Experimental Investigation on Mechanical Properties of Cemented Paste Backfill under Different Gradations of Aggregate Particles and Types and Contents of Cementing Materials

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Received 7 August 2018; Accepted 9 December 2018; Published 15 January 2019

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Obtaining the optimal gradation of aggregate particles is beneficial for improving the strength of cemented paste backfill (CPB). Consequently, the uniaxial compression tests with acoustic emission (AE) monitoring were performed on CPB, for which the aggregate particles satisfied the Talbot grading theory. The effects of the Talbot indices of aggregate particles and types and contents of cementing materials on the mechanical properties of CPB were analyzed. The AE characteristics and stress-strain behaviors of CPB were discussed. The results show that the specific Talbot index reflected the optimal strength and deformation properties of CPB is 0.45, and the maximum UCS is 7.6 MPa. The mechanical properties of CPB also can be optimized by changing the type of cementing material and increasing the content of cementing material. The effects of the Talbot indices of aggregate particles and types and contents of cementing materials on the crack damages reflected by the AE signals of CPB are mainly observed in the OA stage and AB stage during the loading process.

1. Introduction

Filling mining is a new technology which uses waste rocks, tailings, construction wastes, and other waste solid materials to crush, screen, bond, and then fill in goaf [1, 2]. The advantages of this technology are as follows: controlling the rock movement, protecting the aquifer, and reducing the risks such as seepage disaster and rock burst [3–6]. Therefore, it is important to study the mechanical properties of cemented paste backfill (CPB) to reduce the surface subsidence and overlying strata failure [7]. At present, the studies on CPB mainly focused on the selection and proportion of cemented filling material and the factors that can affect the strength of CPB [8–10]. To ensure the safety of underground stope, the cement and high-water materials were usually used in engineering. However, due to their high cost, they were usually replaced with fly ash, gypsum, clay, and other cementing materials [11–13]. Consequently, lots of scholars studied the effect of the binder type on the mechanical properties of CPB [14, 15]. To improve the filling effect, some scholars proposed to increase the content of cementing material, mix several different cementing materials in a certain ratio, and add some auxiliary materials [16–20]. Taking into account the differences in the hydration processes, some studies analyzed the effect of the environmental conditions on the strength and deformation characteristics of CPB [21–25].

CPB is composed of three parts, aggregate particles, cementing materials, and pores, and among them, the cementing material has the most significant effect on the
mechanical properties of CPB [26, 27]. However, the achieving approaches and types and contents of the cementing material are always restricted by the conditions and economic benefits of the actual engineering [28]. The internal pore of CPB mainly depended on the filling technology in the engineering site and the contacting difficulty between the CPB and goaf roof [2]. The above studies mainly discussed the effect of the curing temperature, curing time, and types and contents of cementing material on the mechanical properties of CPB, and most of those involved the aggregate particles with a kind of particle size distribution [29, 30]. Under severe conditions, the grading aggregate particles of CPB can improve the filling effect and reduce the filling cost [31]. Consequently, it is necessary to study mechanical properties of CPB, for which the aggregate particles satisfy the grading theory.

In this paper, the uniaxial compression tests with acoustic emission (AE) monitoring on CPB were performed, for which the aggregate particles satisfied the Talbot grading theory. The effects of the Talbot indices of aggregate particles and types and contents of cementing materials on the mechanical properties of CPB were analyzed. The AE characteristics and stress-strain behaviors of CPB were discussed.

2. Experimental Methods

2.1. Experimental Materials. Portland composite cement is a widely used cementing material in CPB, which can provide sufficient strength [32]. However, due to its high cost, it is often replaced by fly ash, gypsum, and clay. In this study, the clay, gypsum, and Portland composite cement were used as the binders, and their primary physical and chemical properties are presented in Table 1. The waste rock was obtained from Qianyingzi coal mine in Suzhou, China. Its average UCS of standard rock specimens was 47.19 MPa, and the average density was 2.39 g/cm³. According to the test standard [33], the maximum size of waste rock particles used in this experiment was 15 mm. The waste rock should be crushed and sieved into the particle size ranges of 0.0–2.5 mm, 2.5–5.0 mm, 5.0–8.0 mm, 8.0–10.0 mm, 10.0–12.0 mm, and 12.0–15.0 mm. To obtain the optimal filling result, the CPB specimens made of aggregate particles of six kinds of sizes are required to determine the optimal mechanical parameters of CPB in six-dimensional space \((Y_1, Y_2, Y_3, Y_4, Y_5, Y_6)\). Consequently, to overcome the curse of dimensionality, the Talbot grading theory was used to determine the mass ratios of the aggregate particles of six kinds of sizes. The maximum size of particles is \(d_{\text{max}}\), according to Talbot grading theory, and the ratio of the mass \((M)\) of particles with sizes below or equal to \(d\) to the mass \((M_t)\) of the total particle mass is

\[
\frac{M}{M_t} = \left(\frac{d}{d_{\text{max}}}\right)^n,
\]

where \(n\) is the Talbot index.

