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Grey correlation analysis between strength of slag cement and particle fractions of slag powder

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Abstract

The particle size distributions of slag powder were investigated by Laser Scatter equipment. The influence of particle fractions of slag powder on the compressive strength of slag cement composed of 50% slag powder and 50% Portland cement was also studied by the method of grey correlation analysis. The results indicated that the volume fraction of particles 5–10 μm had a maximum positive effect on the mortar compressive strength of slag cement at 7 d and the volume fraction of particles 10–20 μm had a maximum positive effect on the mortar compressive strength at 28 d, whereas the volume fraction of particles larger than 20 μm had a negative effect on the mortar compressive strength at 7 and 28 d.

Keywords: Slag powder; Particle fraction; Mortar compressive strength; Grey correlation analysis

1. Introduction

Fly ash, slag powder and silica fume are effective admixtures used in various types of high performance concrete (HPC) [1–4]. The HPC made by Li and Yao [5] has a compressive strength of 100 MPa, which is related with specific area of admixture intimately. In fact, the activity of slag powder indicated only by specific area is not suitable. The particle size distribution of admixture powder has also a great effect on its activity.

Many studies have been done to examine the relationships between cement particle size distribution and the hydration kinetics and hardened paste strength properties [6–11]. For a given water-to-cement ratio, a reduction in median particle size generally results in an increased hydration rate and, therefore, improved early properties such as high early strength. For this reason, the fineness of Portland cement has been generally increased over the years. Bentz et al. [12] explored the effect of cement particle size distribution on a variety of performance properties via computer simulation and a few experimental studies. Some investigators have studied the relationship between the particle size distribution of admixture powder and its properties, too. Ranganath et al. [13] examined the role of different size fraction of pounded ash on the lime-reactivity strength of ash-lime-sand mortar by classifying pounded ash into three different size fractions. Olorunsogo [14] reported an investigation into the influence of particle size distribution of ground granulated blast furnace slag with different PSDs (as represented by the parameters of the Rosin–Rammler distribution function) on the bleeding characteristics of slag cement mortar. Grzeszczyk and Lipowski [15] investigated the effect of content and particle size distribution of high-calcium fly ash on the rheological properties of cement pastes. Mehta [16] has studied the particle size distribution of low calcium fly ash. The results indicated that the activity of fly ash and the volume fraction of particles had a positive relationship when particles were less than 10 μm and had a negative relationship when particles were larger than 45 μm. In this paper, a slag sample from steel factory was used to study the relationship between the activity of slag cement and particle fractions of slag. The slag sample was ground into different particle

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size distributions. Some slag cement samples made from slag powder and Portland cement were prepared and the relationship between the mortar compressive strength and slag powder fraction was studied by grey correlation analysis. The research on the micro-analysis of the slag cement pastes proved the macro test and grey correlation analysis. The purpose of the study is to differentiate which fraction of slag powder is favorable to slag cement and which fraction of slag powder is disadvantageous to slag cement. That will help us to develop improved slag cement from slag powder and Portland cement by adjusting the particle size distribution of slag powder.

2. The principle of the grey correlation analysis

The principle of the grey correlation analysis [17,18] is based on the macro or micro geometric approachment between the behavior factors. The more similar are the array curves, the closer connection they have. Fig. 1 is a statistics graph of agriculture production in a certain district in China. From the figure we can see that the most similar curve with the total agriculture production value (called main-array or main-factor) is the total planting production value (called sub-array or sub-factor). Therefore, the planting production is essential for the agriculture production in that district and stock raising, forest and fruit production are minor. The detailed calculation formulas are as follows.

