Development of Fly Ash Composite Binder and Optimization of Slurry Ratio

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Abstract. In view of the high cost of cement filling, the new cementitious materials are developed by using solid waste resources. Firstly, on the basis of material physicochemical analysis, the fly ash composite cementation ratio test and optimization test are carried out to determine the optimal ratio. Then, the filling body strength and pipeline transportation characteristics test are carried out to analyze they influence law. Finally, the genetic algorithm is used to optimize the slurry ratio. The results show that the strength of cemented backfill increases linearly with the increase of slurry concentration; The slump and bleeding rate of slurry decrease with the increase of slurry mass fraction, and increase with the decrease of binder sand ratio, the optimal proportion of fly ash (FA) based composite binder is w(FA): w(clinker): w (desulfurized gypsum (DG)): w (slag powder (SP)) =40:12:12:36; The optimum slurry ratio is 1:4 of binder/sand and 72% of concentration.

Keywords. Filling mining, fly ash, slag, composite binder, optimization, filling slurry

1. Introduction

Mining industry is a traditional rough industry. For filling mining, the research shows that the cost of cementitious materials accounts for about 70% of the filling cost. At present, most mines use cement as filling cementing agent, but the cost of cement is high and the mine benefit is low. Therefore, it is urgent to develop filling cementitious materials with low cost and excellent properties [1-2]. Using solid waste resources to develop new filling cementitious materials can not only reduce the cost of filling materials, but also realize industrial application by using solid waste resources [3]. Compared with cement, the new cementitious material is a kind of cementitious material which uses alkali, salt or composite activator to excite a class of potentially active pozzolanic materials such as slag, fly ash, steel slag, red mud and coal gangue, etc. [4-5], so as to make it hydraulic, On the premise of meeting the requirements of mine strength and rheology, the optimization of slurry ratio not only significantly reduces the cost, but also innovates the filling technology and process to a certain extent [6-7].

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2. Analysis of Physicochemical Properties of Test Materials

FA and SP were used as active materials, DG and clinker were used as activators to develop binder. The chemical composition of the test material was analyzed by XRF, and the results are shown in table 1. The tailings are used as aggregate. The particle size gradation analysis of the materials, the results are shown in figure 1. the characteristic particle is calculated. It can be seen that the content of SP, FA, DG, clinker and tailings +200 mesh is 93%, 75.6%, 94.78%, 78.14% and 21.74% respectively.

Table 1. Analysis results of chemical composition of test materials.

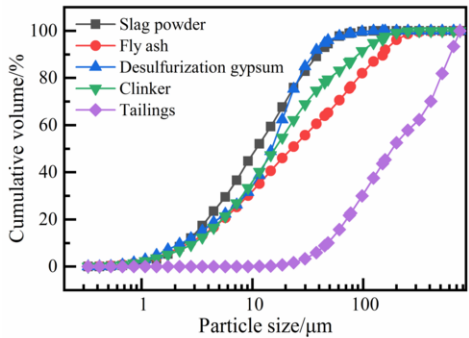| Materials	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	MnO	TiO_2	Activity coefficient	Alkalinity coefficient	Quality coefficient
SP (%)	32.02	10.19	1.31	40.99	9.33	0.24	2.82	0.318	1.192	1.724
FA (%)	56.16	21.02	5.17	8.90	2.34	—	1.27	0.374	0.145	0.562
DG (%)	5.68	1.48	1.91	44.51	4.06	0.02	0.10			
Clinker (%)	21.46	4.44	4.69	64.69	2.89	—	—			

Figure 1. The particle size distribution curve of test material.

3. Proportioning Test of Fly Ash Composite Binder

3.1. Test Scheme and Results

The test scheme of the activator ratio of fly ash-based cement for tailings aggregate is determined as follows: orthogonal test with 3^3 is adopted, including 40%-50% of the FA, 10%-20% of clinker, 8%-12% of DG, the test adopts 1:4 of binder/sand (B/S) and 70% concentration (C_w) to prepare slurry, after mixing evenly, pour to 7.07cm×7.07cm×7.07cm mold, standard curing. Measure the strength after curing to the corresponding age. The specific test plan and results are shown in table 2.

3.2. Analysis of Test Results

In order to determine the influence weight of each test factor on strength and the optimal proportion of fly ash composite binder, the range analysis of test results in table 2 is carried out, and the results are shown in figure 2, It can be seen that the order of the

influence of various factors on the 7d and 28d strength of backfill is w(FA)$>$$w$(clinker)$>$$w$(DG); Range analysis shows that the optimal proportion of 7d strength is w(FA):w(clinker):w(DG): w(SP)=40:12:10:38, while the optimal proportion of 28d strength is w(FA):w(clinker): w(DG):w(SP)=40:16:8:36.

