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Study on Ratio of Filling Material in Open-pit Coal Mine Based on Orthogonal Test

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Abstract

The reasonable filling performance of backfill is a prerequisite for the promotion and application of end slope filling mining in open-pit mines. A four-factor, three-stage test was designed to investigate the effects of aggregate gradation, cement-to-sand ratio, fly ash content, and slurry concentration on the working and mechanical properties of backfill. The filling body aggregate originated from the stripping waste rock of an open-pit mine. The main rocks were fine sandstone, marl and mudstone. Results show that, slump is primarily influenced by slurry concentration, aggregate gradation, fly ash content and cement-sand ratio. The 7-day compressive strength is mainly affected by the cement-sand ratio, slurry concentration, fly ash content, and aggregate gradation. The influence on 28-day compressive strength decreases in the following order: cement-sand ratio, aggregate gradation, fly ash content, and slurry concentration. After comprehensive analysis, the optimal ratios are determined as follows: aggregate gradation of 0.4, cement-sand ratio 1:6, fly ash content 20%, and slurry concentration 72%. The conclusions obtained in this study demonstrate the feasibility of using waste rock as a filling material in mines.

Keywords: Open-pit mine, Backfilling, Orthogonal method, Componence ratio

1. Introduction

In recent years, the emissions of coal-based solid waste in China have exceeded one billion tons, accounting for over one half of the total industrial solid waste. To mitigate its environmental impact, the coal-based solid waste is processed into filling materials for coal mines, thereby reducing the environmental damage caused by solid waste storage and providing materials for mining filling. The implementation of filling mining is crucial for promoting environmental friendliness and the development of mineral resources, as it can provide safe and efficient technical support for mineral extraction.

Some studies have made significant progress in the field of green mineral resource utilization, particularly in areas such as overburden deformation, backfill deformation, filling materials, preparation of filling slurry, and the transportation of filling slurry under various conditions, including solid gangue filling, dense gangue filling, solid waste paste filling and paste filling. However, many challenges persist, such as insufficient sources of filler aggregate [1, 2].

Different types of mines require different selections of filling methods and materials. The study of new filler materials' preparation and application is necessary. The current mainstream filling process relies on graded tailings as aggregate. However, the self-produced graded tailings are often inadequate, with a productivity rate generally ranging from 30% to 50% [3]. Additionally, there is high consumption of cementing materials, leading to elevated filling costs. High-concentration fill technology presents difficulties in concentrating, filtering, and dehydrating all tailings. The process is complex, with challenges in slurry preparation, resulting in failure to achieve expected concentrations [4].

Filling mining has been widely utilized in metal mines and underground coal mines. While the end-wall mining of open-pit coal mines requires a comprehensive study of filling materials in conjunction with filling mining techniques. In this regard, the use of stripping waste rock as an ideal filling aggregate is crucial. Surprisingly, there has been limited research on the ratio of stripping waste rock as a filling material in open-pit coal mines. Therefore, this study aims to investigate the influence of various factors on the performance of waste rock cemented filling bodies through orthogonal experiments, in order to establish the appropriate ratio and lay part of the experimental foundation for end-wall filling mining.

2. State of the art

Extensive research has been conducted on the selection and preparation of coal mine filling materials. Li et al. [5] designed cementation strength tests with different mass ratios of gypsum to cement clinker, and used thermogravimetric analysis and differential scanning calorimetry, X-ray diffraction, and scanning electron microscope methods to explain the mechanism of hydration products. Yin et al. [6] comprehensively used 3D surface visualization analysis and multivariate nonlinear regression analysis to explore the relationship between paste, cement, pumping agent, and the early strength of backfill. Fall & Pokharel [7] investigated the coupling effect of temperature and sulfate on the strength of cement paste backfill. Mohammed et al. [8] used the response surface method to simulate the influence of grade fly ash, mixed with and

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without papermaking waste residue, on the slump and compressive strength of concrete.

In the filling ratio test, the orthogonal test method is the key method for research and analysis. In order to realize the efficient utilization of fly ash and blast furnace slag, Hua & Wang [9] carried out a series of orthogonal optimization tests to explore the effects of fly ash content, $Ca(OH)_2$, Na_2SO_4, and slurry concentration on the compressive strength, fluidity, and setting time of slag-based cemented filling materials. Liu et al. [10] used the orthogonal test method to test a sludge paste filling material, and discussed the influence of the ratio of sludge, cement, and fly ash mass fractions on the slump, setting time, and compressive strength of the filling paste. Wu et al. [11] used Bayer red mud and fly ash to prepare mine filling materials. The orthogonal test method and MATLAB were used to carry out linear regression prediction and create a 3D visualization model, and the regression equations affecting the filling strength, slump, and bleeding rate of the red mud-based paste were obtained.

