loading part of the seepage test system for coal and rock masses, the triaxial compaction test was carried out on broken coal and rock masses with different mixing ratios. Through the test, the relationships of strain, porosity, bulk factor, and degree of compaction with stress on samples during the compaction of coal and rock masses were acquired. Afterward, the law of breakage behavior of particles in coal and rock masses in the compaction process was revealed. Finally, the particle size gradation and fractal characteristics of samples under different stresses were analyzed.

2 | **TEST METHODS**

2.1 | **Test equipment**

The test equipment used was the loading system of the seepage test equipment for coal and rock masses and the test system is shown in Figure 2. The test system includes axial- and confining-pressure loading systems. The axial-pressure loading system was used to apply the axial pressure on samples by using an automatic pressure pump for axial pressure (with the loading range of 0-70 MPa), which is directly controlled by a computer. The confining-pressure loading system was adopted to apply confining pressure on samples by applying an automatic hydraulic pump (the range of applied water pressure: 0-20 MPa). During the test, the broken coal and rock masses were compacted in the colloid sleeve in the high-pressure kettle whose internal diameter and height were both 150 mm, and the diameter and height of the colloid sleeve were 50 and 125 mm, respectively.

2.2 | **Sample preparation**

The broken coal and rock masses were taken from the 121109 working face in Xinji No.2 Coal Mine in Huainan, Anhui Province, China, and their mechanical parameters are displayed in Table 1. The large coal-rock samples collected from the working face were first artificially crushed,
and then, two sieves with the pore sizes of 6.8 and 10.2 mm were used to separately screen 10 kg of broken coal and rock masses with the particle sizes of 6.8-10.2 mm. In order to investigate the breakage characteristics and fractal characteristics of broken coal and rock masses with different mixing ratios in the compaction process, the samples used for the test were divided into five groups according to different volumetric proportions (the mixing ratios of 1:0, 1:1, 1:2, 1:4, and 0:1) of coal and rock masses. The five groups of samples were separately marked as G1-G5, and the coal-rock samples prepared according to the above mixing ratios are displayed in Figure 3 in which samples with ratios of 1:0 and 0:1 separately represent the pure coal masses and pure rock masses. The proportioning scheme for the compaction test is shown in Table 2.

### 2.3 Test scheme

In order to investigate the breakage characteristics and fractal characteristics of broken coal and rock masses with different mixing ratios in the compaction process under different stresses, 20 compaction tests were designed, as shown in Table 3. The specific steps of each test are displayed as follows:

1. According to the mixing ratios of various samples in Table 2, the broken coal and rock masses were weighed and then the weighed broken coal and rock masses were uniformly mixed.
2. The colloid sleeve was put into the high-pressure kettle, in which the uniformly mixed broken coal and rock masses were put, shook and tamped in order that the upper surface of the broken coal and rock masses was in a horizontal plane. Afterward, the initial height $h_0$ of broken coal and rock masses in the colloid sleeve was measured by using a vernier caliper and then recorded.
3. The other parts of the equipment were installed so as to further conduct the compaction tests according to the test scheme shown in Table 3.
4. After finishing the tests, the broken coal and rock masses were taken out and screened by using sieves. Afterward, the screened coal and rock masses with different particle sizes were weighed and recorded.
2.4 Data processing method

2.4.1 Strain calculation

As shown in Figure 4, the initial height of the broken coal and rock masses was $h_0$ and the compression-induced displacement at the vertical direction recorded by using the displacement transducer during the triaxial compaction test was $\Delta h$. Therefore, the axial strain $\varepsilon$ of broken coal and rock masses during the whole test can be calculated as follows:

$$\varepsilon = \frac{\Delta h}{h_0} \quad (1)$$

2.4.2 Calculation of porosity

Owing to axial pressure was equal to the confining pressure during the whole test (namely, at a hydrostatic pressure state) and the broken coal and rock masses is isotropic, it is supposed that the radial strain was equal to the axial strain of broken coal and rock masses. Therefore, the diameter $d_1$ of coal and rock masses in the triaxial loading process can be expressed as follows:

$$d_1 = d_0 (1-\varepsilon) = d_0 \left(1 - \frac{\Delta h}{h_0}\right) \quad (2)$$
It is assumed that the true densities of coal and sandstone were $\rho_1$ and $\rho_2$. Moreover, the masses of broken coal and rock masses during each test were $m_1$ and $m_2$ and the initial diameter of the colloid sleeve was $d_0$. Based on Equation (2) and Figure 4, it can be seen that the porosity $\varphi$ of broken coal and rock masses during the test can be calculated as follows:

$$
\varphi = \frac{\frac{\pi}{4}d_1^2 (h_0 - \Delta h) - (\frac{m_1}{\rho_1} + \frac{m_2}{\rho_2})}{\pi\rho_1 d_0^2 (h_0 - \Delta h)}
$$

