Experimental analysis on the optimal proportion of paste filler for a coal mine in China

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ABSTRACT. *This paper attempts to determine the optimal proportion of paste filler for a coal mine in China. For this purpose, an orthogonal test was designed with three factors and five levels. Then, the filler strength was measured on the 7th and 28th day of the test. Visual analysis and variance analysis show that the filler strength was mainly affected by cement content and paste concentration on the 7th day, and by cement content and fly ash-gangue ratio on the 28th day. After that, a filler strength prediction model was established through multivariate statistical analysis, and the optimal proportions for the 7th and 29th days were derived through Gaussian elimination: the cement content of 12.705%, the fly ash-gangue ratio of 0.400 and the paste concentration of 77.498%. Finally, these proportions were verified on the 7th and 29th days. The research results shed new light on the preparation of paste filler for engineering purposes.*

RÉSUMÉ. *Cet article tente de déterminer la proportion optimale de boue de remplissage pour une mine de charbon en Chine. À cette fin, un essai orthogonal à trois facteurs et cinq niveaux a été conçu. Ensuite, la force du remplissage a été mesurée les 7e et 28e jours de l'essai. Les analyses visuelles et les analyses de variance montrent que la force du remplissage a été principalement affecté par la teneur en ciment et la concentration en boue le 7e jour, et par le taux de ciment et le rapport cendres volantes-gangue le 28e jour. Après cela, un modèle de prévision de la force du remplissage a été établi par des analyses statistiques multi-variées, et les proportions optimales pour les 7e et 29e jours ont été calculées par la méthode d'élimination de Gauss: la teneur en ciment de 12,705%, le rapport cendres volantes-gangue de 0,400 et la concentration en boue de 77,498%. Enfin, ces proportions ont été vérifiées les 7e et 29e jours. Les résultats de la recherche ont jeté un nouvel éclairage sur la préparation de la boue de remplissage à des fins d'ingénierie.*

KEYWORDS: *filler strength, orthogonal test, multivariate statistical analysis.*

MOTS-CLÉS: *force du remplissage, essai orthogonal, analyse statistique multi-variée.*

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1. Experimental analysis

1.1. Experimental method

Orthogonal experimental design is the one most important design method of multiple factors experiment .It is the experimental analysis method of multiple factors and levels according to the fractional principle of factor design, adopts the orthogonal table which is derived from combination theory to design the experiment and conduct statistic analysis to the results. The advantages of the experimental method are:

(1) Reduce the number of experiments, for experiment, the experiment of "four factors and for levels" need 256 times experiments, but with orthogonal design which just need 16 times, it significantly reduces the workload and it can quantitatively evaluate different levels of the same factor, thus to predict the combination of untested factors;

(2) Orthogonal experimental design makes the distribution of the sample points with balance, which can further illustrate by space model of $L_4\,(2^3)$ in figure 1, the eight vertices of the cube represent the eight experimental points of the full-scale experiment, the four sample points (black points) which determined by orthogonal table are evenly distributed in it (Chang *et al*., 2009; Yang *et al.*, 2014; Yao, 2010).

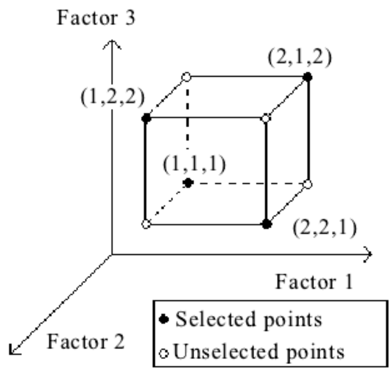

Figure 1. Space model of $L_4(2^3)$

1.2. Orthogonal experiment design

There are many paste filling mines in our country. The three factors in this orthogonal experiment are determined by referring to filling material ratio of other coal mine: cement percentage (mass of cement / total mass of solid material), coal gangue proportion (mass of fly ash / mass of broken gangue) and paste concentration (mass of solid material/ mass of paste body). The ranges of the value of the three factors are as follows:

Table 1. Orthogonal experimental design table and experimental results

No.	Factors			Results of 7th day	Results of 28th day
	A/%	B	C/%		
1	1(5)	1(0.4)	1(86)	0.96	2.88
2	1(5)	2(0.8)	2(80)	0.89	2.84
3	1(5)	3(1.2)	3(78)	0.81	2.81
4	1(5)	4(1.6)	4(74)	0.77	2.76
5	1(5)	5(2.0)	5(70)	0.71	2.71
6	2(9)	1(0.4)	2(82)	0.90	3.11
7	2(9)	2(0.8)	3(78)	0.83	3.08
8	2(9)	3(1.2)	4(74)	0.79	3.04
9	2(9)	4(1.6)	5(70)	0.74	2.98
10	2(9)	5(2.0)	1(86)	0.97	2.95
11	3(13)	1(0.4)	3(78)	0.89	3.31
12	3(13)	2(0.8)	4(74)	0.84	3.25
13	3(13)	3(1.2)	5(70)	0.80	3.20
14	3(13)	4(1.6)	1(86)	1.03	3.18
15	3(13)	5(2.0)	2(82)	0.95	3.15
16	4(17)	1(0.4)	4(74)	0.89	3.43
17	4(17)	2(0.8)	5(70)	0.86	3.39
18	4(17)	3(1.2)	1(86)	1.08	3.36
19	4(17)	4(1.6)	2(82)	1.04	3.32
20	4(17)	5(2.0)	3(78)	0.96	3.29
21	5(21)	1(0.4)	5(70)	0.91	3.57
22	5(21)	2(0.8)	1(86)	1.14	3.54
23	5(21)	3(1.2)	2(82)	1.09	3.50
24	5(21)	4(1.6)	3(78)	1.03	3.47
25	5(21)	5(2.0)	4(74)	0.98	3.45

A-the cement percentage is 5% to 21%, B-the ash gangue is 0.4 to 2.0, C-the paste concentration percentage is 70% to 86% (Liu, 2013; Zhang *et al.*, 2012). By taking comprehensive consideration of the experiment purpose and the range of values of each factor, we determined that the experiment should be characterized by ‘three factor and five levels”. Five levels of cement percentage A numbered 1, 2, 3, 4, 5 are 5%, 9%, 13%, 17%, 21% respectively, five levels of ash gangue ratio B numbered 1, 2, 3, 4, 5 are 0.4, 0.8, 1.2, 1.6, 2.0 respectively and five levels of paste concentration C numbered 1, 2, 3, 4, 5 are 86%, 82%, 78%, 74%, 70% respectively. We design orthogonal experiment according to the construction method of orthogonal experimental scheme, as is shown in tab.1. During the experimental process, 200 same experimental specimens are divided into 50 groups. The size of each specimen is 25cm×15cm×15cm (as is shown in figure 2), each group contains 4 specimens, and each specimen is polished into a test sample which the size is 15cm×10cm×10 cm (Dong *et al.*, 2012; Yu *et al.*, 2010; Wu *et al*., 2006). We test the strength of test sample when it’s crushed (as is shown in figure 3) and calculate the mean value of them (as is listed in table 1.)

Figure 2. Pouring model for experiment

Figure 3. The state of the test specimen when it reaches the ultimate strength

1.3. Result of experiment analysis

At first, visual analysis method is adopted to figure out the mean value of corresponding results of every level in each column. For example, we figure out the $\overline{A_1}$ which is the mean value of figures on 1 level of element A which is obtained in the 7 days' experiment.

$$\overline{A_1} = \frac{0.96+0.89+0.81+0.77+0.71}{5} = 0.828 \tag{1}$$

Similarly, we can figure out the mean value of results on other levels of other elements on the seventh and twenty-eighth day and then list the mean value of different levels of factors in table 2. We choose the value of different levels of each factor as X-coordinate and the value of uniaxial compressive strength as Y-coordinate and the draw a trend diagram.(as is shown in figure 4 and figure 5)

Table 2. Visual analysis results of orthogonal test

Levels	Experimental results of 7th day			Experimental results of 28th day		
	A/MPa	B/MPa	C/MPa	A/MPa	B/MPa	C/MPa
1	0.828	0.910	1.036	2.800	3.260	3.182
2	0.846	0.912	0.974	3.032	3.220	3.184
3	0.902	0.914	0.904	3.218	3.182	3.192
4	0.966	0.922	0.854	3.358	3.142	3.186
5	1.030	0.914	0.804	3.506	3.110	3.170