As a scientific method for efficiently addressing multi-factor optimization problems, Niu et al. [12] employed a comprehensive experimental design, taking slurry mass concentration and sand-cement ratio as experimental factors. They used slurry fluidity and the uniaxial compressive strength of the cement body as response variables to conduct ratio experiments, thereby establishing the ideal range of ratios for both indicators. Given the poor testing conditions for the tailings filling material ratio experiment in the field, Liu et al. [13] performed uniaxial compression tests on cemented on-site waste rock fragments and found that curing temperature had a significant impact on the early-stage strength of the filling body. They proposed a scheme to preheat the mixing water for cemented filling. Based on the research status [14-17], the orthogonal experimental method was frequently used to study the effects of aggregate gradation, ash-sand ratio, fly ash content, and slurry concentration on the performance of open-pit mine waste rock cemented filling. The rest of this study is organized as follows: Section 3 elaborates on the experiment materials and process. Section 4 presents the results and discusses, and the conclusions are summarized in Section 5.

3. Methodology

3.1 Experimental materials

The filling body aggregate originated from the stripping waste rock of an open-pit mine. The main rocks were fine sandstone, marl and mudstone. Due to the large volume of the collected waste, the waste was first crushed to less than 40 mm using a PE-150X250 jaw crusher. Then, the crushed waste was further crushed to less than 10 mm with a PEX-60X100 jaw crusher. The sample after jaw crushing is shown in Fig. 1.

(a) PE-150×250 (b) PE-60×100

Fig. 1. Crusher discharge drawing.

The crushed waste was sifted through a sieve. The particle size ranges were 0-0.5 mm, 0.5-1.25 mm, 1.25-3 mm, 3-6 mm, 6-8 mm, and 8-10 mm. The different particle size ranges are shown in Fig. 2. The aggregate mass distribution within each particle size range corresponding to the Talbot series is presented in Table 1.

Table 1. The mass distribution of aggregate particles under different Talbot grading indexes (%).

n	**The mass ratio of each particle size interval (mm)**					
	0-0.5	**0.5-1.25**	**1.25-3**	**3-6**	**6-8**	**8-10**
0.2	54.93	11.05	12.62	11.69	5.35	4.36
0.4	30.17	13.36	18.25	19.74	9.94	8.54
0.6	16.57	12.15	19.84	25.04	13.87	12.53

(a) 0-0.5 mm (b) 0.5-1.25mm (c) 1.25-3 mm (d) 3-6 mm (e) 6-8 mm (f) 8-10 mm

Fig. 2. Interval diagram of different particle sizes.

The maximum particle size in the sample is d_{max}. According to the Talbot gradation theory [18], the aggregate mass fraction M_x in the sample that is less than the particle size d_x is:

$$M_x = \left(\frac{d_x}{d_{max}} \right)^n \tag{1}$$

where, n is the Talbot grading index.

According to the above formula, the total mass of aggregate within the particle size range between (d_1, d_2) can be obtained as follows:

$$M_{(d_1,d_2)} = \left(\frac{d_2}{d_{max}} \right)^n - \left(\frac{d_1}{d_{max}} \right)^n \tag{2}$$

It can be obtained from Eq. (2) that the mass ratio of each particle size range for Talbot series values of 0.2, 0.4, and 0.6 is shown in Table 1.

After the cement is mixed with water, the clinker minerals immediately react with water to produce a large amount of heat and form hydration products. The cement slurry gradually thickens and consolidates, and the mixed aggregate is cemented. Ordinary portland cement P.O. 42.5 has the characteristics of low bleeding rate, high early strength, and low dry shrinkage. It has been widely used in the field of mine filling. The cement used in the test is shown in Fig. 3.

Fig. 3. Cement used in the test.

Fly ash is the product of thermal power plants and the main solid waste discharged from them. The main oxides in fly ash are: SiO_2, Al_2O_3, FeO, Fe_2O_3, CaO, TiO_2, etc. With the development of the power industry, fly ash emissions from coal-fired power plants have increased. A large amount of fly ash produces dust and pollutes the atmosphere. If it is discharged into water, river siltation and the toxic chemicals cause harm to humans.

