crystals

Article

Experimental Study on the Effect of Compound Activator on the Mechanical Properties of Steel Slag Cement Mortar

Junfeng Guan [1], Yulong Zhang [1], Xianhua Yao [1,*], Lielie Li [1], Lei Zhang [2] and Jinhua Yi [3]

[1] School of Civil Engineering and Communication, North China University of Water Resources and Electric Power, Zhengzhou 450045, China; shuaipipi88@126.com (J.G.); 18838089801@163.com (Y.Z.); 1000-lilili@163.com (L.L.)
[2] Institute of Engineering Mechanics, Yellow River Institute of Hydraulic Research, Zhengzhou 450045, China; hkyzhanglei@163.com
[3] Institute of Road and Bridge Engineering, Hunan Communication Polytechnic, Changsha 410132, China; y371926012@163.com
* Correspondence: yaoxianhua@ncwu.edu.cn

Abstract: In this study, activator, metakaolin, and silica fume were used as a compound activator to improve the activity of steel slag powder. The influence of activator, steel slag powder, metakaolin, and silica fume on the resulting strength of steel slag cement mortar was investigated by orthogonal experiments. For four weight fractions of steel slag powder (10%, 20%, 30%, 40%), the experimental results indicate that the compressive strength of mortar can reach up to more than 85% of the control group while the flexural strength can reach up to more than 90% of the flexural strength of the control group. Through orthogonal analysis, it is determined that the activator is the primary factor influencing the mortar strength. According to the result of orthogonal analysis, the optimal dosages of activator, steel slag powder, metakaolin, and silica fume are suggested. The GM (0, *N*) prediction model of compressive strength and flexural strength was established, and the compressive strength and flexural strength of mortar with the optimal dosage combinations were predicted. The prediction results show that by using the optimal dosage combination, the mortar strength can reach the level of P·O·42.5 cement. Considering the different strength and cost requirements of cementitious materials in practical engineering, the economic benefits of replacing cement with steel slag powder activated by compound activator in various proportions and equal amounts were presented. The results show that the method proposed in this study can reduce the cost of cementitious materials.

Keywords: steel slag powder; compound activator; mortar strength; orthogonal experiment; GM (0, *N*) model

Citation: Guan, J.; Zhang, Y.; Yao, X.; Li, L.; Zhang, L.; Yi, J. Experimental Study on the Effect of Compound Activator on the Mechanical Properties of Steel Slag Cement Mortar. *Crystals* **2021**, *11*, 658. https://doi.org/10.3390/cryst11060658

Academic Editors: Chuanqing Fu, Peng Zhang, Peter Taylor and Yifeng Ling

Received: 19 May 2021
Accepted: 6 June 2021
Published: 10 June 2021

Highlights:
- A method for using a compound activator to improve the activity of steel slag powder is proposed.
- The optimal dosage combination of activator, steel slag, metakaolin, and silica fume is suggested.
- The economic benefit analysis is carried out on the steel slag powder activated by the compound activator to replace part of the cement.

1. Introduction

Steel slag is a byproduct of steel production, which accounts for about 15% of the mass of steel production [1–3]. In China, the generation of steel slag is huge, whereas the total utilization rate is low [4]. The accumulation of steel slag not only takes up a lot of land but also pollutes the surrounding environment [5]. Therefore, it is imperative to improve the utilization of steel slag [6–8]. The composition of steel slag is similar to that of cement, and as such, it has the potential of replacing cement as a cementitious material. If steel slag can be effectively used in the cement industry, it will benefit the solid waste utilization, energy conservation, and environmental protection [9–13]. However, the inherent low activity of steel slag restricts its application in the cement industry [14–16].

In order to address this issue, researchers have been employing different methods to improve the activity of steel slag. Commonly used activation methods include physical activation, chemical activation, thermal activation, and steel slag restructuring. The physical activation method increases the specific surface area of the steel slag by grinding the steel slag into ultra-fine powder by using a ball mill, thereby increasing the hydration rate. Zhu et al. [17] used a grinding aid mixed with sulfonate, alcohol, and metaphosphoric to grind steel slag, which increased the early hydration rate of steel slag. Altun et al. [18] ground steel slag to 4000 cm^2/g and 4700 cm^2/g specific surface area and used 30% of it to replace Portland cement in mortar preparation which led to the 28-days compressive strength of mortar to be 38.5 MPa and 45.8 MPa, respectively. Chemical activation enhances the activity of steel slag by changing the mineral formation process, primarily including alkali activation and acid activation [19–21]. Peng et al. [22] used water glass as a steel slag activator, and the 28-days compressive strength of the mortar with 40% steel slag dosage reached 51.4 MPa. Sun et al. [23] used water glass to activate the steel slag activity, and the results showed that the pore structure of hardened cement paste was more compact than that of the steel slag paste activated by sodium silicate, while the compressive strength of alkali–activated steel slag hardened pastes was only 30–40% of the strength of ordinary cement pastes. Huo et al. [20,24] used phosphoric acid and formic acid to activate the activity of steel slag, and research result showed that the compressive strength of the activated steel slag pastes significantly improves at 3 days and 7 days ages. Zhang et al. [25] used water glass, industrial residues, and a mixture of sodium hydroxide, calcium oxide, and alum as the compound activator for steel slag; and the 28 days compressive strength of steel slag blended cement was reported as 47.7 MPa. Du et al. [26] used dihydrate gypsum and silica fume as steel slag compound activator in a ratio of 1:4, which greatly improved the strength of steel slag cementitious materials at the early and late ages. Thermal activation can depolymerize the vitreous phase in the steel slag, thereby increasing the activity. Lin et al. [27] investigated the effect of using thermally activated steel slag-fly ash-gypsum system (the autoclave temperature was 100 °C). It was shown that the 28 days compressive strength reached 46.8 MPa and 43.5 MPa for the pretreatment material dosages of 35% and 40%, respectively. Steel slag reconstruction is the addition of different materials to adjust the chemical composition of steel slag to cause a chemical reaction at high temperature for absorbing free calcium oxide to generate reactive substances such as dicalcium silicate, tricalcium silicate, tricalcium aluminate, which improved the activity of steel slag. Kang et al. [28] mixed basic oxygen furnace steel slag and electric arc furnace steel slag in an appropriate ratio and reheated these at a high temperature in the laboratory, which significantly improved the activity of steel slag. Yin et al. [29] reconstructed the steel slag by reducing FeO_x to improve the hydraulic activity of the steel slag, and the result confirmed that the activity index was 92% when direct reduction slag replaced the cement with a mass ratio of 30%. Zhao et al. [30] reconstructed the steel slag by adding electric furnace slag and fly ash to the converter steel slag. The compressive strength of the paste with 30% reconstructed steel slag dosage could reach 99.9% of that for the pure cement paste. Many studies have shown that the physical activation takes a long time and has little effect on the activity of steel slag at a later age. Also, the cost of the chemical activator is much higher than the other methods. Whereas steel slag reconstruction can improve its activity to a certain degree, it still lags behind the cement clinker. Other methods can also improve the activity of steel slag, but these are still in the experimental stage [31,32].

There are many researches on chemical alkaline activation methods, but alkaline activation has high cost. Therefore, the compound activator composed of neutral materials (some salts such as sodium sulfate, sodium aluminate, and some mineral admixtures such as silica fume) was used to activate the activity of steel slag powder in this paper, and the optimal dosage of each component of compound activator in cementitious material was determined through experiments. A grey prediction model GM (0, *N*) was established to predict the strength of steel slag cement mortar with the optimal dosage of each component. The effectiveness of the proposed activation method was verified by the test results and the model prediction results. Furthermore, considering the different requirements of engineering for cementitious materials, economic benefit analysis is carried out for different mix proportions to check whether the proposed method will reduce the cost of cementitious materials and the extent of reduction to provide basis for engineering.