The arrays are as follows:

$$\{X_0^{(0)}(r)\}, \quad r = 1,2,3,\ldots,N_0$$
$$\{X_1^{(0)}(r)\}, \quad r = 1,2,3,\ldots,N_1$$
$$\{X_2^{(0)}(r)\}, \quad r = 1,2,3,\ldots,N_2$$
$$\ldots$$
$$\{X_k^{(0)}(r)\}, \quad r = 1,2,3,\ldots,N_k$$

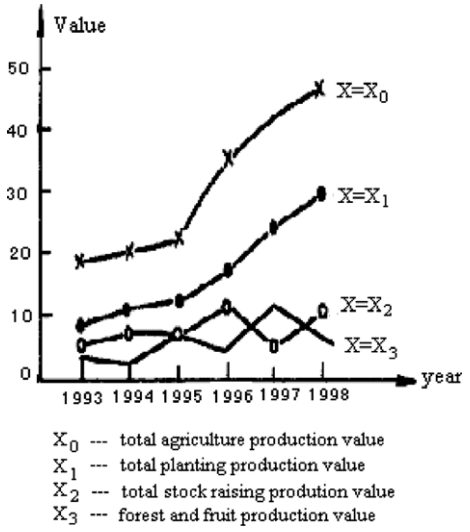

Fig. 1. Statistics of agriculture production in a certain district in China from 1993 to 1998.

Among them, N_1, N_2, …, N_k belong to natural number and they may be not equal. The k arrays express k factors. The array $\{X_0^{(0)}(r)\}$ is assigned to main-array and $\{X_m^{(0)}(r)\}$ $(m = 1,2,\ldots,k)$ to sub-arrays.

The average of $\{X_m^{(0)}(r)\}$, $r = 1,2,3,\ldots,N_m$, $m = 0,1,2,\ldots,k$ is $\overline{X}_m$

$$\overline{X}_m = \frac{1}{N_m}\left[\sum_{r=1}^{N_m} X_m^{(0)}(r)\right]$$

The conversion $Y_m(r) = X_m^{(O)}(r)/\overline{X}_m$ is made and then following arrays called inverted arrays can be obtained:

$$\{Y_0(r)\}, \quad r = 1,2,3,\ldots,N0$$
$$\{Y_1(r)\}, \quad r = 1,2,3,\ldots,N1$$
$$\{Y_2(r)\}, \quad r = 1,2,3,\ldots,N2$$
$$\ldots$$
$$\{Y_k(r)\}, \quad r = 1,2,3,\ldots,N_k$$

In fact, the transformation from $\{X_m^{(0)}(r)\}$ into $\{Y_m(r)\}$ can be regarded as a reflection.

Table 1
Chemical compositions of raw materials

Material	Si_2O_3	Fe_2O_3	Al_2O_3	CaO	MgO	f-CaO
Clinker	20.66	5.18	6.03	64.7	1.21	0.67
Gypsum	5.97	0.43	1.78	30.34	1.26	–
Slag	33.18	1.53	13.19	39.25	9.36	–

Table 2
The LS results of slag powder

Particle size (μm)	Sample					
	Sa	Sb	Sc	Sd	Se	Sf
Undersize product, V (%)						
1	2.54	6.33	7.69	3.93	7.32	8.92
2	6.11	10.7	18.1	8.23	14.0	18.3
3	9.27	15.7	28.1	12.3	21.2	28.9
4	12.2	21.4	36.6	16.1	28.3	38.6
5	15.0	27.3	43.5	19.5	35.1	46.8
6	17.7	33.1	49.3	22.7	41.3	53.3
8	22.7	43.3	58.4	28.3	51.4	62.8
10	27.3	51.7	65.2	32.9	58.9	69.0
15	37.2	66.2	76.7	41.7	70.6	77.6
20	45.5	75.9	84.8	48.9	78.3	83.5
25	52.7	83.2	90.3	55.2	83.9	87.8
30	58.8	88.4	93.6	60.5	87.8	90.6
40	68.6	94.5	96.9	69.3	92.5	94.3
50	76.1	97.4	98.3	76.0	94.9	96.3
60	82.0	98.8	99.0	80.9	96.4	97.4
80	90.2	99.8	99.5	86.8	97.8	98.8
90	92.9	99.96	99.7	88.7	98.2	99.1
100	94.8	99.99	99.7	90.2	98.4	99.3
150	98.6	100	99.9	94.3	99.5	99.6
200	99.3	100	100	96.0	99.7	99.7
Average diameter (μm)	35.45	16.61	10.98	33.98	12.26	10.43
Blaine fineness (m^2/kg)	233	405	533	256	493	563

