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ORIGINAL RESEARCH PAPER

Mix Proportion Optimization of Grouts Used in Two-Stage Concrete

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Abstract

Two-stage concrete (TSC) is known as preplaced aggregate concrete, which is defined as concrete produced by placing coarse aggregate in the formwork, then filling the voids with a special grout mixture. The strength performance of grout and the ability of grout to flow around the aggregates is essential for TSC. In this study, a new grout for TSC was analyzed; it is composed of cement, water, and various admixtures. Using the response surface methodology, the result of the fluidity test was analyzed, regressing the relationship between the content of each admixture and fluidity. The results show that the water reducer has the greatest effect on fluidity, followed by silica fume and then fly ash. In addition, according to the results of the strength test, the relationship between the strength variability and content of each additive is regressed by the binary logistic regression analysis. Moreover, the mix proportion optimized by the logit model is verified to effectively reduce the variability of the compressive strength. Based on the obtained results, an optimal composition is proposed.

Keywords Two-stage concrete · Grout · Fluidity · Compressive strength · Flexural strength

1 Introduction

Two-stage concrete (TSC) is a type of concrete made by placing coarse aggregate in the formwork in advance, and then filling the voids of the aggregate with a special form of grout [1, 2]. The TSC grouting process can be performed either by considering gravity or by pressure pumping [3, 4]. Gravity grouting is a preparation method, in which the grout passes through the coarse aggregate to the bottom of the formwork under its own weight [5, 6]. The second method involves pumping the grout into the aggregate gap from the bottom through a network of pipes, as shown in Fig. 1. The preparation of grout with good fluidity can ensure that the preplaced aggregate is filled densely, thus improving the denseness of the TSC. Owing to the uniqueness of the TSC preparation technology, grout must be modified using various additives [7–12]. Many researchers have studied the factors affecting the fluidity of grout from different perspectives and put forward schemes on how to improve the fluidity. Shannag considered that superplasticizers and mineral admixtures could be added to meet the requirements of high-performance mortar. High-performance grout with high fluidity, no segregation, and no bleeding was obtained with the addition of mineral admixtures, such as quartz sand, superplasticizer, silica fume, and natural pozzolan. Experimental results showed that the grout had the characteristics of high strength and corrosion resistance [13]. Hu et al. studied the effect of fly ash, slag, and silica fume doses on the compressive strength, flexural strength, and fluidity of cement-based self-leveling mortar. The results showed that the fluidity and strength of the mortar increased and then decreased with the increase of the fly ash. When compounded, the fluidity of the mortar with equal amounts of slag, fly ash, and silica fume was most significantly improved. The strength was also higher than that of other mortars of the same age [14]. Du et al. prepared high-fluidity sulphoaluminate cement-based grouting material (SAGM). They verified through

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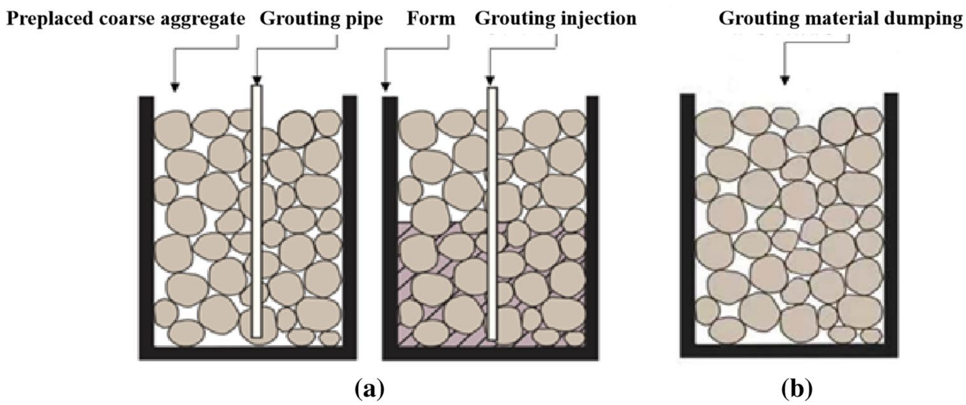

Fig. 1 Photograph of (a) pressure grouting process and (b) gravity grouting process

experiments that SAGM had high fluidity and micro-expansion, which could increase the interfacial adhesion between the grout and aggregate [15]. Huang et al. investigated the influence of limestone, silica fume, and fly ash on the fluidity of grouting materials. Their results demonstrated that the fluidity of the grouting material increased remarkably with the decrease in the dosage and grain size of limestone. However, with an increase in the dosage of silica powder and fly ash within certain limits, the fluidity of the grouting material increased. Therefore, they concluded that the fluidity improvement of the mineral admixture was closely related to its physical form, including the particle morphology, particle size, hydrophilicity, and surface smoothness of the mineral admixture. After adding mineral admixtures, the cementitious system changed from simple cement to a composite cementitious system. As such, the particle morphology, size, microstructure, and distribution changed. This change can be summarized as the "particle effect," "morphology effect," and "dispersion effect" of the mineral admixtures [16].

