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*Research Article*

# Compression Characteristics of Solid Wastes as Backfill Materials

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A self-made large-diameter compression steel chamber and a SANS material testing machine were chosen to perform a series of compression tests in order to fully understand the compression characteristics of differently graded filling gangue samples. The relationship between the stress-deformation modulus and stress-compression degree was analyzed comparatively. The results showed that, during compression, the deformation modulus of gangue grew linearly with stress, the overall relationship between stress and compression degree was approximately nonlinear, and the deformation of gangue was rather large during the initial portion of the test. Gangue sample mixed with Talbot Formula provides the best deformation resistance capacity, followed by fully graded and single-graded gangue samples. For applications, with adjustment of the gradation of filling materials and optimal design of compacting equipment, surface subsidence may be better controlled.

## 1. Introduction

At present, coal is still the primary source of global energy. For example, in China, coal has already accounted for nearly 70% of the country's primary energy consumption since the year 2000 [1, 2]. The exploitation of coal resources is accompanied by large amounts of waste materials such as gangue and fly ash. According to official statistics, the amount of deposited gangue in China has already reached more than 5.5 billion tons, increasing by 0.4–0.6 billion tons annually, occupying an area of about 15,000 hectares [3, 4]. With the exception of a few small-scale underground waste disposal operations, for example, backfill of abandoned chambers and roadways, most of this waste is usually stockpiled close to collieries [5, 6]. This may result in nonproductive land and pose potential threats to air and water quality. It may also lead to failure of waste embankments. These problems could be alleviated by disposing of the waste underground [7–10]. In addition, an estimated 13.79 billion tons of coal reserves is trapped under buildings, railway, and water bodies, among which coal reserves under buildings account for 9.468 billion tons or 69% of total reserves. In some countries, partial mining methods such as room and pillar mining and strip mining have been successfully employed to extract these coal reserves, but with massive coal pillars left in the gob [11].

In recent years, a solid backfill mining technology has been developed to solve the existing problems described above. Such a technology utilizes specific backfill equipment and backfill techniques to convey gangue into the gob where the solid material is backfilled [12, 13]. Gangue on the surface is transported to the underground part of the mine via a vertical feeding hole after having been successively crushed and screened. Usually, the wastes are stored temporarily in an underground bunker connected to the vertical feeding hole. When needed, the wastes are delivered to a working panel and backfilled into the gob area void space by the compactor at the back of the hydraulic support (generally, the compacting force of this compactor is 2 MPa), so that solid stowing can be realized. The backfill material used in this method is gangue due to its availability and low cost. The grain size of the backfill gangue is usually 0–50 mm.

Field experiments show that the compression deformation characteristics of backfill materials could influence the deformation magnitude and the extent of overlying strata, which consequently dominate surface subsidence [5, 14, 15]. It is, therefore, important to study the basic compression