Fly ash can be used as a resource, such as an admixture for concrete, to replace part of the cement. Cement accounts for about 50% of the cost of filling materials. With the increase in the proportion of fly ash, the filling cost decreases.

In this study, the fly ash produced by a power plant in Shuozhou was selected. Fly ash is grayish black, powdered, and grade one, as shown in Fig. 4.

Fig. 4. Class I fly ash in power plant.

Fly ash can replace part of the cement. The SiO_2 and Al_2O_3 in fly ash can also react with $Ca(OH)_2$ produced by the hydration of Portland cement, reducing the alkalinity of the filler slurry and hydration heat, and preventing the filler body from cracking. The fly ash additives can reduce the resistance of pipeline transportation and improve the pumpability of the filler. Adding fly ash to the slurry with a high coarse particle content can reduce the bleeding rate to prevent segregation.

Three types of early strength accelerators, namely organic matter, inorganic salts, and composite early strength accelerators, can shorten the curing time and improve the early strength of the filler, having little effect on the later strength. According to previous study, the optimum addition amount of early strength accelerator is 2% of the cement mass [19].

Expansive agent causes the filler to expand during the hardening process, reducing the shrinkage caused by chemical and thermodynamic reactions during cement hydration, minimizing the cracks produced during hardening, and enhancing the strength of the filler. Besides the filling process, the filling slurry produces bleeding and settlement during the curing process, which also affect the filling effect. According to previous studies [19-21], the optimum dosage of expansive agent is 5% of the cement mass.

3.2 Experimental process

The proportions were weighed according to the orthogonal experimental design. After weighing, put them into the barrel and stir them with a stirrer. After thoroughly stirring, the slump test was carried out.

The slump cylinder was placed on the steel plate, and the pedals were pressed with feet on both sides. The mixed filling slurry was evenly poured into the slump cylinder in three layers. Load each layer of mixture and screw the punch from the edge to the center 25 times. After compaction, the height of each layer of mixture was approximately one-third of the height of the barrel. After the last layer of the mixture was compacted, the excess mixture was flattened at the barrel mouth. The slump cylinder was lifted in 3-7 s. When the mixture was no longer collapsing or the collapse time reaches 30 s, the distance between the height of the cylinder and the highest point of the mixture was measured with a ruler as the slump value of the mixture.

This test standard refers to GB/T50008-2016 in China. Three cube molds with inner dimensions of 7.07 cm × 7.07 cm × 7.07 cm were coated with oil, and the mixed mixture was poured into the molds, with the top surface leveled off. After 12 h, the molds were demoulded. After demoulding, the samples were put into a curing box for curing. The curing box was an SHBY-40B constant temperature and humidity curing box, with the temperature was set to 20 ± 2 °C and the relative humidity at 95 %.

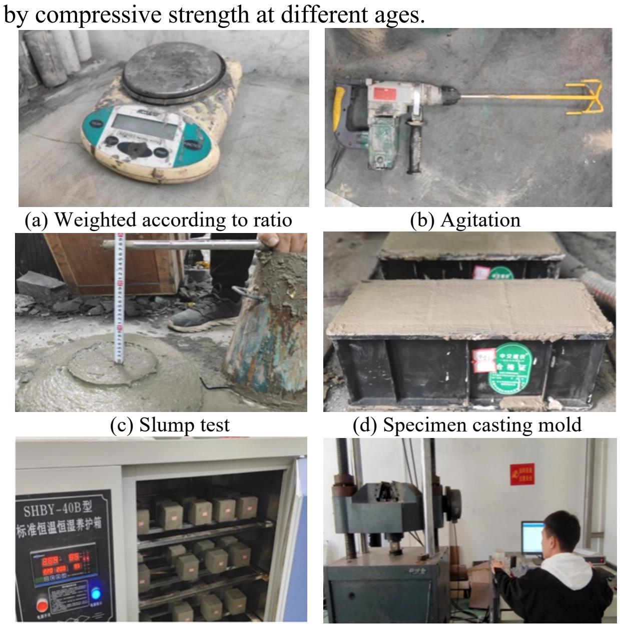
Uniaxial compression tests were carried out on specimens with curing ages of 7 d and 28 d, respectively. Three test blocks were selected for the uniaxial compression test under each ratio, and the average value was taken as the compressive strength of the filling body under that ratio. The test steps are shown in Fig. 5.

