# Research on the Performance of Cement-Sodium Silicate Grout for Synchronous Grouting in Shield Tunnel

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**Abstract .** Compared to single-fluid grout, cement-sodium silicate grout have the characteristics of shorter gel time and faster early strength. Based on filling the annular void at the shield tail, they can effectively prevent the flotation of segments. Therefore, it is necessary to analyze the performance of cement-sodium silicate grout and determine the optimal ratio for construction. To investigate the grout performance under different water-cement ratios and the volume ratio of liquid A to liquid B, this paper designed indoor grout experiments with different grout ratios and tested the gel time, initial setting time, final setting time, and compressive strength of the grout. The main conclusions are as follows: the gel time of the grout is positively correlated with the water-cement ratio and negatively correlated with the volume ratio of the grout; the initial setting time and final setting time of the grout are positively correlated with the water-cement ratio and the volume ratio of the grout; the strength of the grout is negatively correlated with the water-cement ratio and the volume ratio of the grout. Furthermore, by conducting function fitting for the gel time, initial setting time, final setting time, and compressive strength of the grout under different water-cement ratios and grout volume ratios, this study provides a basis for selecting ratios for subsequent projects using cement-sodium silicate grout and offers scientific guidance for grout adjustment during tunnel construction.

**Keywords:** shield tunnel, synchronous grouting, cement-sodium silicate grout, grout properties

## 1 INTRODUCTION

During shield tunnel construction, due to the fact that the excavation diameter of the cutter head is larger than the diameter of the segments, an annular void forms between the segments and the surrounding soil. If grout is not used to fill this void, it may cause excessive surface settlement and uneven stress on the segments during construction. Additionally, synchronous grouting can improve the impermeability of the segments, serve as a strengthening layer for the tunnel, and restrain the segments from floating [1,


B. Yuan et al. (eds.), *Proceedings of the 2024 8th International Conference on Civil Architecture and Structural Engineering (ICCASE 2024)*, Atlantis Highlights in Engineering 33,
https://doi.org/10.2991/978-94-6463-449-5_61

2]. For synchronous grouting, a commonly used type is single-fluid cement grout, composed mainly of cement, bentonite, fly ash, sand, and water, with a setting time of 1 to 2 days [3-5]. However, due to the long setting time and slow early strength development, tunnels constructed using single-fluid grout often encounter problems such as segment flotation, misalignment, and damage, affecting construction quality. In recent years, with increasing attention to tunnel construction quality, some shield tunnel projects have adopted cement-sodium silicate grout (C-S grout) construction with good results, such as Beijing East Sixth Ring Road Reconstruction Project [6], the Suzhou Metro Line 5 [7], and Guangzhou Central Business District Underground Comprehensive Corridor Project [8].

Many scholars have conducted research on the formulation and performance of C-S grout. Chen Peng et al. conducted in-situ tests on C-S grout synchronous grouting relying on the negative loop segment of the Beijing East Sixth Ring Road Jingha Expressway to Luyuan North Street shield tunnel project, exploring pressure distribution and filling effects [9]. Jia Yi et al. analyzed the gel time, fluidity, bleeding rate, elastic modulus, and compressive strength of different C-S grout mixtures, showing that the gel time of C-S grout gradually increases with the increase of water glass dosage, and the bleeding rate of solution A decreases as the water-cement ratio increases [10]. Li Ke et al. studied the strength and triaxial test of C-S grout, demonstrating that with the increase of cement strength and sodium silicate modulus, the peak strength increases [11]. Chen Yiyuan studied the influence of powder ratio, sodium silicate dosage, and water-cement ratio on the flowability, stability, and gelation of C-S grout, summarizing the optimal blending ratio suitable for shield tunnel synchronous grouting construction [12]. Most studies focus on qualitative research on the physical mechanics of grout with different grout ratios or materials, such as strength, setting time, and viscosity, without establishing quantitative descriptive relationships, making it difficult to apply in practical construction.

Previous research has shown that the water-cement ratio of the grout and the volume ratio of liquid A to liquid B have a significant impact on grout performance. However, quantitative descriptions of the relationship between grout ratio and grout performance have been lacking. This study conducted experiments with different water-cement ratios and volume ratios liquid A to liquid B to test gel time, initial setting time, final setting time, and compressive strength. It established quantitative relationships between the water-cement ratio and the volume ratio of liquid A to liquid B and the aforementioned slurry performance, aiming to provide reference for the construction of shield tunnels using C-S grout.