Table 2. Orthogonal test results of the ratio of fly ash composite binder.

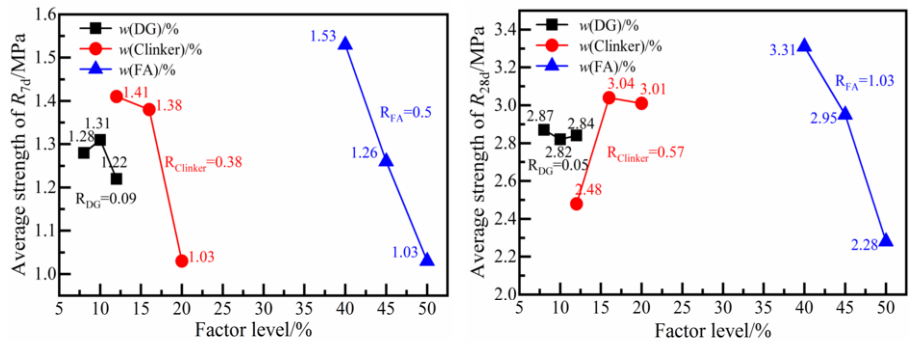| NO.	FA (%)	Clinker (%)	DG (%)	SP (%)	Compressive strength (MPa)	
					7d	28d
A1	40	12	8	40	1.57	2.82
A2	40	16	10	34	1.73	3.63
A3	40	20	12	28	1.27	3.47
A4	45	12	10	33	1.48	2.56
A5	45	16	12	27	1.22	2.99
A6	45	20	8	27	1.07	3.29
A7	50	12	12	26	1.17	2.07
A8	50	16	8	26	1.18	2.50
A9	50	20	10	20	0.73	2.28

Figure 2. Range analysis results of orthogonal test on the ratio of fly ash composite binder.

3.3. Proportioning Optimization Test of Fly Ash Composite Binder

In order to determine the proportion of fly ash composite binder, on the premise of meeting the requirements of mine filling, the proportion of binder is optimized by reducing the amount of cement clinker. The orthogonal test is carried out by fixing the w(FA)=40%, reducing the w(clinker) =8%-12%, increasing the w(DG)=10%-14%. The optimization test is also carried out by using the B/S is 1:4, and the concentration is 70%. The specific test scheme and test results are shown in table 3. It can be seen that the 7d strength is greater than 1.5MPa, which meets the mine requirements, and the 28d strength is greater than 2.5MPa except for B1 and B3; And through the range analysis, it is concluded that the optimal proportions of 7d and 28d are w(FA): w(clinker): w(DG): w(SP) = 40:12:12:36. The material cost is 156 yuan/t, which is 58.9% lower than the 42.5 cement.

Table 3. Orthogonal test results of optimum proportion of fly ash composite binder.

No.	FA (%)	Clinker (%)	DG (%)	SP (%)	Strength (MPa) 7d	28d	Cost (Yuan.t^{-1})
B1	40	8	10	42	1.65	2.31	150
B2	40	8	12	40	1.72	2.62	147
B3	40	8	14	38	1.71	2.34	145
B4	40	10	10	40	1.67	2.57	155
B5	40	10	12	38	1.76	2.78	152
B6	40	10	14	36	1.60	2.55	150
B7	40	12	10	38	1.69	3.01	160
B8	40	12	12	36	1.67	2.97	156
B9	40	12	14	34	1.79	2.73	155
P.O 42.5					3.08	5.15	380
Cost/yuan.t^{-1}: FA=120, Clinker=410, DG=34.5, SP=156							

4. Proportioning Test of Fly Ash Composite Binder and Tailings Filling Slurry

4.1. Strength Test of Cemented Backfill

In view of the low-cost fly ash composite binder, the tailings are used as aggregate to carry out the strength test of backfill with different binder/sand and concentration. The specific test scheme is as follows: the B/S is 1:4, 1:6 and 1:8, and the C_w is 72%, 74%, 76% and 78%. The results are shown in figure 3. It can be seen that the strength of backfill increases linearly with the increase of concentration; When the ratio of cement to sand is 1:4, the slurry concentration increases to 76%, and the growth rate of 7d and 28d strength increases; When the B/S=1:4, the 7d strength and 28d strength of the backfill with C_w=72%~78% are all greater than 1.5MPa and 2.5MPa respectively; When B/S= 1:6, the 7d strength and 28d strength of backfill with C_w greater than 76% also meet the mine requirements.
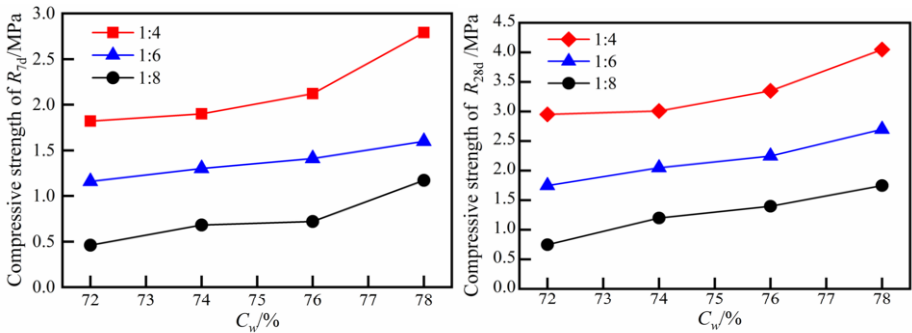

