Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 10, No. 1, 2024

Experimental Study on Optimizing Grouting Material Ratio for Rebar Sleeve Connections

Ziqi Wang

School of Environment and Architecture, University of Shanghai for Science and Technology, Shanghai 200093, China

Abstract: In response to the inadequate performance reliability of existing prefabricated sleeve grouting materials, this study used an orthogonal experimental design method to prepare 16 sets of grouting materials based on C52.5 cement and ordinary river sand, with different water-cement ratios and varying amounts of additives including silica fume, defoamers, water reducers, and expansive agents. The effects of silica fume, defoamers, water reducers, expansive agent dosage, and water-cement ratio on the compressive strength, vertical expansion rate, and fluidity of the grouting material were studied. Based on the experimental results and comprehensive analysis, a formulation for high-performance grouting material with high reliability was determined, providing a greater safety margin for practical engineering applications.

Keywords: Prefabricated construction; High-performance sleeve grouting material; Orthogonal experimental design.

1. Introduction

A With the rapid progress of urbanization and continuous updates in construction technology, prefabricated construction [1] has seen significant development. Promoted vigorously in various countries and especially in the core areas of large cities, prefabricated construction methods have become mainstream. In prefabricated construction, the most important and challenging aspect is the connection method and reliability of prefabricated components. The current mainstream construction methods mainly include dry connection and wet connection [2], with dry connections like bolted and mechanical connections, and wet connections like dovetail anchorage and grout sleeve connections. Among these, grout sleeve connections, due to their high reliability and controllable construction process, are the most widely used connection method for prefabricated components.

In grout sleeve connection technology, the work performance of grouting material is a critical guarantee for connection performance and reliability, holding significant research significance. Many scholars have studied the structural performance of steel sleeve grout connections [3-6]. However, the grouting materials commonly used in engineering projects are prefabricated materials produced by specialized factories, with basic performance only meeting the lower limits of specifications. Given the practical deviations in construction, the reserved safety margins often fail to meet the engineering requirements. In this study, 16 different grouting materials were prepared through experiments by the author, and various performance tests were conducted on standard specimens, followed by result analysis.

2. Experimental Design

2.1. Materials

The grouting materials used in this study were prepared by the author based on the requirements stipulated in JG/T408-2019 “Cementitious grout for sleeve of rebar splicing,” [7] using C52.5 cement and ordinary river sand as the base. Five factors were considered for the study, including silica fume, polyether-based defoamer agent, polycarboxylate-based water reducing agent, plasticizing expansive agent, and water-cement ratio. The properties of the additive materials are presented in Table 1, and the appearance of the materials is shown in Figure 1.

Table 1. Material properties of grouting materials

Component	Properties
P.O52.5 Cement	Compressive Strength at 3 days: 32.2MPa, Specific Surface Area: 382m^2/kg
Silica fume	Dark grey powder, SiO2 content: 91.6%, Average Particle Size: 0.1~0.3μm, Specific Surface Area: 20~28m^2/g
River sand	Ordinary river sand: 10 mesh~20 mesh; 20 mesh~40 mesh; 40 mesh~60 mesh
Polycarboxylate water reducing agent	White powder, Recommended Dosage: 0.16~0.3% of cementitious materials
Plastic expansive agent	Light yellow powder, Specific Surface Area: 250m^2/kg
Polyether defoaming agent	White powder, pH value: 6~8
Water	Ordinary tap water



(a) Cement (b) Silica fume (c) River sand



(d) Expansive agent (e) Defoaming agent (f) Water reducing agent

Figure 1. Material appearance

2.2. Grouting material performance indicators and testing methods

This study selected compressive strength, vertical expansion ratio, and fluidity as the key indicators of the performance of the grouting materials prepared for research and analysis.

2.2.1. Compressive strength

In this experiment, the compressive strength was determined according to GB/T17671-2021 “The method of cement mortar strength (ISO method)” [8], as shown in Figure 2.

Figure 2. Compressive strength test

2.2.2. Vertical expansion ratio and fluidity

The vertical expansion ratio and fluidity of the mortar were determined using the contact type vertical expansion ratio measurement method and fluidity test method in the appendix of JG/T408-2019 “Cementitious grout for sleeve of rebar splicing,” as shown in Figures 3 and 4.

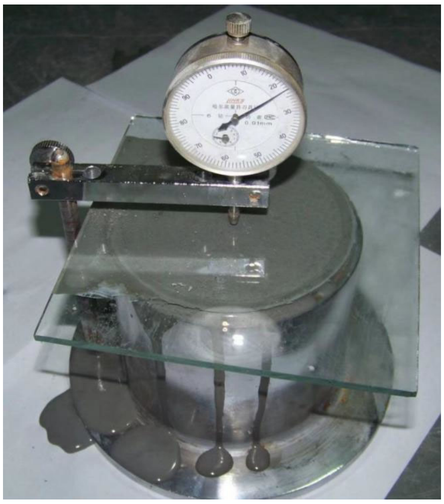

Figure 1. Vertical expansion ratio test

Figure 2. Fluidity test

3. Experimental Design

This study used orthogonal experimental design for experimental planning. Orthogonal experimental design is a method that reduces the number of test groups and improves test efficiency while still ensuring a high degree of reliability in studying the impact of various factors on the target results and the optimal combination of factors.