2. Experimental and Methods

2.1. Raw Materials

Seven different kinds of raw materials were used in the experimental program of this study: cement, sand, steel slag powder, activator, metakaolin, silica fume, and water. The cement was P·O·42.5 Portland cement with an apparent density of 3150 kg/m^3. The sand used in the study was ISO standard sand. The steel slag powder was produced by Taiyuan Iron & Steel Group Co., Ltd. in Taiyuan, China, with a specific surface area of 450 m^2/kg. The activator was composed of various materials, and the corresponding components and mass percentages are shown in Table 1. Water quenched slag and stone powder in the activator can accelerate the hydration reaction. In addition, the particle size of water quenched slag is larger than that of steel slag powder, so the water quenched slag can be combined with steel slag powder to optimize the grading. Metakaolin was obtained by calcining kaolin at 700 °C for 24 h. Silica fume was purchased from the market with a density of 2.3 g/cm^3. Ordinary potable water was used as well. The chemical compositions of cement, steel slag powder, metakaolin, and silica fume are shown in Table 2, while the particle size distribution is given in Figure 1. The actual samples of cement, steel slag powder, activator, metakaolin, and silica fume are shown in Figure 2.

Table 1. Components of activator (wt %).

Silica Fume	Sodium Aluminate	Sodium Sulfate	Sodium Tripolyphosphate	Water Quenched Slag	Desulfurization Gypsum	Stone Powder
6.25	0.63	1.25	0.62	21.25	3.13	66.87

Table 2. Main chemical compositions of materials (wt %).

Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	MgO	Na_2O	MnO	K_2O
Cement	19.31	5.86	3.15	60.33	4.42	3.03	0.12	-	1.13
Steel slag powder	14.24	1.94	19.69	46.19	-	10.06	-	1.36	-
Metakaolin	55.36	35.46	1.83	0.54	-	0.03	0.04	-	0.26
Silica fume	91.33	0.85	0.57	0.47	0.47	1.55	0.42	-	1.38

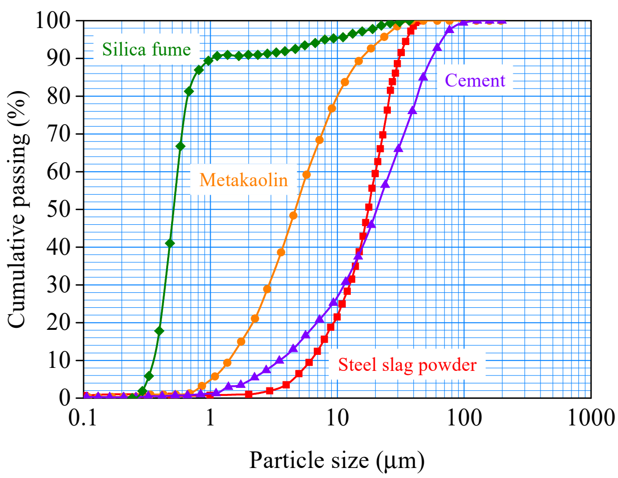

Figure 1. Particle size distribution of materials.

Figure 2. Samples of cementitious material components in this study (**a**) cement; (**b**) steel slag powder; (**c**) activator; (**d**) metakaolin and (**e**) silica fume.

2.2. Mix Proportions

The experimental design method is often chosen according to the experimental purpose [33–35]. In order to study the influence of various factors on the mortar strength, the orthogonal method was adopted for designing the experimental mix proportions. Activator, steel slag powder, metakaolin and silica fume were taken as four factors. The dosage of each factor was set at several levels according to the mass percentage of cementitious material. Due to the low activity of steel slag powder itself, the activation method is difficult to have a good influence on the strength of steel slag cement mortar with excessive steel slag powder dosage, so the dosage of steel slag powder is set to 10%, 20%, 30%, and 40%, a total of four levels. Al_2O_3 in metakaolin can accelerate the hydration reaction of SiO_2 in cementitious materials, so as to improve the strength of steel slag cement mortar. A small amount of metakaolin can have positive effect on the strength of steel slag cement mortar, so the dosage of metakaolin is set at four levels: 5%, 10%, 15%, and 20%. The silica fume can improve the strength of steel slag cement mortar, but excessive dosage will lead to high cost, so the silica fume dosage is set at 4 levels: 2%, 4%, 6%, and 8%. Level details of factors are shown in Table 3. According to the orthogonal design method, sixteen groups of mix proportions were designed. Another group of pure cement mortar specimens was also designed as the control group for comparative study. The mix proportions are given in Table 4.

Table 3. Level details of factors (wt %).

Dosage Level	Factor			
	Activator	Steel Slag Powder	Metakaolin	Silica Fume
1	5	10	5	2
2	10	20	10	4
3	15	30	15	6
4	20	40	20	8

Table 4. Mix proportions (g).

Experimental Group	Activator	Steel Slag Powder	Metakaolin	Silica Fume	Cement	Sand	Water
G0	0	0	0	0	450	1350	225
G1	22.5	45	22.5	9	351	1350	225
G2	22.5	90	45	18	274.5	1350	225
G3	22.5	135	67.5	27	198	1350	225
G4	22.5	180	90	36	121.5	1350	225
G5	45	45	45	27	288	1350	225
G6	45	90	22.5	36	256.5	1350	225
G7	45	135	90	9	171	1350	225
G8	45	180	67.5	18	139.5	1350	225
G9	67.5	45	67.5	36	234	1350	225
G10	67.5	90	90	27	175.5	1350	225
G11	67.5	135	22.5	18	207	1350	225
G12	67.5	180	45	9	148.5	1350	225
G13	90	45	90	18	207	1350	225
G14	90	90	67.5	9	193.5	1350	225
G15	90	135	45	36	144	1350	225
G16	90	180	22.5	27	130.5	1350	225

2.3. Test Methods

The mortar was mechanically mixed by a mixer. Before mixing, the activator and steel slag powder was mixed uniformly. Then, metakaolin, silica fume, and cement were gradually added to obtain the cementitious materials mix, and the mixing was further continued. The mixing is done according to the following steps. First, water was added to the mixing pot followed by the addition of all the cementitious materials. The machine was started and the materials in the pot were slowly mixed at low speed for 30 s. The sand was uniformly added after 30 s, and the mixing was continued at high speed for an additional 30 s after the sand was fully added. The mixing was stopped for 90 s, and a rubber scraper was used to scrape off the paste on the blade and the wall of the mixing pot. Then, it was further mixed at high speed for 60 s. The detailed mixing procedure is shown in Figure 3. The mortar should be formed immediately after preparation. The specimens were cast in three connected test molds, each having a size of 40 mm × 40 mm × 160 mm. The mortar should be put into the test molds in two layers, and a vibrating table should be used for vibrating the layers. Each time it was vibrated 60 times. Then, the mortar molds were put into a curing box with humidity of 95% and a temperature of 20 °C for curing. After 24 h, the demolding was done, and the test block was cured for 180 days under standard curing conditions. Then, the mechanical properties of mortar were tested according to GB/T 17671-1999 [36]. The flexural strength testing machine is an electric flexural testing machine model DKZ-5000 with 5 kN measuring range, manufactured by Wuxi Jianyi Instrument & Machinery Co., Ltd. in Wuxi, China. Load control was selected as the test procedure of flexural strength, and the loading rate was 50 N/s. The compressive strength testing device is Hualong universal testing machine model WAW-600 with 600 kN measuring range, manufactured by Shanghai Hualong Test Instrumens Co., Ltd. in Shanghai, China. Load control was selected as the test procedure of compressive strength, and the loading rate was 2500 N/s.

Figure 3. Mixing progress of steel slag mortar.

