Study on Test and Ratio Optimization of Waste Rock-Fly Ash Aggregate Filling Slurry

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Abstract. To obtain the optimum proportion of fly ash alternative for preparing filling slurry instead of waste rock, the effect of fly ash dosage on the filling body strength is predicted by utilizing BP neural network model on the basis of experimenting the particle size distribution, filling body strength and slurry working characteristics of waste rock-fly ash binary aggregate system under various fly ash dosages. As the results revealed, the waste rock-fly ash binary mixture system attains the densest accumulation when the fly ash dosage is 30%. At this point, the compressive strengths at all ages reach the maximum, according to the BP neural network model predictions. The minimum cost for preparing filling slurry is obtained to be 121 yuan/m$^3$ based on the cost optimization model. At this time, the fly ash dosage is 26%, the cementitious material consumption is 286 kg/m$^3$, the slurry concentration is 81%, the 3d strength is 1.26 MPa, the 7d strength is 1.52 MPa, the 28d strength is 5 MPa, the expansion degree is 51.4 cm, and the bleeding rate 5.7%. Both the filling body strength and slurry fluidity conform to the requirements, while the fly ash dosage is almost identical to that obtained from the particle size distribution and filling body strength tests.

1. Introduction
Capable of improving the ore recovery rate and preventing the earth surface subsidence, filling mining method has unique advantages in realizing wasteless mining and green mines. Moreover, filling mining enjoys an increasingly important position in mining due to the national policy requirements for environmental protection [1-2]. Promotion of the filling method, however, faces cost issues. The research on filling materials has become a hot topic among mining scholars in recent years [3-4]. Major ways to lower the cost of filling mining include the development and popularization of green filling cementitious materials, and the use of waste rock and solid waste for mine filling [5-6]. Waste rock, which originates from the downhole environment, has been applied to the backfilling of mined-out areas in a growing number of mines [7-8]. In view of the undemanding strength requirement on the pillar filling body, the insufficient tailings problem can be alleviated by adding the waste rock filling into the process of tailings backfilling. An application research of waste rock filling in the cemented filling was carried out by He for the Shizishan mining area [9]. He et al.’s study on the reasonable matching between waste rock cemented filling body and sandy shale found that the damage coefficient of the filling body increased exponentially with its strain. Moreover, the peak stress damage value and specific stress energy of waste rock cemented filling body increased with the elevating loess content, while decreased with the elevating cement content. Lastly, they gave a reasonable matching coefficient between the filling body and the sandstone from the particle size perspective [10]. Wu et al. investigated the relationship between strength and water-cement ratio of waste rock tailings cemented...
filling body, thereby offering a rational guidance for seeking the optimum ratio of slurry composition \[11\]. Through RSM-BBD-based tests on the mix proportion and strength of waste rock-aerol sand cement, a set of slurry mix ratios was optimized using regression model and established cost function for filling material, which was confirmed through field test to meet production requirements \[12\]. Wu et al. studied the strength and deformation characteristics of continuously graded waste rock cemented filling body. They found that in engineering, the gradation of backfill skeleton grains and obtaining their best ratio were conducive to improving the strength of filling body \[13\]. However, none of the above studies has tackled the optimum slurry ratio problem of waste rock mixed filling aggregate from the perspective of cost of preparing filling slurry from waste rock aggregate. The primary reason for slurry delamination and segregation found with the waste rock coarse aggregate filling used by the Longshou Mine of Jinchuan Company is the discontinuous gradation of coarse aggregate size. Due to the low content of -20 μm fine particles, high concentration slurry can hardly be formed, which not only causes the delamination and segregation of slurry, but also reduces the strength of cemented filling body. In this regard, experimental study is carried out to optimize the size gradation of coarse waste rock aggregate, the strength of cemented filling body and the working characteristics of slurry, which is achieved by adding fine fly ash aggregate. From the preparation cost perspective, the optimum ratio for preparing waste rock-fly ash mixed aggregate filling slurry is derived, thus addressing the delamination and segregation problems of coarse aggregate slurry.

2. Materials and methods

2.1. Filling materials

The cement used in the tests was non-standard 38.5 cement for mine filling manufactured by Jinchang Cement Company. Meanwhile, the slag was powder material manufactured by Xijin Energy-saving Building Materials Co., Ltd. in Yongchang, Gansu. The waste rock aggregate was collected from the crushed waste rock in the Longshou Mine of Jinchuan Company, which was crushed with a jaw crusher and sieved to obtain -12 mm coarse waste rock aggregate. Besides, the fly ash was industrial waste of Jinchuan Power Plant. In Figure 1, the particle size distributions of waste rock and fly ash are displayed.

