Study on Damage Energy Consumption Characteristics and Mechanical Behaviour of Mixed Aggregates Cemented Backfill Before Peak Stress

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Abstract. Mixing coarse aggregates into cemented paste backfill can significantly affect its mechanical properties. Many mixed aggregates cemented backfill samples were carried out uniaxial compression tests to see how the coarse aggregate replacement rate affects its uniaxial compressive strength, and analyze the influence on the damage energy consumption characteristics of the backfill before peak stress based on damage mechanics theory. Then taking Jinchuan No. 2 Mine as an example, study the stability and mechanical behaviour of the backfill in the stope by means of numerical simulation. The results show as following: The uniaxial compressive strength of the backfill at different curing ages has a quadratic function curve relationship with an increasing coarse aggregates replacement rate. This indicates that there exists an optimal replacement rate of 60%. When the content of coarse aggregate exceeds the optimal value, the strain value of the backfill sample corresponding to the peak stress damage value decreases, which means that the more the content of coarse aggregate, the more the backfill sample is prone to brittle failure. The peak stress specific energy increases first and then decreases with increasing coarse aggregate replacement rate, shows a similar change with its uniaxial compressive strength, so the backfill with the higher uniaxial compressive strength have stronger energy storage mechanism. The numerical simulation results show that the backfill with the optimal coarse aggregate replacement rate can effectively relieve the stress concentration of the rock mass in the stope, however the filling body has obvious tensile damage due to the mining activities.

1. Introduction

With the depletion of shallow resources in China metal mines, many domestic mines have shifted to deep mining in which they often face key problems such as rock burst, ground pressure, and severe rock deformation. The paste backfill technology has many advantages in controlling the mining site pressure, preventing rock burst, and improving the ore recovery rate, and has been widely used in many mines at home and abroad [1-3]. However, for some precious metal mines, when using the downward slicing paste backfill mining method to mine deep stope ore bodies, the filling body needs higher strength because it is used as an artificial false top. If only full tailings are used as filling aggregate, the strength could not meet the design requirements of the backfill. Therefore, to increase the strength, it has to increase the proportion of cement material, which inevitably increases the cost while the strength is not...
much improved. In the daily underground mining process, the filling body was used as an artificial ore pillar or artificial roof. Once it is damaged, it will endanger workers’ life and cost heavy financial loss. Studying the damage characteristics and energy consumption characteristics of backfill under load can help to avoid such risks [4-6]. After filling the mined-out area, the backfill body forms a system with the upper rock mass, the lower ore body and the surrounding rock mass to resist the external pressure and interact with each other, and the system stability is closely related to the mechanical properties of the filling body [7-9]. Therefore, in the mining state, there is a need for further study on whether the strength of the filling body is up to the standard and can stably support the overburden. This paper reveals the mechanical behaviour of the filling body in the mining filling process, and provides some technical guidance for the application of the backfill mining method.

Many studies have found that mixing waste rock with whole tailings as a mixed paste filling material can change the strength, and recommended suitable material ratios to meet strength and flow performance requirements [10-13]. Some studies have carried out uniaxial compression experiments to analyse the damage and failure laws and energy consumption characteristics of backfill with different factors [14-17]. The addition of waste rock has an effect on the mechanical properties of the filling body, which is beneficial to slow the growth rate of the damage variable and improve the residual bearing capacity [18]. The numerical simulation method can effectively study the interaction mechanism between the backfill and surrounding rock [19], the stress distribution and deformation characteristics of the backfill [20], and the mechanical behaviour of the filling body in large-scale backfill mines [21].

Most of the studies focus on the damage and energy consumption characteristics of the full tailings cemented filling body in the whole failure process under the uniaxial compression test. However, it is rare to study the characteristics of damage and energy consumption of multi-component aggregate cemented backfill at a particular deformation stage. This paper takes the Jinchuan No.2 mining area in China as the engineering research background. The No.2 mine area currently uses downward horizontal layered filling and mining methods, which have high requirements on the strength of the filling body. Only full tailings are used as filling aggregate, its strength cannot meet the strength requirements. Waste rock can be used as coarse aggregate to replace part of the full tailings to increase strength. Uniaxial compression test was carried out using multiple mixed aggregate cemented filling samples to analyse the effect of different coarse aggregate replacement rates on the damage energy consumption characteristics of the filling body before reaching the peak stress, and combined with the FLAC3D numerical simulation method, the mechanical behaviour of the filling body during mining and filling process was revealed.