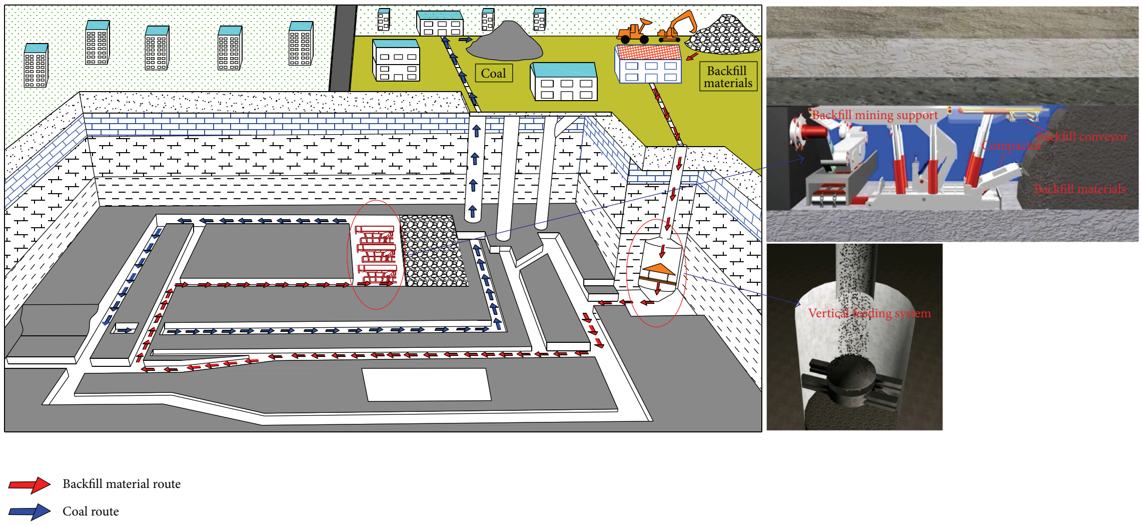


Figure 1: Basic principle of solid backfill mining.

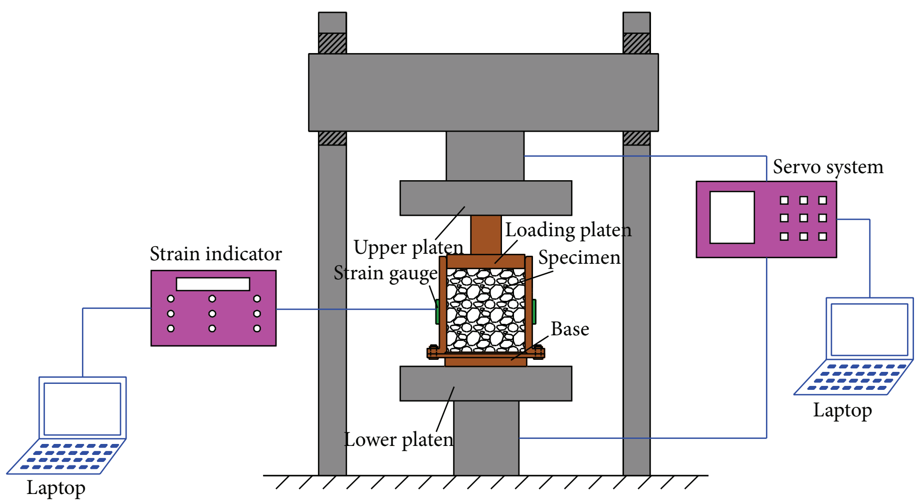


Figure 2: Schematic diagram of test system.

deformation characteristics of solid filling materials to better control surface deformation. In this paper, the relationships between stress and deformation modulus and between stress and compression degree were studied for gangue samples of different gradation, using a large-diameter compression steel chamber and a SANS material testing machine.

## 2. Basic Principle of Solid Backfill Mining

The basic principle of solid backfill mining is as shown in Figure 1. First, at the surface, the backfill material, such as gangue, is crushed to break it down to a grain size smaller than 50 mm. The crushed material is transported through a vertical feeding system to an underground storage silo, from which, when required, it is moved to the backfill mining panel through an underground transportation system. Finally, through special devices on the backfill mining panel, the backfill material is filled into the gob, in which it produces a dense backfill, thus supporting the roof, reducing movement of the overlying strata, and controlling surface subsidence.

## 3. Compression Test

*3.1. Test Materials.* Solid materials were gangue samples from a coal preparation plant at the Changcun coal mine, Shanxi Lu'an Group. These gangue samples were fine sandstones with high hardness and sizes smaller than 50 mm which were sorted using sieves of the following sizes (mm): 10, 20, 31.5, 40, and 50. In the collection process, the artificial destruction of the backfill material needed to be avoided as much as possible. Thus the test materials were all kept with their natural water content of 3.25%; no other water was added during the test process.

*3.2. Test Apparatus.* Test system was comprised of a compression device and a testing machine, as shown in Figure 2.