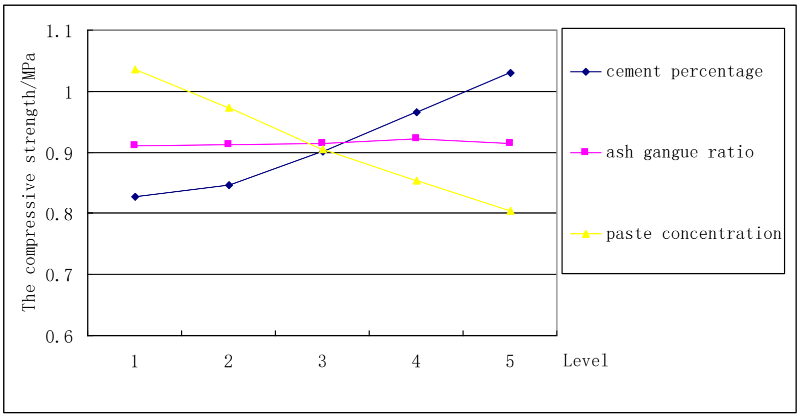

Figure 4. Three factors and material strength tendency in the sevenths day

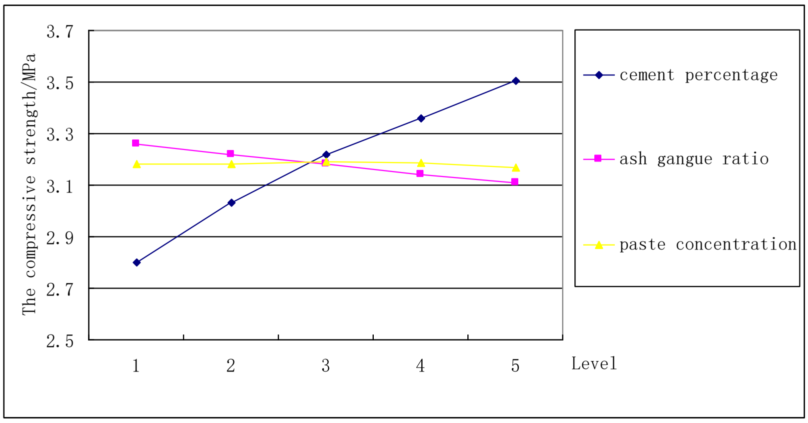

Figure 5. Three factors and material strength tendency in the twenty-eighths day

As can be seen From Figure 4, on the seventh day, the uniaxial compressive strength increase with the increase of the cement percentage ,and increase with the increase of paste concentration and the ash gangue ratio has little effect on the experimental result. As can be seen from figure 5, on the twenty-eighth day ,the uniaxial compressive strength increase with the increase of cement percentage and decrease with the ash gangue ratio and the paste concentration has little effect on the experimental result.

The method of visual analysis cannot analyze the impact of each factor on the result of the experiment and thus we adopted variance analysis method to remedy this flaw. With this method we can figure out the square of deviance S and significance index F. By comparing the values of F we can analyze the impact of each factor on the experimental results. The greater the value of F is the higher impact significance each factor has on the experimental result, and vice versa. The experiment results on the seventh day and twenty-eighth day are presented in table 3.

Table 3. Results of experimental variance analysis

Factor	Experimental results of 7th day			Experimental results of 28th day		
	Square of deviance	F	Significance	Square of deviance	F	Significance
A	0.1416	364	strong	1.5283	6440	stronger
B	0.0004	1	weak	0.0715	301	strong
C	0.1714	440	strong	0.0013	5	weak

As can be seen from table 3, on the seventh day, cement percentage and paste concentration have strongly impacted on the experimental results while the ash gangue hardly has impact on the experimental result. On the twenty-eighth day, the cement percentage has strongly impacted on the experimental result while the ash gangue impact strongly and the paste concentration hardly has impact on the result.