2. Experimental materials
The experimental materials were taken from China Jinchuan No. 2 Mining Area. The chemical composition of the filling material is shown in Table 1, and the particle size distribution is shown in Figure 1. Waste rock has a maximum particle size of 15 mm. The particle size composition of the whole tailings is shown in Figure 1 (a), The d20, d50, and d90 are the mesh diameters through which the cumulative content of 20%, 50%, and 90% particles could pass. Where d20 = 2.221µm, d50 = 16.892µm, d90 = 95.991µm, the unevenness coefficient is 0.087 means the compactness is good. Waste rock as a kind of gradation continuous aggregate, the Talbol particle gradation theory can solve the problem of excessively large data space dimension caused by the continuous distribution of particle size. Calculate the M (mass of the aggregate particle size not greater than the index x) in the test sample, the Mt (total mass of the test sample), to determine the mass of the particle size particles in a certain interval, as followed:

$$\frac{M}{Mt} = 100 \times \left(\frac{x}{x_{max}}\right)^n$$

Where n is the Talbol particle gradation index; $x_{max}$ is the maximum particle size in the sample.

According to formula (1), the particle size of waste rock aggregate is fitted. The results show that the Talbol particle gradation index of waste rock aggregate is 0.687 as shown in Figure 1 (b), which is greater than the ideal Fuller gradation index of 0.5, indicating that the coarse particles content of waste
Rock aggregate is too large. So, the waste rock needs to be mixed with a part of fine aggregate to form a denser packing body, which can prevent severe segregation of the slurry and adversely affecting the filling quality due to excessive coarse aggregate.

### Table 1. Chemical composition of filling materials (mass fraction)\%

| Ingredients   | SiO₂ | CaO  | MgO  | Al₂O₃ | Fe₂O₃ | K₂O | TiO₂ | MnO | others |
|---------------|------|------|------|-------|-------|-----|------|-----|--------|
| Tailing       | 42.20| 3.73 | 32.71| 4.04  | 12.14 | 0.39| 0.33 | 0   | 4.22   |
| Waste rock    | 47.71| 16.39| 15.22| 7.81  | 7.17  | 1.95| 0.54 | 0.12| 0.12   |
| Cement        | 28.36| 48.28| 2.50 | 11.87 | 2.88  | 1.07| 0.60 | 0.12| 4.31   |

![Particle size distribution curve of filling materials](image)

**Figure 1.** Particle size distribution curve of filling materials

### 3. Experimental method

If the coarse aggregate is directly selected with reference to the definition of coarse aggregate in concrete, the size range of the selected coarse aggregate will be too large, which will easily cause the slurry segregation and affect the filling quality. In order to eliminate the “size effect” of coarse particles on the test results [22], we selected waste rock with a particle size range of more than 1 mm and less than 10 mm [23-24].

The samples were all made in accordance with the requirements of "General Concrete Design Regulations" JGJ55-2011, using cylindrical molds with a diameter of 50 mm and a height of 100 mm. A total of 9 types of mixed aggregates cemented backfill samples with different coarse aggregate replacement rates were tested for uniaxial compression. The coarse aggregate replacement rate in the experiment ranged from 40% to 80%, and the experiment gradually increased at 5% intervals. Mixed evenly the whole tailings (fine particles), waste rock (coarse particles), PC32.5R composite Portland cement and natural water according to the ratio of cement to tailings 1:4 and the concentration 76%, then poured the slurry into the cylindrical mold quickly. After the initial setting of the slurry, smoothed out the samples surface. 24h later, removed the samples from the mold and place them in a standard curing box for curing (curing temperature is 20 °C, humidity is 93%). When the curing age reaches 3d, 7d and 28d, each sample was weighed with an error of 0.1g, then the sample was subjected to a uniaxial compression test with RMT-150C rock mechanics test system. The maximum output of RMT-150C has two options 1000kN and 100kN, with an accuracy of 3 ‰ F.S. Because the strength of the filling body is much lower than the strength of rock and concrete, the press output is selected to be 100kN, and the test error is only 0.3kN, which is within the acceptable range for the uniaxial compressive strength test of the filling body. The test loading mode adopts the displacement control mode. Three samples were tested at each coarse aggregate replacement rate, and the average value of the three samples was taken as the test data.