Figure 3. Strength of backfill of fly ash composite cementitious material and tailings.

4.2. The Pipeline Transportation Characteristics Test of Filling Slurry

Slump tube and bleeding rate tube were used to measure the slump and bleeding rate of filling slurry, and the test data were recorded and analyzed. The test results are shown

in figure 4. It can be seen that the slump and bleeding rate of slurry decrease with the increase of slurry mass concentration. Taking the B/S=1:4 as an example, when the C_w increases from 72% to 78%, the slump and bleeding rate decrease by 5.7% and 76.5% respectively; However, the pipeline characteristics increase with the decrease of the ratio of cement to sand. Taking the C_w=72% as an example, the slump and bleeding rate increased by 2.7% and 50% respectively when the B/S decreased from 1:4 to 1:8.
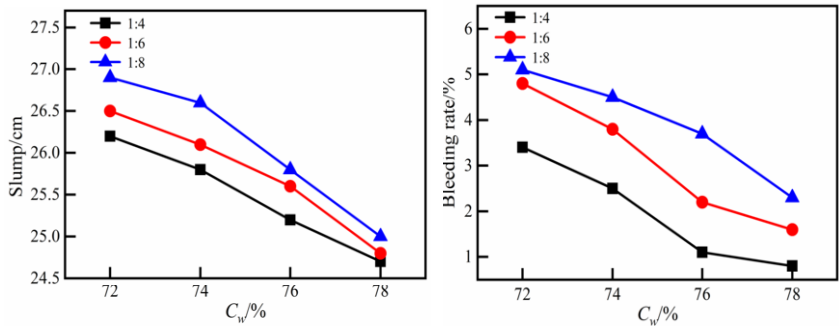

Figure 4. Test results of pipeline transportation characteristics of filling slurry.

4.3. Multi-objective Optimization of Filling Slurry Ratio

On the premise of meeting the requirements of mine filling, the filling cost should be reduced as much as possible. Therefore, it is necessary to optimize the filling slurry ratio in order to obtain the optimal filling slurry ratio. The mine requires that the strength of 7d and 28d is not less than 1.5MPa and 2.5MPa respectively, while the reasonable range of slump is 15~30cm, and the ideal value is 18cm and the bleeding rate is less than 10% [8-9]. According to the test results, 7d and 28d strength can be regarded as benefit index, while slump, bleeding rate and filling cost can be regarded as cost index. In this paper, under the condition of meeting the filling requirements, taking the cementitious material dosage (x_1), tailings dosage (x_2) and water dosage (x_3) of filling slurry per unit volume as independent variables, the functional relationships between backfill 7d strength (R_{7d}), 28d strength (R_{28d}), slump (T), bleeding rate (M) and filling cost (P) and independent variables were established by genetic programming. Among them, magnesium slag cementitious material is 156 yuan/t, tailings freight is 2 yuan/t, and water unit price is 1.5yuan/t. The optimization objective is: $R_{7d} \geq 1.5$MPa, $R_{28d} \geq 2.5$MPa, M, T and P are minimum; The constraint conditions are as follows: $1:8 \leq (x_1/x_2) \leq 1:4$, $72\% \leq C_w(x_1+x_2)/(x_1+x_2+x_3) \leq 78\%$. In the multi-objective genetic algorithm, there are five objective functions, namely $R_{7d}(x_1,x_2, x_3)$, $R_{28d}(x_1,x_2, x_3)$, $M(x_1,x_2, x_3)$, $T(x_1,x_2, x_3)$ and $P(x_1,x_2, x_3)$, among $P(x_1,x_2, x_3)=156 \times x_1+2 \times x_2+1.5 \times x_3$, The other objective functions are established by fitting the experimental results, that is, the optimization objective is:

$$\begin{cases} max\ R_{7d}\left(x_1, x_2, x_3\right) \\ max R_{28d}\left(x_1, x_2, x_3\right) \\ min\quad T\left(x_1, x_2, x_3\right) \\ min\quad M\left(x_1, x_2, x_3\right) \\ min\quad P\left(x_1, x_2, x_3\right) \end{cases} \tag{1}$$