![Figure 1. Particle size distribution curve of waste rock-fly ash mixed aggregate](image)

The theoretical formula for maximum density curve modified by Talbot \[14\] can be expressed as follows:

\[ P = 100\left(\frac{d}{D}\right)^n \]
Where \( d \) — size of a certain particle in the swarm, mm; \( n \) — gradation index; \( P \) — sieve passing mass percentage of particles sized \( d \), %; and \( D \) — maximum particle size in the aggregate. Considering the skeleton effect of aggregate, \( D \) was denoted by \( D_{95} \), mm in this paper, which refers to the mesh size of sieve through which 5% of aggregate fails to pass in the screening experiment.

The curve is Fuller curve when \( n = 0.5 \). According to the theoretical analysis and experiment by Talbot, the filling material has an acceptable compactness at \( n = 0.3 \text{–} 0.7 \), and preferable working characteristics at \( n = 0.3 \text{–} 0.45 \). For instance, the value range of \( n \) is set between 0.35–0.45 in Japan, whereas in the United States, \( n = 0.45 \) is used as the basis for setting standard gradation. In Figure 1, the Fuller curves of waste rock-fly ash binary aggregate with various fly ash contents are presented. The R-square differences are all greater than 0.95, the fitting degrees are high, and the gradation index \( n \) is less than 0.45, which is attributed to the incorporation of fly ash powder material. With the continuous addition of fly ash, the Talbot's curve gradually shifts upwards, and the corresponding Talbot index declines gradually. The waste rock contains 4.11% of -75 μm powder and shows a gradation index of 0.56. The -75 μm powder increases markedly as the fly ash is incorporated. At a fly ash dosage of 15%, the waste rock-fly ash contains 15.41% of -75 μm powder, and the gradation index is less than 0.45, which decreases with the increasing fly ash dosage. The incorporation of fly ash leads to a gradually increasing powder content of waste rock-fly ash binary aggregate. At a coal ash dosage of 30%, \( n \) equals to 0.33, at which point the binary aggregate reaches the densest filling state, according to the Andreasen equation [15].

2.2. Test methods

2.2.1. Strength test of mixed aggregate filling body. Filling body strength test was designed with three factors of fly ash dosage, cementitious material consumption and slurry mass concentration, in order to investigate the influence of fly ash dosage on the filling body strength. Based on the parameters of industrial filling slurry, the mass concentrations of filling slurry were selected to be 77%, 79% and 81%. The filling aggregate was a binary mixture of waste rock from a Jinchuan mine with different dosages of fly ash, where the contents of fly ash were 15%, 20%, 25%, 30% and 35%, respectively. The cementitious materials for actual in-situ filling were used, which had a cement-slag ratio of 7:3 and added at dosages of 270 kg/m³, 290 kg/m³ and 310 kg/m³. Triple specimens sizing 7.07 cm×7.07 cm×7.07 cm were prepared as per the standard operation requirements, and then cured to the specified age for determination of uniaxial compressive strengths. Table 1 displays the test procedure and results.

2.2.2. Working characteristics test of filling slurry. Since the cemented filling slurry for mining is transported generally via pipeline, it is crucial whether the slurry can achieve stable pipeline transportation. The filling slurry from Jinchuan mine needs to be transported to the goaf through long-distance pipelines. This imposes higher fluidity requirement on the filling slurry. That is, the filling slurry must satisfy the high flow, anti-segregation, self-compacting and even self-leveling requirements of goaf filling. The slurry fluidity, which characterizes the difficulty of slurry transportation via pipeline, is generally measured by slump and expansion of the slurry. As for slurry stability, which is indicative of the non-delamination, non-segregation and water saturation degrees of the slurry, is often characterized by slurry bleeding rate. In the working characteristics test, the slurry fluidity and stability were investigated by measuring the expansion and bleeding rate of slurry materials at different ratios. Table 1 lists the test results.

| No. | Fly ash /% | Cementitious materials /kg m³ | Mass concentrations /% | Compressive strength /MPa 3d | Slumps /cm | Expansion rate /cm | Bleeding rate /% |
|-----|------------|-------------------------------|-------------------------|-----------------------------|------------|-------------------|-----------------|
| A1  | 15         | 270                           | 0.5                     | 1                           | 2          | 24.8              | 87.5            | 18.76          |
3. Results and discussion

3.1. BP neural network model of cement strength

Artificial neural network modeling was performed to reveal the influence rule of fly ash dosage on the backfill strength of the binary mixed aggregate system.