### 4. Experiment result

#### 4.1. Uniaxial compressive strength test result

Fitted the uniaxial compressive strength obtained from the test. The curve between the uniaxial
compressive strength and the coarse aggregate replacement rate are shown in Figure 2. With increasing the coarse aggregate replacement, the uniaxial compressive strength of the samples at different curing ages shows a trend of increasing first and then decreasing. When the coarse aggregate replacement rate is 60%, an optional replacement rate, the uniaxial compressive strength of the sample reaches the maximum value. Using waste rocks to replace a part of the whole tailings can affect the uniaxial compressive strength of the mixed aggregates cemented backfill which mainly by changing the packing density of the filling aggregates [25]. When the coarse aggregate replacement rate increases from 40% to 60%, the packing density of the mixed aggregates cemented backfill gradually increases and reaches the optimal value at optional replacement rate 60%. In this process, a more and more dense skeleton support system can be formed inside the filling body sample, so that the uniaxial compressive strength of the backfill gradually increases and reaches the maximum value optional replacement rate 60%. As the coarse aggregate replacement rate continues to increase, when it exceeds 60%, the coarse aggregate content in the filling aggregate is too high, and the fine particles cannot effectively exert the "filling" effect (the fine particles are not enough to fill the pores between the coarse particles), resulting in a large amount of pore structure inside the filling body. When such a filling body with a large number of pores is subjected to external load, stress concentration is easy to occur, thereby reducing the bearing capacity of the filling body.

Figure 2. Fitting curves of uniaxial compressive strength of filling samples at different curing ages

4.2. Damage constitutive model of mixed aggregates cemented backfill

The mixed aggregates cemented backfill is regarded as an isotropic continuous medium. In the case of one-dimensional elasticity, the Mazars model and the Lemaitre strain equivalence principle are used to establish the damage evolution model before and after peak stress for the filling bodies at different curing ages [26]. Before the filling body reaches the peak stress \( \sigma_p \), \( \varepsilon \leq \varepsilon_p \), the crack inside the filling body expands to a small extent. At this stage, the damage value \( D \) of the sample is as follows [27]:

\[
D = A \varepsilon^\beta
\]

(2)

Where \( A \) and \( \beta \) are constants.

Taking the filling body as an isotropic continuous medium, according to the Lemaitre strain equivalence principle, the damage constitutive equation of the filling body before the peak stress can be obtained as shown in the following formula:

\[
\sigma = E \varepsilon - E A \varepsilon^{\beta+1}
\]

(3)

According to the boundary conditions and the stress-strain curve of the filling body, we can obtain:

\[
\begin{align*}
\varepsilon &= \varepsilon_p, \sigma = \sigma_p \\
\frac{d\varepsilon}{dt} &= 0
\end{align*}
\]

(4)

Substituting equation (2) and equation (3) into equation (4) gives:

\[
\begin{align*}
\beta &= \frac{\sigma_p}{(E \varepsilon_p - \sigma_p)} \\
A &= \frac{1}{(\varepsilon_p^\beta + \beta \varepsilon_p^\beta)}
\end{align*}
\]

(5)

Where \( \sigma_p \) is the peak stress; \( \varepsilon_p \) is the peak strain.

Peak stress and peak strain can be obtained by processing the uniaxial compression stress-strain curve of the mixed aggregates cemented backfill with the curing age of 28d. These values are then substituted into equation (5) for calculation to obtain the values of \( \beta \) and \( A \), so that the constitutive equation of the
pre-peak damage of the mixed aggregates cemented backfill can be established as shown in Table 2.