3.3 Experimental design

According to the orthogonality, some key points were selected from the comprehensive experiment. Orthogonal experimental design is the main method of fractional factorial design. The representative factors and levels with the characteristics of uniform dispersion, regularity, and comparability are selected. This is a quick and effective experimental method. It can reduce the number of tests, shorten the testing cycle, and reflect the change rule of test indices.

3.3.1 Factor and level

The performance of the filling body was classified into working performance and mechanical performance. The working performance was usually characterized by slump, while the mechanical properties were typically characterized by compressive strength at different ages.



(a) Weighted according to ratio (b) Agitation (c) Slump test (d) Specimen casting mold (e) Sample maintaining (f) Uniaxial compression test

Fig. 5. Test process.

The main factors affecting the performance of the filling body are aggregate gradation, cement-sand ratio, fly ash content, and slurry concentration. Therefore, these factors were studied, and the level of each factor is shown in Table 2.

Table 2. Orthogonal test factors and levels.

n	Cement and sand ratio	Fly ash content (%)	Slurry concentration (%)
0.2	1:6	10	72
0.4	1:8	15	75
0.6	1:10	20	78

3.3.2 Extremum difference analysis

Variance analysis and range analysis were used to analyze the results of the orthogonal test. Range analysis has high practicability and it is easy to understand, which is widely used in the study of filling materials. Therefore, this study chooses the range analysis method to determine the primary and secondary relationship between various factors affecting the performance of the filling body.

The principle of range analysis is as follows: Q_{ij} is the jth level of factor i. The orthogonal experiment has x factors. The number of levels corresponding to each factor is y, where $i = 1, 2, 3,..., x$, and $j = 1, 2, 3,..., y$. The same factor is tested at the same level. Y_{ijk} represents the result of the kth test under Q_{ij}. When the orthogonal experiment has n groups of tests, $k = 1, 2, 3, ..., y$, the statistical parameter K_{ij} of factor i at the j level is discribed in Eq. (3).

$$K_{ij} = (\sum_{k=1}^{y} Y_{ijk}) / y \quad (3)$$

The range R_j is:

$$R_{\mathrm{j}} = max\left\{K_{i1}, K_{i2}, \cdots, K_{ij},\right\} - min\left\{K_{i1}, K_{i2}, \cdots, K_{ij},\right\} \quad (4)$$

The influence of each factor on a certain test index can be directly seen by the range. The larger the range, the greater the influence of the factor on the test index. According to the order of the ranges, the order of the influence of different factors on the test index can be obtained.

4. Results analysis and discussion

4.1 Analysis of slump test results

The slump, 7 d and 28 d, average compressive strength of each test scheme are shown in Table 3. The range analysis method is used to obtain the optimal ratio of waste rock cement backfill.

As shown in Fig. 6, the range of the slurry concentration factor in the slump test results of waste rock cement filling body is the largest, 8.87, and the range of the cement-sand ratio factor is the smallest, 1.04, indicating that the slurry concentration has the greatest influence on the slump of the waste rock cement filling body, and the cement-sand ratio has the least influence on the slump of the waste rock cement filling body. Among these factors, the corresponding range of aggregate gradation is 5.2, which is also an important factor affecting slump, indicating that good particle gradation can increase the fluidity of fillers.

Table 3. The orthogonal test scheme and test results.

Test	*n*	Cement and sand ratio	Fly ash content (%)	Slurry concentration (%)	Slump (cm)	Mean carrier frequency compressive strength (MPa)	
						7 d	28 d
1	0.2	1:6	10	72	24.1	2.583	5.939
2	0.2	1:8	20	75	19.2	2.860	6.421
3	0.2	1:10	15	78	14.6	1.645	4.545
4	0.4	1:6	20	78	17.9	4.985	10.67
5	0.4	1:8	15	72	26.9	2.093	7.587
6	0.4	1:10	10	75	24.7	2.146	4.579
7	0.6	1:6	15	75	26.6	3.974	8.939
8	0.6	1:8	10	78	19.4	2.073	6.659
9	0.6	1:10	20	72	27.5	1.399	4.266

The friction resistance between particles increases when the aggregate size is small. As the aggregate size increases, the friction resistance decreases. The corresponding range of fly ash content is 1.2, indicating that its influence on slump is not significant.

4.2 Analysis of compressive strength test results

As shown in Fig. 7, for the 7 d compressive strength test results of waste rock cemented backfill soil, the cement-sand ratio range is the largest 2.117, and the aggregate gradation range is the smallest at 0.712. This indicates that the cement-sand ratio has the greatest influence on the 7 d compressive strength of cemented backfill soil, while aggregate gradation has the least influence. The slurry concentration is the second most influential factor on 7 d compressive strength, with a range of 0.968. The fly ash content has the third highest influence on the compressive strength of 7 d, with a range of 0.811.

