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Performance Analysis of Tunnel Water Plugging Engineering Slurry Based on Polycarboxylate Superplasticizer

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In response to the low efficiency of water plugging slurry in high temperature tunnel engineering, this research explores the optimization configuration of tunnel water plugging slurry. Through the analysis of the gel time, fluidity, stability and mechanical properties of the slurry fused with polycarboxylate superplasticizer, the response surface analysis method and central composite design are used to optimize the design of the slurry for water shutoff projects. Experimental verification showed that the performance of grouting was optimal when the ratio of 12.48 % fast hardening sulfoaluminate cement 425, 0.91 % polycarboxylate superplasticizer, 3.03 ‰ calcium lignosulfonate, and 1.00 ‰ hydroxypropyl methylcellulose was formulated. The gel time of the slurry prepared at 90 °C was 12 min, the viscosity was 2064 mPa · s, the water separation rate was 2.87 %, and the compressive strength of the slurry prepared 3 days later was high as 21.35 mPa, meeting the requirements for tunnel water plugging construction. The results showed that fast hardening sulfoaluminate cement 425 had the greatest impact on the performance of the slurry, while polycarboxylate superplasticizer had obvious effects on the stability and flowability of the slurry. The optimal configuration scheme proposed in the study has positive application significance in high surface temperature tunnel water plugging engineering. This optimal solution provides theoretical basis and technical support for tunnel water plugging engineering, and improves the effectiveness of grouting configuration.

Keywords: tunnel water plugging engineering, polycarboxylate superplasticizer, concrete slurry, high surface temperature, R·SAC425, response surface analysis.

1. INTRODUCTION

Affected by modern engineering construction, tunnel engineering, as a key link in building construction, affects the application and safety of railways, subways, highways, etc. in terms of construction safety and engineering quality. However, during the construction process of tunnel engineering, groundwater infiltration problems are often encountered, which not only affect the construction progress but also threaten the safety of the engineering structure [1]. Traditional water plugging methods, such as cement grouting, can solve problems to some extent, but they have drawbacks such as high cost, long construction period, and significant environmental impact [2]. Therefore, developing effective tunnel water plugging technology is crucial to ensure the smooth progress of tunnel engineering.

In recent years, with the advancement of materials science and engineering technology, the polycarboxylate superplasticizer (PCE) has provided new ideas for improving the workability of concrete and other slurries [3]. PCE is a high-performance waterborne polymer with excellent dispersing properties and a water reduction effect, which can improve the fluidity of concrete, reduce water consumption, and enhance the strength and durability of concrete. In addition, the molecular structure of PCE can be optimised by introducing different functional groups to suit different engineering needs. Therefore, scholars have carried out various application research on PCE. To reduced PCE performance caused by clay containing sand and gravel in concrete, Li et al. proposed a strategy to enhance the flowability of clay containing concrete by changing the clay layer and PCE structure. This optimized the concrete performance and saved costs caused by increased raw material and PCE usage [4]. In response to the early strength development defects of cement-based materials, Zhang et al. optimized cement-based materials using PCE/calcium silicate hydrate (C-S-H) nanocomposites as reinforcing agents. The co-precipitation method was used to prepare and test different calcium silicon ratios. PCE could better graft on the vacancies of the silicate chain of C-S-H, thereby improving the performance of C-S-H [5]. To improve the negative impact of montmorillonite on PCE efficiency, Sha et al. synthesized a PCE polymer by copolymerizing isopentene polyoxyethylene ether with trans-2-succinic acid. Mixing different proportions of PCE polymer and montmorillonite into cement slurry enhanced the adsorption capacity of PCE and the fluidity of cement slurry [6]. Harichane et al. discussed the rheological and mechanical properties of PCE chemical structure in cement slurry in order to enhance the workability and mechanical strength of high-performance concrete after hardening. Three PCE-based superplasticizers and cement sold in the Algerian market were tested. A significant positive correlation existed between the zeta potential of PCE polymer and the compressive strength of cement slurry [7].

PCE can enhance the fluidity and workability of concrete, playing an important role in modern tunnel water plugging engineering. Ma et al. proposed a PCE grouting

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technology based on fully mechanized tunnel construction method to address the abnormal settlement in subway cross passage construction. A cantilever/constrained multi foundation beam model was developed for construction modeling, which corrected abnormal settlement in cross passages and controlled structural deformation [8]. Wang et al. optimized the grouting sealing scheme to solve the water discharge problem when tunnels pass through low-pressure water rich fractured zones. Through numerical simulation experiments, the full sealing grouting combined with cement, water glass, and PCE could enhance the effect of the precipitation funnel and enhance the water plugging effect [9]. El Mekari et al. explored a physical simulation on the changes in crack pressure during concrete grouting, focusing on the waterproofing problem of polymers in concrete cracks. Experimental verification was conducted by changing parameters such as injection pressure, duration, volume, injection point and pressure reading port position, as well as dynamic viscosity of the fluid, thereby improving the understanding of factors affecting pressure inside cracks and optimizing the injection process [10]. In order to reduce the cost of prefabricated concrete pipe support systems used in tunnel boring machines, Chakeri et al. added steel fibers to the concrete slurry configuration process that integrated PCE. By monitoring the strengthening effect of steel fibers under different loads on the workability of concrete, placing fibers perpendicular to the load could improve its compressive strength [11].