The total mass of waste rock particles in a specimen was 900 g. The mass distribution of the aggregate particles in the six sizes can be calculated according to formula (1), and Table 2 gives the mass distribution of rock particles under the Talbot indices of 0.2, 0.4, 0.6, and 0.8.

2.2. Experimental Equipment. For the production of CPB specimen, a device was developed, mainly composed of a cylindrical tube, a compacting rod, a pedestal, bolts, and a hydraulic puller, as shown in Figure 1. The hydraulic puller is used to control the internal porosity of the CPB specimen, and the maximum load that can be applied is 500 kN. The inner diameter of the cylindrical tube is 80 mm, the outer diameter is 120 mm, and the height is 260 mm. The diameter of the compacting rod is 79.9 mm, and the height is 195 mm. The diameter of the compacting rod is smaller than the diameter of the cylindrical tube by 0.1 mm, which can facilitate the movement of the compacting rod up and down in the cylindrical tube. To make the specimen interact with the external environment, ventholes with a diameter of 1 mm are set in the middle of the pedestal. The base edge is provided with six bolt holes that can be fixed to the cylinder. By using this apparatus, any specimens with a diameter of 80 mm and a height of 60–200 mm can be produced.

The loading device is the MTS815 mechanical test system, which has the maximum axial pressure of 4600 kN, loading rate range of \(10^{-5}–1\) mm/s, fatigue frequency of \(0.001–0.5\) Hz, and frame stiffness of \(10.5 \times 10^4\) N/m. The AE21C system is used for AE monitoring, the detectors are the piezoelectric ceramic AE sensors, the gain and threshold are 35 dB, the impact time is 50 μs, the impact interval is 300 μs, and the acquisition rate is 100 ms/time. The AE signals are picked up by the detector and then preamplified, mainly discharged and denoised by the AE instrument to form the AE parameters.

2.3. Experimental Specimens. The waste rock samples were prepared according to Talbot grading theory. The water and cementing materials were mixed for 10 min to form the uniform slurry and then blended with the crushed waste rock samples for 10 min according to the program given in Table 3. The venthole on the base of the homemade device must be plugged in to prevent the slurry from flowing out. Then, the homogeneous slurry is poured into the device and oscillated. The hydraulic puller is used to precisely control the volume so that the initial porosity of the specimen reaches the designated value. The entire device needs to be placed horizontally, and the venthole should be opened in the control process of the hydraulic puller so that excess gas can be removed and slurry loss prevented. After completing these steps, the venthole must be plugged in and the device must be placed vertically. The CPB specimen is transferred from the homemade device to the curing box after the final setting of the cementing materials. In the coal mine filling, even in the case of using hydraulic supports, the backfill withstands the pressure of the coal roof at the early age [4, 34]. So, the curing time is 15 d, the curing humidity of cement is 85%, the curing humidity of gypsum is 3%, the curing humidity of clay is 15%, and the curing temperature is 25°C.
2.4. Experimental Process. The cured CPB specimen was removed from the curing box, and both ends of the specimen were ground to control the nonparallelism and the nonperpendicularity within ±0.02 mm. The CPB specimens with some defects from the production process were omitted to ensure the consistency of all the samples. All the produced
CPB specimens have a diameter of 80 mm and a height of 97 mm. Four specimens with the same proportion are prepared to test. Vaseline was applied between both ends of the specimen and the indenters to eliminate the effect of the indenter loading on the AE signals. According to the test procedure [35], the MTS815 system was controlled to load CPB specimens at a loading rate of 1 mm/min [36]; meanwhile, the AE21C system was activated to monitor AE signals during the loading process.