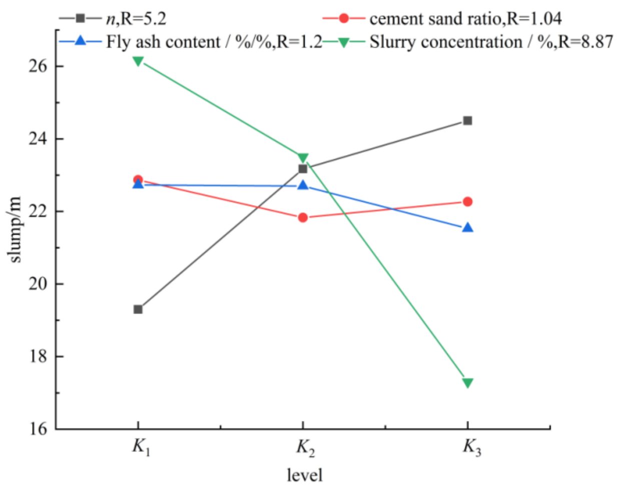


Fig. 6. Range analysis curve of slump test results.

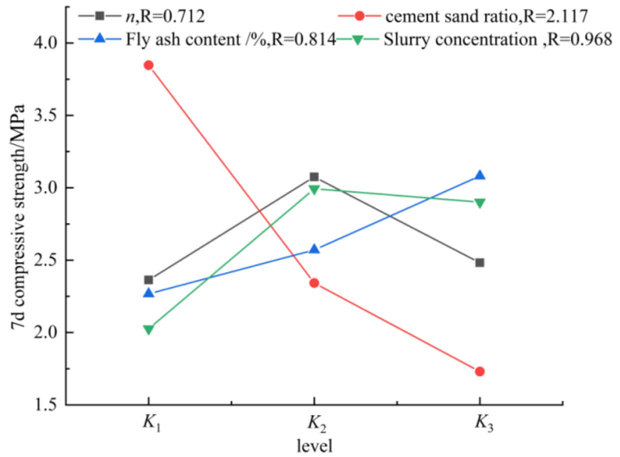
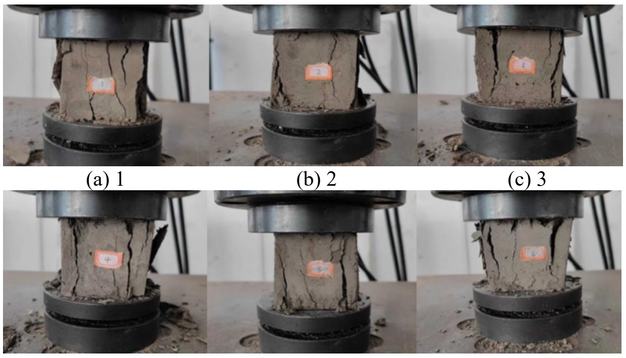


Fig. 7. Range analysis curves of 7d compressive strength test results.

The failure mode of 7 d waste rock cemented backfill in the uniaxial compression test is shown in Fig. 8. It can be seen from the test results that the fracture pattern of the sample is distinct. Axial splitting failure is the failure mode, and each specimen exhibits a nearly complete failure.

As shown in Fig. 9, for the 28 d compressive strength test results of waste rock cemented backfill soil, the cement-sand ratio range is the largest, at 4.053, and the slurry concentration range is the smallest, at 1.360. This indicates that the cement-sand ratio has the greatest influence on the 28 d compressive strength of the cemented backfill soil, while the slurry concentration has the least influence. The influence of aggregate gradation on 28 d compressive strength is second, with a value range of 1.977. The influence of fly ash content on 28 d compressive strength is third, and the range value is 1.393.



(g) 7 (h) 8 (i) 9

Fig. 8. 7 d failure mode of cemented waste rock backfill under different uniaxial compression tests.