## 2 EXPERIMENTAL DESIGN

### 2.1 Experimental Materials

C-S grout components mainly include liquid A and liquid B, where liquid A consists of cement, bentonite, stabilizer, and water, while liquid B mainly consists of sodium silicate. The cement used in the test is ordinary Portland cement with a strength grade of 42.5 MPa produced by HeLin in Jiangsu, with a compressive strength of 59.6 MPa at

27 days, initial setting time of 188 minutes, and final setting time of 236 minutes; the bentonite is sodium-based bentonite produced by RiverSea in Anhuzi; the stabilizer mainly consists of oligosaccharides, which prevent grout segregation and inhibit the solidification of cement components in the grout; the modulus of sodium silicate is 3.28, with a concentration of 39.7°Bé, produced by HongSheng in Huzhou. The above materials all meet the corresponding construction specifications for material requirements.

## 2.2 Experimental Conditions

The different proportions of grout components will have varying effects on the performance of C-S grout. This paper mainly focuses on the effects of different water-cement ratios (*W/C*) and different volume ratios of liquid A to liquid B ($V_A/V_B$) on the grout performance. The *W/C* selected for the grout are 1.9:1, 2.1:1, 2.3:1, 2.5:1, and 2.7:1 for study, while the $V_A/V_B$ are chosen as 5.7:1, 10.7:1, 15.7:1, 20.7:1, and 25.7:1. Based on the aforementioned design, experiments were conducted on the basis of cement:bentonite:stabilizer:water = 350kg:30kg:3.5kg:813kg, with Experiment Group 3 and Experiment Group 8 serving as experimental control groups. The grout proportions and specific ratios for each experimental group are shown in Table 1.

**Table 1.** Grouts test grouping and ratio design

| Experimental group | Cement | Bentonite | Stabilizer | Water | ***W/C*** | $V_A/V_B$ |
|---|---|---|---|---|---|---|
| Test 1 | 428kg | 30 kg | 3.5 kg | 813 kg | 1.9:1 | |
| Test 2 | 387kg | 30 kg | 3.5 kg | 813 kg | 2.1:1 | |
| Test 3 | 350kg | 30 kg | 3.5 kg | 813 kg | 2.3:1 | 15.7:1 |
| Test 4 | 325kg | 30 kg | 3.5 kg | 813 kg | 2.5:1 | |
| Test 5 | 301kg | 30 kg | 3.5 kg | 813 kg | 2.7:1 | |
| Test 6 | | | | | | 5.7:1 |
| Test 7 | | | | | | 10.7:1 |
| Test 8 | 350kg | 30 kg | 3.5 kg | 813 kg | 2.3:1 | 15.7:1 |
| Test 9 | | | | | | 20.7:1 |
| Test 10 | | | | | | 25.7:1 |

## 2.3 Test Content and Methods

The main testing content includes gel time, initial setting time, final setting time, and compressive strength. According to the testing standards specified in the "Code for Testing of Cement and Cement Concrete in Highway Engineering"[13], the testing methods are as follows:

(1) Gel time: The slump test method is used to test the gel time of the slurry. liquid A slurry is 200ml, and the volume of liquid B is determined according to the grout ratio of each experimental group. Timing starts when mixing begins, and ends when the

grout transitions from a liquid flowing state to a plastic state, i.e., when the grout no longer flows down the wall. This duration is considered the gel time. The test is repeated three times, and the average is taken.

(2) Initial and final setting time: The Vicat apparatus is used to test the initial and final setting times of the grout according to the testing standards specified[13].

(3) Compressive strength: The uniaxial pressure tester is used to test the grout samples at different ages. The size of the grout sample is 5cm×5cm×5cm. Each age period undergoes three tests, and the final result is the average of the three tests. The testing ages for each experimental group include 1 day, 3 days, 5 days, and 7 days.

# 3 EXPERIMENTAL RESULTS

## 3.1 Gel Time

The gel time test results for each experimental group are shown in Figure 1 and 2. Each group was tested three times, and the final experimental result is the average of the three tests.