Researchers improve the durability of cement paste by adding various admixtures, and explore the influence of admixtures on the shrinkage durability and mechanical properties of cement [17, 18]. In the case of TSC, avoiding its shrinkage is difficult after grouting, and this causes decrease in the bond strength, thus reducing the strength of TSC. Collepardi et al. studied the effects of shrinkage reducers and lime-based expansive agents on mortar shrinkage. Their experimental results showed that owing to the synergistic effect of this composite admixture, the specimens expanded effectively in a humid environment and maintained low shrinkage in a dry environment after demolding [19]. Rongbing et al. observed that the dry and self-shrinkage of mortar decreased with an increase in shrinkage reducer. When the specimens were formed and removed without moisture curing, the dry-shrinkage rate of the specimens with the expansion agent was higher than that of the specimens with the shrinkage reducing the agent. This indicated that in the absence of water, the anti-shrinkage effect of the shrinkage reducer was better than that of the expansion agent [20]. Liu and Song studied the effects of fly ash, sand, and anti-crack waterproof agents on the self-shrinkage of grout. The test results showed that the sand and fly ash can effectively reduce the self-shrinkage rate of grout. An increase in the content of the anti-crack waterproof agent could also reduce the self-shrinkage of grout, but the content must be controlled to be within 10%. The addition of the anti-crack waterproof agent could supplement part of the self-shrinkage and achieve the effect of reducing the self-shrinkage rate [21]. He et al. investigated the effect of hydroxypropyl methylcellulose on the performance of mortars. The results indicate that HPMC reduces the fluidity of fresh mortar, and the compound use of HPMC and water reducer can improve the anti-bleeding property at similar fluidity. Appropriate content of HPMC improves the homogeneity of mortar, thereby increasing the compressive strength. HPMC refines the pore structure, reduces the porosity, and thus reducing the drying shrinkage and exerting positive effects on long-term durability [22].

The high strength variability of grout will lead to that of TSC after forming and hardening. Gong stated that with the increase of silica fume content, the compressive strength variability of ultra-high-performance concrete fluctuates up and down, and does not show an obvious law [23]. Ma et al. advocated that adding silica fume would increase the strength variability of mortar. However, there is a little of research on the strength variability of cement mortar [24]. Mineral admixtures are widely used as supplementary cementitious materials (SCMs) of mortar [25–28]. This paper discussed the influence of the proportion of mineral admixtures on the strength variability of grout mortar.

At present, the grout of TSC is difficult to meet the requirements of high fluidity and high strength at the same time, and there is also the problem of excessive strength variability. In summary, it is necessary to develop a new kind of grout with high fluidity, micro-expansion, no bleeding, good stability, and the strength.

In this paper, the experimental work investigated how to improve the grout fluidity and strength by different grout admixtures. The effect of water reducer, fly ash, and silica fume on the grout fluidity was studied by response surface methodology (RSM). Meanwhile, the logit model was used to optimize the mix ratio, which solved the problem of excessive variability of the compressive strength. The purpose of this research was to obtain the grout that meet requirements with low strength variability.

2 Materials and Methods

2.1 Raw Materials

Cement: For the preparation of all the grout mixtures in this experiment, P·O 42.5 Ordinary Portland cement produced by the Tianjin cement plant was used. The test results were given by professional testing institutions. The quality test results of various properties of the cement are shown in Table 1. Fly ash: The morphological effect of fly ash is mainly manifested as a spherical glass body with a relatively smooth surface, fine particle size, dense texture, and a small water-absorption force, which can reduce internal friction and has the effect of lubrication and water reduction. In this experiment, first-grade fly ash was used. Silica fume: Silica fume, a gray white powder, was used to fill the gap between cement particles, significantly improving the compressive and flexural strength and reducing segregation and bleeding. Water reducer: The selected water reducer is a polycarboxylic acid water reducer (powder). The shrinkage ratio (28 days) is 102%, and the compressive strength ratio is 190%, 177%, 171%, and 159% for 1, 3, 7, and 28 days, respectively. The analysis results of the components and properties of the three main admixtures are listed in Table 2.

Expansion agent: Expansion agents can effectively compensate for the shrinkage of concrete to improve its crack resistance and waterproof ability. The compound expansion agent used in this test was a yellow powder, with the limiting expansion rates of 0.05% (7 days in water), 0.083% (28 days in water), and 0.021% (28 days in air). Cellulose: These are 400 viscosity hydroxypropyl methylcellulose. After being dissolved in water, the cellulose was evenly distributed in the grout to wrap the solid particles to make the interior more lubricated; this further stabilizes the internal lubrication, and the water retention and workability are improved. Defoamer: A powder defoamer was selected with a grayscale of 35% (800 °C), the density of 340 g/L (20 °C), and a pH value of 7.2. Mixing water: Tianjin city tap water was used in this study, as mixing water cannot contain much chloride ions for more than 350 mg/L.