3.1.1. Selection of network model. The nonlinear effects of three influencing factors, namely the fly ash dosage, cementitious material consumption and slurry mass concentration, on the 3d, 7d and 28d uniaxial compressive strengths of cemented backfill were studied using a 3-Hn-1 three-layer BP neural network structure in the following conditions: Training accuracy goal= 1e-7; iteration number epochs= 10000; and minimum performance gradient min_grad= 1e-5. The transfer function was tansig for the hidden layers; and logsig for the output layer. The training function was trainlm, which used the L-M algorithm. As a combination of gradient descent and newton methods, the L-M algorithm had fewer iterations, faster convergence and higher accuracy than the conventional BP and other improved algorithms. The node number was computationally compared between multiple hidden layers by taking fly ash dosage, cementitious material consumption and slurry mass concentration as the input layer; and the 3d, 7d and 28d uniaxial compressive strengths as the output layer. Comparison revealed that preferable accuracy could be attained when the number of hidden layer nodes was 8.

3.1.2. Numerical normalization. The sample input and output data were normalized prior to training the network since excessively large or small value would affect the learning effect. This helped accelerate the network learning and computational convergence efficiencies. After inverse normalization processing, the predicted data were real results. To avoid the submergence of small data information by big data information, the normalized input data were distributed within a [0,1] interval. During normalization, the variation range of cementitious material consumption was set between 270~290 kg/m3, the variation range of slurry concentration was between 76%~85%, and the fly ash dosage was extended to 0%~50% while taking into account the model prediction range. This facilitated studying the influence of fly ash dosage on the strength of waste rock-fly ash aggregate backfill at different ages. The output data were normalized within a [0.05, 0.95] interval, so that the network output had sufficient room for growth. The first fifteen sets of data in Table 2 were chosen as
the learning samples of the network, while the remaining two data sets were used as the network test samples. In Figure 2, the training effect of 3 d compressive strength network is illustrated.

![Figure 2. BP neural network model of 3d compressive strength of backfill](image)

(a) Training error curve of neural network with 8 nodes  (b) Sample training function fitting curve

The black dotted line in Figure 2(a) indicates the set standard line 10^-7 for network training target error, where the optimum training error reaches 10^-10. From Figure 2(b), it can be seen that the correlation coefficient R of sample training and fitting is 1, and the relative error between the test derived and model predicted data is close to zero, showing considerably high precision. As shown in the figure, the training error of BP network using L-M algorithm decreases rapidly with the increasing training times, which is already less than the set target after training 25 times. Besides, the BP neural network model exhibits good degree of fitting and high reliability. For the 3 d compressive strength network model, the connection weight IW{1,1} and threshold b{1} of the input and hidden layers; and the connection weight LW{2,1} and threshold b{2} of the hidden and output layers were derived as follows:

\[
IW\{1,1\}=\begin{bmatrix}
-3.0387 & 4.6159 & 5.1908 \\
11.0748 & 2.5065 & -0.6193 \\
-1.0625 & -2.2655 & 4.5564 \\
2.4967 & 1.9801 & -2.1222 \\
2.6116 & 3.7093 & 1.0550 \\
-1.0705 & -4.4955 & -3.2817 \\
1.7653 & 0.5596 & 9.2660 \\
2.0935 & -6.5659 & 1.7366
\end{bmatrix}
\]

\[
b\{1\}=\begin{bmatrix}
-1.4946 \\
-3.7456 \\
4.0440 \\
-6.2969 \\
-6.6574 \\
2.4998 \\
-8.2440 \\
0.0109
\end{bmatrix}^T
\]

\[
LW\{2,1\}=\begin{bmatrix}
-1.6186 \\
1.7027 \\
1.3607 \\
0.2476 \\
1.4946 \\
0.1072 \\
3.1258 \\
-0.8629
\end{bmatrix}
\]

\[
b\{2\}=\begin{bmatrix}
2.0601
\end{bmatrix}
\]

Meanwhile, the 7 d and 28 d compressive strengths were subjected to neural network training by L-M algorithm. The computational error converged quickly, and the accuracy was rather high. Reliable neural network models were obtained separately. Figure 3 depicts the modeling process. Ultimately, the BP neural network models of 3d, 7 d and 28d backfill strengths were obtained separately. As shown in Figure 4(a), the experimental values of compressive strengths at various ages almost coincide with the calculated values, with small errors.
Given the significant impacts of slurry concentration and cementitious material consumption on the compressive strength of filling body, only the compressive strength results at different dosages of fly ash were considered when modelling the neural networks for the three ages of 3d, 7d and 28d. Accordingly, during the neural network-based prediction of the compressive strength at various ages, the optimum consumption of cementitious material was set at 310 kg/m$^3$, the optimum mass concentration of slurry was 81%, while the variation range and gradient of fly ash dosage were 0~50% and 5%, respectively. Under these settings, the influence of fly ash dosage on the filling body strength was studied at different ages. In Figure 4(b), the compressive strength predictions based on neural network models are presented.

