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Research Article

Surface Subsidence Control Mechanism and Effect Evaluation of Gangue-Backfilling Mining: A Case Study in China

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Comprehensive mechanization solid backfilling mining is a new technology developed in China for coal mining and surface subsidence control. Based on a gangue-backfilling project in the Yangzhuang Coal Mine, the characteristics of underlying strata and surface deformation were studied by similar-material simulation method. When the ratio of the sponge to foam was 1 : 3, the mixture can simulate well the deformation characteristics of gangues in the similar-material model. On this basis, the movement and deformation characteristics of the overlying strata caused by gangue-backfilling mining were studied. The findings indicate that compared with caving mining, the expansion coefficient of overlying strata, the interlayer fracture, and the subsidence value were smaller in backfilling mining, with the integral overlying strata subsidence occurring. Meanwhile, the reduction ratio of surface subsidence after backfilling mining was more than 85%, verified by the subsidence-monitoring results. The research outcomes in this paper have significance for coal resource exploitation of similar mines around the world.

1. Introduction

Coal mining creates a large amount of gangues, which are deposited in gangue dumps on the ground. According to statistics [1], China may have around 4.5 billion tons of accumulated gangue emissions with a total area of about 150 million hectares. Moreover, with the highly intensive exploitation of coal resources, coal gangues are growing by 150 million to 200 million tons per year. Also, annual emissions of coal ash from power plants within mining areas are currently about 500 million tons, and the annual new exploitation is 50 million to 70 million tons per year. Due to long-term exposure to the air, the harmful substances in coal gangues, such as sulfur, will seep into the underground in the rain, causing soil contamination and underground water contamination [2]. On the other hand, considerable coal resources are buried under buildings, railways, and water bodies, in which about 13.79 billion tons of coal resource are buried in the coal mines of China according to the literature [3]. For example, in the Kailuan coal mine, the coal ratio under the buildings, railways, and water bodies reached 86%, while in several other coal mines, the proportion even reached 100%.

With this background, comprehensive mechanization solid backfilling mining technology emerged in China. In 2008, the Xinwen Mining Group cooperated with the China University of Mining and Technology to conduct comprehensive theoretical research and technological innovation. They successfully developed a new comprehensive mechanization gangue-backfilling system, which improved the gangue-backfilling effect in the gob area and realizing safe coal mining under buildings [4, 5]. Miao et al. [6], Zhang et al. [7], Ju et al. [8], and Seryakov [9] investigated the system and equipment of the comprehensive mechanized solid backfilling and promoted the development of backfilling mining technology. Currently, solid backfilling coal mining technology has been applied to dozens of large mines to exploit coal resources buried under buildings, railways, and water bodies, including the Zhaizhen Coal Mine of the Xinwen Mining Bureau, Jining No. 3 Coal Mine of the Yanzhou Mining Bureau, Yangzhuang Coal Mine of the Huaibei Mining Bureau, and Tangshan Coal Mine of the Kailuan Mining Bureau [10–13].

Solid backfilling coal mining technology is an environmentally compatible solid waste-processing technology and is the main technology for surface subsidence control. Filling the gob area with solid materials (such as gangue, coal ash, drift sand, and waste disposal) which occupy the space previously occupied by coal mining operations, solid backfilling reduces the moving space between roof strata and the floor strata, thereby realizing the goal of surface subsidence control. However, in previous researches, there was a lack of systematic analysis and evaluation of the surface subsidence effect of comprehensive mechanization solid backfilling mining. Therefore, this paper analyzed the surface subsidence control mechanism of gangue-backfilling mining by the physical simulation method and evaluates the actual control effect of gangue-backfilling mining on surface subsidence through the experiment completed by the research group.

2. Overlying Strata Movement of Solid Waste Backfilling Mining through Similar-Material Simulation

Surface subsidence is primarily caused by underground mining. The most direct and effective method to control surface subsidence is to fill the gob area during underground mining. This section used the physical simulation method to analyze the subsidence control mechanism of gangue-backfilling mining.

2.1. Similarity Theory and Similar-Material Model Principles. Based on a similar principle, the rock size is reduced according to a certain proportion. The model is made of similar materials (including sand, gypsum, and mica sheet) and then coal mining is simulated in the model, observing the movement and damage of the rock formation. In the field of coal mining, the similar-material model is an effective method to study the failure phenomenon of rock mass due to coal mining [14–18].