3. Experimental Results and Discussions

3.1. The Stress-Strain Behavior of CPB Specimens under Uniaxial Compression. To analyze the influences of the Talbot indices of aggregate particles and types and contents of cementing materials on the mechanical properties of CPB, the reproducibility of CPB specimens should first be discussed. The uniaxial compression tests were performed on four specimens with the same proportion ($n = 0.4$, $\phi = 0.15$, cemented by $m = 100$ g gypsum), the uniaxial compressive strengths (UCS) are 7.31, 7.49, 7.56 and 7.63 MPa, the average is approximately 7.50 MPa, and the coefficient of variation is only 1.83%. The peak strain $\epsilon_{1c}$ is 18.19, 17.39, 19.67, and $21.40 \times 10^{-3}$, respectively; the average is about $19.16 \times 10^{-3}$; and the coefficient of variation is approximately 9.21%. In summary, the dispersion among the specimens is minor, and the produced CPB can be used for investigation.

In addition, to discuss the mechanical and AE characteristics of CPB, the stress-strain behavior should first be analyzed. The typical axial stress-axial strain curve can be divided into five stages, as shown in Figure 2 [37–39]. (1) The oa stage of pore compaction shows a concave stress-strain curve, (2) the ab stage of elastic deformation shows a linear relationship between stress and strain, (3) the bc stage of localized deformation shows a convex stress-strain curve, (4) the cd stage of strain softening shows the major load framework of CPB specimen being destroyed, and (5) the de stage of residual strength shows that the specimen can load a small axial stress depending on the unbroken bonding elements among the rock particles.

3.2. Talbot Index of Aggregate Particles Effect on the Mechanical Properties of CPB. The previous studies considered that the cementing material was the major factor affecting the mechanical properties of CPB [40, 41]. Some methods such as optimizing the bonding properties of cementing material and increasing the contents of cementing material were proposed to increase the stability of CPB [42]. However, the achieving approaches and types and contents of cementing material are always restricted by the engineering conditions. Obtaining the optimal gradation of aggregate particles is beneficial for improving the strength of CPB, and it also can save the cementing material to a certain extent and bring some economic benefits to engineering. Figure 3 plots the complete stress-strain curves of CPB specimens with different Talbot indices. It is noteworthy that the initial porosities of all the specimens with different Talbot indices of aggregate particles are the same, $\phi = 0.15$. However, the oa stage of the $n = 0.4$ specimen is the shortest among the specimens, as shown in Figure 3. Its UCS and elastic modulus are higher than other specimens, but its peak strain is lower than others. This proves that the Talbot index of aggregate particles can affect the strength and deformation characteristics of CPB. There is a specific Talbot index of aggregate particles that can optimize the strength and deformation characteristics of CPB. Therefore, Figure 4 gives the relationship between the UCS of CPB and the Talbot index of aggregate particles. It can be seen that the UCS of CPB increases and then decreases with the increase of the Talbot index. The relationship can be characterized by a quadratic polynomial, which has a high correlation coefficient of 0.98 to fit the average experimental results. Based on the relation, the UCS of the CPB specimen reaches a maximum of 7.6 MPa when the Talbot index $n = 0.45$. This is consistent with the results obtained by Baram and
Herrmann [43]. They think that the structure of a material is the most stable and the strength is the largest when the fractal dimension of aggregate particles is in the interval of (2.474, 2.588), obtained through the fill established by different polyhedrons composed of spherical units. The corresponding Talbot index should be represented as being in the interval of (0.412, 0.526). To verify this result, two specimens with Talbot index of 0.45 were generated for the interval of (0.412, 0.526). To verify this result, two specimens with Talbot index of 0.45 were generated for testing, and the other conditions were ensured to be the same. The obtained experimental values of 7.97 and 7.53 MPa were close to the calculated value of 7.6 MPa from the relation. Therefore, the optimization gradation of aggregate particles can improve the strength of CPB, and thus it can be conducted in engineering.

Figure 5 presents the AE distribution curves of CPB specimens with different Talbot indices of aggregate particles, and it is easy to see that the influence of particle gradation on the AE characteristics is not large. The AE distributions of CPB specimens with different Talbot indices of aggregate particles seem to be similar. It should be noted that the peak of the AE counts in the CPB specimen with 0.2 Talbot index appears in the oa stage, while those in the CPB specimens with Talbot index of 0.4 and 0.8 appear in the ab and bc stages. This means that the crack damages of CPB with different distributions of aggregate particles occur in different stages during loading, and then it affects the mechanical properties of CPB. About the effect of the particle size distribution on the AE distribution of CPB, the more detailed experiments need to be developed in the future.