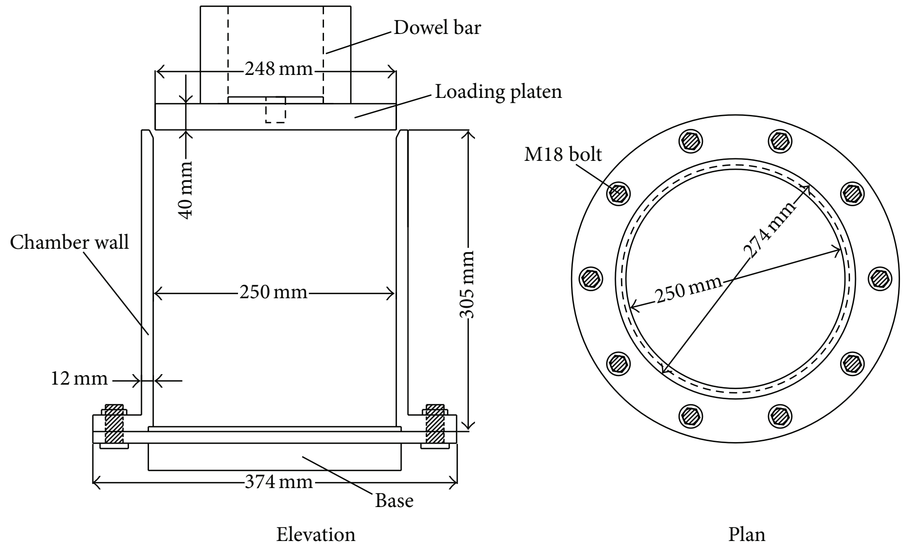


Figure 3: Plan and elevation views of compression device.

Table 1: Load deformation test series with different parameters.

| Category | Test | Percentage (by weight) | | | | |
|---|---|---|---|---|---|---|
| | | 50–40 mm | 40–31.5 mm | 31.5–20 mm | 20–10 mm | 10–0 mm |
| Single-graded size | 1 | 100 | | | | |
| | 2 | | 100 | | | |
| | 3 | | | 100 | | |
| | 4 | | | | 100 | |
| | 5 | | | | | 100 |
| Maximum particle size | 6 | | | | 46.3 | 53.7 |
| | 7 | | | 40.3 | 27.6 | 32.1 |
| | 8 | | 11.8 | 35.5 | 24.4 | 28.2 |
| | 9 | 9.5 | 10.8 | 32.2 | 22.0 | 25.5 |
| Full-scale gradation | 10 ($n = 0.3$) | 6.5 | 7.7 | 9.8 | 14.3 | 61.7 |
| | 11 ($n = 0.4$) | 8.5 | 10.0 | 12.2 | 16.8 | 52.5 |
| | 12 ($n = 0.5$) | 10.6 | 11.9 | 14.3 | 18.5 | 44.7 |
| | 13 ($n = 0.6$) | 12.5 | 13.9 | 15.9 | 19.6 | 38.1 |

Note: $n$ is Talbot's exponent.

Since there are currently no standards for a granular material compression test, the compression device used in this test was self-made [16, 17], as shown in Figure 3. The test apparatus was composed of two parts: a steel chamber and a loading platen. The steel chamber was made out of 250 mm ID by 305 mm pipe with a thickness of 12 mm. The loading platen consisted of 248 mm diameter by 40 mm thick steel plate. The clearance between the platen and the inside walls of the chamber was 1 mm. The loading machine was a SANS material testing machine with a force loading speed ranging from 0.3 to 15 kN/s, a displacement loading speed between 0 and 250 mm/s, and a stroke of 0 to 200 mm. SANS is the leading manufacturer and supplier of static material testing instruments in China, which are capable of performing a full spectrum of material tests, including tension, shear, and compression. During the tests, the loading speed was set at 1 kN/s until a maximum load of 300 kN was reached. The load and displacement were measured at 0.1 s intervals.