(3)

2.4.3 | Calculation of bulking factor

The bulking factor of rocks reflects the bulking property of rocks and is equal to the ratio of the volume of loose crushed rocks to that of intact rocks before being damaged. Therefore, as shown in Figure 4, the bulking factor $k$ of broken coal and rock masses during the whole compaction test can be calculated as follows:

$$
k = \frac{\frac{\pi}{4}d_1^2 (h_0 - \Delta h)}{\frac{m_1}{\rho_1} + \frac{m_2}{\rho_2}} = \frac{\frac{\pi}{4}d_1^2 (h_0 - \Delta h)}{4(\rho_2 m_1 + \rho_1 m_2) h_0^2}
$$

(4)

2.4.4 | Calculation of the degree of compaction

Degree of compaction refers to the compacted degree of broken rocks under the effect of external forces during the compaction, which can be calculated by using the ratio of the volume of compacted broken rocks to the total volume of rocks in the original loose state. Thus, the degree of compaction $i$ of broken coal and rock masses during the test can be calculated as follows:

$$
i = \frac{\frac{\pi}{4}d_1^2 (h_0 - \Delta h)}{\frac{\pi}{4}d_0^2 h_0} = \frac{(h_0 - \Delta h)^3}{h_0^2}
$$

(5)

3 | TEST RESULTS AND DISCUSSION

3.1 | Relationships of strain and porosity with stress during the compaction of coal and rock masses

By substituting the monitored data obtained during the experimental process into Equation (1) and (3), the fitting curves of strain and porosity with stress can be calculated and drawn, as shown in Figure 5. It can be seen from Figure 5 that with increasing stress, the strain gradually rose while the porosity of samples gradually declined. However, the change rates of strain and porosity gradually decreased. The whole compaction process can be divided into stages A (rapid compaction) and B (slow compaction). Stage A meant the initial loading stage during which a large number of pores existed in the broken coal and rock masses and therefore the resistance of particles to structural deformation is low, thus showing a rapid deformation. At stage B, as the stress gradually rose, a great number of particles were crushed and crushed small particles filled in pores. Therefore, the porosity of broken coal and rock masses reduced and the resistance of broken coal and rock masses to structural deformation gradually increased. Thus, the increase rate of strain gradually declined. However, coal-rock samples with different mixing ratios showed different increase rates of strain and reduction rates of porosity during the compaction test. As shown in Figure 5, the increase rates of strain and reduction rates of porosity of various
samples in the compaction process were always displayed in a descending order as G1, G2, G3, G4, and G5, which can be explained by using the secant moduli of samples in their compaction process. According to the stress-strain data of various samples, the relationship curves between the secant moduli of and stress on various samples can be obtained, as shown in Figure 6. It can be speculated from the figure that in the whole compaction process, the secant moduli of various samples were always displayed in an ascending order as G1, G2, G3, G4, and G5. Owing to the secant moduli of rocks reflect the average stiffness of rocks, the strengths of various samples during the whole compaction process were shown in an ascending order as G1, G2, G3, G4, and G5. Therefore, the increase rates of strain and reduction rates of porosity of various samples during the whole compaction process were always displayed in a descending order as G1, G2, G3, G4, and G5. Additionally, it can be seen from Figure 6 that as the stress increased in the compaction process of samples from G1 to G5, the secant modulus gradually increased, namely, the strength gradually rose, and thus the change rates of strain and porosity of samples gradually decreased. It conformed to the change law of the strain and porosity of samples shown in Figure 5. It can be speculated from the figure that the fitting curves of the strain and porosity of broken coal-rock samples with stress in the compaction process both appeared as a cubic function of stress. The fitting equations are displayed in Table 4. As shown in Table 4, the correlation coefficients of each fitting equation were all larger than 0.99, showing a high fitting degree.