Table 2 Chemical and physical properties of additives

Chemical and physical analysis	Fly ash	Silica fume	Water reducer
Water demand ratio	93%	–	–
Ignition loss	4.4%	–	–
Fineness	10%	4.8%	–
SO_3	2.4%	–	–
SiO_2	–	94.96%	–
PH	–	9.5	8.8
Water reduction rate	–	–	27%
Gas content	–	–	4.8%
Cl^- content	–	–	≤0.03%

This study mainly focused on the change of water reducer and mineral admixture to achieve a set fluidity and ensure that all standards could be achieved, from which the optimal proportion can be selected to achieve normal use in the field construction. The fluidity of the cement paste was set to less than 17 s.

The doses of defoamer, expansion agent, and cellulose in the raw materials were determined as 1 g each. Accordingly, the dosage ranges of the other materials were determined. The cement dosage was 2600 g and the amount of water was 840 mL. The amount of water reducer was determined when the doses of silica fume and fly ash remained constant. Similarly, in the case of a constant amount of water reducer, the ranges of the other doses were determined.

2.2 Test Procedures

2.2.1 Grout Preparation

After all the weighing is completed, water was poured into the mixing pot; and the admixture was added for mixing. After mixing evenly, the cement was added in two parts. The cement and admixture were fully mixed along one direction. After mixing roughly, the mixing pot was installed on the mixer to begin mixing. The mixer speed

Table 1 Test results of the main technical indexes of cement

Testing items	Normal consistency (%)	Setting time(min)		Soundness (mm)	Compressive strength (MPa)		Flexural strength (MPa)	
		Initial setting	Final setting		3d	28d	3d	28d
Technical indexes	≤30	≥45	≤600	≤5	≥21	≥42.5	≥4.0	≥6.5
Testing results	27.3	140	320	1	23.2	45.1	4.2	7.5

was 1004 r/min and the mixing time was 8 min. After stirring was completed, the fluidity of the grout was checked, and the expansion and bleeding of the grout that meet the requirements were observed.

2.2.2 Fluidity Test

According to the test methods of cement and concrete for highway engineering specified in JTG E 30–2005, the fluidity affects the subsequent grouting process and the fullness of the TSC grouting. In this test, a flow cone was used to measure the flow time. The test steps are as follows:

Calibration of test equipment: Fix the flow cone on the tripod to ensure that the cone is perpendicular to the ground. Plug the outlet of the lower end with a finger, and then inject 1725 mL of water into the flow cone. If the water outflow time is 8.0 ± 0.2 s, this flow cone can be used for fluidity testing.

Specific procedures: The indoor temperature should be kept at 20 ± 2 °C, and the inverted cone should be moistened with water 1 min before its use. The outlet should be blocked with fingers. Pour the grout into the cone until it slows down when approaching the pointer until the volume is 1725 ± 5 mL. Release the finger and simultaneously stop the stopwatch; start the stopwatch again when the grout flows out intermittently.

2.2.3 Strength Test

The specific steps of the test are as follows. A prism mold of 40 mm × 40 mm × 160 mm was used to form three specimens at the same time using a group of mix proportions. Because the grout is liquid, the gap outside the mold should be blocked with cement to prevent grout leakage. The evenly mixed grout was poured into the test molds, and the specimens were cured in the laboratory environment (25 °C, 40% relative humidity) for 24 h. Then the formwork was removed and specimens were placed in water at room temperature for curing. The specimens were taken out after 7 days for conducting tests on the compressive and flexural strengths (Fig. 2).

Compressive strength test: The compressive strength test was conducted on the side of the half prism using a compressive strength testing machine. During the entire loading process, the loading rate was 2400 ± 200 N/s until the specimens were damaged. Compressive strength R_C is calculated as follows:

$$R_c = \frac{F_c}{A} \tag{1}$$

In Eq. (1), F_c is the maximum load at damage (N) and A is the compressed area (mm^2).

Flexural strength test: One side of the specimen was placed on the supporting cylinder of the testing machine, with its long axis perpendicular to the supporting cylinder. The loading cylinder was uniformly and vertically applied to the opposite side