Chang et al. proposed the use of polyether macromonomers with high reactivity to prepare PCEs with different interfacial adsorption properties (acid-ether ratios) in order to enhance the flow and strength of the cement. The flowability of the cement paste was enhanced and the 3-day compressive strength was strengthened through the optimisation of the acid-ether ratio to 3 [12]. In order to meet the environmental and high efficiency requirements for precast concrete products and concrete pipe sheets in the metro and precast construction industries, Dong et al. synthesised a new ultra-early-strengthening PCE by rationally designing the molecular structure and introducing ultra-long polyoxyethylene side chains, functional monomers and cationic monomers [13]. Sheikh et al. addressed the problem of graphene oxide (GO) nano-reinforcements in enhancing the strength and durability of concrete while decreasing the workability, and proposed to improve the strength and workability of GO cement/mortar by adding PCE. The interaction between PCSP and GO was found to lead to colloidal instability and particle aggregation [14].

Based on the above, adding PCE to tunnel water plugging grouting materials can significantly improve the concrete slurry performance. However, existing research has mostly focused on improving concrete configuration equipment or optimizing configuration ratios, while the performance analysis of concrete slurry with PCE fusion has mostly focused on conventional tunnel construction environments. The effectiveness analysis of using PCE fused slurry for tunnel water plugging construction in high-temperature hot water tunnel projects in volcanic gathering areas remains a challenge in the current construction field. Therefore, the study was carried out to analyse the grouting performance of water plugging project incorporating PCE in a tunnel project with high surface temperature and groundwater seepage in Xinjiang, China. In the study, rapid hardening sulfoaluminate cement (R-SAC425) was used. This cement is characterised by high early strength and rapid hydration, which enables the formation of high strength hydration products in a short period of time, thus quickly reaching the design strength. In addition, calcium lignosulfonate (CLS) was introduced as an air-entraining agent, which is a natural polymer compound that improves the concrete's compatibility and frost resistance. And hydroxypropyl methyl cellulose ether (HMCE) was used as a thickener to increase the viscosity of the paste and prevent particle settling, thus improving the homogeneity and filling properties of the paste. By using a combination of these materials, the study aims to develop a high-performance slurry suitable for high-temperature tunnel water plugging projects. By optimising the material ratios and slurry properties, it is expected that the efficiency and reliability of tunnel water plugging can be improved, and construction costs and environmental impacts can be reduced. The novelty lies in the optimization design of grouting materials for tunnel water plugging engineering with high and low temperature hot water, and the performance of the proposed grouting material is comprehensively analyzed.

2. METHODS AND MATERIALS

The study first introduces the sources and relevant information of the experimental materials to be used. Secondly, the experimental plan is designed. Finally, the performance test verification method and required test equipment information of the water plugging grouting material fused with PCE are introduced.

2.1. Experimental materials

Experimental cement: Ordinary Portland cement with Chinese standard number P.O42.5, with a calcium oxide (CaO) content of 63.32 %, magnesium oxide (MgO) of 3.4 %, sulfur trioxide (SO3) of 2.2 %, loss on ignition of 4.0 %, and cement fineness of 1.2 %, was used and was produced by Tangshan Yandong Group Huacheng Cement Co., Ltd. Fast hardening sulfoaluminate cement (R·SAC425), with a CaO of 44.41 %, MgO of 1.94 %, and SO_3 of 17.1 %, produced by Dengdian Group Cement Co., Ltd. Air entraining agent: CLS, analytical grade (≥ 99 %), produced by Hubei Wande Chemical Co., Ltd. Thickener: 2-HMCE, with a viscosity 200,000 mPa · s, active ingredient content ≥ 99 %, produced by Northern Tianpu Chemical Co., Ltd. Water reducing agent: high-performance liquid PCE, with a water reduction rate of 30 %, vertical expansion rate of 1.5 % after 3 hours, compressive strength of 40 mPa, and solid content of 16.0 %, produced by Zhengde Building Materials Technology Co., Ltd.