2.4. GM (0, N) Prediction Model

In practice, we often encounter problems such as the lack of data, grey characteristics of the data itself, and the need to consider the correlation between predictive variables and multiple factors [37,38]. Grey system theory provides a method to solve such problems. GM (0, N) and GM (1, N) are common multi-factor grey prediction models [39,40]. GM (1, N) is a little complicated because it involves the first-order differentiation, whereas the GM (0, N) model is relatively simple to establish as it has high prediction accuracy [41,42]. The establishment of the GM (0, N) model is as follows [42]:

Take $X_1^{(0)} = \left(x_1^{(0)}(1), x_1^{(0)}(2), \cdots, x_1^{(0)}(n)\right)$ as the system characteristic data sequence, and

$$\begin{aligned} X_2^{(0)} &= (x_2^{(0)}(1), x_2^{(0)}(2), \cdots, x_2^{(0)}(n)) \\ X_3^{(0)} &= (x_3^{(0)}(1), x_3^{(0)}(2), \cdots, x_3^{(0)}(n)) \\ &\cdots \\ X_N^{(0)} &= (x_N^{(0)}(1), x_N^{(0)}(2), \cdots, x_N^{(0)}(n)) \end{aligned}$$

as the relative factors data sequences. $X_i^{(1)}$ is the 1-AGO sequence of $X_i^{(0)}$ ($i = 1, 2, \cdots, N$), then call

$$x_1^{(1)}(k) = \sum_{i=2}^{N} b_i x_i^{(1)}(k) + a \quad (1)$$

as the GM (0, N) model.

$$B = \begin{bmatrix} x_2^{(1)}(2) & x_3^{(1)}(2) & \cdots & x_N^{(1)}(2) & 1 \\ x_2^{(1)}(3) & x_3^{(1)}(3) & \cdots & x_N^{(1)}(3) & 1 \\ \vdots & \vdots & & \vdots & \vdots \\ x_2^{(1)}(n) & x_3^{(1)}(n) & \cdots & x_N^{(1)}(n) & 1 \end{bmatrix}, Y = \begin{bmatrix} x_1^{(1)}(2) \\ x_1^{(1)}(3) \\ \vdots \\ x_1^{(1)}(n) \end{bmatrix}$$

Then the least-squares estimate of the parameter column $\hat{b} = [b_2, b_3, \cdots, b_N, a]^T$ is

$$\hat{b} = (B^T B)^{-1} B^T Y \quad (2)$$

3. Analysis of Results

The 180 days compressive strength and flexural strength test results of the control group G0 (pure cement mortar specimens) are 48.0 MPa and 9.2 MPa, respectively. The orthogonal experimental results are shown in Table 5.

Table 5. Orthogonal experimental results of mechanical properties.

Experimental Group	Activator (%)	Steel Slag Powder (%)	Metakaolin (%)	Silica Fume (%)	Compressive Strength (MPa)	Flexural Strength (MPa)
G1	5	10	5	2	43.4	8.2
G2	5	20	10	4	37.2	7.8
G3	5	30	15	6	45.6	8.3
G4	5	40	20	8	44.6	7.9
G5	10	10	10	6	44.2	8.8
G6	10	20	5	8	40.6	8.7
G7	10	30	20	2	29.8	7.4
G8	10	40	15	4	28.4	7.6
G9	15	10	15	8	47.9	8.2
G10	15	20	20	6	24.3	3.0
G11	15	30	5	4	31.1	3.7
G12	15	40	10	2	29.0	8.4
G13	20	10	20	4	16.0	4.0
G14	20	20	15	2	14.5	2.5
G15	20	30	10	8	12.5	2.4
G16	20	40	5	6	11.5	2.2

The compressive strength test results are shown in Table 5 and Figure 4a. When the steel slag powder dosage is 10%, the mix proportion G9 has the highest compressive strength (47.9 MPa). The dosages of activator, metakaolin, and silica fume are 15%, 15%, 8%, respectively. When the steel slag powder dosage is 20%, the compressive strength of the mix proportion G6 is the highest (40.6 MPa), and the corresponding dosages of activator, metakaolin, and silica fume are 10%, 5%, and 8%, respectively. When the steel slag powder dosage is 30%, the mix proportion G3 has the highest compressive strength (45.6 MPa), and the corresponding dosages of activator, metakaolin, and silica fume are 5%, 15%, and 6%, respectively. Furthermore, when the steel slag powder dosage is 40%, the mix proportion G4 has the highest compressive strength (44.6 MPa), and the corresponding dosages of activator, metakaolin, and silica fume are 5%, 20%, and 8%, respectively. As shown in Figure 4a, with the change of dosage of steel slag powder (10–40%), the highest compressive strength at each dosage level is more than 85% of the compressive strength of the control group. As shown in Figure 4a, the compressive strength of steel slag cement mortar shows an overall trend of decline from G1 to G16, while the dosage of activator (5–20%) is gradually increasing. The reason why the strength of steel slag cement mortar decreases may be that the content of stone powder increases with the increase of the activator dosage, and excessive stone powder will have negative effect on the strength of steel slag cement mortar. G9 is the mix proportion with the highest compressive strength among 16 mix proportions. The reasons may be divided into two aspects. On the one hand, the dosage of steel slag powder (10%) is relatively low, and the negative effect of low activity of steel slag powder on steel slag cement mortar is relatively small. On the other hand, it may be related to the relatively large dosage of metakaolin (15%) and silica fume (8%). SiO_2 in metakaolin and silica fume hydrate to form calcium silicate, which improves the compressive strength. In addition, it is difficult to identify the main cause in the condition of many factors, and further analysis is needed to determine the cause.

The flexural strength test results are given in Table 5 and Figure 4b. When the steel slag powder dosage is 10%, the mix proportion G5 has the highest flexural strength (8.8 MPa), and the corresponding dosages of activator, metakaolin, and silica fume, are 10%, 10%, and 6%, respectively. When the steel slag powder dosage is 20%, the mix proportion G6 has the highest flexural strength (8.7 MPa), and the dosages of activator, metakaolin, and silica fume are 10%, 5%, and 8%, respectively. At 30% dosage of steel slag powder, the mix proportion G3 has the highest flexural strength (8.3 MPa), and the corresponding dosages of activator, metakaolin, and silica fume are 5%, 15%, and 6%, respectively. When the steel slag powder dosage is 40%, the mix proportion G12 has the highest flexural strength (8.4 MPa), and the corresponding dosages of activator, metakaolin, and silica fume are 15%, 10%, and 2%, respectively. As shown in Figure 4b, with the change of steel slag powder dosage (10–40%), the highest flexural strength at each level of dosage is greater than 90% of the flexural strength of the control group. As shown in Figure 4b, there is little difference in the flexural strength of steel slag cement mortar of G1–G9, and the flexural strength of G10, G11, G13, G14, G15, and G16 is relatively low, while the flexural strength of G12 is relatively high. Similar to the compressive strength, it is difficult to find out the influence law of each factor only from the test results, and further analysis is needed to determine the cause.