The absolute difference $\Delta_{om}(r)$ between $\{Y_m(r)\}$ and $\{Y_0(r)\}$ at $t = r$ is:

$$\Delta_{om}(r) = |Y_O(r) - Y_m(r)|, \quad r = 1, 2, 3, \ldots$$

The minimum value and the maximum value among $\Delta_{om}(r)$ can be found out and named as Δ_0m (min) and Δ_0m (max), and then the minimum value (expressed as Δ(min)) and the maximum value (expressed as Δ(max)) among all the values of Δ_0m(min) and Δ_0m(max) can be found out, too. The grey correlation coefficient $\xi_{om}(r)$ at $t = r$ is

$$\xi_{om}(r) = [\Delta(\min) + K\Delta(\max)]/[\Delta_{om}(r) + K\Delta(\max)]$$

K is recognition coefficient in the formula and defined as 0.5.

The grey correlation degree of Y_m and Y_0 is:

$$\varsigma_{om} = \left[\sum_{r=1}^{N} \xi_{om}(r)\right] \Big/ N$$

Because $\Delta_{om}(r) = |Y_O(r) - Y_m(r)|$ is used, the grey correlation polarity between factors cannot be separated. The formulas below are used to judge it:

$$Q_m = \sum_{r=1}^{N} rY_m(r) - \sum_{r=1}^{N} Y_m(r) \sum_{r=1}^{N} r/N$$

$$Q_r = \sum_{r=1}^{N} r^2 - \left(\sum_{r=1}^{N} r\right)^2 \Big/ N.$$

When $\text{sign}(Q_m/Q_r) = \text{sign}(Q_o/Q_r)$, Y_m and Y_0 are positive correlation. When sign $(Q_m/Q_r) = -\text{sign}\ (Q_o/Q_r)$, Y_m and Y_0 are negative correlation.

The grey correlation degree is a quantitative value of the correlation between the factors. If the value of grey correlation degree is higher, the main-factor and sub-factor are more relevant. Positive correlation between main-array and sub-array indicates that the sub-factor will enhance the main-factor. However, negative correlation between main-array and sub-array indicates that the sub-factor will weaken the main-factor.

Table 3
The mortar compressive strength of slag cement (MPa)

Age	Sample					
	CSa	CSb	CSc	CSd	CSe	CSf
7 d	26.6	35.3	41.0	35.3	42.9	45.8
28 d	56.2	70.2	57.8	63.0	67.2	63.7

3. Experimental procedure

3.1. Material

Blast furnace slag, clinker and gypsum were obtained from the cement factory. Table 1 shows the chemical com-

Table 5
The mortar compressive strength of special slag cement (MPa)

Age	Sample	
	TX	TC
7 d	47.8	21.2
28 d	69.7	46.3

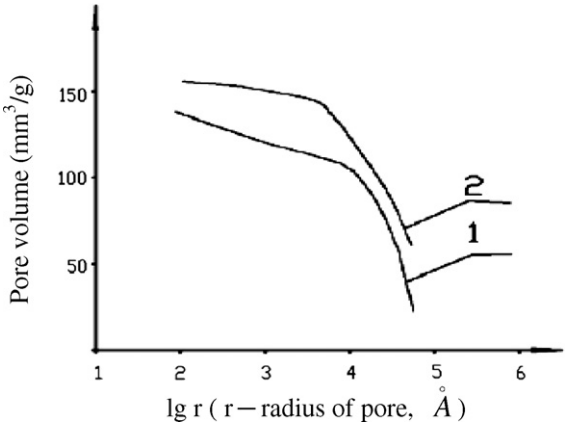

Fig. 2. Pore radius distribution in hardened paste TX (1) and TC (2).