Because of the different scales between coal fields and laboratory experiments, model materials must be selected to maintain a meaningful physical proportion to the field conditions. The modeling materials need to be tested, and their properties should satisfy similarity theory principles [16, 19]. According to similarity theory, strength, velocity, and time should follow the relationship described below:

$$\frac{C_l}{c_v c_t} = 1, \tag{1}$$

where C_l is the constant of geometry similarity, C_v is the constant of velocity similarity, and C_t is the constant of time similarity between prototype and model. C_l, C_σ, and C_ρ can be calculated as follows:

$$\begin{aligned} c_l &= \frac{l_p}{l_m}, \\ c_v &= \frac{v_p}{v_m}, \\ c_t &= \frac{t_p}{t_m}, \end{aligned} \tag{2}$$

where the subscript p stands for the prototype, m stands for the model, l stands for the length, v stands for the velocity, and t stands for the time.

The reliability of similarity model test results depends on the correct selection and rational proportion of a series of similar materials. The physical and mechanical parameters of the rock stratum were determined by Brazilian and compressive tests of rock, and the rock of the modeling material was calculated according to the similarity theory. Reference [16] and previous experience were used to calculate the proportion of different types of materials. The samples were prepared according to the ratios of the different types of materials they were calculated from, and then the compression and Brazilian test was carried out to adjust the material ratio.

Table 1: Strata simulation material ratio scheme in the physical model.

Lithology	Quality ratio (sand : mica : cement)	Cement quality ratio (gypsum : calcium carbonate)
The floor (fine sandstone)	71 : 13 : 16	7 : 3
Coal	80 : 17 : 3	7 : 3
Sandy mudstone interbed	71 : 23 : 6	3 : 7
Siltstone	79 : 16 : 5	5 : 5
Fine sandstone	74 : 16 : 10	5 : 5
Fine siltstone interbed	74 : 16 : 10	3 : 7
Weathered mudstone	73 : 23 : 4	5 : 5
Topsoil	80 : 18 : 2	3 : 7

2.2. Similar-Material Simulation Experimental Scheme. Based on the geological and mining conditions of the working face in the Yangzhuang Coal Mine (as shown in Table 1), the physical simulation method is adopted to study the rock strata movement characteristics during the backfilling mining process. The physical dimension of the physical model is 3 m × 0.3 m × 1.1 m. The 100 cm unexploited area is left as the boundary of the model, while the excavated length is 100 cm and 5 cm for each excavation. Close-range photogrammetry [20] has been applied to monitor the displacement and fracture development of the model. The

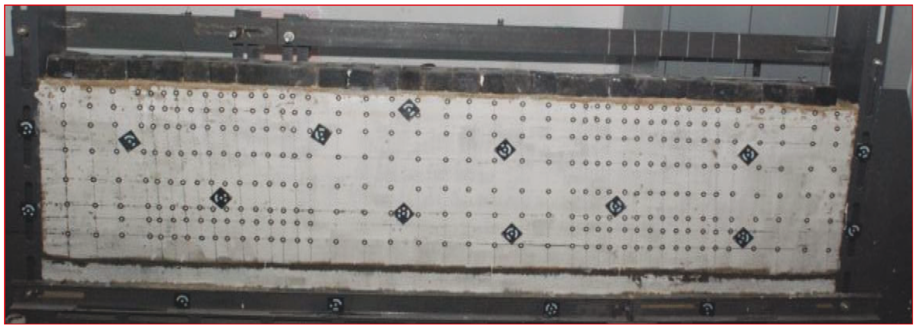

Figure 1: Photo of similar-material model.

displacement monitoring precision of the model can reach 0.5 mm, and Figure 1 shows the layout of the model. In order to compare the overlying strata and surface deformation by backfilling mining and caving method, a comparative model whose roof is controlled by the caving method has been made (other conditions are the same except for the roof control). Figure 2 shows the gangue compression stress-strain relationship of the Yangzhuang Coal Mine.

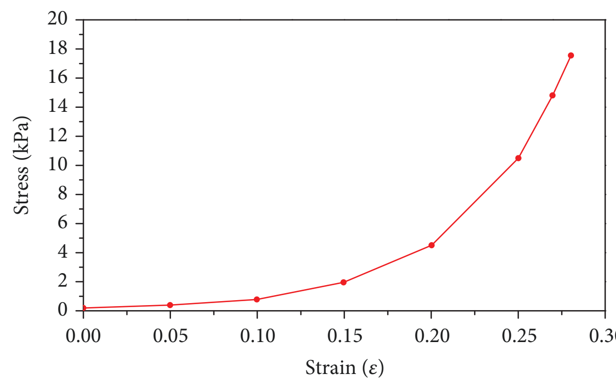

Figure 2: The gangue compression stress-strain relationship.