4.3. Damage evolution characteristics of mixed aggregates cemented backfill before peak stress

Substituted the values of the damage parameters $\beta$ and $A$ of the mixed aggregates cemented backfill in Table 2 into equation (2). The damage value corresponding to the peak stress of the mixed aggregates cemented backfill at different coarse aggregate replacement rates and its damage evolution equation before the peak stress were obtained, as shown in Table 3. The origin numerical processing software was used to fit the damage evolution equation in Table 3, and the relationship between the damage coefficient D and the strain before the peak stress of the backfill were obtained as shown in Figure 3. It can be seen from Figure 3 and Table 2: As the coarse aggregate replacement rate increases, the peak stress damage value of the sample increases first and then decreases. When the sample is under load, as the strain increases, the damage value D tends to increase gradually. When the coarse aggregate replacement rate exceeds 60%, the strain value corresponding to the peak stress damage value of the sample with a higher coarse aggregate content decreases, indicating that the sample can reach the peak stress after relatively small deformation. It also means that the backfill samples with more coarse aggregate content are more prone to brittle failure.

Figure 3. Relationship between damage value and strain of mixed aggregates cemented backfill
4.4. Energy dissipation characteristics of mixed aggregates cemented backfill

China Jinchuan No. 2 Mine adopts downward layered cemented backfill mining method to mine underground ore body. During the mining process, at least one side of the upper layered filling body is in a free surface state after the mining of the lower layered ore body is completed. Establish a model for a filling body assumed as a most dangerous ore body situation, and simplify the model. The filling body is regarded as only received a force in one dimension (as shown in Fig. 4). The upper layered filling body is subjected to compression deformation due to the pressure of the surrounding rock, and the filling body stores the compression energy. According to the effective stress energy equivalence principle proposed by Sidoroff [28], assuming that the cemented filling body is an isotropic continuous medium, the elastic deformation energy stored in the filling body can be calculated according to the effective stress received in one-dimensional case. Select a micro-element $\text{d}x\text{d}y\text{d}z$ from the filling body as an object. When the stress on the micro-element gradually increases from 0 to $\sigma_i$, the deformation of the micro-element is $\varepsilon_i$, and the elastic deformation energy $\text{d}w$ of the micro-element is calculated as follows:

$$\text{d}w = \int_0^{\varepsilon_i} \sigma_i d\varepsilon_i (\text{d}x\text{d}y\text{d}z)$$ (6)

When the filling body reaches the peak stress $\sigma_p$, its peak strain is $\varepsilon_p$. From equations (6) and (3), the peak stress specific energy $U_p$ of each unit of mixed aggregates cemented backfill after compression deformation is calculated as follows:

$$U_p = \frac{\text{d}w}{\text{d}v} = \frac{\text{d}w}{\text{d}x\text{d}y\text{d}z} = \int_0^{\varepsilon_p} E\varepsilon (1 - A\varepsilon^\beta) d\varepsilon = \frac{1}{2} E\varepsilon_p^2 - \frac{E_A}{\beta + 2} \varepsilon_p^\beta$$ (7)

According to formula (7), the peak stress specific energy $U_p$ of the mixed aggregates cemented backfill with different material ratios was calculated, as shown in Table 4. Used Origin numerical processing software to fit the two parameters of peak stress specific energy and coarse aggregate replacement rate in Table 4, and their relationship was shown in Figure 5. The peak stress specific energy $U_p$ of mixed aggregates cemented backfill increases first and then decreases with the increase of the coarse aggregate replacement rate. When the coarse aggregate replacement rate ranges from 40% to 60%, The peak stress specific energy $U_p$ increases exponentially as the coarse aggregate replacement rate increases. When the coarse aggregate replacement rate ranges from 60% to 80%, the peak stress specific energy $U_p$ decreases with an exponential function as the coarse aggregate replacement rate increases. It can see that the peak stress specific energy $U_p$ and uniaxial compressive strength have a similar change rule: as the coarse aggregate replacement rate continues to increase, both of them show a trend of increasing first and then decreasing. It shows that the specimens showing higher uniaxial compressive strength after being subjected to uniaxial loading have a stronger energy storage mechanism, which is conducive to controlling the stability of the stope surrounding rock.