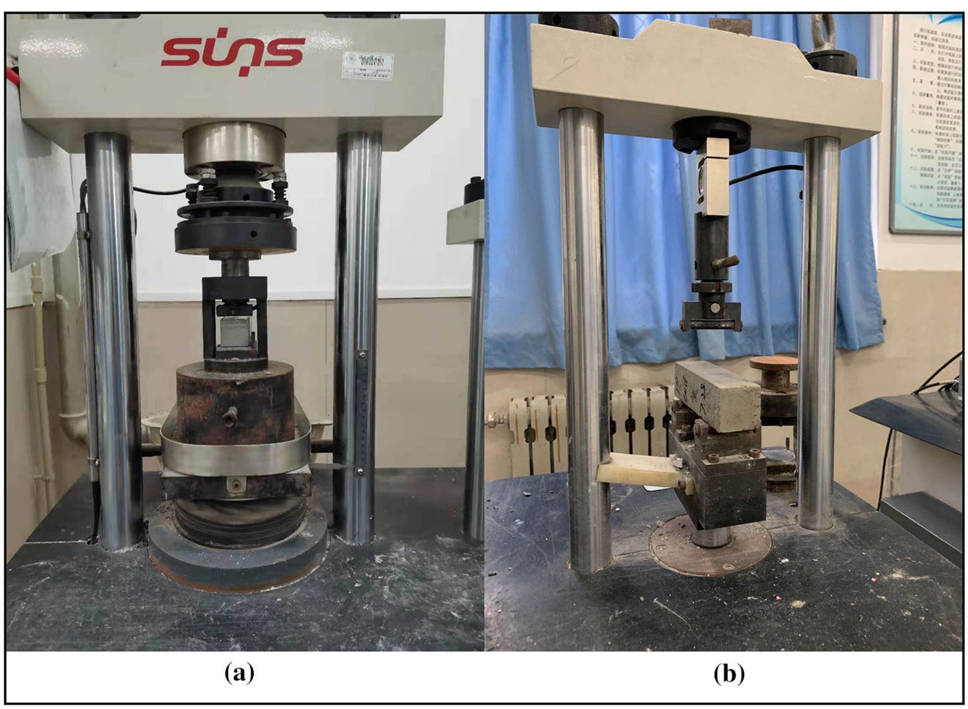

Fig. 2 Photograph of (a) compressive strength test and (b) flexural strength test

of the prism at a rate of 50 ± 10 N/s until it broke. The two half prisms were maintained in a wet state until the compression test. Flexural strength R_f can be calculated as follows:

$$R_f = \frac{1.5F_f L}{b^3} \tag{2}$$

In Eq. (2), F_f is the load applied to the middle of the prism when damaged (N), L is the distance between the supporting cylinders (mm), and b is the side length of the square section (mm).

2.3 Statistical Design

2.3.1 Design of Experiments

The response surface methodology (RSM) was used to establish response surfaces and contour plots for the properties investigated. The response surfaces and contour plots were obtained from the regression models expressed through equations [29, 30]. To investigate the effects of silica fume, fly ash, and water reducer on the grout fluidity, this study used the Box–Behnken design with fluidity as the response value. Three main processing parameters were considered, namely the contents of silica fume, fly ash, and water reducer, each with three levels. A mix at the central point was replicated three times to estimate the experimental error and improve the model reliability. The experimental design is described in Table 3.

2.3.2 Logit Model Formulation

Strength variability is an important index for evaluating the quality of concrete strength. To study the relationship between strength variability and additive content, a binary logistic model was established. Although the forms of variation of the compressive strength are different, only two kinds of variation exist: "variation" or "no variation". This characteristic is in line with the binary response and can be simulated using the logit model:

$$P = P\left(Y_i = 1 | X_i = x_i\right) = \frac{\exp\left(\beta_0 + \beta_i X_i\right)}{1 + \exp\left(\beta_0 + \beta_i X_i\right)} \tag{3}$$

Table 3 Coding and levels of the variables

Factor	Factor level and coding		
	– 1	0	+ 1
Water reducer (g)	17	18	19
Silica fume (g)	170	180	190
Fly ash (g)	189	199	209

$$\log it\,(P) = \log\left(\frac{P}{1-P}\right) = \beta_0 + \beta_i X_i \tag{4}$$

where Y is the binary response variable; Yi = 1 and 0 if the strength variation coefficient is more and less than 10%, respectively. Xi is a set of explanatory variables for observation. The independent variables include the contents of the water reducer, silica fume, and fly ash. β_i indicates the change in the natural logarithm of the ratio when factor X_i increases by 1 g. The positive and negative values of β_i indicte positive and negative correlations, respectively.

3 Results and Discussion

3.1 Influence of Additive Amount on Fluidity

The amounts of defoamer, expansion agent, and cellulose in the raw materials were determined as 1 g each. The initial test results to determine the dosage range of various additives are listed in Table 4.

The results of various experiments showed that when the amount of cement is reduced and that of the water reducer is constant, the fluidity time reduces and the amounts of silica fume and fly ash increase. The morphological effect of fly ash is mainly manifested as a spherical glass body with a relatively smooth surface, fine particle size, dense texture, and a small water-absorption force, which can reduce internal friction and has the effect of lubrication and water reduction Adding silica fume and fly ash can save cement and reduce hydration heat, when preparing grout. Moreover, due to the morphological effect and micro-aggregate effect

Table 4 Initial test results of fluidity test

Group	Water reducer (g)	Silica fume (g)	Fly ash (g)	Cement (g)	Fluidity (s)
1	17	140	140	2700	16.56
2	18	140	139	2700	16.4
3	19	140	138	2700	16.28
4	17	190	190	2600	15.82
5	16	180	201	2600	17.97
6	18	200	179	2600	15.28
7	18	200	250	2529	17
8	18	190	189	2600	16.25
9	18	180	149	2650	17.37
10	18	210	169	2600	16.86
11	18	180	199	2600	15.82
12	18	170	209	2600	15.27
13	18	160	219	2600	16.22
14	18	150	229	2600	15.97

of admixture, it can also improve the workability, strength, and durability of concrete. Denser internal pore structure can also be obtained. In addition, the incorporation of admixtures in concrete has an inhibitory effect on the alkali–aggregate reaction.