2.3. The Ratio Scheme of Similar Gangue Material. In order to simulate the compression process of the actual backfilling bodies, the compression stress-strain relationship of simulated materials should be consistent with the stress-strain relationship of gangue. After many experiments, sponge and foam were chosen as the similar simulation material of gangues [10]. Due to the different properties of gangues, such as the type of mother rock, lumpiness, and backfilling density, there exist certain differences between compaction degree and compression modulus of the filling bodies. Although the chosen materials have stable compression performance, especially the sponge and foamed plastics, it is difficult to reflect the requirements of different compression ratios for the simulated materials. In view of the fact that the stress-strain relationship between the simulated material and the gangue-backfilling material is consistent with the logistic model, a method to change the mining thickness is proposed to improve its closeness. The principle of the method is to consider simulated materials and the coal seam as a kind of mixture of the backfilling bodies and simulated materials based on the same strain. The stress-strain curve of the mixture is then changed by altering the thickness of the coal seam to improve the closeness between simulation materials and gangues.

In this paper, the plastic foam and no. 40 sponge are mixed in a ratio of 1 : 3, 1 : 2, and 1 : 1 (as shown in Figure 3). Figure 4 shows the stress-strain relationship.

As shown in Figure 4, there are large differences between the different proportions of the mixture. These differences are related not only to the ratio but also to the hardness of the two materials. Therefore, a double-layer mixed material or multilayer mixed material can be used to simulate different gangue-filling materials. By comparing the stress-strain relationship of gangues in the physical model with the stress-strain relationship of sponge and foam mixed materials in different ratios, it can be found that when the ratio is 1 : 3, the stress-strain relationship of the mixed material is consistent with the gangue's stress-strain relationship in real-world conditions, as shown in Figure 5.

As shown in Figure 5, the stress-strain relationship calculated by the native gangues according to the similarity ratio requirements is effectively consistent with the stress-strain relationship calculated by mixed materials of sponge and foam by the proportion of 1 : 3; when the strain is less than 4 kPa, the two curves are basically overlapping. After 4 kPa, the two curves begin to separate, but there was no big difference. When the strain reaches 15 kPa, the strain are 0.27 and 0.274, respectively. If the mining thickness is 5 m, the actual subsidence difference is approximately 20 mm, which is caused by the different similar-material ratios. Obviously, this is far less than other aspects of errors (such as rock strata ratio error, thickness error of the coal seam, and model shrinkage), so this scheme is entirely feasible to simulate the raw gangue.

2.4. Comparative Analysis of Overlying Strata Deformation between Gangue-Backfilling Mining and Caving Mining. The similar-material model and excavation experiments were conducted according to the experimental framework described above. The results of similar-material simulation in backfilling mining indicate that the structure of the overlying strata presents continuous medium characteristics and there is no evidence of general destruction during the working face exploitation. Figure 6 displays the overburden

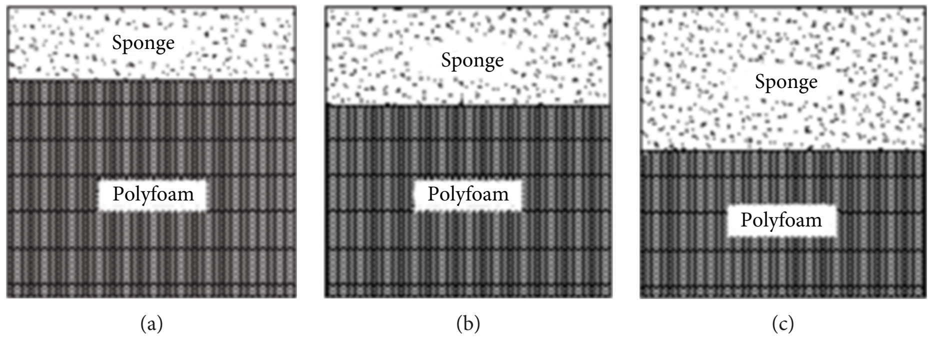

FIGURE 3: Sketch map of foam and sponge with different ratios.