Table 4: Peak stress specific energy of mixed aggregates cemented backfill

| Group | Coarse aggregate replacement rate/% | Uniaxial compressive strength /MPa | Peak stress specific energy /kJ |
|-------|------------------------------------|----------------------------------|-------------------------------|
| A     | 40                                 | 5.21                             | 130.2                         |
| B     | 45                                 | 5.41                             | 139.1                         |
| C     | 50                                 | 5.51                             | 152.1                         |
| D     | 55                                 | 5.58                             | 190.6                         |
| E     | 60                                 | 5.82                             | 206.3                         |
| F     | 65                                 | 5.26                             | 119.4                         |
| G     | 70                                 | 4.52                             | 97.7                          |
| H     | 75                                 | 3.99                             | 89.6                          |
| M     | 80                                 | 3.59                             | 66.9                          |
Figure 4. Mechanics model between backfilling and rock mass

Figure 5. Relationship between peak stress specific energy and coarse aggregate replacement rate

5. Numerical analysis of mechanical behaviour of filling body
When the filling body is used as an artificial false roof for the mining of the lower layered ore body, the local stress and stability of the filling body are the key factors for ensuring the recovery of the layered ore body. In this paper, the FLAC3D numerical simulation method is used to numerically simulate the mining process of the underground orebody in Jinchuan No. 2 Mining Area, China, and to analyze the stability and mechanical behaviour of the filler body during mining and filling.

5.1. 3D model creation
The second phase of the project first mines the rich ore in the range of 1 # ore body (vertical height 250m) at an altitude of 1250 ~ 1000m. It is divided into a middle section by 50m, and the middle sections that have been excavated at present are 1350m, 1300m, 1250m, 1200m, 1150m and 1000m. The middle section is divided into sections, and the height of each section is 20m. In this simulation, two middle sections with an altitude of 1150-1000m were used as the numerical simulation research objects to simulate the mining and filling process of four sections. According to the actual excavation space range, the Y direction of the model represents the trend of the ore body, the X direction represents the vertical ore body trend, and the Z direction represents the height of the ore body. The boundary around the model constrains the horizontal displacement and the lower boundary displacement. The model established this time is 100m long in the X direction, 400m in the Y direction and 240m in the Z direction. The upper and lower sections of the model are all arranged in parallel. After mining one segment, fill it, and then mine the next segment ore body. The inclination of the ore body in the stope is 70°. The model established in this paper simulates the mining and filling process of 4 segmented ore bodies in total as shown in Figure 6. The model parameter settings are shown in Table 5. The mechanical parameters of the filling body with the coarse aggregate replacement rate of 60% at the curing age of 28 days are set as the filling body model parameters.
### Table 5. Mechanical parameters of numerical simulation

| Parameter          | Bulk weight /KN/m³ | Cohesive force /MPa | Internal friction angle /° | Elastic Modulus /GPa | Poisson's ratio | Tensile strength /MPa | Uniaxial compressive strength /MPa |
|--------------------|-------------------|---------------------|-----------------------------|----------------------|-----------------|-----------------------|-----------------------------------|
| Filling body       | 21.5              | 0.73                | 46.5                        | 2.54                 | 0.24            | 0.85                  | 5.82                             |
| Surrounding rock   | 29.3              | 2.875               | 38                          | 15.25                | 0.19            | 1.60                  | 75.0                             |
| Ore body           | 30.5              | 7.0                 | 43.5                        | 52                   | 0.30            | 1.10                  | 53.0                             |

#### 5.2. Displacement distribution of stope rock mass

Taking the number of orebody sections numbered 1 ~ 4 (numbered sequentially from top to bottom) as the abscissa, the vertical displacement of the surrounding rock of the stope after mining the orebody and filling the mined area is taken as the ordinate, the processed data curve is shown in Figure 7. After mining the orebody, the roof rock surrounding the stope has been displaced vertically downward, and continue to mine the ore body in the lower section, the amount of descending displacement gradually increased; while the floor rock mass of the stope has obvious bulging phenomenon, but with the mining of the lower section ore body, the displacement of the floor rock body is basically unchanged. After filling each section of the mined-out area, the displacement of the stope roof and stope floor showed a significant downward trend, indicating that filling the mined-out area can effectively limit the displacement of the rock mass in the stope.