The parameters were selected based on the data obtained through several groups. The doses of the water reducer, silica fume, and fly ash were 17–19 g, 170–190 g, and 189–209 g, respectively, while the amounts of the defoamer, cellulose, and expansive agent remained constant. In addition, the RSM was used to determine the optimal mix proportion. Table 5 shows the regression analysis results based on fluidity.

After the response value was fitted with each factor, the regression equation was obtained as follows:

Table 5 Results of regression analysis based on fluidity

Source	Sum of squares	*df*	Mean squares	*F* value	*P* value
Model	3.91	9	0.43	7.30	0.0079
A Water reducer	2.71	1	2.71	45.56	0.0003
B Silica fume	0.20	1	0.20	3.38	0.1084
C Fly ash	0.003612	1	0.003613	0.061	0.8126
AB	0.024	1	0.024	0.40	0.5456
AC	0.24	1	0.24	3.95	0.0873
BC	0.17	1	0.17	2.82	0.1369
A^2	0.23	1	0.23	3.82	0.0915
B^2	0.31	1	0.31	5.51	0.0575
C^2	0.008526	1	0.008526	0.14	0.7164
Lack of fit	0.30	3	0.10	3.44	0.1321
Pure error	0.12	4	0.029		

$$Y = 15.76 - 0.58X_1 - 0.16X_2 + 0.021X_3 + 0.077X_1X_2 + 0.24X_1X_3 + 0.2X_2X_3 + 0.23X_1^2 + 0.27X_2^2 - 0.045X_3^2 \quad (5)$$

where X_1, X_2, and X_3 are the contents of the water reducer, silica fume, and fly ash, respectively.

The amount of water reducer is the most significant factor affecting fluidity. In addition, the fitting equation helps express that the influence of various factors on fluidity is reliable.

In Eq. (5), 15.76 is a constant, indicating that the average fluidity of the grout is at a medium level, and the fluidity has a more obvious relationship with the admixture amount. According to this relationship, the order of the influence of the three additives is as follows: water reducer, silica fume, and fly ash.

The contour and response surface of the influence of various factors on the fluidity of the grout are shown in Fig. 3. The interaction between the water reducer and the other two admixtures has a more significant influence on fluidity. The interaction between the silica fume and fly ash has little effect on fluidity, and is reflected on the response surface [29, 31], which is relatively smooth and spherical. This is consistent with the analysis of the regression equation. The water reducer is a more significant influencing factor than silica fume and fly ash on fluidity, mainly because it is the main factor in improving the fluidity. In this case, the response surface is relatively steep, indicating that the water reducer is the main factor affecting fluidity. As shown in Fig. 4, the effect of the water reducer is considerable when its dosage is 18–19 g.

The grouting material with the water reducer, silica fume, and fly ash as the main admixtures can effectively improve the fluidity. Furthermore, the addition of silica fume and fly ash improves not only the fluidity but also the strength. As a dispersant for cement, the water reducer can reduce the water consumption for mixing without affecting the fluidity.