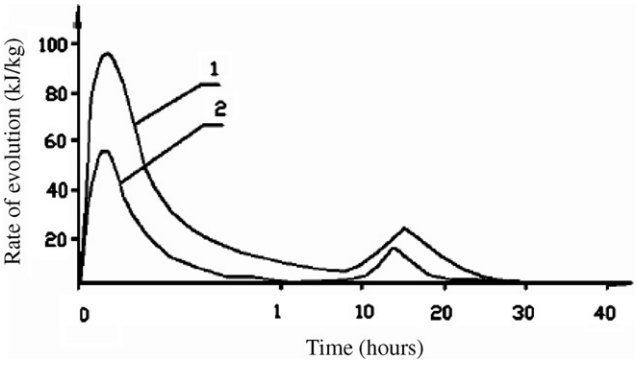

Fig. 3. Heat evolution curves of special slag cement pastes TX (1) and TC (2).

Table 4
The LS results of slag powder X and C

Sample	Particle size (μm)							
	5	10	15	20	30	40	50	60
Undersize product, V (%)								
X	28.9	56.7	78.1	95.2	100	100	100	100
C	0	0	1.16	6.04	30.5	48.9	59.7	71.8

Table 6
The main-arrays and sub-arrays

Sample	Time-array						
	*Y*01 (7 d)	*Y*02 (28 d)	*Y*1 (0–5 μm)	*Y*2 (5–10 μm)	*Y*3 (10–20 μm)	*Y*4 (20–40 μm)	*Y*5 (>40 μm)
CSa	26.6	56.2	15.0	12.3	18.2	23.1	31.4
CSb	35.3	70.2	27.3	24.4	24.2	18.6	5.50
CSc	41.0	57.8	43.5	21.7	19.6	12.1	3.10
CSd	35.3	63.0	19.5	13.9	16.0	20.4	30.7
CSe	42.9	67.2	35.1	23.8	19.4	14.2	7.50
CSf	45.8	63.7	46.8	22.2	14.5	10.8	5.70

position. Portland cement was made of 93% clinker and 7% gypsum (percentage by weight) in laboratory mill.

3.2. Experimental program

Slag powder samples which were of different particle size distributions were made by controlling different grinding time and using two groups of grinders marked as Ma and Mb in laboratory mill. Sample Sa, Sb and Sc were ground by group Ma under duration time 30 min, 80 min and 140 min. Sample Sd, Se and Sf were ground by group Mb under duration time 30 min, 80 min and 140 min. The particle size distribution and the Blaine fineness of the slag powder samples were tested by LS-230 Laser Particle Size