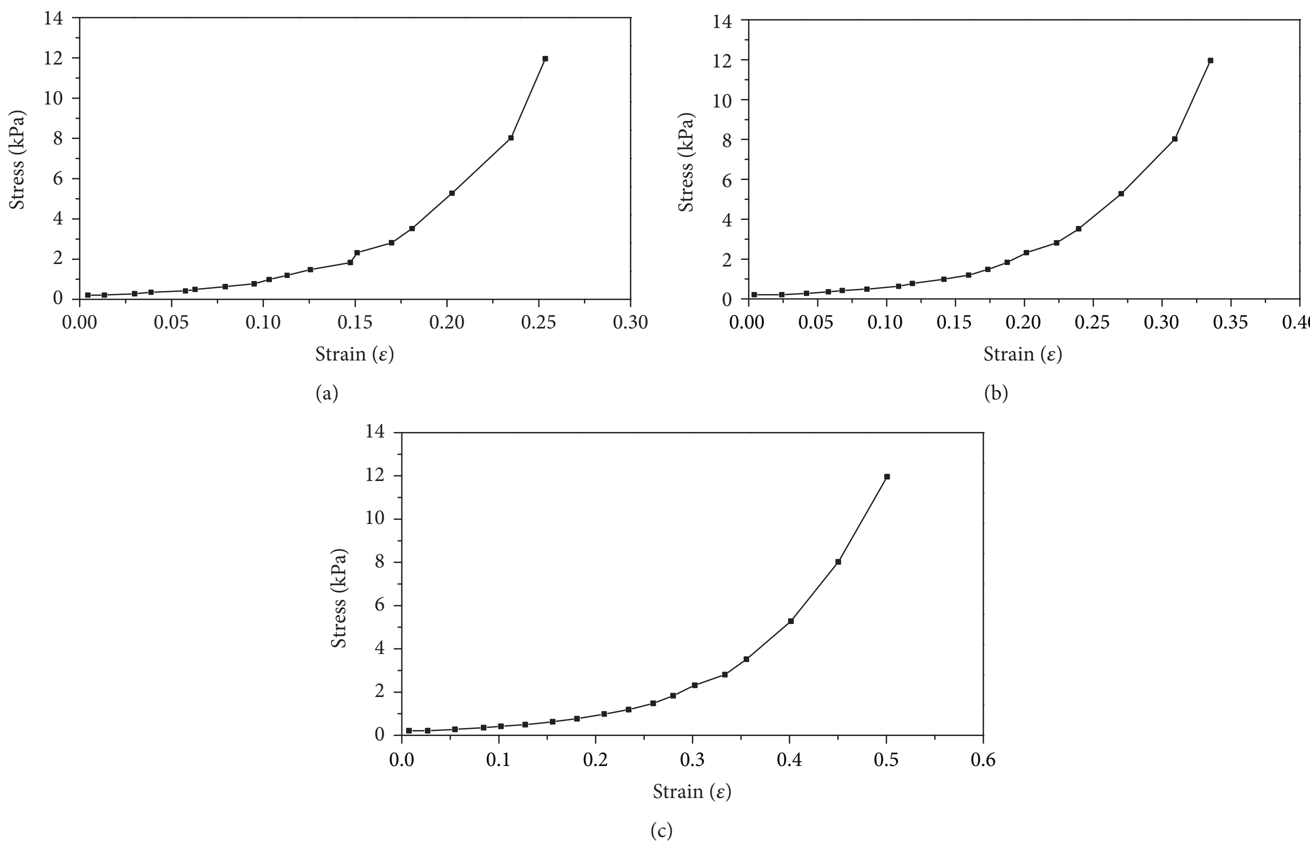

FIGURE 4: Mixture's stress-strain relationship with different ratios: (a) sponge and foam 1 : 3; (b) sponge and foam 1 : 2; (c) sponge and foam 1 : 1.

failure characteristics during the model excavation by the backfilling mining method. Figure 7 shows the overburden failure characteristics during model excavation by the caving method.