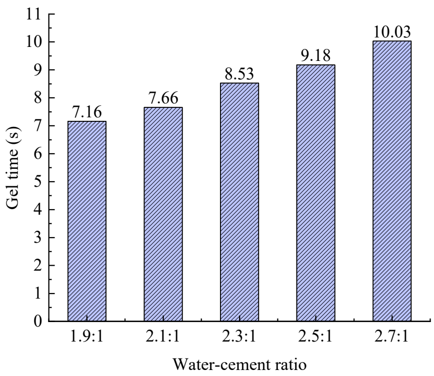



**Fig. 1.** Different water-cement ratio

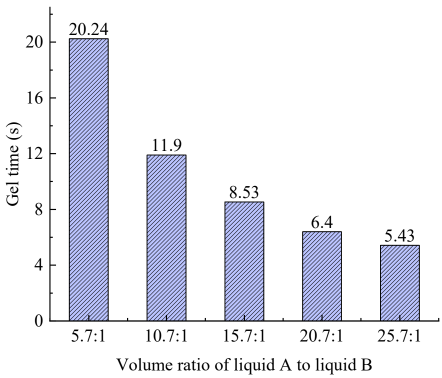



**Fig. 2.** Different volumes

Based on the data from experiments, it is observed that the gel time of the grout ranges from 7.16 to 10.03 seconds when the *W/C* varies from 1.9 to 2.7. Additionally, the gel time increases with the increase in *W/C*. Similarly, when the $V_A/V_B$ ranges from 5.7 to 25.7, the gel time of the grout varies from 5.43 to 20.24 seconds, and the gel time decreases as the $V_A/V_B$ increases.

## 3.2 Initial and Final Seting Time

The initial and final setting times of the grout were tested using a Vicat apparatus. Each experiment was conducted three times in parallel, and the average of the three tests was taken as the experimental result, as shown in Figure 3 and 4. When the *W/C* ranged from 1.9 to 2.7, the initial and final setting times of the grout were between 63 to 99 minutes and 250 to 270 minutes, respectively. When the $V_A/V_B$ ranged from 5.7 to 25.7, the initial and final setting times of the grout were between 41 to 314 minutes and 71 to 708 minutes, respectively.

From the experimental results, it can be observed that both the initial and final setting times of the grout increase as the cement content decreases (*W/C* increases). Additionally, both the initial and final setting times of the grout increase as the volume ratio of liquid B decreases. The impact of liquid B content on the initial and final setting times of the grout is more significant compared to the cement content.

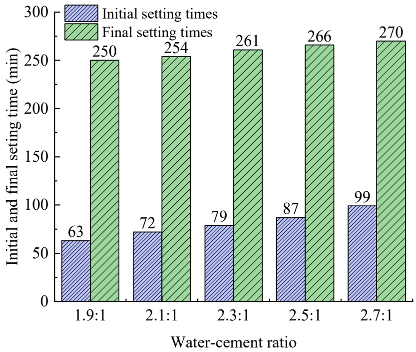



**Fig. 3.** Different water-cement ratio

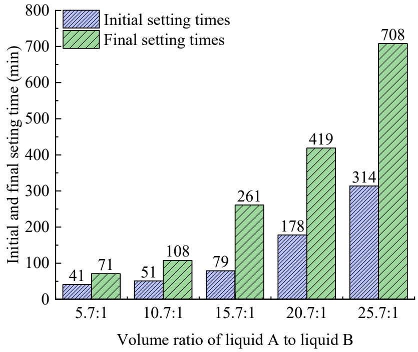



**Fig. 4.** Different volumes

## 3.3 Compreesive Strength

The compressive strength tests were conducted three times at ages of 1 day, 3 days, 5 days, and 7 days, and the average of the test results was taken, as shown in Figure 5 and 6. From the experimental results, it is observed that the strength of the grout under different ratios increases with the age period, indicating that the longer the age period, the greater the strength of the grout. Under the same age conditions, the strength of the grout decreases with an increase in the *W/C*, and it decreases as the $V_A/V_B$ increases.