3.2 Relationships of bulking factor and degree of compaction with stress during the compaction of coal-rock samples

By substituting the monitored data acquired during the tests into Equation (4) and (5), the fitting curves of bulking factor and degree of compaction with stress can be drawn, as shown in Figure 7. The fitting equations are displayed in Table 5. It can be seen from Figure 7 and Table 5 that:

1. The bulking factor and the degree of compaction of samples declined with increasing stress. In the initial loading stage, the bulking factor and the degree of compaction of samples decreased at a great amplitude. With the increase of stress, the reduction rate of bulking factor and degree of compaction of samples lowered.

2. The larger the proportion of coal masses in broken coal-rock samples in the compaction process was, the faster the reduction rates of the bulking factor and the degree of compaction of samples.

3. The fitting curves of bulking factor and degree of compaction of broken coal-rock samples with stress in the compaction process both appeared as a cubic function of stress, with the correlation coefficients all larger than 0.99, showing a high fitting degree.

| Sample ID | Fitting equation of strain(ε) and stress(σ) | Fitting equation of porosity(φ) and stress(σ) |
|-----------|--------------------------------------------|---------------------------------------------|
| G1        | $ε = 5.38E-5σ^3 + 0.02σ$                    | $φ = −5.34E-5σ^3 − 0.02σ + 0.47$            |
|           | $R^2 = 0.99$                                | $R^2 = 0.99$                                |
| G2        | $ε = 4.89E-5σ^3 + 0.02σ$                    | $φ = −5.03E-5σ^3 − 0.02σ + 0.46$            |
|           | $R^2 = 0.99$                                | $R^2 = 0.99$                                |
| G3        | $ε = 3.62E-5σ^3 + 0.02σ$                    | $φ = −3.05E-5σ^3 − 0.01σ + 0.49$            |
|           | $R^2 = 0.99$                                | $R^2 = 0.99$                                |
| G4        | $ε = 3.40E-5σ^3 + 0.01σ$                    | $φ = −2.63E-5σ^3 − 0.01σ + 0.48$            |
|           | $R^2 = 0.99$                                | $R^2 = 0.99$                                |
| G5        | $ε = 3.19E-5σ^3 + 0.01σ$                    | $φ = −2.07E-5σ^3 − 0.01σ + 0.48$            |
|           | $R^2 = 0.99$                                | $R^2 = 0.99$                                |

**FIGURE 6** Relationship curves between the secant modulus of and stress on samples in the compaction process.
0.99, showing a high fitting degree. Therefore, the degree of compaction of goaf and the backfill effect of backfill materials during the backfill mining can be quantitatively evaluated by using the cubic functions of the bulking factor and the degree of compaction with the stress shown in Table 5.

### 3.3 Crushing behavior of coal and rock particles in the compaction process

After various broken coal-rock samples were subjected to the compaction tests under different stresses, the unbroken samples were screened by using a sieve and weighed. Afterward, according to the weighed results, the crushing amounts of various samples under different stresses and those of samples within different stress ranges were calculated. The former was calculated by dividing the mass amount of crushed particle samples under a certain stress by the original mass of particle samples; while for the latter, the crushing amount in the stress range of \( \sigma_1 - \sigma_2 \) was computed by subtracting the crushing amount under \( \sigma_1 \) from that under \( \sigma_2 \). The crushing amounts of various samples under different stresses and stress ranges are displayed in Figure 8.

It can be seen from Figures 8A and B that:

1. With increasing stress, the crushing amount of samples gradually rose while the increase rate of crushing amount gradually declined. During the whole compaction, samples underwent two stages: rapid and slow crushing. In the rapid-crushing stage (stress was in the range of 0-8 MPa), a great number of sample particles were crushed under the effect of pressure, causing a large increase rate of crushing amount of samples. In the slow-crushing stage (the stress was ranged from 8 to 16 MPa), the crushing amount of sample particles was low under the effect of the pressure, thus resulting in a low increase rate of the crushing amount of samples. The above results showed
that during the compaction of broken coal-rock samples, breakage of particles mainly appeared before the stress reached to 8 MPa while the crushing amount of particles in coal and rock masses was low after the stress was larger than 8 MPa. It conformed to the previous conclusion obtained by other scholars that breakage of particles in rocks mainly occurred under a low stress on the condition that rocks were compacted.21