In Figure 6, the overlying strata has no obvious caving zone, only the fissure zone and the bending zone. There are no apparent vertical fractures in the working face. During the mining process, the smaller horizontal fissures will occur between the rock strata. As the working face advances, the horizontal fissures will be compacted and disappear under the overburden pressure. Meanwhile, the overlying strata subsidence will arise, but the subsidence is relatively slow and the subsidence velocity does not change suddenly. In Figure 7, the distribution of the caving zone, fissure zone, and bending zone is very clear in the overlying strata of the caving model. In addition, the vertical fractures are obvious in the working face, and the subsidence of overlying strata is fiercely uneven. In order to compare and analyze the overlying strata deformation conditions in the backfilling and caving model, the monitoring result is used for comparison, as illustrated in Figure 8. As can be seen in the backfilling mining model, the roof subsidence is slow, while roof subsidence is acute in the caving model. The decrease rate of the roof subsidence is 73%, proving that backfilling mining can effectively control the movement and deformation of overlying strata.

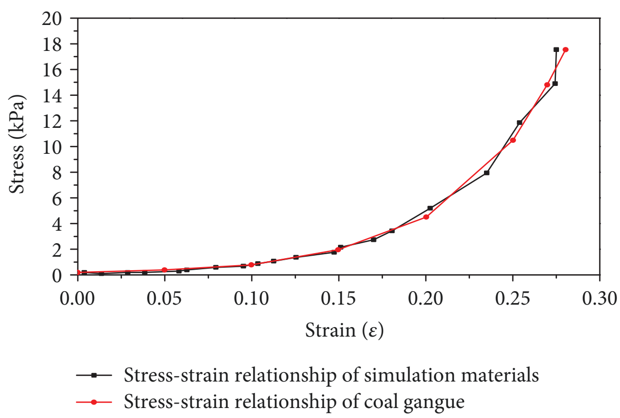

Figure 5: Contrast of stress-strain relationship between coal gangue and simulation materials.

In order to analyze the differences of surface point movement velocity between backfilling mining and caving mining, the surface points in the middle of the goaf (point L in Figure 7) are selected to draw the correlation curves of the surface point subsidence velocity by caving mining and backfilling mining.

From Figure 9, the surface subsidence velocity of backfilling mining is much less than that of caving mining. In addition, the change in surface subsidence velocity is not noticeable, without an apparent stage of increase and decrease of subsidence velocity.

In order to quantitatively compare and analyze the interlayer fractures in the backfilling mining model and the caving mining model, the vertical expansion evaluation index of the rock strata is introduced into the model. The vertical expansion coefficient is defined as the distance ratio before and after the strata movement at two adjacent points of the same vertical level [21]. Wang defines the distance ratio as

$$k = \frac{h'_{n-n+1}}{h_{n-n+1}}, \quad (3)$$

where h'_{n-n+1} is the distance between the two points after the mining-induced deformation (m), and h_{n-n+1} is the distance between the two points before the mining-induced deformation (m).

Based on this definition, the rock expansion of the roof in the backfilling mining model and caving mining model was obtained from calculation (K in Figures 6 and 7). The comparison results can be seen in Figure 10. It shows that in the backfilling mining, the expansion coefficient of overlying strata is smaller, the interlayer fracture is lesser, and the integral overlying strata subsidence occurs.

When the mining area is large enough (bigger than the critical mining area), the surface subsidence W_g can be expressed as

$$W_g = m - h - \Delta. \quad (4)$$

Correspondingly, the subsidence coefficient q_g can be expressed as

$$q_g = 1 - \frac{h + \Delta}{m}, \quad (5)$$

where h is the height of the filling body after compression of the overlying strata (m), m is the thickness of the coal seam (m), and Δ is the bulking of the overlying strata.

The analysis of the above formulas shows that the control degree of surface subsidence caused by gangue-backfilling depends on the height of the filling body under the influence and bulking of the overlying strata. The simulation results indicate that gangue-backfilling mining has less disturbance in the overlying strata. There is no caving zone in the overlying strata and the height of fracture zone is lower, resulting in a smaller amount of bulking. At this point, the height of the filling body after compression is the key to control the subsidence due to gangue-backfilling mining. The ratio of the height of compacted filling body to the thickness of the coal seam is defined as the filling ratio. With the development of China's gangue-backfilling technology, the filling ratio of gangue-backfilling mining can reach more than 85%. Therefore, by ignoring the bulking of the overlying strata, the surface subsidence coefficient can be less than 0.15 by dense gangue filling. When considering the effects of bulking of overlying strata, the subsidence coefficient may be much smaller.