According to the mine requirements, the constraint conditions are determined as follows:

$$\begin{cases} R_{7d} \geq 1.5 \\ R_{28d} \geq 2.5 \\ \dfrac{1}{8} \leq \dfrac{x_1}{x_2} \leq \dfrac{1}{4} \\ 72\% \leq \dfrac{x_1 + x_2}{x_1 + x_2 + x_3} \leq 78\% \end{cases} \tag{2}$$

Then, Matlab genetic algorithm is used for optimization. Because Matlab solves the minimum problem by default, the benefit index needs to be negative, so the total objective function is constructed as follows [10]:

$$F = w_1.T + w_2.M + w_3.P - w_4.R_{7d} - w_5.R_{28d} \tag{3}$$

where: w_1, w_2, w_3, w_4 and w_5 are the weights of 7d, 28d strength, slump, bleeding rate and filling cost respectively. For convenience of calculation, they are all taken as 0.2.

The optimal ratio of filling slurry per unit volume can be obtained by using genetic algorithm. The optimal ratio of filling slurry of unit volume is obtained, which is 296kg/m^3 of cementitious material, 1184kg/m^3 of tailings, 575kg/m^3 of water, namely, the B/S=1:4 and C_w=72%. The results showed that the strength of 7d, 28d, slump and bleeding rate is 1.89MPa, 3.08 MPa, 26.0cm and 3.6% respectively, and all indexes met the mine requirements.

5. Conclusion

(1) The results of the range analysis of the orthogonal test of the fly ash-based composite binder show that the factors affecting the strength of 7d and 28d are all w(FA)>w(clinker)>w(DG); and it is determined by the optimization test of the ratio The optimized ratio is: w(FA): w(clinker): w(DG): w(SP) =40:12:12:36.

(2) The test results of mortar strength and slurry transportation characteristics show that the strength of cemented backfill increases linearly with the increase of slurry concentration; When the ratio of B/S=1:4, the C_w=76%, and the growth rate of 7d and 28d strength increases; The slump and bleeding rate of slurry decrease with the increase of slurry mass concentration, and increase with the decrease of the ratio of cement to sand.

(3) The genetic algorithm is used to optimize the filling slurry ratio with multi-objective, and the optimization model is established with the requirements of strength and slurry working characteristics of the mine as constraints. The lowest cost scheme meeting the requirements of filling strength and slurry pipeline transportation characteristics is obtained, that is, the fly ash composite binder, the B/S=1:4, and the C_w=72%, the 7d, 28d strength, slump and bleeding rate are 1.89MPa, 3.08MPa, 26.0cm and 3.6% respectively.

Reference

[1]   Yang X B 2020 *Study on Collaborative Preparation of Filling Materials with Low Quality and Multi-solid Wastes and Their Pressure Drop in Pipeline Transportation* (Beijing: University of Science and Technology Beijing).

[2]   Yin B C 2013 Research on cemented filling technology with fine-grained full tailings for a Shandong mine *Metal Mine* (04) 57-60.

[3]   Ma X M, Ni W and Xu D 2018 Research progress of backfill binders prepared with industrial solid wastes *Metal Mine* (04) 11-17.

[4]   Wei W, Yang Z Q and Gao Q 2013 Cementing action of neotype whole-tailing cementitious material *Journal of Building Materials* **16** (5) 881-887.

[5]   Zhu L P, Ni W, Huang D, et al. 2011 Research on whole-tailings paste and paste-like backfilling material with red mud *Mining Research and Development* (11) 175-178.

[6]   Zhang Q L, Li X P and Yang W 2013 Optimization of filling slurry ratio in a mine based on back propagation neural network *Journal of Central South University* (Science and Technology) **44** (7) 2867-2874.

[7]   Zhou K P and Gu D S 2001 Genetic optimization design of the cement-sand ratio of tailings consolidated filling in Anqing copper mine *Metal Mine* (07) 11-13.

[8]   Zhao G Y, Ma J, Peng K, et al. 2013 Mix ratio optimization of alpine mine backfill based on response surface method *Journal of University of Science and Technology Beijing* (5) 559-565.

[9]   Fall M, Benzaazoua M and Saa E G 2008 Mix proportioning of underground cemented tailings backfill *Tunnelling & Underground Space Technology* **23** (1) 80-90.

[10] Liu Z X, Gong Y C and Li X B 2017 Study on the backfilling material properties based on fractal theory and BP neural network *Gold Science and Technology* **25** (02) 38-44.