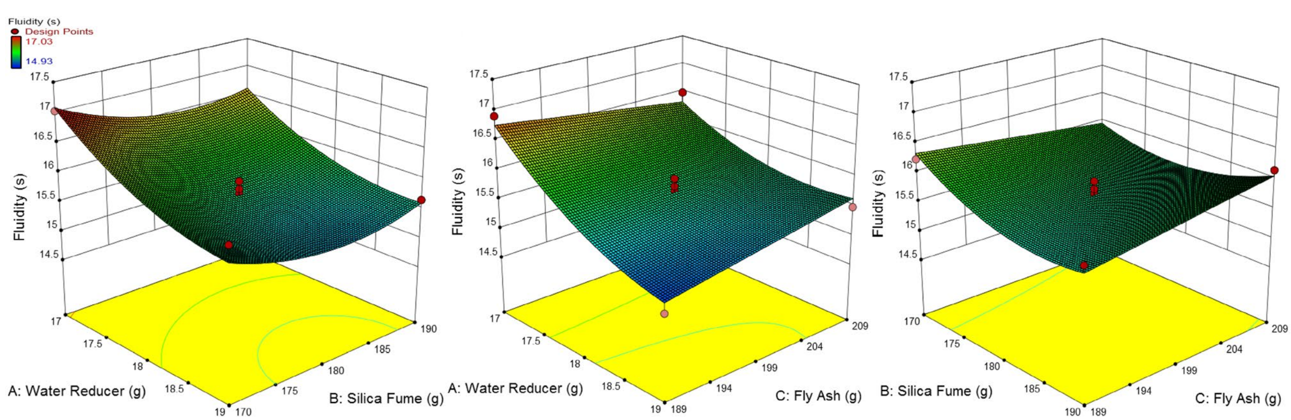

Fig. 3 3D response surface plots with different parameters

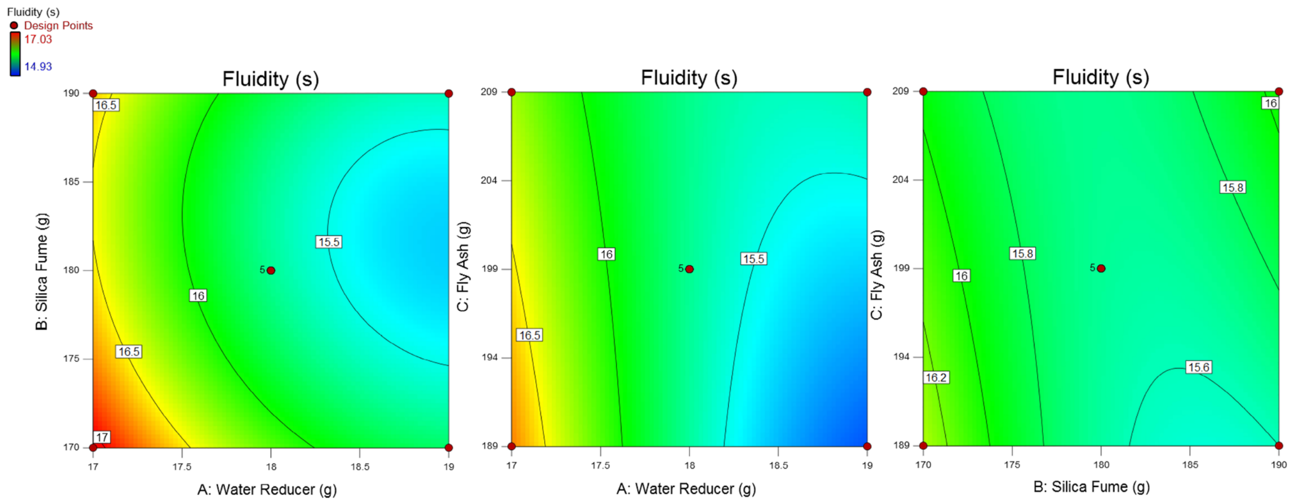

Fig. 4 Contour map with different parameters

In this test, polycarboxylate water reducer was used; it is a water-soluble polymer formed by the polymerization of various vinyl monomers, and this increases the contact area between cement and water, enhances the hydration reaction, and prevents cohesion. Although the addition of silica fumes will strengthen the matrix and interface transition zone of concrete, it increases the temperature of the early hydration reaction and increases the cost. This problem can be solved by the addition of low-water activity fly ash, and thus improve the later strength of TSC. This cement–silica fume–fly ash ternary cementitious material further stabilizes the grout and can effectively prevent bleeding and delamination. In general, the effect of the water reducer on the grout fluidity is more significant than that of silica fume and fly ash.

3.2 Influence of Additive Amount on Strength

The test results of the compressive and flexural strengths of each group of the response surface are shown in Table 6. This testing was conducted according to the method of testing cement-determination of strength specified in

Table 6 Test results of compressive and flexural strengths

Group	Water reducer (g)	Silica fume (g)	Fly ash (g)	7d Compressive strength (MPa)			7d Flexural strength (MPa)		
				AVG	S.D	C.V	AVG	S.D	C.V
1	18	180	199	51.0	3.14	6.2%	10.2	1.76	17.3%
2	17	180	189	51.2	7.33	14.3%	11.6	2.35	20.3%
3	18	180	199	51.1	6.67	13.1%	7.5	0.30	4.0%
4	18	190	209	46.3	6.13	13.2%	9.3	1.87	20.1%
5	18	170	209	48.6	6.72	13.8%	10.2	1.00	9.8%
6	19	170	199	47.9	12.80	26.7%	10.0	1.16	11.6%
7	18	180	199	49.5	8.07	16.3%	7.8	0.35	4.4%
8	18	170	189	43.2	9.88	22.9%	10.1	1.17	11.6%
9	17	170	199	48.8	6.82	14.0%	9.7	0.85	8.8%
10	18	180	199	51.2	6.71	13.1%	10.1	0.36	3.6%
11	19	180	209	43.3	3.71	8.6%	11.4	0.55	4.8%
12	19	180	189	54.7	9.47	17.3%	10.5	2.02	19.3%
13	17	180	209	47.3	6.31	13.3%	9.8	1.90	19.5%
14	18	190	189	54.7	9.41	17.2%	10.6	1.25	11.8%
15	19	190	199	48.9	4.38	8.9%	10.5	2.59	24.7%
16	18	180	199	50.1	4.96	9.9%	10.3	0.72	7.0%
17	17	190	199	47.2	14.61	30.9%	9.2	1.84	20.0%

GB/T 17671–1999. The test standard of flexural strength involves the calculation of the average of the results of a group of three test pieces. Among the three intensity values, anyone that exceeds ± 10% of the average value should be eliminated, then the remaining values will be averaged as the experimental result. The test standard of compressive strength is based on the arithmetic mean of the measured values of six compressive strengths in a set of three specimens obtained as the experimental result. If one of the six measured values exceeds ± 10% of the six average values, this result should be eliminated and the average of the remaining five is calculated as the result. If any of the five measured values exceeds ± 10% of their average, the result is considered invalid.