*3.3. Test Schemes.* These tests were designed to analyze the impacts of maximum grain size and grain size grading on the deformation characteristics of the samples in the process of compression. In China, for solid backfill mining, method of compaction testing of solid backfill materials issued by China National Energy Administration is used to guide the compaction laboratory tests [18]. Table 1 shows that the physical parameters varied during different compression tests. Tests 1–5 were designed to analyze the characteristic behavior of different single-graded gangue samples, while Tests 5–9 were used to examine the influence of maximum grain size on the compression characteristics. The gangue samples used in Tests 9–13 were all fully graded (smaller than 50 mm) with different gradations. Tests 10–13 were prepared according to Talbot Theory. Talbot Theory has important implications for the design of material proportion. It is used to find the optimal ratio of the backfill materials, that is, which one is the least deformable. The Talbot Formula is defined by the following equation:

$$p = 100\left(\frac{d}{D}\right)^n, \tag{1}$$

where $p$ is the pass percentage of particles with radius smaller than $d$ and $D$ is the maximum grain size of the material.

During the tests, the gangue samples were placed in the compression device and the loading machine was used to compact the materials until the loading strength reaches the maximum load of 300 kN. Data were then collected to analyze the compression characteristics of the gangue samples.

## 4. Test Results and Analysis

*4.1. Stress-Deformation Modulus Relationship.* As a discrete medium, there is no applicable theory to accurately describe the mechanical properties of the constitutive relationship theory of gangue samples. To study this relationship in the process of compression, the deformation modulus $E$ is defined in

$$E = \frac{\sigma}{\varepsilon}, \qquad \varepsilon = \frac{\Delta h}{h}, \tag{2}$$

where $\sigma$ is the compression stress, $\Delta h$ is the cumulative displacement of the material, and $h$ is the initial height of the test material.

The relationship between stress and deformation modulus for Tests 1–13 is shown in Figure 4.

For all of the gangue samples, a strong, positive linear correlation between deformation modulus and stress is observed. Under the same compacting strength, the deformation modulus of Tests 1–13 was in the order $n = 0.4 > n = 0.3 > n = 0.5 > n = 0.6$ (similarly with 0–40 mm) > original sample (similarly with 0–31.5 mm and 0–20 mm) > 0–10 mm > 10–20 mm > 20–31.5 mm > 31.5–40 mm > 40–50 mm. This implies that the gangue samples with Talbot's grading have a higher deformation modulus, followed by the maximum particle gangue and the single-graded size. This suggests that the gangue graded by Talbot's exponent could be nondeformable to a large degree. Talbot's grading guarantees a perfect gap and matching in the gangue samples, which could provide good resistance to deformation.

In view of the stress-deformation modulus relationships of all of the tests above, the deformation moduli corresponding to stresses of 2 and 12.5 MPa were also obtained (Table 2).

Based on the data given in Table 2 and the stress-deformation curve in Figure 4, the following were concluded: (a) the stress-deformation modulus relationships of all tests are linear; that is, the deformation modulus increases with increasing stress; (b) generally, the deformation modulus of fully graded gangue is higher than that for gangue with the maximum grain size, while the deformation modulus of the gangue with the maximum grain size is higher than that for single-graded gangue. In other words, full-scale grading can result in speeding up the process of compacting backfill materials. In terms of controlling the movement and subsidence of the roof in the gob area, this is the optimal scheme.

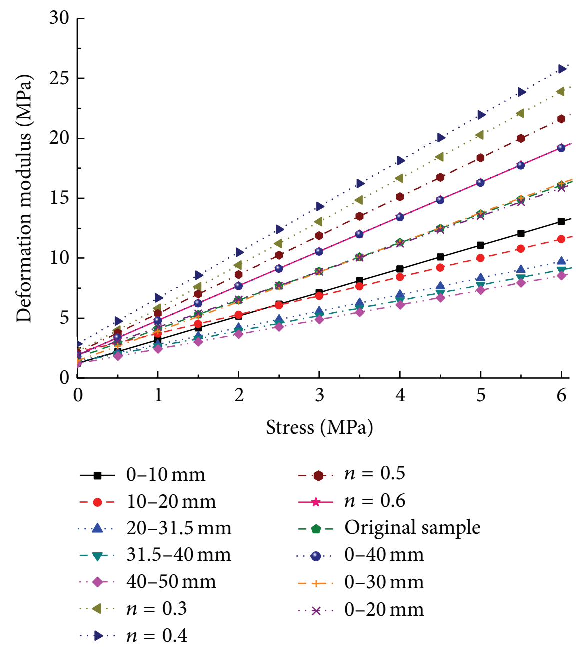


FIGURE 4: Stress versus deformation modulus for all graded samples.