2. With the increase of stress, the crushing amounts of various samples gradually rose. However, the increase rates of crushing amounts of different samples were different. The larger the proportion of coal in samples, the larger the increase rate of crushing amounts of samples with increasing stress, namely, the increase rates of crushing amounts of samples were displayed in a descending order as G1, G2, G3, G4, and G5. The primary reason was that the coal strength (uniaxial compressive strength: 13.66 MPa) was far lower than the strength (the uniaxial compressive strength: 124.85 MPa) of sandstone. Hence, under the same stress, the coal was crushed prior to that of sandstone, so the larger the proportion of coal in samples was, the larger the crushing amount of samples, thus accelerating the increase rate of crushing amount of samples. Figure 9 shows the coal and rock particles before and after the G2 sample (the volumetric ratio of coal and sandstone was 1:1) were compacted under the stress of 16 MPa. Before conducting the compaction test, the volumetric ratio of coal and sandstone was 1:1, with the particle size of 6.8-10.2 mm. After carrying out the compaction test, the sandstone particles with the particle size of 6.8-10.2 mm were significantly more than the coal particles with the same particle size in the mixed particles.
However, the coal particles with the particle sizes of 4.6-6.8 mm, 2.8-4.6 mm, 1-2.6 mm and lower than 1 mm were greatly more than the sandstone particles with these particle sizes in the crushed mixed particles. It implied that the crushing amount of coal was significantly larger than that of sandstone under the same stress.

By analyzing the stress-strain curves (Figure 10A), crushing amount curves (Figure 10B) and changes of void space between particles (Figure 10C) under each stress range of broken coal-rock samples, the crushing behavior of particles during the compaction of samples can be divided into I, II, and III stages. The stress range during the I stage was from 0 to 4 MPa, during which the strain rate of samples was large (as shown in Figure 10A). The reasons were that on the one hand, the porosity of samples greatly declined due to structure re-arrangement of particles, as shown in Figure 10C. On the other hand, the crushing amount of particles was large under the stress range (Figure 10B) and crushed fine particles filled into void space to result in the subsequent reduction of the porosity of samples, as shown in Figure 10C. Therefore, the stage can be regarded as the stage of structure re-arrangement and crushing of particles. The stage during the II stage was in the range of 4-8 MPa, during which the strain rate of samples was not large (Figure 10A) while there was a large crushing amount of sample particles (Figure 10B). It can be speculated that the major reason why the strain in the stage reduced was that particles were crushed into fine particles and filled into the void space, as shown in Figure 10C. Thus, the stage can be called a stage of particle breakage. The III stage showed the stress range of 8-16 MPa, during which the strain rate was also not large, similar to the II stage. However, the crushing amount of particles was far lower than that during II stage (Figure 10B), which revealed that the reduction of strain in the stage was not caused by the fact that particles were crushed and filled into void space. This was because pores between particles had been basically filled with previously crushed fine particles, and thus, the reduction of strain was mainly caused by the compressive deformation of particles under the external load, as shown in Figure 10C. Therefore, the stage can be called a stage of compressive deformation of particles. During the stage, broken coal and rock particles were mutually compressed to form a cementitious body, as shown in Figure 10D.

3.4 Size gradation curve and fractal characteristics of samples in the compaction process

After conducting the compaction test, the broken coal and rock masses were screened and weighed by using sieves with the pore sizes of 1, 2.8, 4.6, and 6.8 mm, respectively. Afterward, according to data of screened and weighed samples after being compacted, the size gradation curves (Figure 11) of each sample before and after being compacted and those (Figure 12) of samples under different stresses were drawn by using mesh size as X coordinate and sieving rate (calculated by dividing the mass of samples screened by a certain level of sieve by the total mass of samples) as Y coordinate.