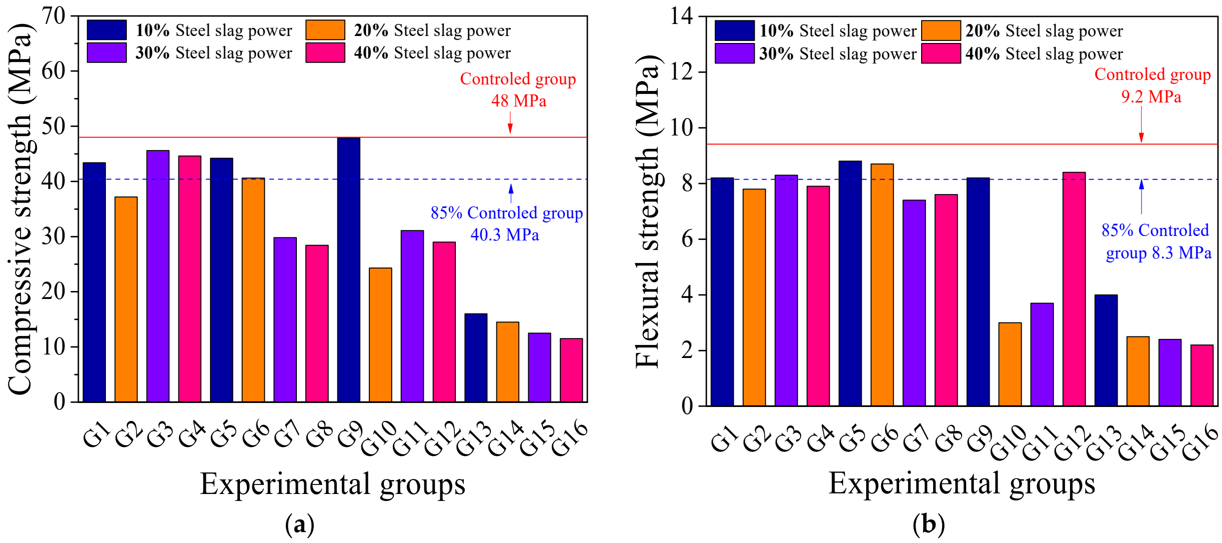

Figure 4. Strength of steel slag cement mortar with different mix proportions: (**a**) Compressive strength of experimental groups; (**b**) Flexural strength of experimental groups.

4. Orthogonal Analysis

The analysis methods of orthogonal experimental results include range analysis and variance analysis. Range analysis is a method to analyze the influence of each factor on the system value in a multi-factor system. It can not only determine the primary factor influencing the system value but also gives the optimal level combination of several factors. Variance analysis is also a method of multi-factor system analysis, which can not only estimate the error size but also represents the significant degree of influence of each factor on the system value [43]. The above two methods are used to analyze the experimental results.

4.1. Compressive Strength Analysis

The results of the compressive strength range analysis are shown in Table 6. According to the range (R) of compressive strength caused by the change of dosage level, the factors are in order as follows: activator (29.0 MPa) > steel slag powder (9.5 MPa) > silicon powder (8.2 MPa) > metakaolin (5.4 MPa). Activator dosage has the most significant influence on the experimental results of compressive strength. It indicates that the activator is the primary influencing factor of compressive strength. The results of compressive strength variance analysis are shown in Table 7. Activator, steel slag powder, metakaolin, and silica fume have a very profound effect on the compressive strength. The influence degree of each factor on compressive strength can be further characterized according to the value of '*F*' of each factor. The greater the value of '*F*' of each factor, the more significant the influence is. Therefore, the order of the various factors according to the influence degree of compressive strength from large to small is the activator, steel slag powder, silica fume, and metakaolin. The results of range analysis and variance analysis indicate that the activator had the greatest influence on the compressive strength and is the primary factor influencing the compressive strength.

The relationship curve between the compressive strength and the dosage levels of each influencing factor is shown in Figure 5. The influence of the activator dosages on the compressive strength is shown in Figure 5a. The compressive strength decreases gradually with the increase of the activator dosage, and it is at maximum when the activator dosage is 5%. The influence of steel slag powder dosage on the compressive strength is shown in Figure 5b. The compressive strength decreases gradually with the increase of the steel slag powder dosage, and it reaches the maximum when the steel slag powder dosage is 10%. The influence of metakaolin dosage on compressive strength is shown in Figure 5c. The compressive strength first increases and then decreases with the increase of metakaolin dosage. The compressive strength reaches the maximum when the metakaolin dosage is 15%. The influence of silica fume dosage on compressive strength is shown in Figure 5d. The compressive strength first decreases and then increases with the increase of silica fume dosage. The compressive strength reaches the maximum value when the activator content is 8%. The compressive strength of steel slag cement mortar with 10% steel slag powder dosage is significantly different from that with 20%, 30%, and 40% steel slag powder dosage. The reason is that the activity of steel slag powder is low, and it is difficult to achieve a higher compressive strength even if the activation method is adopted. With the increase of the activator dosage, the content of stone powder also increases, and the negative effect caused by excessive stone powder is greater than the activation effect of activator on steel slag. When the dosage of metakaolin is 20%, the compressive strength is lower than the compressive strength corresponding to dosages of 5–15%, so the dosage should not be exceed 15%. With the increase of silica fume dosage (4–8%), the compressive strength of steel slag cement mortar increases greatly. The dosages corresponding to the maximum compressive strength are taken as the optimal dosage. Therefore, for the compressive strength of mortar, the optimal dosage combination of the four factors is activator 5%, steel slag powder 10%, metakaolin 15%, and silica fume 8%.

Table 6. Range analysis of compressive strength.

Index	**Compressive Strength (MPa)**			
	Activator	**Steel Slag Powder**	**Metakaolin**	**Silica Fume**
K_1	170.8	151.4	126.6	116.6
K_2	142.9	116.6	122.9	112.7
K_3	132.3	119.0	136.3	125.6
K_4	54.6	113.5	114.7	145.6
k_1	**42.7**	**37.9**	31.7	29.2
k_2	35.7	29.2	30.7	28.2
k_3	33.1	29.8	**34.1**	31.4
k_4	13.7	28.4	28.7	36.4
MAX	42.7	37.9	34.1	**36.4**
MIN	13.7	28.4	28.7	28.2
R	29.0	9.5	5.4	8.2

Note: K_i is the sum of multiple test results at a certain level, k_i is the mean value of multiple test results at a certain level, and R is the range of mean value of test results at different levels.

Table 7. Variance analysis of compressive strength.

Material	SS	d_f	MS	F	Significant Degree
Activator	5562.2	3	1854.1	154.6	**
Steel slag powder	703.0	3	234.3	19.5	**
Metakaolin	181.0	3	60.3	5.0	**
Silica fume	485.8	3	161.9	13.5	**
Se_1	300.9	3		$F_{0.01}$ (3, 35) = 4.4	
Se_2	118.8	32		$F_{0.05}$ (3, 35) = 2.9	
Se	419.7	35	12.0	$F_{0.2}$ (3, 35) = 1.6	
Sum	7232.9	47			

Note: *SS* is the sum of squares; d_f is the degrees of freedom; *MS* is the mean square; Se_1 is the System error; Se_2 is the experiment error; Se is the overall error; *F* is the *MS*/*Se*; ** is very significant ($F > F_{0.01}$ (3, 35)).