2.2. Experimental plan design

On the basis of the actual construction situation of the project site, the benchmark allocation ratio of grouting materials for water plugging engineering was simulated at a temperature of 90 ℃ in the laboratory, and was adjusted according to different temperature changes. Based on the construction site conditions, the initial water-cement ratio

(WCR) is set to 0.45. After determining the ratio of grouting liquid, the performance of the slurry under different temperature environments (60 °C, 80 °C, and 90 °C) and various WCRs (0.40, 0.45, 0.50) is analyzed to optimize the content of grouting materials. The study uses response surface methodology (RSM) to analyze the factors affecting the slurry performance. The addition content of R·SAC425, PCE, CLS, and HMCE are used as influencing factors. The experiment is conducted using acentral composite design (CCD). Based on relevant engineering construction experience and previous single factor experiments, a test plan is designed in the Design-expert 12 software using a slurry ratio randomly set by CCD. The horizontal boundaries of the four influencing factors in RSM are clarified, as shown in Table 1.

Table 1. Influence factor boundaries for the RSM test

Category	Designation	Minimum	Maximum
A1	R·SAC425, %	5.0	25.0
A2	PCE, %	0.5	1.5
A3	CLS, ‰	1.0	5.0
A4	HMCE, ‰	1.0	5.0

According to the boundary values of the four influencing factors in Table 1, the study obtained 17 mix formulation schemes based on RSM and CCD. The objective is to optimise the gel time, fluidity, stability and mechanical properties of the slurry, and the composition content of each scheme needs to meet the needs of high temperature tunnel water plugging project. Specifics is shown in Table 2.

2.3. Experimental methods and equipment

According to the four material mixing schemes randomly designed by CCD, four material mixed schemes are obtained. The entire experimental process is shown in Fig. 1. In Fig. 1, the research mainly analyzes the performance of grouting materials fused with PCE from the grout gel time, stability, mechanical properties and flow performance. Among them, the slurry gel time test method refers to the test method of Xu et al [15]. The stability performance test adopts the water separation rate testing method specified in the "Technical Specification for Cement Grouting Construction of Standard Hydraulic Structures" (SL/T62-2020) [16]. The mechanical property test is conducted conforming to the Chinese standard "Method for Testing the Strength of Cement Mortar" (GB/T17671-2021) [17]. The flow performance test uses a rotational viscometer for viscosity detection. The test equipment information involved in the four tests is as follows: 1) Gel time detection: HH-2A magnetic stirring water bath (produced by Changzhou Ronghua Instrument Manufacturing Co., Ltd.); Vika instrument (produced by Cangzhou Jinghong Engineering Instrument Co., Ltd.); 2) Stability performance testing: HH501 super constant temperature water bath (produced by Baita Xinbao Instrument Factory in Jintan District); Measuring cylinder (produced by Cangzhou Zhengyang Plastic Products Sales Co., Ltd.); 3) Mechanical property testing: NDJ-5S rotary viscometer (produced by Hebi Ruipu Instrument Co., Ltd.); Beaker (produced by Yixing Jingke Optical Instrument Co., Ltd.); 4) Flow performance testing: 40 mm × 40 mm × 60 mm triple mold (produced by Hebei Century Hangkai Instrument Equipment Co., Ltd.); Self-made vibration table; SY-84 cement mortar rapid curing box (produced by Cangzhou Zerui Testing Instrument Co., Ltd.); Electric bending tester (produced by Cangzhou Zerui Testing Instrument Co., Ltd.); Universal testing machine (produced by Jinan Wuxing Testing Instrument Co., Ltd.).

Table 2. Mixed formulation scheme of the 4 materials

Serial No.	R·SAC425, %	PCE, %	CLS, ‰	HMCE, ‰	Serial No.	R·SAC425, %	PCE, %	CLS, ‰	HMCE, ‰
1	25.0	0.5	5.0	5.0	10	20.0	1.0	3.0	3.0
2	25.0	0.5	5.0	1.0	11	15.0	1.0	2.0	3.0
3	25.0	1.5	1.0	5.0	12	15.0	1.0	4.0	3.0
4	5.0	1.5	5.0	1.0	13	15.0	1.0	3.0	2.0
5	25.0	1.5	1.0	1.0	14	15.0	1.0	3.0	4.0
6	5.0	0.5	1.0	5.0	15	15.0	0.8	3.0	3.0
7	5.0	1.5	5.0	5.0	16	15.0	0.3	3.0	3.0
8	5.0	0.5	1.0	1.0	17	15.0	1.0	3.0	3.0
9	10.0	1.0	3.0	3.0	–	–	–	–	–