Only the test data of groups 1, 11, 15, and 16 met the requirements. The specimens of groups 6, 8, and 17 have lower compressive strength values, and therefore the test results were revised to determine the impact of intensity variability.

The experimental data of group 11 show an optimal mix proportion with better fluidity than the other groups, and its compressive variability meets the requirement. In addition, the same parallel test was performed on this group to determine, whether this mix proportion fully meets the requirements. The results are shown in Table 7.

The experimental results showed that the six sets meet the specification requirements. Therefore, the best mixing proportion was given which included the water reducer, silica fumes, fly ash, and cement of 19, 180, 209, and 2589 g, respectively, with 1 g content each of the cellulose, defoamer, and expansion agent.

Although the strength of most specimens meets the requirements, the strength variation coefficient of most specimens exceeded the allowable value. To determine which type of admixture has a greater influence on the intensity variation coefficient, the following test was conducted by replacing silica fumes or fly ash with cement. Modifications were made to the mix proportions of groups 6, 8, and 17, and the measurement results of their corresponding compressive strengths are shown in Table 8.

The experiment results showed that the first eight groups displayed a significant variability with only the addition of silica fume. The remaining five groups with only the addition of fly ash showed a significant decrease in strength

Table 7 Parallel test results of compressive and flexural strengths for the optimal mix proportion

Group	Water reducer (g)	Silica fume (g)	Fly ash (g)	Fluidity (s)	7d Compressive strength (MPa)			7d Flexural strength (MPa)		
					AVG	S.D	C.V	AVG	S.D	C.V
1	18	180	199	15.5	66.2	3.61	5.4%	14.0	0.31	2.2%
2	17	180	189	16.9	71.8	8.30	11.6%	13.4	0.70	5.2%
3	18	180	199	15.7	67.1	4.74	7.1%	11.7	0.23	2.0%
4	18	190	209	16.15	67.9	4.78	7.0%	11.2	1.11	9.8%
5	18	170	209	15.84	56.7	8.62	15.2%	9.8	1.30	13.3%
6	19	170	199	16.03	64.1	5.35	8.3%	12.2	0.62	5.1%

Table 8 Results of compressive strength test of the modified mix proportion

Group	Water reducer (g)	Silica fume (g)	Fly ash (g)	Fluidity (s)	7d Compressive strength (MPa)			7d Flexural strength (MPa)		
					AVG	S.D	C.V	AVG	S.D	C.V
1	17	180	–	2800	51.3	11.27	22.0%	12.0	1.32	11.0%
2	18	180	–	2799	38.3	7.67	20.0%	11.0	1.32	12.0%
3	18	190	–	2789	53.2	9.13	17.2%	13.6	4.06	29.8%
4	18	190	–	2789	53.5	13.77	25.7%	11.7	2.54	21.7%
5	18	170	–	2809	54.6	14.00	25.6%	12.9	0.49	3.8%
6	19	170	–	2808	46.8	7.44	15.9%	13.5	1.48	11.0%
7	19	180	–	2798	51.0	20.45	40.1%	10.5	2.23	21.2%
8	17	190	–	2790	54.3	15.82	29.1%	12.2	0.93	7.6%
9	18	–	199	2780	60.1	7.31	12.1%	12.3	0.44	3.5%
10	18	–	199	2780	47.8	5.84	12.2%	12.0	1.05	8.7%
11	18	–	189	2790	50.6	3.45	6.8%	12.1	0.60	5.0%
12	17	–	199	2781	55.4	4.90	8.8%	14.5	1.44	9.9%
13	19	–	189	2789	48.5	8.18	16.9%	14.0	1.31	9.3%

variability and most of them met the strength requirements. The results showed that silica fume is the main factor affecting strength variability because it can increase heterogeneity of mortar. Thus, stress concentration is occurred when the load is applied on the specimen. The macroscopic manifestation is reflected in the increase of strength variability.

3.3 Compressive-Strength Variability Prediction

If the compressive strength does not meet the standards of the method of testing cement determination of strength, it is considered to have varied. According to the experimental results, variability was not observed in groups 1, 11, 15, and 16. Using the binary logistic regression analysis in the Minitab software to calculate the mix proportion, the following relationship is obtained:

$$\text{Logit}\,(Y) = 90 - 0.163X_1 - 2.77X_2 - 0.045X_3 \quad (6)$$

Equation (6) shows that the coefficients of the water reducer, silica fume, and fly ash are all negative, and this could inhibit the variability of the compressive strength. The coefficient of silica fume is the smallest, and silica fume has the greatest impact on the compressive strength variability. The coefficient of water reducing agent is the second, and the water reducer should not be added in large quantities. An appropriate increase in the proportions of water reducer, silica fume, and fly ash can reduce the variation coefficient of the compressive strength. The final selected mix proportion was as follows: 18 g of water reducer, 209 g of silica fume, 209 g of fly ash, and 1 g each of cellulose, defoamer, and expansion agent.