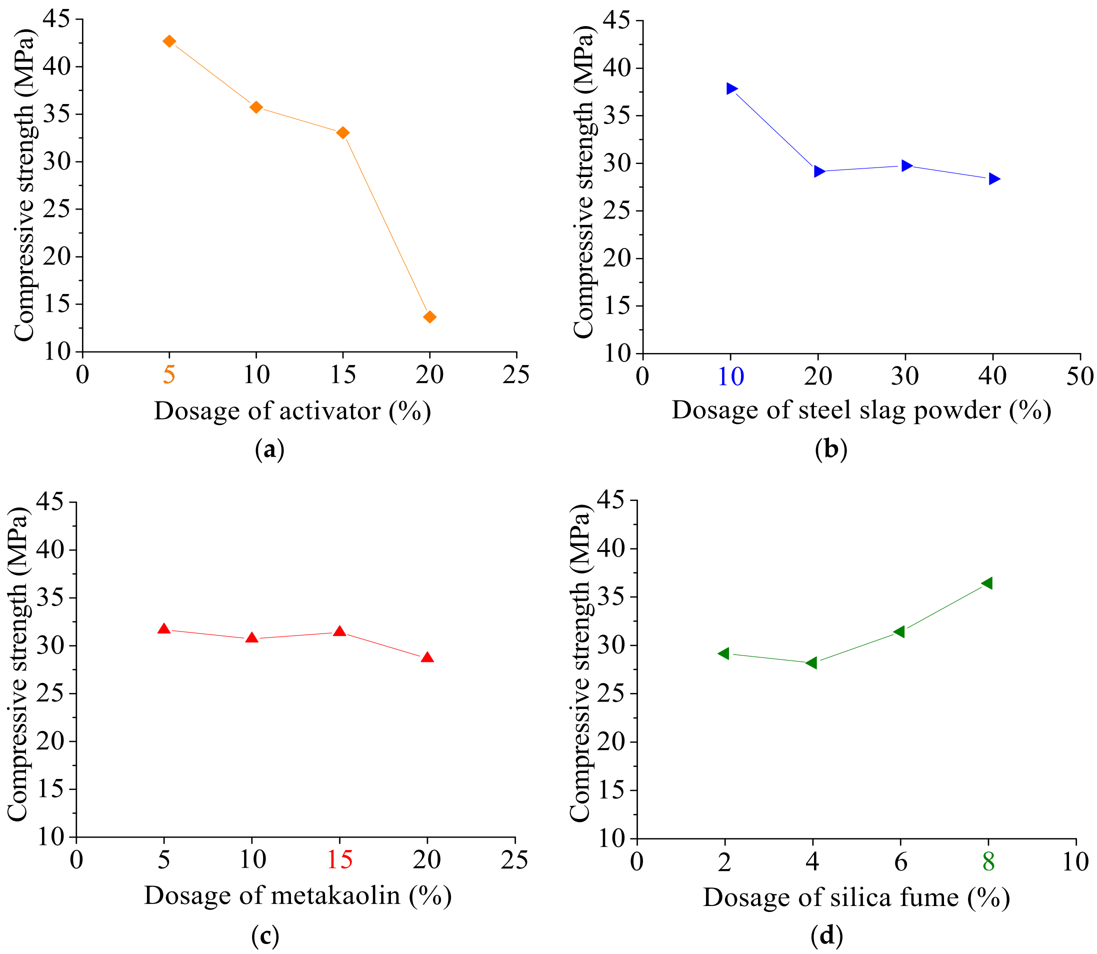

Figure 5. Relationship between compressive strength and dosage levels of each factor: (**a**) activator; (**b**) steel slag powder; (**c**) metakaolin and (**d**) Silica fume.

4.2. Analysis of Flexural Strength

The results of the flexural strength range analysis are shown in Table 8. According to the range (*R*) of flexural strength caused by the change of dosage level, the factors are in order as follows: activator (5.4 MPa)> steel slag powder (1.8 MPa) > metakaolin (1.3 MPa) > silica fume (1.2 MPa). Activator dosage has the most significant influence on the experimental results of flexural strength. It indicates that the activator is the primary influencing factor of flexural strength. The results of the variance analysis of flexural strength are shown in Table 9. Activator, steel slag powder, metakaolin, and silica fume all have a very significant influence on flexural strength. The influence degree of each factor on flexural strength can be further distinguished according to the value of '*F*' of each factor. Therefore, the order of the different factors according to the influence degree of the flexural strength from large to small is the activator, steel slag powder, metakaolin, and silica fume. The results of range analysis and variance analysis indicate the activator had the greatest influence on the flexural strength and is the primary factor affecting the flexural strength.

The relationship curve between the flexural strength and the dosage levels of each factor is shown in Figure 6. The influence of the activator dosages on the flexural strength is shown in Figure 6a. The flexural strength first increases and then decreases with the increase of the activator dosage. The flexural strength reaches the maximum when the activator dosage is 10%. The influence of steel slag powder dosage on the flexural strength, shown in Figure 6b, indicates that the flexural strength decreases gradually with the increase of the steel slag powder dosage. The flexural strength reaches the maximum when the steel slag powder dosage level is 10%. The influence of metakaolin dosage on flexural strength is shown in Figure 6c. The flexural strength first increases and then decreases with the increase of metakaolin dosage. The flexural strength reaches the maximum when the metakaolin dosage is 15%. The influence of silica fume content on flexural strength is shown in Figure 6d. The flexural strength decreases first and then increases with the increase of silica fume dosage, while it reaches the maximum value when the activator content is 8%. Similar to the compressive strength, the steel slag cement mortar with smaller dosage (5%, 10%) of activator has a larger flexural strength, while the steel slag cement mortar with larger dosage (15%, 20%) of activator has smaller flexural strength. When the dosages of metakaolin and silica fume were 10% and 8%, respectively, the corresponding flexural strength reached the maximum, which was very close to 15% and 8% of optimal dosage in compressive strength analysis. In addition, the strength corresponding to 40% dosage of steel slag powder is only smaller than the strength corresponding to 10% dosage, and the strength corresponding to 2% dosage of silica fume is only smaller than the strength corresponding to 8% dosage, as shown in Figure 6. This indirectly explains the reason why G12 has a large flexural strength, which is the result of the combined action of many factors. The dosages corresponding to the maximum flexural strength are taken as the optimal dosages. Therefore, for the flexural strength of mortar, the optimal dosage combination of the four factors is activator 10%, steel slag powder 10%, metakaolin 10%, and silica fume 8%.

Table 8. Range analysis of flexural strength.

Index	**Flexural Strength (MPa)**			
	Activator	**Steel Slag Powder**	**Metakaolin**	**Silica Fume**
K_1	32.2	29.1	22.8	26.4
K_2	32.5	22.0	27.4	23.0
K_3	23.2	21.8	26.6	22.4
K_4	11.1	26.1	22.2	27.2
k_1	8.0	7.3	5.7	6.6
k_2	8.1	5.5	6.8	5.7
k_3	5.8	5.4	6.7	5.6
k_4	2.8	6.5	5.6	6.8
MAX	8.1	7.3	6.8	6.8
MIN	2.8	5.4	5.6	5.6
R	5.4	1.8	1.3	1.2

Note: K_i is the sum of multiple test results at a certain level, k_i is the mean value of multiple test results at a certain level, and R is the range of mean value of test results at different levels.

Table 9. Variance analysis of flexural strength.

Material	*SS*	d_f	*MS*	*F*	Significant Degree
Activator	228.7	3	76.2	51.1	**
Steel slag powder	28.1	3	9.4	6.3	**
Metakaolin	15.6	3	5.2	3.5	*
Silica fume	13.3	3	4.4	3.0	*
Se_1	28.9	3		$F_{0.01}$ (3, 35) = 4.4	
Se_2	23.3	32		$F_{0.05}$ (3, 35) = 2.9	
Se	52.2	35	1.5	$F_{0.2}$ (3, 35) = 1.6	
Sum	314.6	47			

Note: *SS* is the sum of squares; d_f is the degrees of freedom; *MS* is the mean square; Se_1 is the System error; Se_2 is the experiment error; Se is the overall error; *F* is the *MS*/*Se*; ** is very significant ($F > F_{0.01}$ (3, 35)); * is significant ($F > F_{0.05}$ (3, 35)).