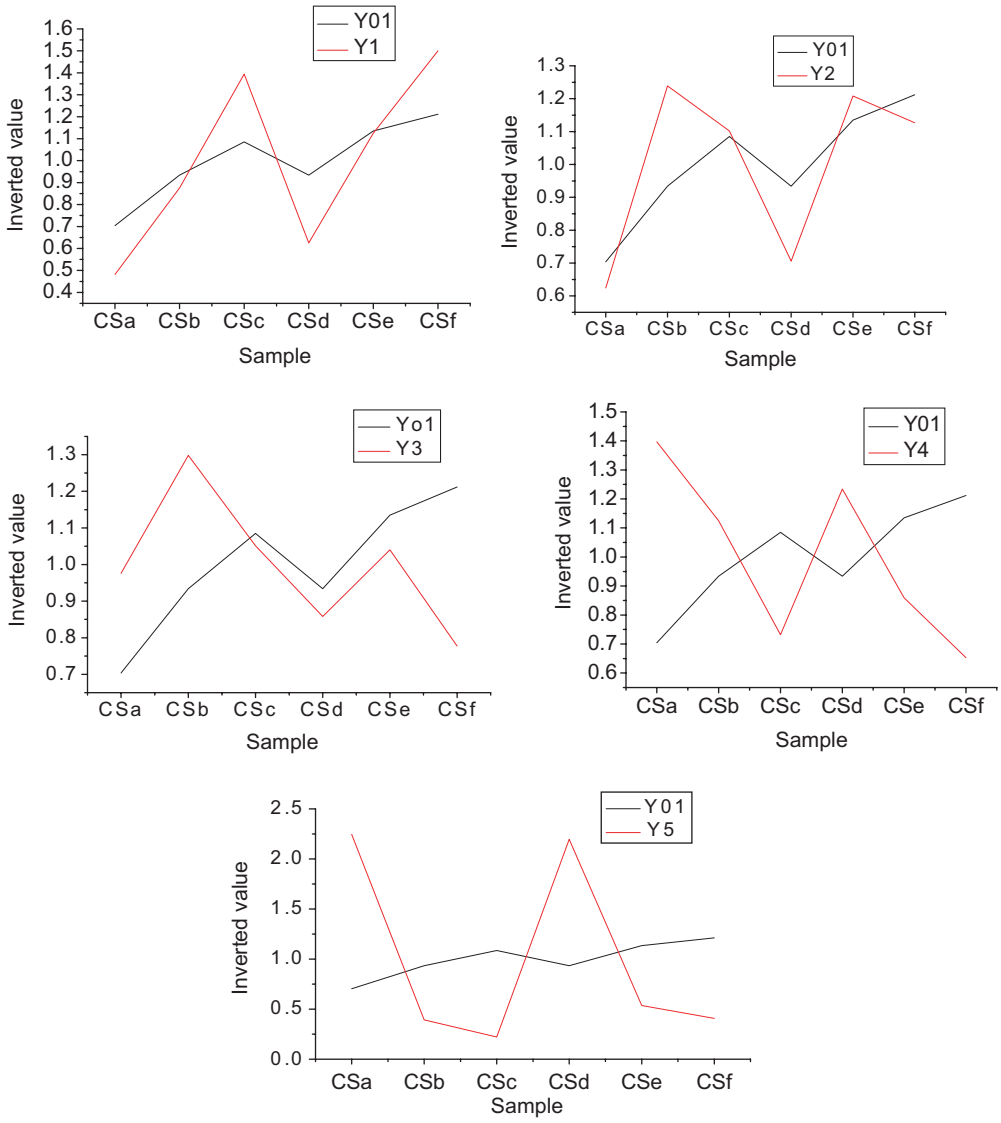

Fig. 4. Main-array and sub-array in pairs *Y*01–*Y*1, *Y*01–*Y*2, *Y*01–*Y*3, *Y*01–*Y*4 and *Y*01–*Y*5.

Apparatus and Blaine Apparatus separately. The results are shown in Table 2. Slag cements were made of 50% slag powder and 50% Portland cement (percentage by weight). The samples marked as CSa, CSb, etc. were made of 50% slag powder Sa and 50% Portland cement, 50% slag powder Sb and 50% Portland cement, etc. (percentage by weight). According to GB177-85 (Chinese norm), mortar specimens composed of slag cement, standard sand and water in the ratio of 1:2.5:0.44 were made and the mortar compressive strengths at 7 d and 28 d were tested. The compressive strength results are shown in Table 3.

To prove the results of the grey correlation analysis, an air classifier was used to classify slag powder into two size fractions, namely a fine fraction X (<20 μm) and a coarse fraction C (>20 μm). The particle size distribution of samples X and C were tested and given in Table 4. The special slag cement samples (TX and TC) were made of 50% X or C and 50% Portland cement (percentage by weight). The mortar compressive strength of TX and TC were tested according to GB177-85. The results were shown in Table 5.

The pore structure analysis of hardened slag cement pastes TX and TC were carried out by J5-90 pore structure equipment at the age of 28 d (water-to-solid ratio equal 0.40). The results are given in Fig. 2.