To test whether the mix proportion optimized by the logit model can effectively reduce the variability of compressive strength, specimens were prepared by adding different amounts of cement according to the optimized mix proportion. 2500 g, 2600 g, and 2700 g cement were added to group 1, 2, and 3, respectively. After curing for 3, 7, and 28 days, the compressive strengths of the specimens were measured, as shown in Fig. 4.

According to Table 8 and Fig. 5, the compressive strength of all specimens meets the requirements. Regarding variability, only the 7-day compressive strength of the first group showed a data error exceeding 10%; after excluding this error, the average error of the other five compressive strengths was calculated as within 10%, which meets the requirements. This shows that the compressive strength of the optimized grout mix proportion completely meets the qualification inspection standard of the method of testing cement determination of strength, thus proving the effectiveness of the optimization of the grout mix proportion using the logit model. In addition, the fluidity, bleeding rate, expansion rate, and other performance

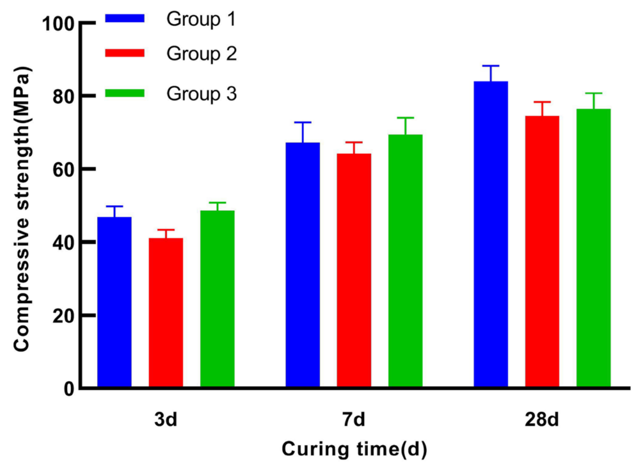

Fig. 5 Results of the compressive strength of the optimal mix proportion

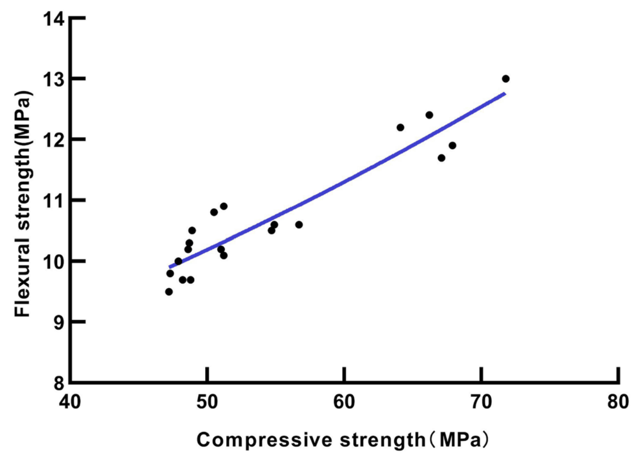

Fig. 6 Flexural strength plotted against compressive strength

indicators of the grout prepared with this mixture proportion meet the requirements.

3.4 Correlation Between Compressive and Flexural Strengths

The results of this investigation show a good correlation between the compressive and flexural strengths. The flexural strength increases with an increase in the compressive strength. Figure 6 shows that the relationship between the compressive and flexural strengths. In the present work, Eq. (7) was formulated through regression analysis to determine the relationship between flexural and compressive strengths.

$$f_f = 0.0006f_c^2 + 0.445f_c + 6.4479 \quad (7)$$

where f_f is the compressive strength (MPa), f_c is the flexural strength (MPa), and the correlation coefficient $r = 0.939$ shows that the regression is reasonable.

4 Conclusion

According to the research conducted on the influence of the amounts of grouting additives on the fluidity and strength, the following conclusions can be drawn.

1 The test results of the RSM showed that the average fluidity of the grout is at a medium level and has a more obvious relationship with the mixing amount of the water reducer, silica fume, and fly ash. The influence of these parameters on the fluidity is in the following order: water reducer > silica fume > fly ash.
2 The calculation of the test results showed that the compressive strength error of most groups exceeded 10% except groups 1, 11, 15, and 16, and thus do not meet the standard qualification inspection standards. Moreover, this phenomenon exists for all ages of the cement. The number of groups accounts for half of the total number, indicating that the mix proportion might be the influencing factor of the excessive strength variability.
3 The water reducer, silica fume, and fly ash can restrain compressive strength variability to some extent. The final optimized results showed the contents of 209 g of silica fume, 18 g of water reducer, 209 g of fly ash, and 1 g each of the expansive agent, cellulose, defoamer. These test results show that the compressive strength meets the requirements, and the variability is significantly reduced. The average error is within 10%. In addition, other performance indicators were observed to meet the requirements, indicating the effectiveness of the application of the logit model to mix proportion optimization.
4 The compressive and flexural strengths were tested after 7 days for all grout proportions. The results showed a positive correlation between the compressive and flexural strengths.

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Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

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