It can be seen from Figure 11 that the size gradation curves of various samples after conducting the compaction test shifted upwards compared with those before the test; namely, after carrying out the compaction test, particles were crushed and therefore the content of fine particles increased. Moreover, the larger the stress was, the larger the crushing amount of samples, which showed that the particle size gradation became reasonable with increasing stress while the rate of particle size gradation becoming reasonable declined. It can be concluded that the more reasonable the particle size gradation of samples was, the lower the crushing amount of sample particles after being compacted. As shown in Figure 12, under the same stress, the reasonability of particle size gradations of samples was displayed in a descending order as G1, G2, G3, G4, and G5, which was caused by strength disparity of various samples. Based on aforementioned analysis, the average stiffnesses (strengths) of samples during the compaction test were displayed in an ascending order as G1, G2, G3, G4, and G5. The G1 samples showed the lowest strength, and therefore, the breakage of particles was the most serious to generate the most fine particles under the same stress, so that sample G1 exhibited the best particle size gradation. Thus, it can be seen that the lower the strength of sample particles was, the more reasonable the particle size gradation after conducting the compaction test. Overall, in order that solid backfill mining shows a favorable control effect on surface subsidence, it is necessary to moderately increase the strength and particle size gradation of solid backfill materials.

The fractal characteristic of granular materials is generally defined by using the relationship between particle size and number of particles. However, the relationship is hard to be directly acquired through tests, so some scholars put forward a fractal model for describing the fractal characteristics of broken rocks by utilizing the mass distribution of particles with different sizes. Therefore, the fractal dimensions of each sample under different stresses are calculated by employing the fractal model based on mass distribution.

According to literatures, it can be speculated that after carrying out the compaction test, the ratio of the mass of broken coal and rock particles in samples with the particle size lower than $d$ to the total mass of the samples can be expressed as follows:

$$\frac{M_d (x < d)}{M_s} = \frac{d^{3-D} - d_m^{3-D}}{d_M^{3-D} - d_m^{3-D}}$$

Where, $M_d$, $M_s$, and $d$ refer to the mass (unit: g) of particles with particle size lower than $d$ in broken coal-rock samples, the total mass (g) of broken coal-rock samples and the...
**FIGURE 10** Crushing behavior of broken coal and rock particles during the compaction of samples; (A) stress-strain curves of samples; (B) crushing amounts of samples under different stress ranges; (C) changes of void space between particles during the compaction of samples; (D) samples particles compacted under the stresses of 4, 8, 12, and 16 MPa.
particle size (mm) of broken coal and rock particles, respectively. Moreover, $d_m$, $d_M$, and $D$ represent the minimum and maximum sizes (unit: mm) of particles as well as the fractal dimension of particles, respectively.

It is supposed that the minimum particle size $d_m$ of particles is 0, and therefore, Equation (6) can be expressed as follows:

$$\frac{M_d(x<d)}{M_s} = \left( \frac{d}{d_M} \right)^{3-D}$$  \hspace{1cm} (7)

By taking the logarithms of two sides of Equation (7), it can be obtained that:

$$\lg \left( \frac{M_d}{M_s} \right) = (3-D)\lg \left( \frac{d}{d_M} \right)$$  \hspace{1cm} (8)
According to Equation (8), it can be obtained that the slope of the straight line \( \log\left(\frac{M_d}{M_s}\right) = (3-D)\log\left(\frac{d}{d_M}\right) \) is \( 3-D \). According to the screening data of samples, the straight line \( \log\left(\frac{M_d}{M_s}\right) = (3-D)\log\left(\frac{d}{d_M}\right) \) can be fitted to calculate the fractal dimension \( D \).

After carrying out the compaction test, the linear fitting was conducted according to the data of particle size gradation obtained by screening various samples and taking \( \log\left(\frac{d}{d_M}\right) \) as X coordinate and \( \log\left(\frac{M_d}{M_s}\right) \) as Y coordinate. The obtained correlation coefficient \( R^2 \) was ranged from 0.8218 to 0.9876, which indicated that particle size gradations of various compacted and crushed samples showed a favorable fractal characteristic and the fractal dimension \( D \) of samples can be solved according to the slope of the fitting straight line. The fitting curve of fractal dimensions of G1 sample after being compacted under the stress of 16 MPa is displayed in Figure 13.

According to the above methods, the fractal dimensions \( D \) of each sample under different stresses were calculated and the relationship between the fractal dimensions \( D \) and stress is displayed in Figure 14. It can be speculated from the figure that:

1. With increasing stress, the fractal dimension \( D \) gradually increased while the increase rate declined, namely, on the condition that the stress was lower than 8 MPa, the

![Figure 12](image12.png)  
**Figure 12** Size gradation curves of samples under different stresses; (A) 4 MPa; (B) 8 MPa; (C) 12 MPa; (D) 16 MPa

![Figure 13](image13.png)  
**Figure 13** Fitting curve of fractal dimensions of G1 sample after being compacted under the stress of 16 MPa
fractal dimension $D$ rapidly rose while it slowly rose after the stress was larger than 8 MPa. The major reason was that the crushing amount of sample particles was large before the stress reached to 8 MPa while it was low after the stress was larger than 8 MPa, as shown in Figure 8B.