A calorimetric study of special slag cement pastes TX and TC was designed to analyze the reaction between solid and water. The water/solid ratio was 0.45, while the temperature was fixed at 25 °C. The results were given in Fig. 3.

4. Results and discussion

4.1. Qualitative analysis

The mortar compressive strength of slag cement at 7 and 28 d were defined as main-arrays (expressed as $Y01$ and

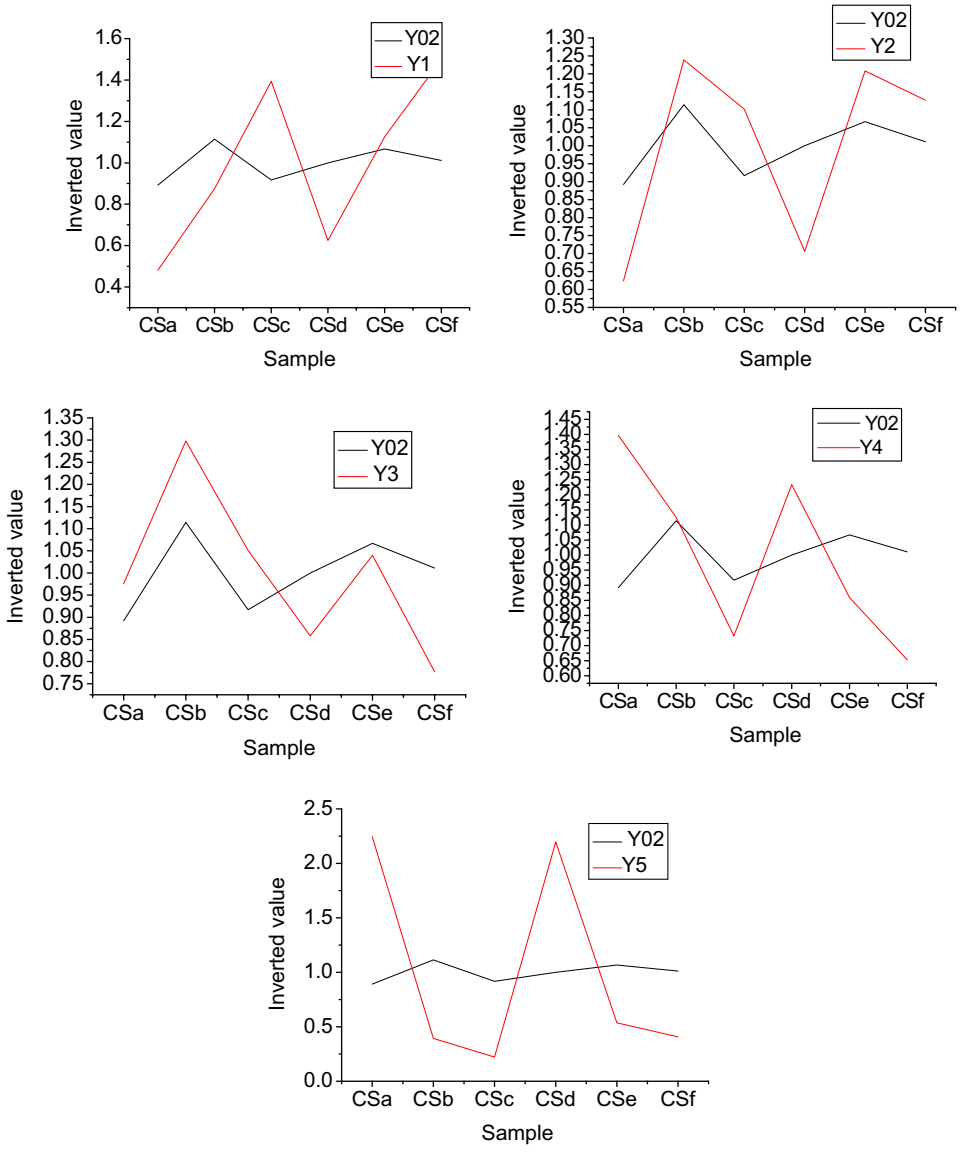

Fig. 5. Main-array and sub-array in pairs $Y02$–$Y1$, $Y02$–$Y2$, $Y02$–$Y3$, $Y02$–$Y4$ and $Y02$–$Y05$.