As can be seen from the figure, the 3d compressive strength increases with the increasing fly ash dosage at dosages less than 30%, which reaches a maximum (1.3 MPa) at a 30% dosage, and then remains almost unchanged with the further increase of fly ash dosage. Regarding the 7d compressive strength, it decreases first and then increases with the variation of fly ash dosage between 10%~30%, which shows a minimum at a 15% dosage. The strength values are close to each other when the fly ash dosage is less than 10%, while almost unchanged at dosages higher than 30%. Thus, the 7d compressive strength values are close to each other when the fly ash dosage is lower than 10% or higher than 30%, reaching a maximum. As for the 28d compressive strength, apparently, its value increases first and then decreases with the increasing fly ash dosage, which reaches a maximum (5.55 MPa) at a 30% dosage. After comprehensively considering the compressive strengths on 3d, 7d and 28d, we find that the compressive strength at every age reaches a maximum when the fly ash dosage is 30%. 

![Figure 3. Neural network training error curve with 8 nodes](image-url)

**3.2. Effect of fly ash on filling body strength**

![Figure 4. Calculated and predicted values of neural network model](image-url)

![Figure 4. Calculated and predicted values of neural network model](image-url)
3.3. Effects of fly ash dosage on working characteristics

In Figure 5, the variation trends of filling slurry slump with the fly ash dosage, cementitious material consumption and slurry mass concentration are illustrated. Clearly, the slump values of filling slurry all satisfy the basic requirements of gravity transportation. As shown in Figure 5(a), the slump initially shows a sharp increase and then a decline with the increasing dosage of fly ash, which reaches a maximum (27.2 cm) at a 25% dosage. This suggests certain variation relationship of the slurry fluidity with the fly ash dosage. Figure 5(b) depicts the variation trend of the filling slurry expansion with the fly ash dosage. The expansion shows a decrease with the increasing dosage, indicating reduced slurry segregation, enhanced water retention and improved slurry stability.

From Table 2, it can be seen that although the slurry slump decreases gradually as the consumption of cementitious material increases, its values all meet the basic gravity transportation requirements of slurry. As the slurry concentration rises, the slump exhibits a slow increase initially and then a drastic decrease, which reaches a maximum at a 79% concentration. The variation trend of consistency is obviously contrary to the slump variations with the fly ash dosage and cementitious material consumption, while consistent with the slump variation with the slurry concentration. The decrease in bleeding rate of filling slurry with the increasing fly ash dosage suggests enhanced water retention and improved stability of the slurry. This is in agreement with the trend of expansion variation.

4. Optimization of filling slurry ratio

4.1. Optimization model building

To prepare the lowest-cost filling slurry which meets the strength and working characteristics requirements, the filling slurry ratio was optimized after regression analyses of the strength and working characteristics data, thereby identifying the optimum parameters for filling slurry preparation. The optimization objective function was created with the objective of minimizing the costs of all the filling materials consumed in the slurry preparation, as shown in formula (1) below. In Table 3, the cost prices of various filling materials are listed.

\[
\text{Min} Z = 320 \times 10^{-3} \times x_1 + 220 \times 10^{-3} \times x_2 + 16 \times 10^{-3} \times x_3 + 60 \times 10^{-3} \times x_4 + 0.8 \times 10^{-3} \times x_5, \quad (1)
\]

Where \( Z \) — filling cost, yuan/m\(^3\); \( x_1 \) — cement consumption kg/m\(^3\); \( x_2 \) — slag consumption, kg/m\(^3\); \( x_3 \) — waste rock consumption, kg/m\(^3\); \( x_4 \) — fly ash consumption, kg/m\(^3\); and \( x_5 \) — tap water consumption, kg/m\(^3\).

| Material Name | cement | slag | waste rock | fly ash | tap water |
|---------------|--------|------|------------|---------|-----------|
| Cost / (Yuan/t) | 320    | 220  | 16         | 60      | 0.8       |
4.2. Constraint conditions