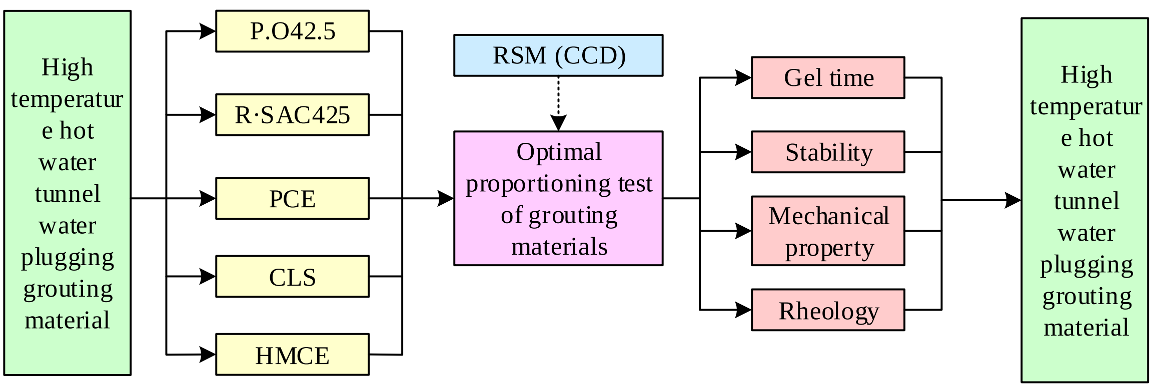


Fig. 1. Test procedure for analyzing grouting performance of tunnel water plugging project integrating PCE

The percentage of water released from the slurry is shown in Eq. 1.

$$p = \frac{w_1}{w_0} \times 100\% , \quad (1)$$

where p is the water separating proportion of the slurry; w_1 is the volume of water separated from the slurry; w_0 is the original slurry volume size. The flexural strength is shown in Eq. 2.

$$F_s = \frac{1.5 H_s d}{w l^2} , \quad (2)$$

where F_s is the flexural strength of the slurry; H_s is the magnitude of the destructive load; d is the distance between two fixture supports; w and l are the width and height of the specimen. The compressive strength is shown in Eq. 3.

$$F_c = \frac{H_c}{S} , \quad (3)$$

where F_c is the strength of the slurry against pressure; H_c is the magnitude of the destructive load; S is the area of the specimen subjected to pressure.

3. RESULTS

The study first analyzes the experimental results through RSM to determine the key factors affecting the slurry performance of tunnel water plugging engineering. On this basis, RSM is used to predict and calculate the optimal ratio. Secondly, different temperature conditions (60 °C, 80 °C, and 90 °C) and WCRs (0.40, 0.45, and 0.50) that may be encountered on the construction site are simulated under strictly controlled laboratory conditions to evaluate the effects of temperature and WCR on the performance of the slurry.

3.1. Analysis of RSM test results

According to the boundary values of four influence factors in the RSM test and 17 mixed preparation schemes obtained by CCD, the research first analyzes the gel performance of grouting materials with different influence factor addition contents. The specific results are shown in Fig. 2. The gel time mainly refers to the time required for the slurry from mixing to losing its fluidity and starting to cure. The gel time directly affects the filling, permeability, and reinforcement effect of grouting materials in the stratum. Fig. 2 displays the contour map of the influence of various contents of R·SAC425, PCE, CLS and HMCE on the grouting gel time. The more the content of R·SAC425, the shorter the gel time of the slurry. The gel time contour lines in Fig. 2 c were more densely distributed, which indicated that HMCE had a more obvious impact on the grouting gel time. The relationship between the numerical changes of the four influencing factors and the gel time shows that R·SAC425 has the greatest impact on the grouting gel time. This may be due to the formed gel shape of aluminum hydroxide in the hydration process of calcium silicate mineral and R·SAC, which promotes the grouting gel. The effect of the addition content on the grouting stability is shown in Fig. 3.