Based on the influence function theory, for the caving method, the surface subsidence W at any point at any time can be expressed as follows:

$$W = W_0 f(t), \quad (6)$$

where $W_0 = mq \cos \alpha$, α is the dip angle of the coal seam, and $f(t)$ is the surface subsidence time function.

$$W_g = W_{g0} f(t), \quad (7)$$

where W_{g0} stands for the final subsidence of the surface point by using backfilling mining.

Based on equations (6) and (7), the ratio of surface subsidence velocity between gangue backfilling and caving mining is as follows:

$$\frac{v}{v_g} = \frac{W_0}{W_{g0}}. \quad (8)$$

The analysis of formula (8) shows that the degree of surface subsidence due to gangue backfilling is less than the caving method, so the surface point subsidence velocity of gangue backfilling is smaller than the caving method. On the other hand, the surface subsidence space by gangue-backfilling mining comes from the compression of the filling body by the overburden pressure. Therefore, the subsidence space gradually reaches the maximum W_{g0} with the recovering of overburden pressure. At this point, the

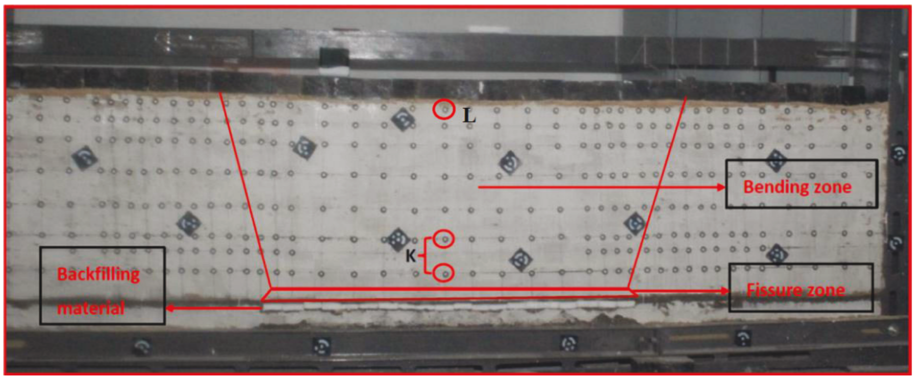

Figure 6: Overburden failure characteristics in model excavation by backfilling mining.

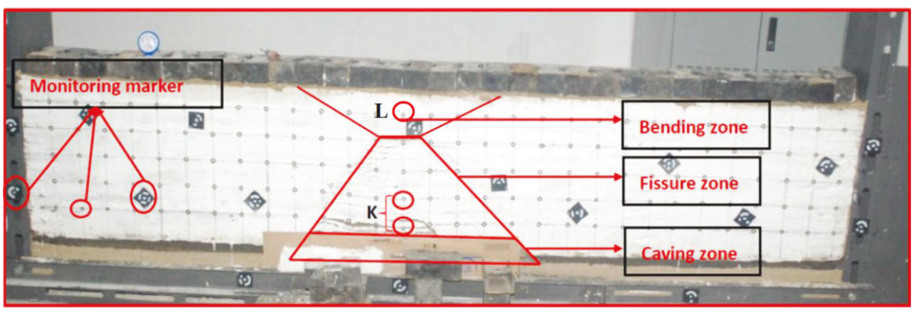

Figure 7: Overburden failure characteristics in model excavation by caving method.

surface subsidence velocity due to gangue backfilling will be further decreased.

3. Surface Subsidence Control Effect Evaluation under Solid Waste Backfilling Mining

The south side of the III644 working face in the Yangzhuang Coal Mine is an unexploited area, and the north side is the III642 working face. The east is the exploited NII624 working face, and the west is the unexploited area. The working face of III644 has an inclination length of 115 m and a strike width of 315 m. Above the working faces are Dongguan village, No. 2 Middle School of Suixi County, the second branch of Kouzi Winery in Suixi County, and many other structures. The ground elevation is around 31.2 m. The coal seams in the III644 working face are relatively stable, and the structure of coal seam is simple with the upper elevation being −328 m and the lower elevation being −483 m. The average thickness of coal seams is 2.7 m and the dip angle is about 18°. The exploitation of the III644 working face started from October 2012 and ended in December 2013. In the mining process, the gangues are filled and compacted into the gob area to achieve effective roof management, which is the first experiment in the Huaibei mining area.