The prerequisites for preparing a low-cost filling slurry were to satisfy both the filling body strength requirement and the gravity transportation requirement. Linear regression analyses were performed on the data from filling body strength and filling slurry fluidity tests, as well as the consumptions of various test materials. Since the function model with high fitting effect was chosen as the constraint conditions, the constraint conditions must include the functions for filling body strength at various ages and the requirements on expansion, bleeding rate, etc. The strength constraints for 3 d, 7 d and 28 d filling body strengths were expressed by formulas (2), (3) and (4). Meanwhile, the expansion constraint was expressed by formula (5); the bleeding rate constraint was expressed by (6); the material consumption constraints were expressed by (7), (8) and (3); and the slurry mass concentration constraint was expressed by (10).

\[ R_{3d} = -0.054 x_1 - 0.125 x_2 - 0.088 x_3 - 0.113 x_4 - 0.252 x_5 + 248.2 \geq 1 \]  
\[ R_{7d} = -0.292 x_1 - 0.682 x_2 - 0.451 x_3 - 0.578 x_4 - 1.271 x_5 + 1265.5 \geq 1.5 \]  
\[ R_{28d} = 1.126 x_1 + 2.628 x_2 + 1.676 x_3 + 2.156 x_4 + 4.674 x_5 - 4692.6 \leq 5 \]  
\[ K = 0.017 x_1 + 0.04 x_2 + 0.148 x_3 + 0.111 x_4 + 0.798 x_5 - 448.7 \geq 50 \]  
\[ M = -0.359 x_1 - 0.837 x_2 - 0.445 x_3 - 0.606 x_4 - 1.168 x_5 + 1261.1 \leq 10 \]  
\[ x_1 : x_2 = 7 : 3 \]  
\[ x_1 / \rho_C + x_2 / \rho_{SG} + x_3 / \rho_{WR} + x_4 / \rho_{FA} + x_5 / \rho_W = 1 \]  
\[ 270 \leq x_1 + x_2 \leq 310 \]  
\[ 380 \leq x_3 \leq 450 \]  

4.3. Optimization model solving

Linear programming analysis was performed using MATLAB to solve the optimization model built based on the constraints in formulas (1)~(10) and the objective function (1). The operational procedure is as follows. The optimum cost of preparing filling slurry was finalized to be 121 yuan/m³. Table 4 shows the optimum material consumption design that satisfies both the filling body strength requirement and the filling slurry fluidity requirement.

| Material Name       | Consumption / (kg/m³) |
|---------------------|-----------------------|
| cement              | 200.2                 |
| slag                | 85.8                  |
| waste rock          | 1017.5                |
| fly ash             | 354.9                 |
| tap water           | 380                   |

In the table, the 3d strength is 1.26 MPa, the 7d strength is 1.52 MPa, the 28d strength is 5 MPa, the expansion is 51.4 cm, and the bleeding rate 5.7%. The filling body strength and filling slurry fluidity parameters all conform to the requirements. At this point, the fly ash dosage is 26%, the cementitious material consumption is 286 kg/m³, and the slurry concentration 81%.

5. Conclusions

(1) The particle size distributions of waste rock-fly ash binary aggregate system with different fly ash contents show a gradual increase in the fine particle fraction and a gradual decrease in the gradation index with the increasing fly ash dosage. When the dosage of fly ash is 30%, n is 0.33, at which point the binary aggregate reaches the densest filling state, according to the Andreasen equation.

(2) The BP neural networks based on L-M algorithm exhibit fast convergence and small computational errors. The calculated values of filling body strength models are almost coincident with the experimental results. Utilizing these models, the effects of fly ash dosage on the backfill compressive strengths at various ages are studied. Comprehensive consideration of the 3 d, 7 d and 28 d compressive strengths finds that the compressive pressures at various ages all reach respective maximums at a fly ash dosage of 30%.

(3) The minimum cost of preparing the filling slurry is derived to be 121 yuan/m³ based on the cost optimization model of filling slurry. At this point, the 3d strength is 1.26 MPa, the 7d strength is
1.52 MPa, the 28d strength is 5 MPa, the expansion is 51.4 cm, and the bleeding rate 5.7%. Besides, both the strength of filling body and the fluidity of filling slurry conform to the requirements. At this time, the fly ash dosage is 26%, the cementitious material consumption is 286 kg/m³, and the slurry concentration 81%. The fly ash dosage is almost identical to that obtained from the study of particle size distribution and filling body strength trends.

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