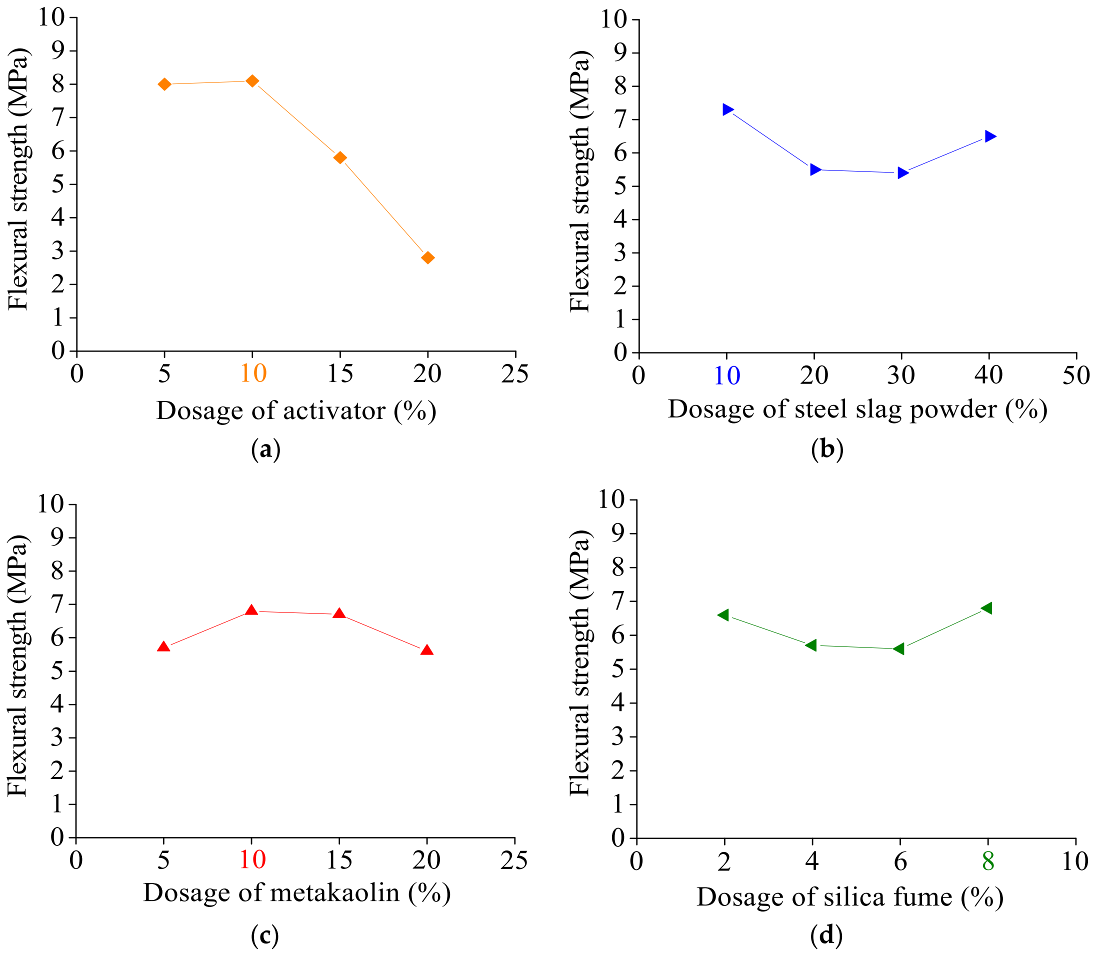

Figure 6. Relationship between flexural strength and dosage levels of each factor: (**a**) activator; (**b**) steel slag powder; (**c**) metakaolin and (**d**) Silica fume.

Through orthogonal analysis, it is determined that the activator is the primary factor affecting the strength of steel slag cement mortar, and the optimal dosages of each factor corresponding to the compressive strength and the flexure strength are obtained. It provides a basis for scientific research and engineering application. At the same time, it was found that excessive content of stone powder in the activator had a negative effect on the strength of steel slag cement mortar.

5. Prediction of Mortar Strength

The principle of orthogonal design method is to perform the overall evaluation of the system by uniformly sampling the level combinations of multiple factors. Therefore, the dosage level combinations of multiple factors adopted in the experiment may not necessarily take into account the optimal dosage level combination. The GM (0, *N*) model can be established to predict the system characteristic data of the optimal level combination obtained by the range analysis method. The data selection used to establish the model has a certain influence on the prediction accuracy of GM (0, *N*) model. Appropriately reducing the number of data used in the model establishment, according to the level value range of the primary factor of the system characteristic data, can improve the accuracy of the prediction model. The results of orthogonal analysis show that the activator is the main factor affecting the strength of mortar while the optimal dosages of the activator for compressive strength and flexural strength are lower 5% and 10%, respectively. Therefore, the GM (0, *N*) model was established by selecting the data of the first eight experimental groups for improving the prediction accuracy.

5.1. Prediction of Compressive Strength

Taking the compressive strength of the first eight groups as $X_1^{(0)}$, that is the system characteristic data sequence, and the dosage of activator, steel slag powder, metakaolin, and silica fume as the relative factors data sequence $X_2^{(0)}$, $X_3^{(0)}$, $X_4^{(0)}$, $X_5^{(0)}$, then

$$X_1^{(0)} = (43.4\ ,37.2\ ,45.6\ ,44.6\ ,44.2\ ,40.6\ ,29.8\ ,28.4\ )$$
$$X_2^{(0)} = (5,5,5,5,10,10,10,10)$$
$$X_3^{(0)} = (10,20,30,40,10,20,30,40)$$
$$X_4^{(0)} = (5,10,15,20,10,5,20,15)$$
$$X_5^{(0)} = (2,4,6,8,6,8,2,4)$$

The data sequence is superimposed at once, and the parameter column satisfying the least-square estimation is obtained through Equation (2).

$$\hat{b} = [-0.541, -0.395, 1.361, 4.557, 41.867]^T \tag{3}$$

Thus, the GM (0, 5) model of compressive strength is obtained:

$$x_1^{(0)}(k) = -0.541x_2^{(1)}(k) - 0.395x_3^{(1)}(k) - 1.361x_4^{(1)}(k) - 4.557x_5^{(1)}(k) + 41.867 \tag{4}$$

As shown in Table 10, the average relative simulation error of GM (0, 5) model of compressive strength is 5.9%, while the accuracy is above 94%, which is a good prediction accuracy. When the optimal dosage combination of compressive strength was substituted into Equation (4), the prediction value of compressive strength was 55.6 MPa. The optimal dosage combination of the flexural strength was substituted into Equation (4) to obtain the prediction value of compressive strength of 51.5 MPa. The results show that the compressive strength of the two mixtures reaches the level of P·O·42.5 Portland cement.

Table 10. Simulation error check of GM (0, 5) model for compressive strength.

Number	Actual Value	Simulated Value	Residual	Relative Simulation Error
2	37.188	39.830	−2.642	0.071
3	45.583	38.612	6.971	0.153
4	44.625	50.581	−5.956	0.133
5	44.188	42.412	1.775	0.040
6	40.625	40.771	−0.146	0.004
7	29.750	29.894	−0.144	0.005
8	28.354	28.253	0.101	0.004
Mean				0.059

5.2. Prediction of Flexural Strength

Taking the flexural strength of the first eight groups as $X_1^{(0)}$, that is, the system characteristic data sequence, and the dosage of activator, steel slag powder, metakaolin, and silica fume as the relative factors data sequence $X_2^{(0)}$, $X_3^{(0)}$, $X_4^{(0)}$, $X_5^{(0)}$, then, the data sequence $X_i^{(1)}$ is superimposed at once to obtain the parameter column satisfying the least-squares estimation through Equation (2).

$$\hat{b} = [0.362, -0.019, 0.158, 0.591, 7.737]^T \tag{5}$$

Thus, the GM (0, 5) prediction model of flexural strength is obtained as

$$x_1^{(0)}(k) = 0.362x_2^{(1)}(k) - 0.019x_3^{(1)}(k) + 0.158x_4^{(1)}(k) + 0.591x_5^{(1)}(k) + 7.737 \tag{6}$$

As shown in Table 11, the average relative simulation error of GM (0, 5) model of flexural strength is 5.3%, while the corresponding accuracy is above 94%, which is a good prediction accuracy. When the optimal dosage combination of the flexural strength was substituted into Equation (6), the prediction value of the flexural strength is obtained as 9.7 MPa, reaching the level of P·O·42.5 Portland cement. By substituting the optimal dosage combination of compressive strength into Equation (6), the prediction value of flexural strength is 8.7 MPa, which is consistent with the strength of the reference group (9.2 MPa).

Table 11. Simulation error check of GM (0, 5) model for flexural strength.