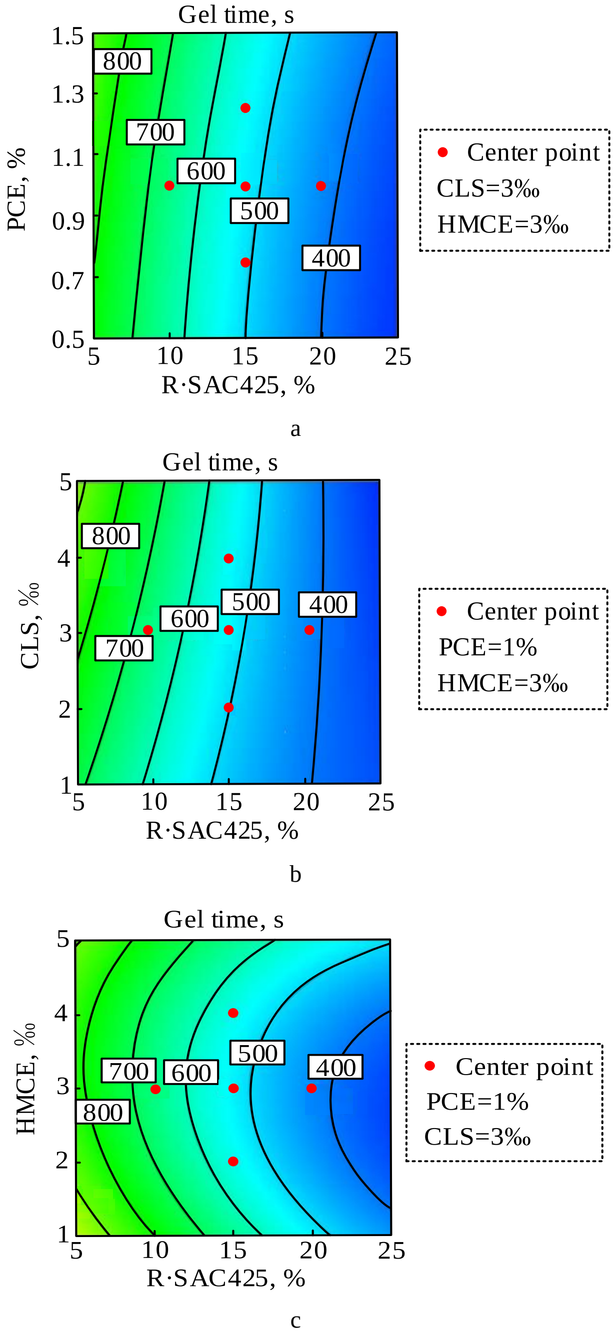
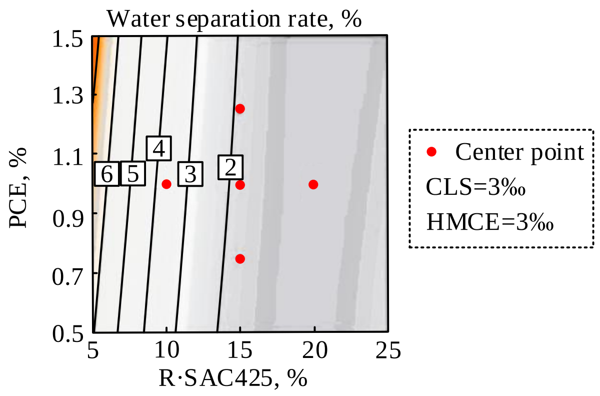


Fig. 2. Effect of different material contents on grouting gel time: a – effect of varying R-SAC425 and PCE contents on slurry gelation time; b – effect of varying R-SAC425 and CLS contents on slurry gelation time; c – effect of varying R-SAC425 and HMCE contents on slurry gelation time

The water separation rate is a key factor affecting the stability performance of grouting materials, which directly relates to the diffusion, filling, and final reinforcement effect of grouting materials in the formation. Fig. 3 shows the effects of different contents of R·SAC425, PCE, CLS, and HMCE on grouting stability. Based on Fig. 3 a and b, when the content of R·SAC425 was 20 %, the water separation rate of the grouting was only 1.15 %, which was 5.55 % lower than that of 5 % R·SAC425 and 0.56 % lower than that of 25 % R·SAC425. In Fig. 3 a, increasing PCE content on the water separation rate showed an increase followed by a decrease.



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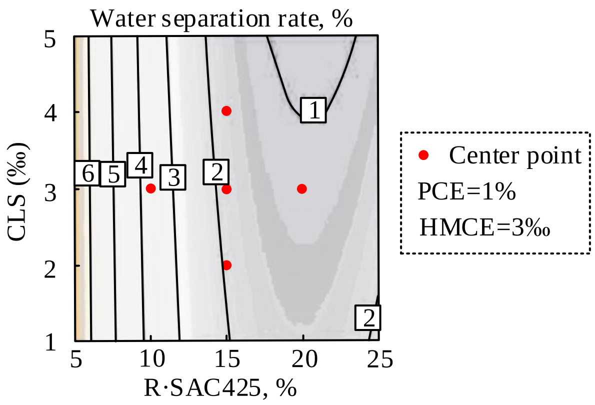

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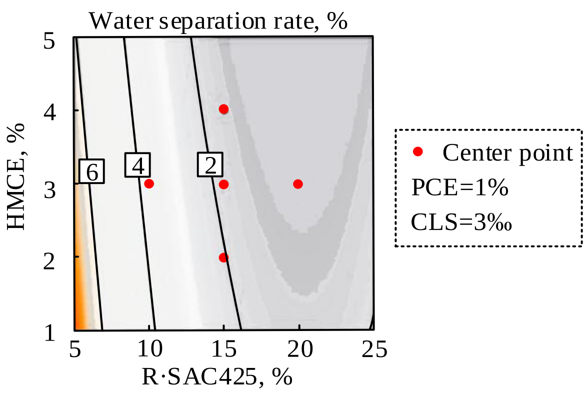