The gangue-backfilling materials are the washing gangues from the coal preparation plant in the Yangzhuang Coal Mine. The gangue was crushed before the backfilling process to control the maximum particle size of the gangue

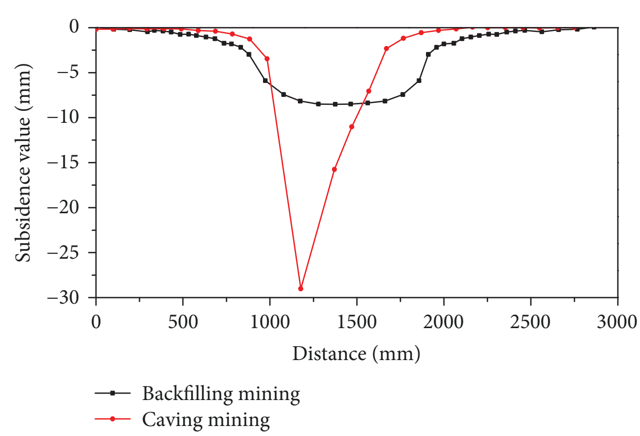

Figure 8: Roof subsidence curve comparison.

to be less than 30 mm. The broken gangues are then screened, and the distribution of particle size is shown in Figure 11. Meanwhile, a compression test is conducted to acquire the gangue compression characteristics. The compressive stress-strain curves of the gangue are obtained.

The gangue-backfilling ratio is designed to be 85%. That is, the height of compressed gangue should be no less than 2.3 m under the original rock stress levels. In the actual backfilling method, the gangues backfilled in the goaf are weighted to ensure the designed backfilling ratio. According to the gangue compressive stress-strain relationships and the density of filling gangues, it is required that the mass ratio

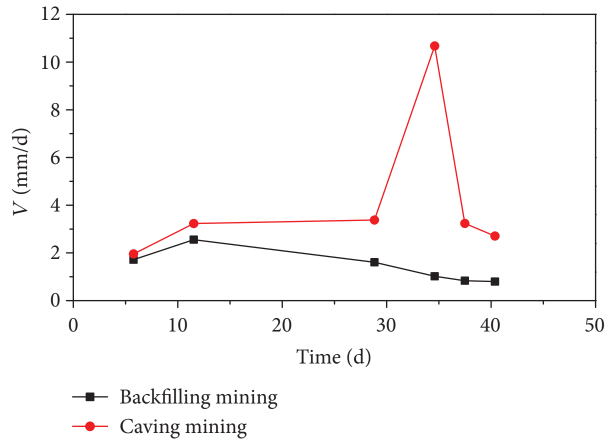

Figure 9: Subsidence velocity curve comparison at point L in the middle of the goaf.

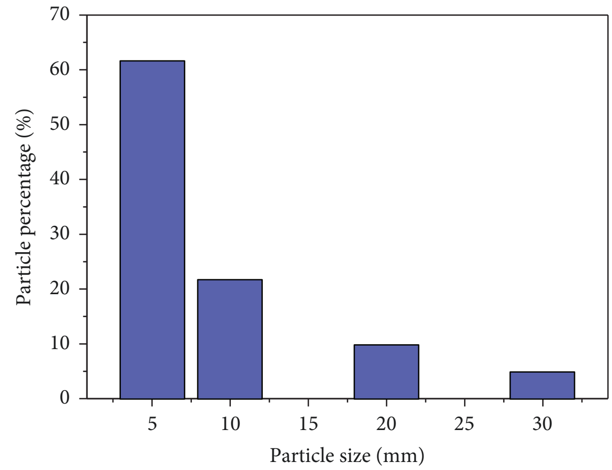

Figure 11: Distribution of particle size.

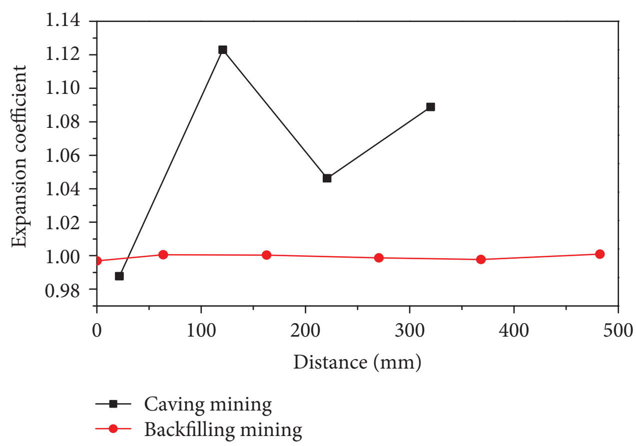

Figure 10: Comparison between interior rock expansion of overlying strata in the backfilling mining model and the caving mining model.