*Y*02) and the volume fractions of particles in different size range of slag powder in slag cement were defined as sub-arrays (expressed as *Y*1, *Y*2, etc.). The results are shown in Table 6. The inverted arrays were shown in Figs. 4 and 5. They are graphs of main-array and sub-array in pairs. Fig. 4 shows that the development trend of main-array *Y*01 was accordant with that of sub-array *Y*1, *Y*2 and *Y*3 (the volume fraction of particles 0–5 μm, 5–10 μm and 10–20 μm of slag powder) well. However, the development trend of main-array *Y*01 was not similar to that of sub-array *Y*04 and *Y*05 (the volume fraction of particles 20–40 μm and >40 μm of slag powder). That means the volume fraction of slag powder 0–20 μm has a positive effect on the mortar compressive strength of slag cement at 7 d while the volume fraction of slag powder >20 μm has a negative effect on it. The results of the relationship between *Y*02–*Y*01, *Y*02–*Y*02, etc. from Fig. 5 corresponded with those from Fig. 4.

4.2. Grey correlation analysis

The grey correlation degrees were then calculated and shown in Table 7. The results indicated that the volume fraction of particles <20 μm of slag powder had a positive correlation with the mortar compressive strength of slag cement at 7 and 28 d. However, the volume fraction of particles >20 μm of slag powder had a negative correlation with the mortar compressive strength of slag cement at 7 and 28 d. The results were accordant with those of qualitative analysis. The volume fraction of particles 5–10 μm had a maximum effect on the mortar compressive strength of slag cement at 7 d and the volume fraction of particles 10–20 μm had a maximum effect on the mortar compressive strength of slag cement at 28 d. They are key factors.

4.3. Macro and micro-analysis of special slag cement paste

Table 5 shows the results of the mortar compressive strengths of cement TX containing 50% fine slag powder (percentage by weight) and cement TC containing 50% coarse slag powder (percentage by weight). The mortar compressive strengths of cement TX at 7 and 28 d were much higher than those of cement TC.

The results of pore structure analysis (Fig. 2) showed that there are considerable differences in volume of pores at different pore size range in hardened paste with fine slag powder *X* and coarse slag powder *C*. The porosity at different pore size range in hardened paste with fine slag powder *X* was much less than that in hardened pastes with coarse slag powder *C*.

Similar situation can be resulted from the heat evolution curves of the cement pastes (Fig. 3). The paste with fine slag powder *X* indicated a better progress of hydration reaction. The total heat evolved after 40 h of hydration from the paste with fine slag powder *X* was much more than that from the paste with coarse slag powder *C*. The tested results consistent with that of macro analysis well.

Table 7
Grey correlation degree

Main-array (compressive strength)	Sub-array				
	*Y*1	*Y*2	*Y*3	*Y*4	*Y*5
Age (d)	(0–5 μm)	(5–10 μm)	(10–20 μm)	(20–40 μm)	(>40 μm)
*Y*01 (7)	+0.8184	+0.8757	+0.6628	−0.6838	−0.4769
*Y*02 (28)	+0.6933	+0.8002	+0.8540	−0.7629	−0.4678

5. Conclusions

The volume fraction of particles 0–20 μm of slag powder had a positive effect on the mortar compressive strength of slag cement at 7 and 28 d while the volume fraction of particles of slag powder larger than 20 μm had a negative effect on it. Among the volume fraction of particles <20 μm, the volume fraction of particles 5–10 μm had a maximum effect on the mortar compressive strength of slag cement at 7 d and the volume fraction of particles 10–20 μm had a maximum effect on the mortar compressive strength of slag cement at 28 d.

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