The silicon fume content, polyether defoamer content, polycarboxylate water reducing agent content, plastic expansive agent content, and water-cement ratio are selected as influencing factors, each with four levels as shown in Table 2. An orthogonal experiment is designed with 3d compressive strength, 3h vertical expansion rate, and initial fluidity as indicators. The $L_{16}(4^5)$ orthogonal table is used for the experimental design, and the measured results are filled in as shown in Table 3.

Table 2. Level setting of orthogonal experiment factors

(A) Silica fume /%	(B) Defoamer agent /‰	(C) water reducing agent /‰	(D) expansive agent /‰	(E) **water-cement ratio**
2.5(1)	0(1)	0(1)	0(1)	0.22(1)
5(2)	3(2)	3(2)	1(2)	0.25(2)
10(3)	6(3)	6(3)	2(3)	0.27(3)
12.5(4)	9(4)	9(4)	3(4)	0.3(4)

Table 1. Orthogonal experimental table

Test number	Test factors					Compressive strength /MPa	Vertical expansion ratio /%	Fluidity /mm
	A	B	C	D	E			
1	1	1	1	1	1	74	0.33	329
2	1	2	2	2	2	87	0.41	371
3	1	3	3	3	3	88	0.47	401
4	1	4	4	4	4	82	0.63	412
5	2	1	2	3	4	118	0.56	428
6	2	2	1	4	3	132	0.71	398
7	2	3	4	1	2	136	0.41	366
8	2	4	3	2	1	126	0.50	317
9	3	1	3	4	2	115	0.58	360
10	3	2	4	3	1	121	0.52	333
11	3	3	1	2	4	124	0.60	403
12	3	4	2	1	3	123	0.37	389
13	4	1	4	2	3	94	0.33	399
14	4	2	3	1	4	101	0.33	407
15	4	3	2	4	1	107	0.64	328
16	4	4	1	3	2	88	0.52	357

4. Data Analysis

Range refers to the difference between the maximum and minimum values of measured indicators at different levels of each factor. A larger range indicates a greater impact of the factor. In this study, range analysis method was used to analyze the three indicators separately. Considering the influencing mechanisms of each factor and the importance of each indicator in practical engineering, a set of optimal factor combinations was determined.

An indicator analysis table was created based on the experimental results, as shown in Tables 4 to 6.

Table 4. Analysis table of compressive strength

		A	B	C	D	E
Analysis results	T1	332	401	418	434	428
	T2	512	441	435	431	441
	T3	483	455	424	415	437
	T4	390	419	432	436	425
	R	180	54	17	21	16
	Primary and secondary order	ABDCE				
	Optimal combination	$A_2B_3C_2D_4E_2$				

Table 5. Analysis table of vertical expansion ratio

		A	B	C	D	E
Analysis results	T1	1.84	1.80	2.16	1.44	1.99
	T2	2.18	1.97	1.98	1.84	1.92
	T3	2.07	2.12	1.88	2.07	1.88
	T4	1.82	1.89	1.89	2.56	2.12
	R	0.36	0.32	0.28	1.12	0.24
	Primary and secondary order	DABCE				
	Optimal combination	$A_2B_3C_1D_4E_4$				

Table 2. Analysis table of fluidity

		A	B	C	D	E
Analysis results	T1	1513	1516	1487	1491	1307
	T2	1509	1509	1516	1490	1454
	T3	1485	1498	1485	1519	1587
	T4	1491	1475	1510	1498	1650
	R	28	41	31	29	343
	Primary and secondary order	EBCDA				
	Optimal combination	$A_1B_1C_2D_3E_4$				

In the table, "Tn" represents the sum of measured values corresponding to the n-th category of factors, and "R" represents the range of these values. Factors with larger ranges have a greater impact on the indicator. Therefore, the order of factors from largest to smallest range determines their importance. The combination of factors corresponding to the optimal indicator values is considered the optimal combination.

Based on the analysis of the three indicators, it is clear that there are prominent main factors influencing all three performance indicators. Therefore, in determining the mix ratio, the three key factors $A_2D_4E_4$ can be first selected. Factors B and C, serving as additive components, do not have a dominant impact on the indicators. According to the analysis results, the combination of B_3C_2, which was found to be optimal for two out of the three indicators, can be considered for use.

5. Conclusion

This study designed an orthogonal experimental plan and experimentally measured three important indicators: compressive strength, vertical expansion ratio, and fluidity. The study analyzed the impact of adding different amounts of silicon ash, air-entraining agent, water reducing agent, expansive agent, and adjusting the water-cement ratio on these three major indicators based on C52.5 cement and ordinary river sand. After comprehensively analyzing the degree of influence and effects, the study determined that the combination of $A_2B_3C_2D_4E_4$ is the optimal one, providing a grouting material mix design with a higher safety margin for practical engineering applications. The following conclusions were drawn from the experimental work:

1) Compressive strength, vertical expansion rate, and fluidity are mainly influenced by the amount of silicon fume, vertical expansion rate, and water-cement ratio, which should be emphasized in practical engineering applications.

2) The grouting material mix design obtained in this study outperforms factory-prepared grouting materials in terms of performance, providing a more reliable safety margin for engineering practices and ensuring better connection effects for prefabricated components.

3) Due to the large amount of experimentation, there may be some experimental errors, and the actual utility of additives that did not play a dominant role in the three major performance indicators examined in this study was not significantly demonstrated. Future research could focus on analyzing these additive components using other performance indicators to reach a more comprehensive conclusion.

4) The orthogonal experimental method used in this study is concise and clear, making it a feasible method for pre-construction experiments by construction site engineers. However, future research should delve deeper into further studying and exploring the interactions between various factors.

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