3.3. Type of Cementing Material Effects on the Mechanical Properties of CPB. Figure 6 presents the effect of the type of cementing material on the strength and deformation characteristics of CPB. The mass of cementing material and Talbot index of aggregate particles are the same, 100 g and 0.4, respectively. The UCS values are 20.51, 7.49, and 4.74 MPa and the peak strains are 33.66, 17.39, and 26.40 × 10⁻³ for CPB specimens cemented by cement, gypsum, and clay, respectively. The mechanical parameters of the CPB specimen cemented by cement are significantly greater than other specimens cemented by clay and gypsum. It is noteworthy that the initial porosities of specimens cemented by different types of cementing material are the same, φ = 0.15. However, the oa stage of the specimen cemented by cement is the longest, as shown in Figure 6. Because the masses of cementing materials are the same, the density of cement is the largest, 3.11 g/cm³. The volume of cement is less than other cementing materials, which caused the differences in the CPB framework structures. It should be noted that the UCS of the CPB specimen cemented by clay also reaches 4.74 MPa. In arid areas or filling areas without groundwater, the clay also can be considered as the cementing material to promote the filling technology. The residual strength after failure is close to the specimen cemented by gypsum, and the ductility in the postpeak stage is high.

The influence of the type of the cementing material on the AE signals of CPB is significant, as shown in Figure 7. The AE counts reach a peak in the oa stage or ab stage of CPB specimens cemented by clay or gypsum, and the AE signals are stronger in both stages than other stages. When the stress of the specimen reaches its peak and the stress drops, the AE events are less frequent than before. The clay and gypsum with weak cementing performance weaken the internal structure of CPB. The cohesion of bonding elements and the bonding strength between bonding elements and aggregate particles are relatively small [44]. These cause more pre-existing fissures and unstable bonding interfaces in the CPB structure [45–47]. The compaction and friction of preexisting fissures and other defects produce the AE signals immediately in the initial stage under loading. Due to the relatively low strength, the dislocations and slips between bonding elements and aggregate particles are generated with the increase of the axial stress. Lots of cracks occur in this stage, which causes the frequent AE signals [48]. The spalling and macroscopic fissures were generated in the latter ab stage during the loading process, which can illustrate lots of cracks were generated in the early ab stage of CPB specimens cemented by clay or gypsum. However, the stable development of AE signals is presented in the loading process of CPB specimens made of cement. The AE events are gradually generated in the oa stage and then increase in the ab stage. When the stress of the specimen reaches a peak and the stress drops, the AE counts reach a peak. It is similar to the AE distribution of a typical brittle-rigid rock; the mechanism can be interpreted as follows. The cohesion of bonding elements and the bonding strength between bonding elements and aggregate particles are relatively large, and thus the stress in the oa stage can be withstood. Some defects are compacted to produce some small AE signals, in contrast to the specimens cemented by clay and gypsum. In the ab stage, the cracks gradually occur with the increase of AE counts. When a large crack occurs or a crack forms throughout the specimen, a large AE count is produced. In the bc stage, lots of inner cracks propagate to form a macroscopic fracture plane. The AE counts reach a peak
when the stress drops. It should be noted that there are some AE signals in the postpeak stage of the specimen because there are some unbroken bonding elements in the specimen.

3.4. Content of Cementing Material Effects on the Mechanical Properties of CPB. Figure 8 plots the complete stress-strain curves of CPB specimens with different contents of cementing material. It can be seen that the UCS and elastic moduli of specimens increase with the contents of cementing materials. The type of cementing material and Talbot index of aggregate particles are the same, gypsum and 0.4, respectively. The UCS values are 3.98, 7.49, and 8.50 MPa for specimens cemented by different contents of cementing material, i.e., 60, 100, and 140 g, respectively. However, the peak strains decrease with the increase in the content of cementing material, which are 32.29, 17.39, and $16.30 \times 10^{-3}$, respectively. It is noteworthy that the peak strains of specimens become shorter with the increase in the content of cementing material, under the same initial porosity, $\phi = 0.15$. It can be explained as the differences in the volumes of the CPB framework structures. The CPB with more cementing materials can produce more hydration products to optimize its structure [27, 36]. There seems to be no difference in other stages of CPB specimens cemented by different contents of cementing materials.

It is easy to observe from Figure 9 that the AE signals significantly enhance in the oc stage during the loading process because of the increase of the gypsum content. The peak AE counts increased with the cementing material content. The AE counts of the specimen cemented by $m = 60 \text{ g gypsum}$ reach a peak of 239 in the latter oa stage.