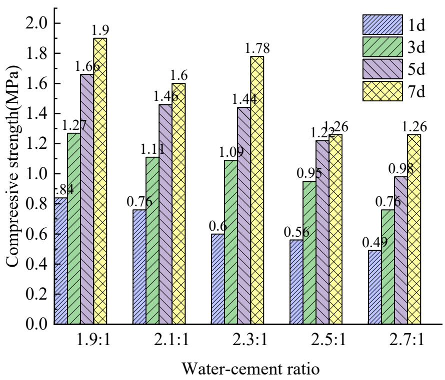



**Fig. 5.** Different water-cement ratio

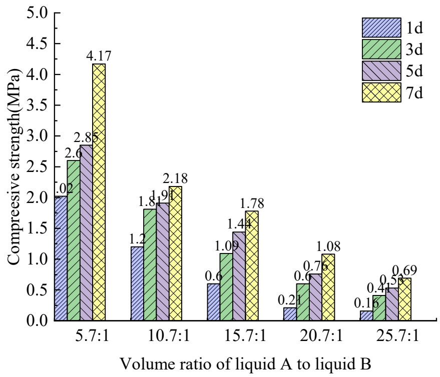
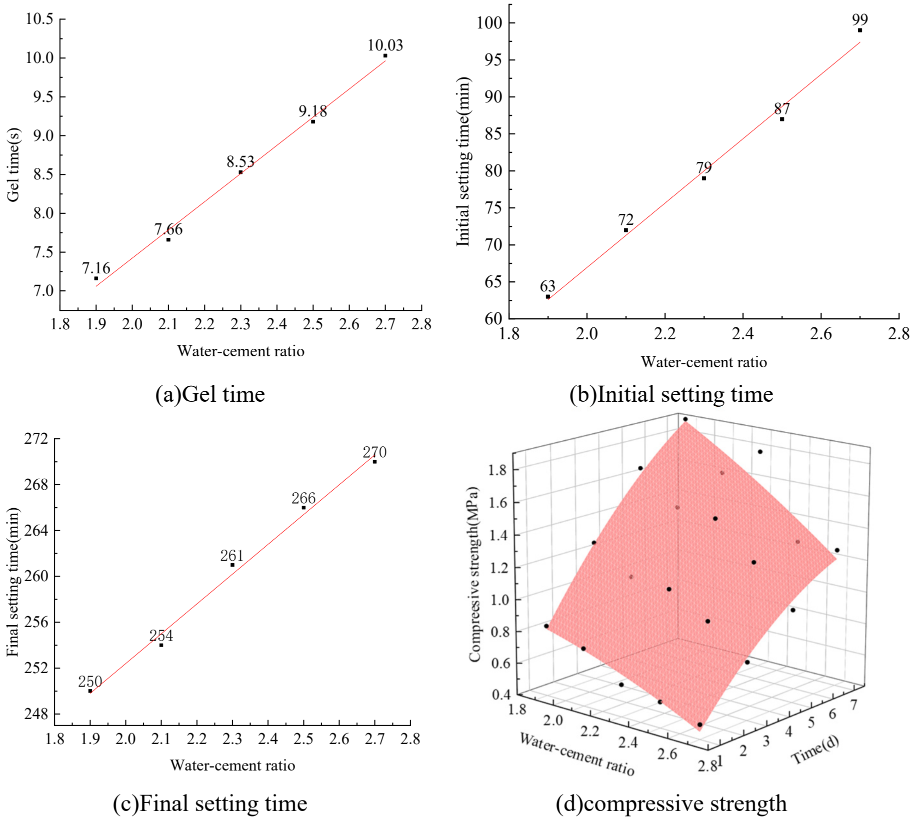



**Fig. 6.** Different volumes

# 4 EXPERIMENTAL ANALYSIS AND DISCUSSION

## 4.1 Influence of Water-Cement Ratio

To clarify the quantitative relationship between the *W/C* and the gel time, initial setting time, final setting time, and compressive strength of the grout, the experimental data was subjected to linear or non-linear fitting based on the characteristics of the experimental data. The results are as shown in Figure 7.




(a)Gel time (b)Initial setting time

(c)Final setting time (d)compressive strength

**Fig. 7.** Effect of water-cement ratio

Gel time, initial setting time, and final setting time were linearly fitted with the *W/C* of the grout, while compressive strength was nonlinearly fitted with both the *W/C* and age period of the grout, yielding the following equations:

$$y_1 = 3.6998a \tag{1}$$

$$y_2 = 43.5a - 20.5 \tag{2}$$

$$y_3 = 26a - 200.4 \tag{3}$$

$$y_4 = 0.3714 + 0.458a + 0.38965T - 0.1875a^2 - 0.01113T^2 - 0.0645aT \tag{4}$$

In the equations, $y_1$, $y_2$, $y_3$ and $y_4$ represent the gel time, initial setting time, final setting time, and compressive strength of the grout, respectively, with units of seconds, minutes, minutes, and megapascals. *a* represents the *W/C* of the grout, with a unit of 1, while *T* represents the age period of the grout, with a unit of days. The determination coefficients of the gel time, initial setting time, final setting time, and compressive strength fittings are 0.99, 0.99, 0.99, and 0.96, respectively, indicating a good fitting effect. These equations can serve as a basis for adjusting the grout ratio.