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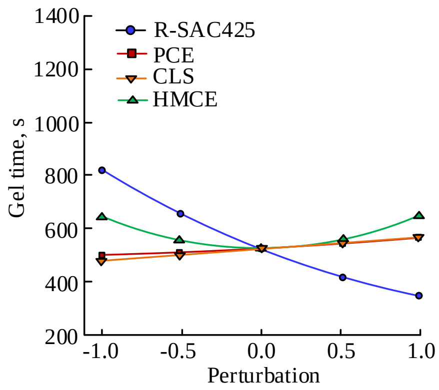
Fig. 3. Effect of different material contents on grout stability: a – effect of varying R-SAC425 and PCE contents on the water separation rate of slurries; b – effect of varying R-SAC425 and CLS contents on the water separation rate of slurries; c – effect of varying R-SAC425 and HMCE contents on the water separation rate of slurries

When the PCE content increased from 0.5 % to 1.0 %, its water separation rate decreased by 0.93 %. When the PCE content increased from 1.0 % to 1.5 %, the water separation rate increased by 0.36 %. The increase in CLS and HMCE in Fig. 3 b and c reduced the water separation rate of grouting. The effect of R·SAC425, HMCE, CLS, and PCE content on grouting stability can be ranked from high to low. On this basis, the study further analyzes the disturbance curve of four influence factors on grouting gel time and stability, as shown in Fig. 4. From Fig. 4 a, the change of R·SAC425 content had the greatest impact on the grouting gel time, followed by CLS, while PCE and HMCE had the smallest impact on the grouting gel time.



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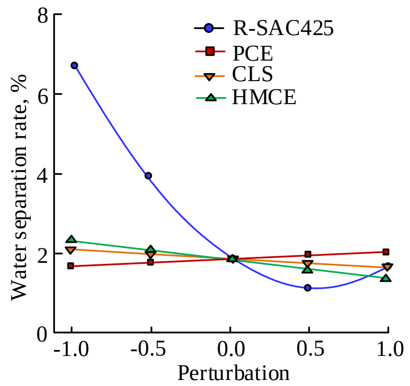


b

Fig. 4. Perturbation curves for grouting gel time and stability: a – gel time perturbation curve; b – water separation rate perturbation curve

When the gel time perturbation curve was all 0, the R·SAC425 was 15 %, the PCE was 1 %, the CLS was 3 ‰, and the HMCE was 3 ‰. When the grouting stability (water separation) disturbance curve in Fig. 4 b was 0, the R·SAC425 was 14.8 %, and other contents were consistent with the content when the gel time disturbance curve was 0. This indicates that the content of R·SAC425 may determine the grouting performance. The effect of four influencing factors on the grouting viscosity is displayed in Fig. 5. From Fig. 5 the change in HMCE content had the greatest impact on grouting viscosity, while the change in CLS content had the smallest impact on grouting viscosity. This may be because the long-chain polymers in HMCE adsorb the water molecules injected, thereby increasing the internal structure viscosity of the slurry. Excessive cement R·SAC425 led to a decrease in grouting viscosity and poorer fluidity of the slurry. This may be because too much R·SAC425 is added to the liquid, carrying more large particles of cement and increasing the water absorption of the slurry, thereby reducing the flow rate of grouting. Meanwhile, the study further analyzes the effects of R·SAC425, PCE, CLS, and HMCE on its mechanical properties. The disturbance curves of compressive strength (CS) and flexural strength at 3d, 7d, and 28d after grouting preparation are obtained through the RSM test, as displayed in Fig. 6. From Fig. 6 a – c, in the CS of grouting, the content of cement R·SAC425 had the greatest impact on the performance, followed by HMCE.