2. Under the same stress, the fractal dimension $D$ grew with decreasing strength of samples; namely, the fractal dimensions of various samples in the compaction process were displayed in a descending order as G1, G2, G3, G4, and G5.

3. When the stress reached to a high level, the fractal dimensions $D$ of various samples tended to be stabilized, having no great change any more. The primary reason was that when sample particles were crushed to a certain degree, the particle size gradation of samples approached to a certain ideal distribution: Particles were completely contacted with each other, and therefore, particles were hard to be crushed. A cementitious body was formed by particles to undergo global compaction-induced deformation, as shown in Figures 10C and D.

3.5 | Contribution of the research result to solid backfill technology for controlling surface subsidence

Surface subsidence frequently occurs after coal mining, causing various problems including ground cracks, building damage, and water and soil loss, as shown in Figure 1. In recent years, the solid backfill technology has been put forward and widely used to control the surface subsidence due to its low cost and a favorable backfill effect.13,23 The schematic diagram of the solid backfill technology is shown in Figure 15.31 The technology for controlling the surface subsidence mainly involves three aspects: prediction of surface subsidence caused by mining, filling design of solid backfill technology, and evaluation of surface subsidence control effect. The research results in the study make contributions to the aforementioned three aspects, as shown in Figure 16. The specific contributions are displayed as follows: the fitting equations of strain, bulking factor, and degree of compaction with stress in Tables 4 and 5 can provide guidance on predicting and calculating the surface subsidence amount induced by mining, calculating the backfill amount during backfill mining and the subsidence amount after the backfilling (control effect). Additionally, some suggestions are proposed; namely, it is necessary to moderately increase the strength and particle size gradation of backfill materials.

FIGURE 14 Relationship curves of fractal dimension of and stress on various samples

FIGURE 15 Schematic diagram of solid backfill technology (refer to [31])
4 | CONCLUSIONS

By utilizing the loading part of the seepage test system for coal and rock masses, the triaxial compaction tests were carried out on broken coal and rock masses with different mixing ratios. The major conclusions are displayed as follows:

1. With increasing stress, the strain of broken coal-rock samples gradually rose while their porosity, bulking factor and degree of compaction gradually declined and the change rate decreased. The whole compaction process of samples can be divided into two stages: rapid and slow compaction. During the compaction of samples, the fitting curves of the strain, porosity, bulking factor, and degree of compaction of samples with stress all appeared as a cubic function of stress and the correlation coefficients of fitting equations were all larger than 0.99.

2. With growing stress, the crushing amount of broken coal-rock samples gradually increased while the increase rate of the crushing amount gradually declined. Moreover, the larger the particle strength was, the lower the increase rate of the crushing amount. Additionally, during the compaction of samples, the breakage of particles mainly took place before the stress reached to 8 MPa while the crushing amount of coal and rock particles was low after the stress was larger than 8 MPa.

3. During the compaction of samples, crushing behavior of particles was divided into I, II, and III stages. The stress during the I stage was from 0 to 4 MPa, which was called structure re-arrangement and crushing stage of particles. The II stage showed the stress range of 4-8 MPa, called the particle breakage stage. In the III stage, samples underwent compaction under the stress from 8 to 16 MPa, which was called the stage of compressive deformation of particles.

4. The particle size gradation of samples gradually became reasonable with growing stress while the rate of becoming reasonable declined. The more reasonable the particle size gradation of samples was, the lower the crushing amount of particles after the samples were compacted. The lower the particle strength of samples was, the more reasonable the particle size gradation after samples was compacted.

5. The particle size gradation of each sample after being compacted and crushed showed a favorable fractal characteristic. With increasing stress, the fractal dimension $D$ gradually rose while the increase rate declined, namely, at a low stress, the fractal dimension $D$ rapidly grew while when the stress reached to a high level, the fractal dimensions $D$ of various samples tended to be stabilized. Additionally, under the same stress, the fractal dimension $D$ increased with decreasing strength of samples.

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