Based on the above fitting data, it is observed that when the cement content decreases (*W/C* increases), the gel time, initial setting time, and final setting time of the grout all increase, while the strength of the grout decreases under the same age conditions. This is mainly due to the hydration of cement in water, which forms colloidal C-S-H and calcium hydroxide insoluble in water. The chemical reaction equations are as follows [14]:

$$3CaO\cdot SiO_2 + nH_2O \rightarrow xCaO\cdot SiO_3\cdot yH_2O(C-S-H) + (3-x)Ca(OH)_2 \qquad (5)$$

$$2CaO\cdot SiO_2 + mH_2O \rightarrow xCaO\cdot SiO_2\cdot yH_2O + (2-x)Ca(OH)_2 \qquad (6)$$

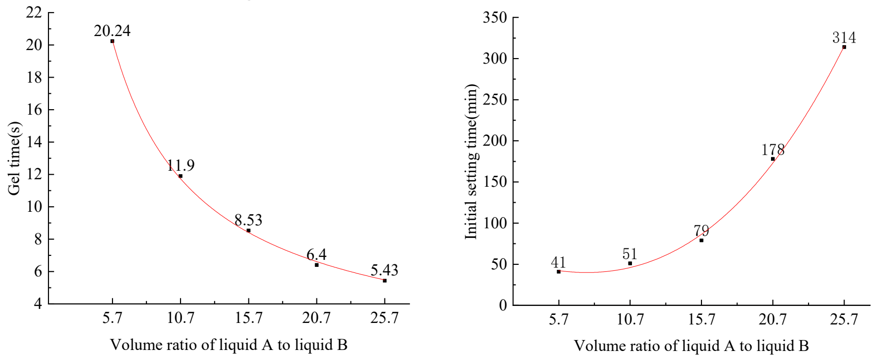
Calcium hydroxide undergoes a chemical reaction with the water glass liquid (liquid B) in the grout, resulting in the formation of colloidal C-S-H with certain strength. The chemical reaction equation is as follows:

$$3Ca(OH)_2 + Na_2O\cdot SiO_2 + mH_2O \rightarrow CaO\cdot nSiO_2\cdot mH_2O + 2Na(OH) \qquad (7)$$

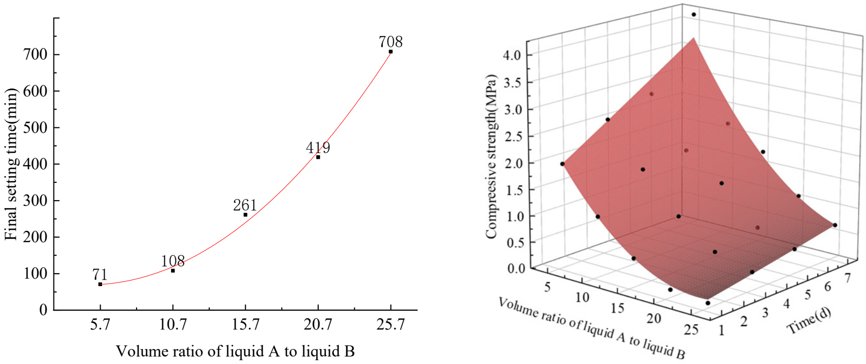
When the cement content decreases, both the formation of C-S-H and $Ca(OH)_2$ in liquid A decrease. When liquid A and liquid B are mixed, the content of $Ca(OH)_2$ involved in the reaction is reduced. Consequently, the production of insoluble gel C-S-H also decreases. This is manifested macroscopically by an increase in gel time, initial setting time, and final setting time, and a decrease in strength.

## 4.2 Influence of Volume Ratio of Liquid A to Liquid B

Similarly, based on the characteristics of experimental data, linear or nonlinear fitting is conducted for the experimental data of grout properties with respect to the $V_A/V_B$. The results are as shown in Figure 8.