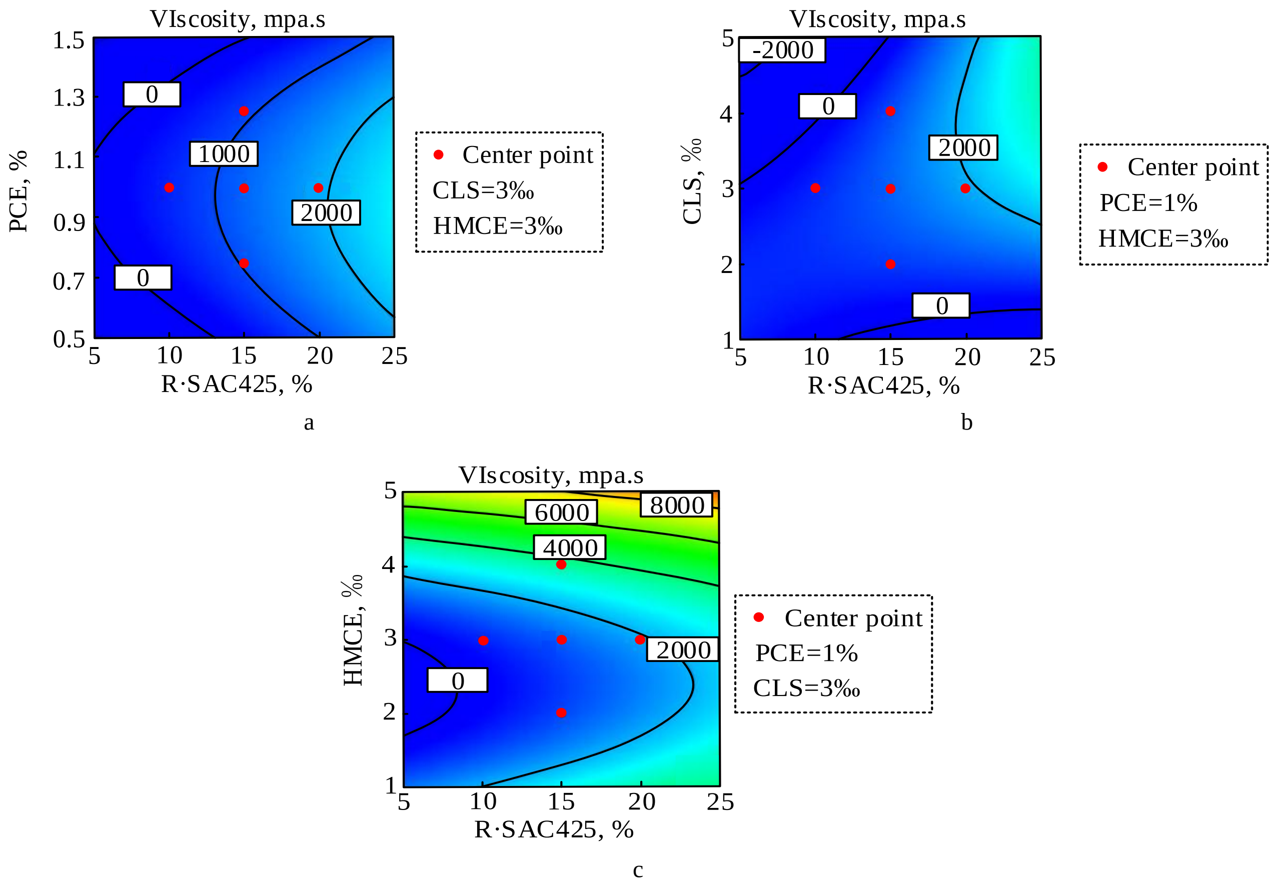


Fig. 5. Effect of different material contents on grouting mobility: a – effect of varying R-SAC425 and PCE contents on slurry viscosity; b – effect of varying R-SAC425 and CLS contents on slurry viscosity; c – effect of varying R-SAC425 and HMCE contents on slurry viscosity