*4.2. Stress-Compression Degree Relationship.* The compression degree of gangue samples can reflect their resistance to deformation. The compression degree $k$ is defined by the following equation:

$$k = \frac{h - \Delta h}{h} = 1 - \frac{\Delta h}{h} = 1 - \varepsilon, \tag{3}$$

where $\Delta h$ is the cumulative displacement of the material and $h$ is the initial height of the test material.

The stress-compression degree curves for Tests 1–13 were obtained by fitting the experimental data, as shown in Figures 5–7.

It can be seen from Figure 5 and the fitting function that (1) the stress-compression degree curves of single-sized gangue samples 1–5 were nonlinear. During the initial stage of the test (0–2 MPa), the decrement in the compression degree was large and the compression proceeded rapidly. As the stress continued to increase and the gangue was further compacted, the decrement in the compression degree decreased, and this tended to be stable; (2) under the same level of compacting strength, the compression degree of Tests 1–5 was 0–10 mm > 10–20 mm > 20–30 mm > 30–40 mm > 40–50 mm. This is because the void ratio of 0–10 mm gangue sample was relatively low and the compression of gangue was therefore smaller, resulting in a higher nondeformability.

Table 2: Summary of deformation modulus-stress test results.

| Category | Test | Deformation modulus/MPa Stress of 2 MPa | Stress of 12.5 MPa | 2–12.5 MPa increments |
|---|---|---|---|---|
| Single-graded size | 1 | 3.65 | 16.50 | 12.85 |
| | 2 | 3.93 | 17.33 | 13.40 |
| | 3 | 4.19 | 18.71 | 14.52 |
| | 4 | 5.30 | 21.81 | 16.51 |
| | 5 | 5.17 | 25.87 | 20.70 |
| Maximum particle size | 6 | 6.56 | 30.94 | 24.38 |
| | 7 | 6.37 | 32.32 | 25.95 |
| | 8 | 7.68 | 37.87 | 30.19 |
| | 9 | 6.49 | 31.68 | 25.19 |
| Full-scale gradation | 10 ($n$ = 0.3) | 9.42 | 47.41 | 37.99 |
| | 11 ($n$ = 0.4) | 10.49 | 50.63 | 40.14 |
| | 12 ($n$ = 0.5) | 8.63 | 42.72 | 34.09 |
| | 13 ($n$ = 0.6) | 7.69 | 37.99 | 30.30 |

Note: $n$ is Talbot's exponent.

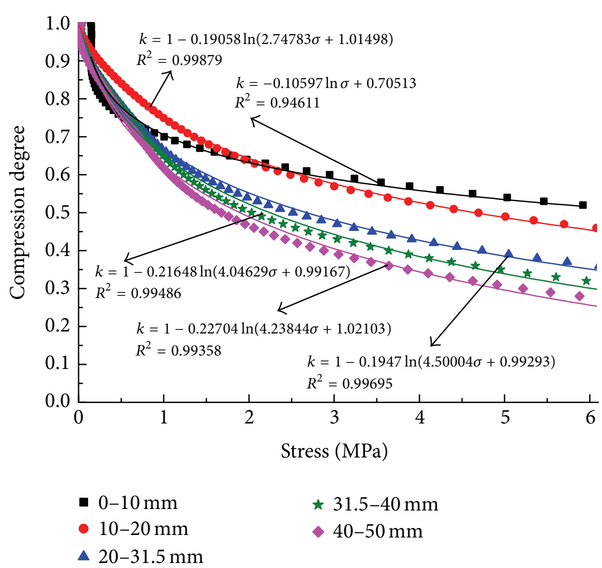


Figure 5: Stress-compression degree for single-graded samples.