(a)Gel time (b)Initial setting time




(c)Final setting time (d)compressive strength

**Fig. 8.** Effect of volume ratio of A liquid to B liquid

The following formula can be obtained by conducting nonlinear fitting of the experimental data on grout properties with respect to the $V_A/V_B$:

$$y_1 = 95.007b^{0.882} \tag{8}$$

$$y_2 = 0.0127b^3 + 0.3263b^2 - 7.2278b + 70.495 \tag{9}$$

$$y_3 = 0.01b^3 + 0.9833b^2 - 7.4199b + 76.109 \tag{10}$$

$$y_4 = 2.9677 - 0.24325b + 0.33303T + 0.00521b^2 + 0.00112T^2 - 0.01025bT \tag{11}$$

In the formula, $b$ represents the $V_A/V_B$ in the grout. The determination coefficients of the fitting for gel time, initial setting time, final setting time, and compressive strength are 0.99, 0.99, 0.99, and 0.96, respectively, indicating a good fitting effect. The formula can serve as a basis for adjusting the grout ratio.

In summary, when the amount of liquid B is reduced (increasing the $V_A/V_B$), the gel time decreases, while the initial setting time and final setting time increase, and the strength of the grout decreases under the same aging conditions. Similarly, when the amount of liquid B is reduced, after mixing liquid A and liquid B, the content of $Na_2O{\cdot}SiO_2$ involved in the reaction decreases, resulting in a decrease in the generated C-S-H gel, corresponding to an increase in the initial and final setting times and a decrease in strength. During the grout preparation process of liquid A, hydrolysis occurs to form $Ca(OH)_2$, which is limited. When adding more liquid B, $Na_2O{\cdot}SiO_2$ reacts rapidly with $Ca(OH)_2$, but the hydrolysis reaction of cement is slow, resulting in $Na_2O{\cdot}SiO_2$ not fully participating in the reaction, thus prolonging the gel time.

## 5 ENGINEERING APPLICATION

The construction project of the dual-channel sewage collection system in Jiangxinzhou adopts the grout for construction, crossing the Yangtze River in Jiajiang. The outer diameter of the segment is 8.8m, the inner diameter is 7.9m, the thickness is 0.45m, and the ring width is 1.5m. It mainly passes through layers of silt, fine sand, and silty clay. To prevent possible buoyancy of the segments during construction, a C-S grout with short gel time and high early strength is used for construction. According to construction experience, the gel time of the grout should be between 5 and 20 seconds, with a compressive strength exceeding 0.5 MPa after 1 day. Considering the ratio of cement, bentonite, stabilizer, and water to be 350kg, 30kg, 3.5kg, and 813kg respectively, with a *W/C* of 2.1:1, the $V_A/V_B$ in the grout is 15.7:1.

During construction, the amount of floating of the segments along the entire line is generally controlled within 10mm, as shown in Figure 9. Compared to similar formations, such as the Ningbo subway tunnel [15] and the Shanghai Xiangyin Road tunnel [16], which were constructed using single-liquid rigid slurries, where the average amount of floating of the segments reached 65.69mm and 120mm respectively, this tunnel effectively controlled the floating of the segments, ensuring good construction quality.

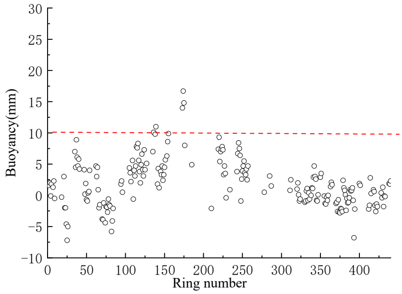



**Fig. 9.** segments uplifting value

# 6 CONCLUSIONS

Through the gel time, initial setting time, final setting time, and compressive strength tests under different grout ratios as described above, the following conclusions can be drawn from the experimental results:

(1) When the cement content decreases (*W/C* increases), the gel time, initial setting time, and final setting time all increase, and the strength decreases under the same aging conditions.

(2) When the content of liquid B decreases (increasing the $V_A/V_B$), the gel time shortens, while the initial setting time and final setting time increase, and the strength decreases under the same aging conditions.

(3) By performing function fitting for the gel time, initial setting time, final setting time, and compressive strength under different *W/C* and $V_A/V_B$, for subsequent construction, if adjustments to the slurry ratio are needed, it can be made based on the quantitative relationship between the slurry ratio and its performance.

(4) By applying the grout ratio obtained from the test results to construction, effective control of segment floating was achieved, which can be promoted for use in similar projects. The performance of the grout under different ratios still needs further exploration, such as flowability, aggregate retention rate, water-to-land strength ratio, bleeding rate, etc.

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