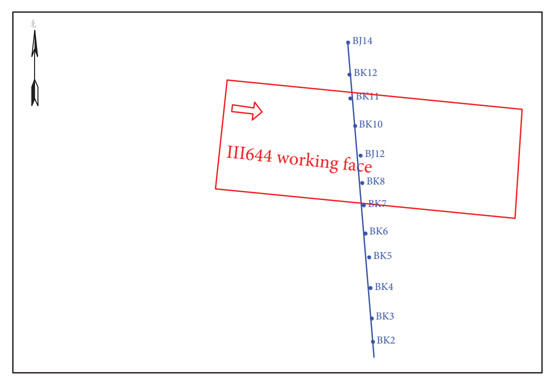

Figure 12: The contrast of the III644 working face and the observation station position.

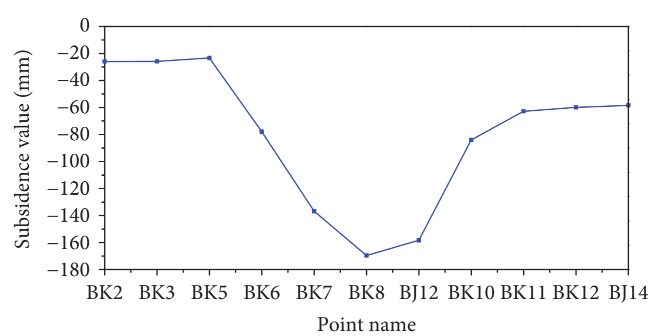

Figure 13: Final curve of surface subsidence in the III644 working face.

of filling gangues to the exploited coal should be no less than 1.3 after many experiments, which can meet the design requirement of the backfilling ratio.

In order to monitor the surface subsidence caused by backfilling mining, an observation line is placed above the III644 working face, as shown by the blue line in Figure 12.

The surface observation station conducted condition 18 subsidence observations from Sept. 15, 2012, to Jun. 7, 2014. Figure 13 is the final curve of surface subsidence in the III644 working face.

It can be seen from Figure 13 that the maximum surface subsidence in the III644 working face is 170 mm at the point of BK8. The final surface subsidence is 1746 mm predicted by the widely used probability integral method and the caving mining method. Therefore, the surface subsidence reduction ratio is 90% after solid backfilling mining, and the maximum surface deformation value is much less than the critical deformation of a common bungalow with a brick-concrete structure. According to the field studies, the surface buildings (structures) are under normal use, without apparent evidence of cracks and destruction, as shown in Figure 14.

4. Conclusions

In this paper, the physical simulation method is used to analyze the overlying strata movement characteristics and

Figure 14: Surface buildings after backfilling mining in the Yangzhuang Coal Mine.

surface subsidence control mechanism of gangue-backfilling mining. Then, the control effect of gangue-backfilling mining on surface subsidence was evaluated through the measurement results. The major conclusions are as follows:

(1) In similar-material simulation experiments, different proportions of foam and sponge materials can be applied to better simulate the stress-strain characteristics of gangue material. When the ratio of sponge and foam was 1 : 3, this mixture can simulate well the deformation characteristics of gangues of the Yangzhuang Coal Mine in the similar-material model.

(2) Similar-material simulation results show that the caving zone in the overlying strata was not obvious, only the fissure zone and the bending zone. Compared with caving mining, the expansion coefficient of overlying strata, the interlayer fracture, and the subsidence value of overlying strata are smaller in the backfilling mining, and integral overlying strata subsidence occurs.

(3) The control effect of surface subsidence during the gangue-backfilling mining is mainly determined by the amount of compression of the backfilling bodies under overburden pressure. According to the existing gangue-backfilling mining technology, the surface subsidence coefficient can reach less than 0.15

(4) The backfilling mining practice in the Yangzhuang Coal Mine of the Huaibei Mining Bureau indicates that solid backfilling mining can effectively control surface subsidence and the subsidence reduction ratio is around 90%. The mining area surface buildings (structures) are under normal use, with on obvious evidence of cracks and destruction.

Data Availability

The data used to support the findings of this study are included within the article. No extra data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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