**Figure 5:** The AE distribution of CPB samples with aggregate particles of different Talbot indices: (a) $n = 0.2$; (b) $n = 0.4$; (c) $n = 0.8$. 
Figure 6: Complete stress-strain curves of CPB samples with different types of cementing material.

Figure 7: The AE distribution of CPB samples with different types of cementing material: (a) clay; (b) gypsum; (c) cement.
Figure 8: Complete stress-strain curves of CPB samples with different contents of cementing materials.

Figure 9: The AE distribution of CPB samples with different contents of cementing materials: (a) \( m = 60 \text{ g} \); (b) \( m = 100 \text{ g} \); (c) \( m = 140 \text{ g} \).
The AE counts of the specimen cemented by $m = 100$ g gypsum reach a peak of 410 in the early ab stage. The AE counts of the specimen cemented by $m = 140$ g gypsum also reach a peak of 553 in the early ab stage. It should be noted that the AE signals of the specimens cemented by $m = 140$ g gypsum are less intense than the specimen cemented by $m = 100$ g gypsum in the de stage. A possible interpretation is that there are fewer unbroken bonding elements in the inner specimen after failure, and thus the AE signals in the specimen cemented by $m = 140$ g gypsum are weak.

4. Conclusion

The uniaxial compression tests with acoustic emission (AE) monitoring were performed on CPB, for which the aggregate particles satisfied the Talbot grading theory. The effects of the Talbot indices of aggregate particles and types and contents of cementing materials on the mechanical properties of CPB were analyzed. The AE characteristics and stress-strain behaviors of CPB were discussed:

(1) The UCS of CPB increased and then decreased with the increase of Talbot index of aggregate particles. By adopting a quadratic polynomial to obtain the relationship between the UCS and the Talbot index of aggregate particles, the specific Talbot index reflected the optimal strength and deformation properties of CPB is 0.45, and the maximum UCS is 7.6 MPa.

(2) The mechanical parameters of the CPB specimens made of cement are significantly greater than other specimens cemented by clay and gypsum. The UCS of the CPB specimen cemented by clay reaches 4.74 MPa. Its residual strength after failure is close to the specimen cemented by gypsum, and the ductility in the postpeak stage is high.

(3) The UCS of the CPB specimen increases with the content of cementing material. However, the peak strain decreases with the increase in the content of cementing material. The differences in the content of cementing material causes the differences in the CPB framework structure, and the oa stage of specimen shortens with the increase in the content of cementing material. The residual strength is not affected by the content of cementing material.

(4) The AE counts reach a peak in the oa stage or ab stage of CPB specimens cemented by clay or gypsum, and the AE distribution is more intense in the oa stage and ab stage. When the stress of the specimen reaches its peak and the stress drops, the AE events are less frequent than before. However, the stable development of AE signals is presented in the loading process of the CPB specimen made of cement. When the stress of the specimen reaches its peak and the stress drops, the AE counts reach a peak. The peak of the AE counts increases with the content of cementing material. However, the crack damages reflected by AE signals of CPB with different distributions of aggregate particles occur in different stages during loading, and then it affects the mechanical properties of CPB. The more detailed investigations about the effect of the particle size distribution on the AE distribution of CPB need to be developed in the future.

Symbols

- $a$: Initial point of elastic deformation
- $AE$: Acoustic emission
- $b$: Terminal point of elastic deformation
- $CPB$: Cemented paste backfill
- $c$: Peak point
- $d$: Initial point of residual stage
- $d$: Particle size
- $d_{\text{max}}$: Maximum size of particles
- $e$: End point
- $o$: Initial point of pore compaction
- $n$: Talbot index
- $UCS$: Uniaxial compressive strength
- $\epsilon_{1c}$: Axial peak strain
- $\sigma_{1c}$: Peak strength, UCS
- $m$: Mass of cementing material
- $M$: Mass of the particles sizes below or equal to $d$
- $M$: Total mass of rock particles

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors have no conflicts of interest.

Authors’ Contributions

Jiangyu Wu and Meimei Feng conceived and designed the experiments. Jiangyu Wu, Xiaoyan Ni, and Guansheng Han performed the experiments. Jiangyu Wu, Meimei Feng, and Zhanqing Chen analyzed the data. Jiangyu Wu and Meimei Feng wrote the paper.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (51404266 and 11502229), the Natural Science Foundation of Jiangsu Province (BK20160433), and the Major State Basic Research Development Program of China (973 Program, 2013CB227900).

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