Number	Actual Value	Simulated Value	Residual	Relative Simulation Error
2	7.766	8.203	−0.437	0.056
3	8.344	7.156	1.188	0.142
4	7.906	8.938	−1.032	0.130
5	8.844	8.556	0.288	0.033
6	8.734	8.758	−0.024	0.003
7	7.359	7.392	−0.033	0.004
8	7.586	7.594	−0.008	0.001
Mean				0.053

6. Economic Benefit Analysis

The cement industry is a material and energy-intensive industry, which not only consumes a lot of natural energy but also pollutes the environment. In practical engineering, cement as a cementitious material has a huge cost, while the cost of steel slag, metakaolin, and activator is relatively low. Activator, steel slag powder, metakaolin, and silica fume were used as cementitious materials in equal amounts instead of cement, and their economic benefits were evaluated. Through market research, the prices of activator, steel slag powder, metakaolin, silica fume, and ordinary silicate P·O·42.5 Portland cement are 170 RMB/ton, 100 RMB/ton, 400 RMB/ton, 1000 RMB/ton, and 450 RMB/ton, respectively. In practical engineering, the strength and cost requirements of cementitious materials are different according to different working conditions. Thus, it is imperative to provide the economic benefit analysis of various dosage combinations for appropriate binder selection. Based on the analysis of the above test results, the experimental group has a total of four steel slag powder dosage levels (10%, 20%, 30%, and 40%). The results of the economic benefit analysis based on the compressive strength and flexural strength are shown in Tables 12 and 13, respectively.

Table 12. Economic benefit analysis on the combination with highest compressive strength in each steel slag powder dosage level.

Dosage Combination of Binding Materials (%)					Cost (RMB/ton)		Reduction Rate (%)
Steel Slag Powder	Activator	Metakaolin	Silica Fume	Cement	Binging Materials in Study	Cement	
10	15	15	8	52	409.5	450	9.00
20	10	5	8	57	393.5		12.56
30	5	15	6	44	356.5		20.78
40	5	20	8	27	330		26.67
Max							26.67
Min							9.00

Table 13. Economic benefit analysis on the combination with highest flexural strength in each steel slag powder dosage level.

Dosage Combination of Binding Materials (%)					Cost (RMB/ton)		Reduction Rate (%)
Steel Slag Powder	Activator	Metakaolin	Silica Fume	Cement	Binging Materials in Study	Cement	
10	10	10	6	64	415	450	7.78
20	10	5	8	57	393.5		12.56
30	5	15	6	44	356.5		20.78
40	15	10	2	33	274		39.11
Max							39.11
Min							7.78

The results of the economic effect analysis indicate that the cost after cement replacement can be reduced by 9.00–26.67% compared to that before the replacement when the compressive strength is used as the benchmark for analysis. When the flexural strength is analyzed, it is seen that the cost after the cement replacement can be reduced by 7.78–39.11% compared to that before the replacement. For practical engineering, it is assumed that 10,000 m^3 of concrete with the required strength of 42.5 MPa, the amount of cementitious material per cubic meter of concrete is 0.4 ton. Using the method proposed in this study, the cost of cement per cubic meter of concrete can save 31–156 RMB. Thus, the total cost of cement replacement can be saved by at least 310,000 RMB and up to the maximum of 1560,000 RMB, which is a significant economic impact on the project.

7. Conclusions

A method of activating the activity of steel slag powder with neutral material is proposed. The validity of the proposed method is verified by experiments. Through orthogonal analysis, the optimal dosage combination of various components in the compound activator is determined. The grey prediction model is established to predict the strength of steel slag cement mortar under the optimal dosage combination of various factors. Considering the different requirements of cementitious materials in engineering, the economic benefits of several mix proportions are analyzed. The conclusions drawn from this study are appended below.

1/The experimental results show that with the change of steel slag powder dosage (10%, 20%, 30%, 40%), the compressive strength of mortar is affected. The highest strength of each dosage can reach more than 85% of the compressive strength of the control group. Similarly, the highest flexural strength can reach more than 90% of the flexural strength of the control group.

2/Through orthogonal analysis, it is ascertained that the activator is the primary factor influencing the strength of the steel slag cement mortar, and the optimal dosage combination of the compressive strength of the mortar is obtained as activator 5%, steel slag powder 10%, metakaolin 15%, and silica fume as 8%, while the optimal dosage combination of flexural strength is determined as activator 10%, steel slag powder 10%, metakaolin 10%, and silica fume 8%.

3/GM (0, 5) prediction models for compressive strength and flexural strength were established, respectively. The compressive strength and flexural strength of mortar were predicted. The prediction results of the compressive strength and flexural strength for the optimal dosage combination of compressive strength are 55.6 MPa and 8.7 MPa, respectively. The compressive strength and flexural strength at the optimal dosage combination for flexural strength are predicted to be 51.5 MPa and 9.7 MPa, respectively, which reach the strength level of P·O·42.5 Portland cement.

4/The research conducted on economic benefit analysis for multiple dosage combinations showed that the method proposed in this study can lower environmental pollution and reduce the project cost to a greater extent on the basis of meeting project requirements.

Author Contributions: J.G. and X.Y. designed the experiments. Y.Z., L.L., L.Z. and J.Y. carried out the experiments. X.Y. and Y.Z. analyzed the experimental results. J.G. and Y.Z. reviewed, and edited the manuscript. J.G. received the funding. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Natural Science Foundation of China, grant number 51779095, Program for Science & Technology Innovation Talents in Universities of Henan Province, grant number 20HASTIT013, and Sichuan Univ, State Key Lab Hydraul & Mt River Engn, grant number SKHL2007. The APC was funded by Program for Science & Technology Innovation Talents in Universities of Henan Province, grant number 20HASTIT013.

Data Availability Statement: All the relevant data and models used in the study have been provided in the form of figures and tables in the published article.

Acknowledgments: This project was sponsored by National Natural Science Foundation of China (51779095), Program for Science & Technology Innovation Talents in Universities of Henan Province (20HASTIT013), Sichuan Univ, State Key Lab Hydraul & Mt River Engn (SKHL2007).

Conflicts of Interest: The authors declare no conflict of interest to this work.

References

1. Pang, B.; Zhou, Z.H.; Hou, P.K. Autogenous and engineered healing mechanisms of carbonated steel slag aggregate in concrete. *Constr. Build. Mater.* **2016**, *107*, 191–202. [CrossRef]
2. Furlani, E.; Tonello, G.; Maschio, S. Recycling of steel slag and glass cullet from energy saving lamps by fast firing production of ceramics. *Waste Manag.* **2010**, *30*, 1714–1719. [CrossRef]
3. Das, B.; Prakash, S.; Reddy, P. An overview of utilization of slag and sludge from steel industrie. *Resour. Conserv. Recycl.* **2007**, *50*, 40–57. [CrossRef]
4. Xiang, X.D.; Xi, J.C.; Li, C.H. Preparation and application of the cement-free steel slag cementitious material. *Constr. Build. Mater.* **2016**, *114*, 874–879. [CrossRef]
5. Guo, Y.; Xie, J.; Zheng, W. Effects of steel slag as fine aggregate on static and impact behaviours of concrete. *Constr. Build. Mater.* **2018**, *192*, 194–201. [CrossRef]
6. Saxena, S.; Tembhurkar, A.R. Impact of use of steel slag as coarse aggregate and wastewater on fresh and hardened properties of concrete. *Constr. Build. Mater.* **2018**, *165*, 126–137. [CrossRef]
7. Cardoso, C.; Camões, A.; Eires, R.; Mota, A.; Araújo, J.; Castro, F.; Carvalho, J. Using foundry slag of ferrous metals as fine aggregate for concrete. *Resour. Conserv. Recycl.* **2018**, *138*, 130–141. [CrossRef]
8. Martinho, F.C.; Picado-Santos, L.G.; Capitao, S.D. Influence of recycled concrete and steel slag aggregates on warm-mix asphalt properties. *Constr. Build. Mater.* **2018**, *185*, 684–696. [CrossRef]
9. Zhang, P.; Zheng, Y.X.; Wang, K.J. A review on properties of fresh and hardened geopolymer mortar. *Compos. Part B Eng.* **2018**, *152*, 79–95. [CrossRef]
10. Sheen, Y.N.; Wang, H.Y.; Sun, T.H. A study of engineering properties of cement mortar with stainless steel oxidizing slag and reducing slag resource materials. *Constr. Build. Mater.* **2013**, *40*, 239–245. [CrossRef]