#### 5.3. Mechanical characteristics of surrounding rock

Taking the number of orebody sections numbered 1 ~ 4 (sequentially numbered from top to bottom) as the abscissa, the principal stress of the surrounding rock of the stope after mining the orebody and filling the mined area is the ordinate, and the processed data curve is shown in Figure 8. Where positive means...
tension and negative means pressure. It can be seen from Fig. 8 that with the mining of segmented ore bodies, the maximum principal stress of the stope roof and stope floor rock bodies is gradually increasing. After the mined-out area was filled, it can effectively alleviate the compressive stress concentration of the rock mass in the stope. It can be seen from the change of the minimum principal stress of the rock body that after mining the orebody, the roof and floor rock bodies of the stope are also subjected to tension, but after filling the mined-out area, the stress of the rock body is converted from the tensile stress concentration to the compressive stress concentration. Because the rock mass has good compressive performance and poor tensile performance, filling the mined-out area can effectively keep the rock mass stable.

**Figure 8. Stress value of surrounding rock in stope**

### 5.4. Stress distribution characteristics of the filling body

When the filling body is used as an artificial false roof during the mining of the lower section ore body, whether the lower section ore body can be safely recovered depends on the local stress condition and stability state of the filling body. From the simulation results, after the first section mined-out area was filled, the maximum principal stress of the filling body is -2.50MPa, and the minimum principal stress is 0.79MPa. Taking the number of orebody sections numbered 2 ~ 4 (in order from top to bottom) as the abscissa, the maximum principal stress and minimum principal stress (positive means tension and negative means pressure) of the filling body after mining orebody and filling mined-out area as the ordinate, the curve is shown in Figure 9. As can be seen from Figure 9, with mining the lower section ore body, the maximum principal stress value of the filling body increases from -2.5MPa to -5.0MPa and tends to be stable. When the mined-out area was filled, the maximum principal stress value of the filling body decreases to -2.5MPa, and tends to be stable.

It can be seen from the change of the minimum principal stress of the filling body that the filling body is subjected to tensile stress in the stope. Continue to mine the lower section orebody, the tensile stress value of the filling body in this section exceeds its tensile strength 0.85MPa, indicating that the filling body in the stope will undergo tensile failure. Therefore, when the mixed aggregate cemented backfill is used in the Jinchuan No. 2 mine area in China, this paper suggests that the uniaxial compressive strength can be met when the coarse aggregate content is 60%. However, the filling body has the risk of tensile damage, and increasing the cement content can only limital increase the tensile strength. Synthetic fibers can be incorporated into the filling body, accounting for 0.2% to 0.5% of the total amount of cementitious material, which can increase the tensile strength of the filling body, thereby ensuring the stability of the filling body.
6. Conclusions

1. When mixing waste rocks with whole tailings as multi-component backfill aggregate is used as aggregate, the uniaxial compressive strength of the backfill at different curing ages has a quadratic function curve relationship with the increasing coarse aggregates replacement rate, which indicates that there is an optimal replacement rate of 60% in this experiment.

2. As the strain increases, the peak stress damage value D of the sample gradually increases, and when the coarse aggregate replacement rate exceeds 60%, increasing the coarse aggregate content, the strain value corresponding to the peak stress damage value of the sample will decrease, indicating that the backfill samples containing more coarse aggregate are more prone to brittle failure.

3. The peak stress specific energy $U_p$ and uniaxial compressive strength have a similar change rule: as the coarse aggregate replacement rate increase from 40% to 80%, both of them show a trend of increasing first and reach maximum values at 60%, then decreasing, indicating that the samples with higher uniaxial compressive strength have a stronger energy storage mechanism when subjected to uniaxial loading.

4. Taking the backfill mining method as an example in Jinchuan No. 2 Mining Area of China, Used FLCA3D numerical simulation method to simulate the stability state and mechanical behaviour of the backfill body during the mining and filling process. The results show that filling the mined-out area can effectively reduce the stress concentration problem of the rock mass around the stope, but the filling body will undergo tensile damage due to mining activity.

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