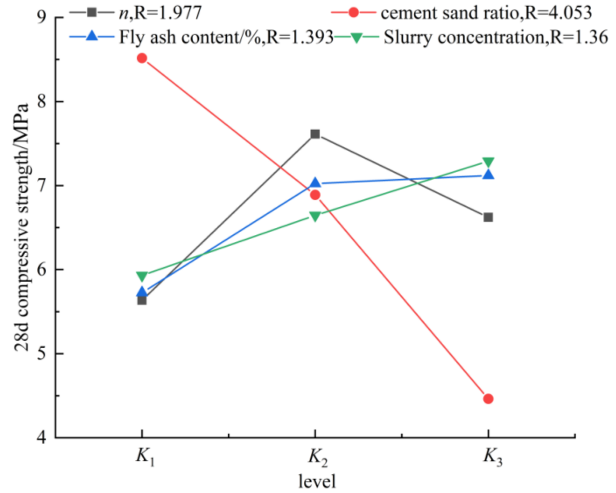


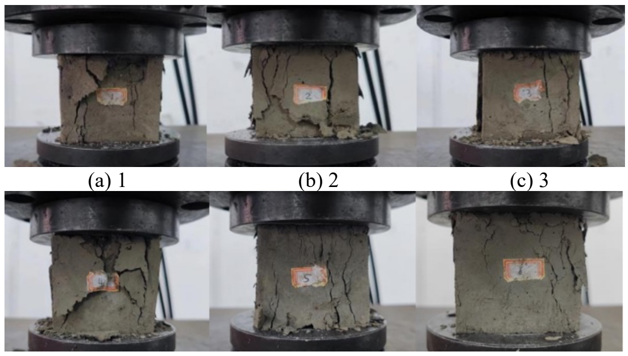
Fig. 9. Range analysis curves of 28d compressive strength test results.

The failure mode of the 28 d cemented waste rock backfill in the uniaxial compression test is shown in Fig. 10. The samples Nos. 1, 2, 4, and 9 in the test exhibited obvious shear failure, while the other samples experienced splitting failure. The failure of the specimens resulted in local debris.

By comparing the compressive strength range analysis tables for 7 d and 28 d waste rock cemented backfill soil, the cement-sand ratio is the most significant factor affecting the strength of the backfill. The higher the cement content, the higher the strength of backfill. It is worth noting that the influence of slurry concentration on the early strength of the filling body is second, while the influence of aggregate gradation on the later strength of the filling body is also second. The strength of the filling body increases and then decreases as the aggregate gradation index increases.

4.3 Determination of optimal ratio

Through the analysis of the range of test results, the influence of aggregate gradation on the compressive strength of 7 d filler is secondary, followed by its influence on the compressive strength of 28 d filler. The influence on slump is also secondary. However, when the aggregate gradation index is 0.4 and 0.6, the slump does not change significantly, whereas the 28 d compressive strength changes considerably, so 0.4 should be selected.




(g) 7 (h) 8 (i) 9

Fig. 10. 28 d uniaxial compression test failure mode of waste rock cemented filling body.

The cement-sand ratio has the greatest influence on the compressive strength of both 7 d and 28 d filling bodies, but it has the least influence on the slump. The optimum cement-sand ratio should be 1:6, but 1:8 can also meet the requirements of the mine for the strength of the filling body, and the corresponding filling cost is low, so the cement-sand ratio should be 1:8. The influence of fly ash content on slump, 7 d and 28 d compressive strength is the third-largest factor, but its influence on 28 d compressive strength is relatively greater, so the fly ash content should be 20%. The slurry concentration has the greatest influence on slump, and 72% should be selected.

5. Conclusions

In order to understand the influence of the interaction between aggregate gradation, cement-sand ratio, fly ash content, and slurry concentration on the working and mechanical properties of filling materials, a four-factor, three-level experiment was designed, and the following conclusions were obtained:

(1) The effects of aggregate gradation, cement-sand ratio, fly ash content, and slurry concentration on the performance of waste rock cemented backfill in open-pit mine are studied through orthogonal test. The slump, 7 d and 28 d compressive strengths of ths backfill are tested.

(2) Through range analysis, the influence of various factors on the experimental indices was obtained. The influence on slump, from greatest to least, is slurry concentration, aggregate gradation, fly ash content, cement-sand ratio. The influence on 7 d compressive strength is cement-sand ratio, slurry concentration, fly ash content, aggregate gradation. The influence on 28 d compressive strength, from greatest to least, is cement-sand ratio, aggregate gradation, fly ash content, slurry concentration.

(3) Through comprehensive analysis, the optimal ratio is determined: aggregate gradation 0.4, cement-sand ratio 1:8, fly ash content 20%, slurry concentration 72%.

The study of filling mechanics is a challenging and complex task. This article only conducted mechanical tests on several commonly used tailings cemented filling materials. In the future, while expanding the scope of the tests, further research should be conducted.

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