2. Determination of the optimal proportion

2.1. Establishment of multiple linear regression model

Multiple discriminant analysis is frequently applied in engineering problems to study the impact multiple variables have on a single variable. It's the optimal method to find the functional relationship between multiple variables and dependent variables (Wang and Meng, 2007; Duan *et al.*, 2012; Duan, 2014; Wang and Ye, 2009; Dai *et al.*, 2014; Ti *et al.*, 2014). On the basis of the data in table 1, we choose y, which is uniaxial compressive strength as dependent variable, and choose x_1,which is the cement percentage and x_2,which is the ash gangue ratio and x_3,which is the paste concentration as independent variables. The function relation of the experimental results of the 7th day and the 28th day are respectively established.

$$y_7 = 0.0128x_1 + 0.0030x_2 + 0.0146x_3 - 0.3953 \tag{2}$$

$$y_{28} = 0.0434x_1 - 0.0946x_2 + 0.0006x_3 + 2.6815 \tag{3}$$

y_7 is the uniaxial compressive strength on the seventh day and y_{28} is that on the twenty-eighth day, the range of x_1 is 5%~21% ,the range of x_2 is 0.4~2.0 and the range of x_3 is 70%~86% . The coefficient of determination of formula (2) is 0.9722 and the coefficient of determination of formula (3) is 0.9876， they are showing that the fitting degrees of those two formulas are both very high and meeting the requirements of production practice .

2.2. Determination of optimal ratio

Among the three filling materials aggregates, cement, fly ash and gangue powder, the cost of cement is the highest. Therefore, the ratio of the lowest cement is the optimal choice when the requirement of filed strength is met. The strength requirements on the seventh days and twenty-eighth day are substituted in equation (2) and (3) and establish two three-variable linear equation, which form restricted equations.

$$\begin{cases} 0.0128x_1 + 0.0030x_2 + 0.0146x_3 = 1.2953 \\ 0.0434x_1 - 0.0946x_2 + 0.0006x_3 = 0.5185 \end{cases} \tag{4}$$

Equation system (4) consists of three unknowns and two equations. Gaussian elimination method was used to solve the problem, it shows that the equation system (4) has multiple solutions and its general solution is as follows :

$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} = \begin{pmatrix} 1 \\ 0.4584 \\ -0.9709 \end{pmatrix} x_1 + \begin{pmatrix} 0 \\ -5.4240 \\ 89.8337 \end{pmatrix} \quad (5)$$

Taking ranges of those three factors into consideration, we determine that when x_1 is 12.705 we get the optimal ratio. The ratios both meet the requirements for strength and minimum cost. The cement percentage is 12.705%, the ash gangue is 0.400, and the paste concentration is 77.498%.

3. Test analysis of optimal ratio

In order to verify the reliability and scientificity of the ratio determination experiment, we make experimental analysis of the strength of the material. The preparation, polishing and compression process remain unchanged .The experimental data are listed in table 4.

Table 4. Test data of optimal ratio experiment

No.	Experimental results of 7th day		No.	Experimental results of 28th day	
	Uniaxial compressive strength	AVG/MPa		Uniaxial compressive strength	AVG/MPa
1	0.92	0.93	1	3.09	3.21
2	0.95		2	3.26	
3	0.88		3	3.15	
4	0.98		4	3.34	

As can be seen from the table 4, on the seventh days, the uniaxial compressive strength of the optimal ratio material is 0.93MPa and on the twenty-eighth day it's 3.21MPa, which meet the design requirements of filling material.

4. Conclusions

(1) Orthogonal experimental design principles are applied to design the strength test of filling materials with different ratios. Multiple linear regression analysis is applied to determine the optimal ratio which both meets the strength requirements and is also economical. The optimal ratio is shown as follows: the cement percentage is 12.705%, the ash gangue is 0.400, the paste concentration is 77.498%.

(2) Visual and variance analysis of the experimental results indicate that the main factors influencing the early strength of filling materials are cement percentage and paste concentration and the uniaxial compressive strength of the filling body increases with increase of the paste concentration and cement percentage. And the main factors affecting the final strength are cement percentage and ash gangue ratio, the cement percentage has strong impact on the final strength.

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