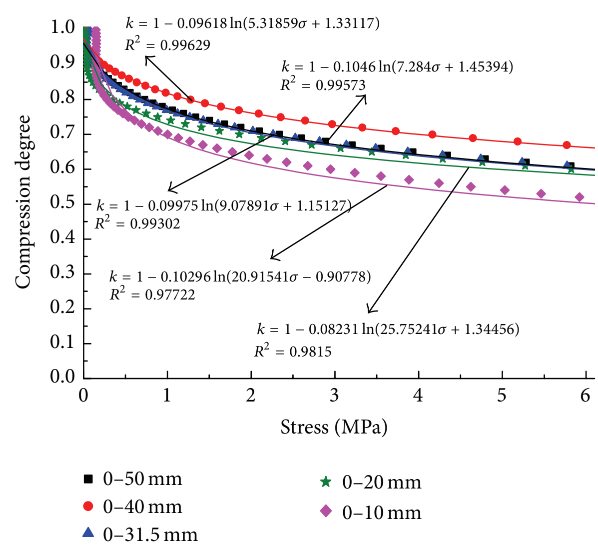


Figure 6: Stress-compression degree for maximum grain size samples.

From Figure 6 and the fitting function, the following were found: (1) the stress-compression degree curves of gangue samples 5–9 with maximum grain size were nonlinear. During the initial stage of the test (0–2 MPa), the decrement in the compression degree was large and the compression proceeded rapidly. As the stress increased and the gangue was further compacted, the compression degree of the samples decreased and finally stabilized; (2) under the same level of compacting strength, the sample of 0–40 mm with respect to compression degree of Tests 5–9 was the best, while the sample of 0~10 mm was the worst. The compression degrees of samples 0–20 mm, 0–31.5 mm, and 0~50 mm were similar to each other. This is because the destroyed fragments can better refill the rest of the gap inside the sample of 0–40 mm after compression and crushing, resulting in a lower void ratio than the other samples. This led to an increased compression degree and nondeformability.

From Figure 7 and the fitting function, the following were found: (1) the stress-compression degree curves of fully graded gangue schemes 9–13 were nonlinear and generally varied similarly to the pattern of Tests 1–9 described above; (2) under the same level of compacting strength, the compression degree of Tests 9–13 (Talbot's exponent $n$ is used to represent the test scheme) was $n = 0.4 > n = 0.3 > n = 0.5 > n = 0.6 >$ original sample. As shown in Figure 6, the gangue sample for $n = 0.4$ had a better grading and could better refill the void space after compression and crushing, resulting in a higher resistance to deformation and compression degree.

Examining all stress-compression degree relationships above, we found the compression degree when the

Table 3: Summary of compression degree-stress test results.

| Category | Test | Compression degree | | |
|---|---|---|---|---|
| | | Stress of 2 MPa | Stress of 12.5 MPa | 2~12.5 MPa increments |
| Single size | 1 | 0.4246 | 0.1493 | 0.28 |
| | 2 | 0.4630 | 0.1958 | 0.27 |
| | 3 | 0.5011 | 0.2427 | 0.26 |
| | 4 | 0.5991 | 0.3451 | 0.25 |
| | 5 | 0.6168 | 0.4166 | 0.20 |
| Maximum particle size | 6 | 0.6770 | 0.5131 | 0.16 |
| | 7 | 0.6910 | 0.5245 | 0.17 |
| | 8 | 0.7448 | 0.5934 | 0.15 |
| | 9 | 0.6936 | 0.5247 | 0.17 |
| Full-scale gradation | 10 ($n$ = 0.3) | 0.8051 | 0.6721 | 0.13 |
| | 11 ($n$ = 0.4) | 0.8245 | 0.6926 | 0.13 |
| | 12 ($n$ = 0.5) | 0.7832 | 0.6458 | 0.14 |
| | 13 ($n$ = 0.6) | 0.7423 | 0.5996 | 0.14 |

Note: $n$ is Talbot's exponent.