11. Calmon, J.L.; Tristão, F.A.; Giacometti, M.; Meneguelli, M.; Moratti, M.; Teixeira, J.E. Effects of BOF steel slag and other cementitious materials on the rheological properties of self-compacting cement pastes. *Constr. Build. Mater.* **2013**, *40*, 1046–1053. [CrossRef]
12. Li, D.X.; Fu, X.H.; Wu, X.Q.; Tang, M.S. Durability study of steel slag cement. *Cem. Concr. Res.* **1997**, *27*, 983–987.
13. Li, Y.X.; Chen, Y.M.; Wei, J.X. A study on the relationship between porosity of the cement paste withmineral additives and compressive strength of mortar based on this paste. *Cem. Concr. Res.* **2006**, *36*, 1740–1743. [CrossRef]
14. Wu, X.; Hong, Z.; Hou, X. Study on steel slag and fly ash composite Portland cement. *Cem. Concr. Res.* **1999**, *29*, 1103–1106.
15. Hu, S.G. Research on Hydration of Steel Slag Cement Activated with Waterglass. *J. Wuhan Univ. Technol. Mater. Sci.* **2001**, *16*, 37–40.
16. Hu, S.G.; He, Y.J.; Lu, L.N. Effect of fine steel slag powder on the early hydration process of Portland cement. *J. Wuhan Univ. Technol. Mater. Sci.* **2006**, *21*, 147–149.
17. Zhu, X.; Hou, H.B.; Huang, X.Q. Enhance hydration properties of steel slag using grinding aids by mechano chemical effect. *Constr. Build. Mater.* **2012**, *29*, 476–481. [CrossRef]
18. Altun, İ.A.; Yılmaz, İ. Study on steel furnace slags with high MgO as additive in Portland cement. *Cem. Concr. Res.* **2002**, *32*, 1247–1249. [CrossRef]
19. Zhang, P.; Wang, K.X.; Wang, J. Mechanical properties and prediction of fracture parameters of geopolymer/alkali-activated mortar modified with PVA fiber and nano-SiO_2. *Ceram. Int.* **2020**, *46*, 20027–20037. [CrossRef]
20. Huo, B.B.; Li, B.L.; Chen, C. Surface etching and early age hydration mechanisms of steel slag powder with formic acid. *Constr. Build. Mater.* **2021**, *280*, 1–11. [CrossRef]
21. Zhang, P.; Wang, K.X.; Li, Q.F. Fabrication and engineering properties of concretes based on geopolymers/alkali-activated binders—A review. *J. Clean. Prod.* **2020**, *258*, 1–22. [CrossRef]
22. Peng, X.Q.; Liu, C.; Li, S. Research on the setting and hardening performance of Alkali-activated steel slag-slag based cementitious materials. *J. Hunan Univ. (Nat. Sci.)* **2015**, *42*, 47–52. (In Chinese)
23. Sun, J.W.; Zhang, Z.Q.; Zhuang, S.Y. Hydration properties and microstructure characteristics of alkali–activated steel slag. *Constr. Build. Mater.* **2020**, *241*, 1–9. [CrossRef]
24. Huo, B.B.; Li, B.L.; Huang, S.Y. Hydration and soundness properties of phosphoric acid modified steel slag powder. *Constr. Build. Mater.* **2020**, *254*, 1–9. [CrossRef]
25. Zhang, T.S.; Liu, F.T.; Liu, S.Q. Factors influencing the properties of a steel slag composite cement. *Adv. Cem. Res.* **2008**, *20*, 145–150. [CrossRef]
26. Du, J.; Liu, J.X. Compound effect of dehydrate gypsum and silica fume on strength of steel slag-cement binding materials. *J. Civ. Archit. Environ. Eng.* **2013**, *35*, 131–136. (In Chinese)
27. Lin, Z.S.; Tao, H.Z. Research for Increasing the Activation of Steel Slag and Fly Ash. *J. Wuhan Univ. Technol.* **2001**, *2*, 4–7. (In Chinese)
28. Kang, L.; Zhang, Y.J.; Zhang, L. Preparation, characterization and photocatalytic activity of novel CeO2 loaded porous alkali-activated steel slag-based binding material. *Int. J. Hydrog. Energy* **2017**, *42*, 17341–17349. [CrossRef]
29. Yin, S.H.; Guo, H.; Yu, Q.J. Steel Slag Reconstruction Experiment by Reduction FeOx and Its Mineral Composition. *J. Chin. Ceram. Soc.* **2013**, *41*, 966–971. (In Chinese)
30. Zhao, H.J.; Yu, Q.J.; Wei, J.X. Effect of Composition and Temperature on Structure and Early Hydration Activity of Modified Steel Slag. *J. Build. Mater.* **2012**, *15*, 399–405. (In Chinese)
31. Wei, R.; Li, H.; Zhang, W. Mechanism and Recent Development of Steel Slag Activating Activity. *Mater. Rep.* **2014**, *28*, 105–108+128. (In Chinese)
32. Yi, L.S.; Wen, J. Research Status and Progress on the Steel Slag Activity Excitation Technology. *Bull. Chin. Ceram. Soc.* **2013**, *32*, 2057–2062. (In Chinese)
33. Guan, J.F.; Yuan, P.; Hu, X.Z. Statistical analysis of concrete fracture using normal distribution pertinent to maximum aggregate size. *Theor. Appl. Fract. Mech.* **2019**, *101*, 236–253. [CrossRef]
34. Yao, X.H.; Li, L.L.; Guan, J.F. Initial cracking strength and initial fracture toughness from three-point-bending and wedge splitting concrete specimens. *Fatigue Fract. Eng. Mater. Struct.* **2021**, *44*, 601–621. [CrossRef]
35. Yao, X.H.; Qin, P.Q.; Guan, J.F. Residual mechanical properties and constitutive model of high-strength seismic steel bars through different cooling rates. *Materials* **2021**, *14*, 469. [CrossRef] [PubMed]
36. *GB/T 17671-1999, Method of Testing Cements-Determination of Strength*; China Standards Press: Beijing, China, 1999. (In Chinese)
37. Guan, J.F.; Hu, X.Z.; Yao, X.H. Fracture of 0.1 and 2 m long mortar beams under three-point-bending. *Mater. Des.* **2017**, *133*, 363–375. [CrossRef]
38. Miah, M.J.; Patoary, M.; Paul, S.C. Enhancement of Mechanical Properties and Porosity of Concrete Using Steel Slag Coarse Aggregate. *Materials* **2020**, *13*, 2865. [CrossRef]
39. Chen, S.F. The Study of Sexual Assault under Age Factors Affection via GM (*0, N*) and Grey Structure Modeling. *J. Grey Syst.* **2015**, *18*, 173–179.
40. Ren, J. GM (*1, N*) method for the prediction of anaerobic digestion system and sensitivity analysis of influential factors. *Bioresour. Technol.* **2018**, *247*, 1258–1261. [CrossRef]

41. Yu, Y.F.; Zhu, S.Y.; Wang, H. A Forecasting Method of Road Freight Volume Based on GM (0, *N*). *J. Wuhan Univ. Technol. (Traffic Sci. Eng.)* **2010**, *34*, 93–96. (In Chinese)
42. Liu, S.F. *Grey System Theory and Application*; Science Press: Beijing, China, 2014. (In Chinese)
43. Zhang, G.X. *Chinese Quality Engineer Handbook*; Enterprise Management Publishing House: Beijing, China, 2002. (In Chinese)