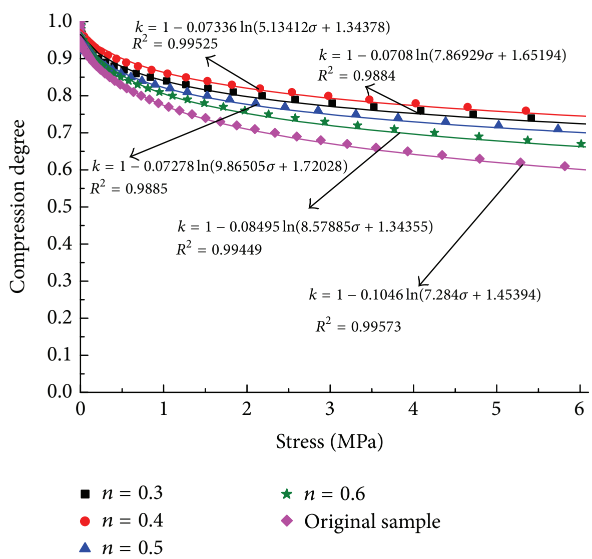


Figure 7: Stress-compression degree for full-scale graded samples.

compacting force was 2 MPa and the stress of primary rock was 12.5 MPa. The details are given in Table 3.

Based on the data in Table 3 and all stress-compression degree curves, the following can be concluded: (a) the stress-compression degree relationships of the three schemes share a similar trend, which is composed of three stages: rapid compression, slow compression, and gradual stabilization; (b) generally, the compression degrees of fully graded gangue, gangue with maximum grain size, and single-graded gangue are in descending order. The compression degree of fully graded gangue shows the minimum change between 2 and 12.5 MPa; that is, the materials have the optimal resistance to pressure and are the best for backfill and controlling the roof in gob areas. When the initial compacting force is around 2 MPa, it is able to compact backfill materials rapidly and ensure the supporting intensity of gangue; and (c) during the initial compression period (0–2 MPa), loose gangue samples under compressive stress showed such characteristics that gaps between gangue samples were quickly filled. The greater the compression, the lower the nondeformability. As the compressive stress increased from 2 to 15 MPa, gangue samples were destroyed again and the destroyed fragments refilled the rest of the gaps, which reduced the void ratio of the gangue sample and increased its nondeformability. As the compressive stress increased further, the gaps were fully filled and the gangue was evenly stressed, which stabilized the compression degree of the gangue sample and enhanced its nondeformability.

As described above, it was found that the gangue samples with Talbot's exponent had the best nondeformability. This is because Talbot's exponent sample is perfectly matched to the different sizes of gangue samples and makes for a smooth gradation curve and a uniform sample, which caused the stress-compression curve to decrease by at least 16.7% compared with the other grading samples. This shows that gangue samples graded by means of Talbot exponent have good backfill properties, which is important for mining and backfill.

## 5. Conclusions

(1) During the compression period, the deformation modulus of gangue samples increased linearly with increase in stress, while the stress-compression degree relationship was nonlinear.

(2) The relationship between stress and compression degree for the three test schemes was similar and could be roughly divided into three stages. When the stress was 0–2 MPa (initial stage), the void ratio of the gangue sample was relatively large and the compression amount of samples presents the largest and most rapid change. Most of the deformation occurred at this stage. When the stress is 2–12.5 MPa, the samples

were compacted slowly. The broken gangue gradually refilled the rest of the space, indicating a slight variation in compression degree. Furthermore, as the stress increased further, the compression degree tended to stabilize and the void ratio was lower.

(3) At the same stress level, samples graded using Talbot's Formula provided the best resistance to deformation, followed by the fully graded gangue sample and the single-graded gangue sample. This is consistent with the smooth gradation curve and the uniformity of the sample.

(4) In practical engineering applications, most of the deformation of the compacted gangue occurs in the initial stage. Therefore, the amount of deformation can be reduced after backfill based on optimal compression agencies and compression force. In addition, grading of gangue to a large extent determines the deformation of the material. Materials with strong resistance to deformation can be obtained by adjusting the grading.

## Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

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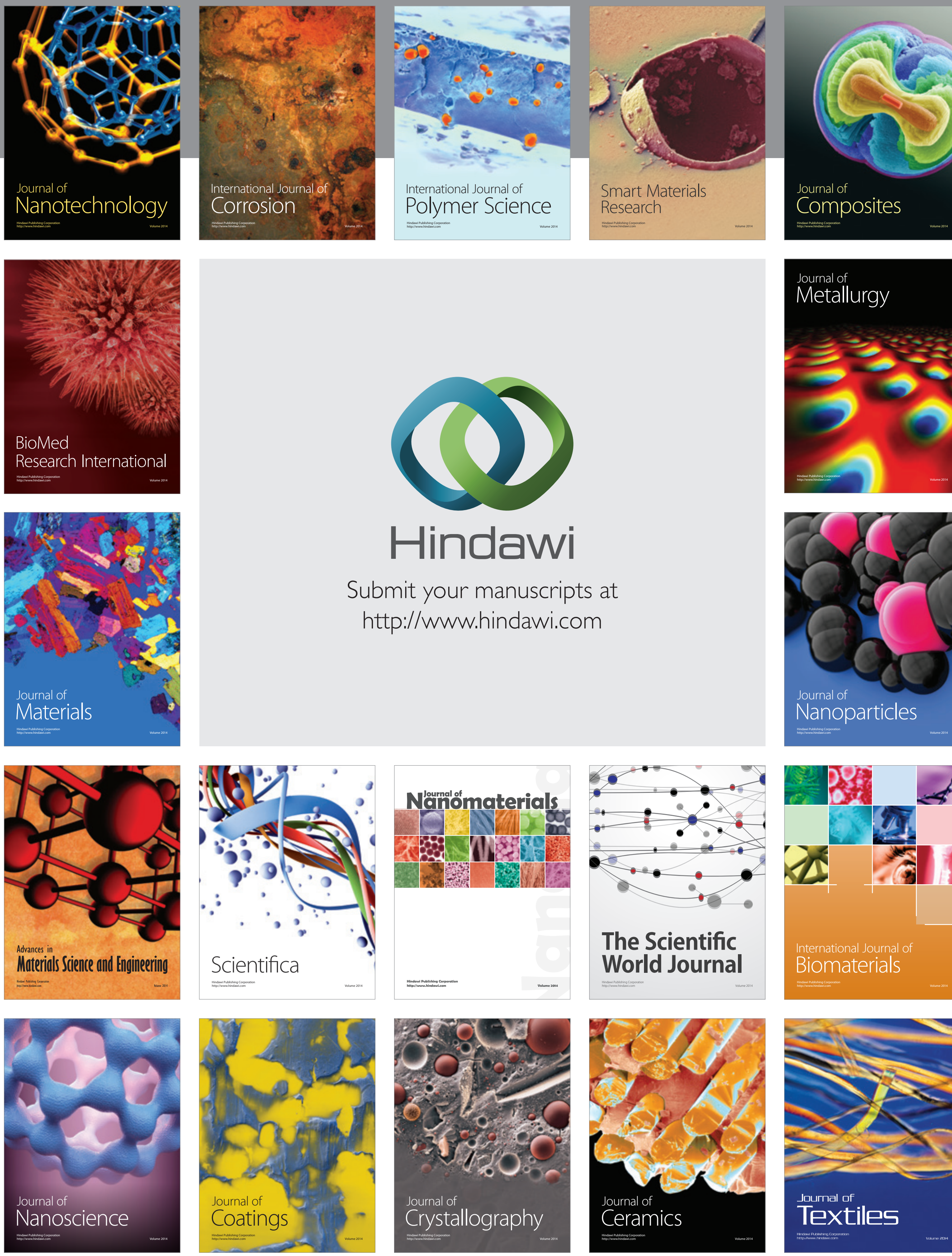
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