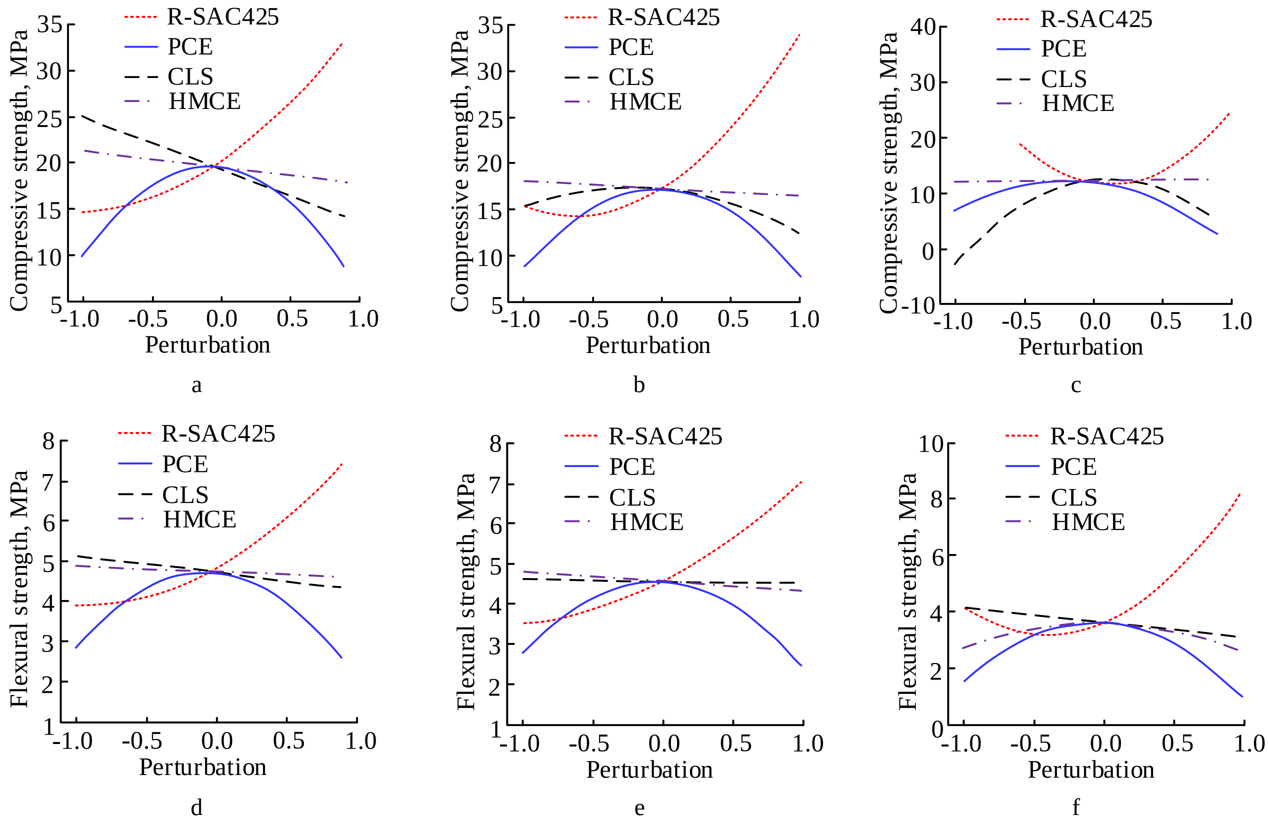


Fig. 6. Effect of four influencing factors on the mechanical properties of grouting: a – 3rd day compressive strength disturbance curve; b – 7th day compressive strength disturbance curve; c – 28th day compressive strength disturbance curve; d – 3rd day flexural strength disturbance curve; e – 7th day flexural strength disturbance curve; f – 28th day flexural strength disturbance curve

The effect of PCE water reducing agent on the CS of grouting increases with the time after grouting preparation. This may be because PCE can solve the CS shrinkage in the later stage of grouting stone body, thereby improving the compressive performance of grouting. Based on Fig. 6 d – f, PCE and CLS had a relatively small impact on the flexural strength of grouting, and the disturbance curves of both had a small change amplitude.

3.2. Analysis of slurry optimization test results

To obtain the optimal configuration scheme, the RSM response results are further validated, as displayed in Table 3. From Table 3, for most influencing factors, the coefficient of determination (R^2) and the adjusted R^2 values were close to 1.0, indicating that the RSM model had a superior fitting to the experimental data. Comparing the adjusted R^2 and predicted R^2 results, the difference between the two was below 0.2, indicating that each influencing factor had an ideal consistency effect. Therefore, the optimal slurry mixture predicted by the RSM model is shown in Table 4. In Table 4, the maximum error of the model in predicting grouting performance was 4.88 %, the minimum error was 0.50 %, and the overall error was below 5.00 %. The model has a good predictive effect on grouting performance. Based on the optimal configuration results of R·SAC425, PCE, CLS, and HMCE output by the model, the grouting performance under different WCRs and water bath temperatures is further analyzed. The changes in grouting gel time and water separation rate under the optimal preparation scheme are shown in Fig. 7. From Fig. 7 a, when the WCR was fixed, the higher the water bath temperature, the less time for grouting gel. At 0.45, the grouting gel time at 90 °C was reduced by 62.58 % and 30.75 % respectively compared with 60 °C and 80 °C. This indicates that the high temperature surface environment will accelerate the hydration rate of grouting and shorten the solidification time. In contrast with different WCRs, the larger the ratio, the more time the grouting gel takes, but its effect is below the water bath temperature change. Based on Fig. 7 b, an increase in the ratio improved the water separation rate of grouting, while an increase in water bath temperature reduced the water separation rate of grouting and lowered its stability. The temperature change of the water bath has the most significant effect on the grouting stability. The influence of different WCRs and water bath temperatures on grouting viscosity is shown in Fig. 8. From Fig. 8 a, when the ratio was fixed, the water bath temperature indicates higher viscosity. When the temperature was 90 °C, the higher the WCR, the lower the grouting viscosity.

Table 3. Validation of RSM model results

Response factor	Gel time, s	Water separation rate, %	Viscosity, mpa.s	Compressive strength, MPa			Flexural strength, MPa		
				3d	7d	28d	3d	7d	28d
R^2	0.9995	0.9824	0.9715	0.9627	0.9726	0.9670	0.9589	0.9417	0.9786
Adjusted R^2	0.9988	0.9706	0.9484	0.9255	0.9429	0.9270	0.9277	0.8834	0.9533
Predicted R^2	0.9703	0.9648	0.9388	0.9017	0.8781	0.8427	0.8379	0.8219	0.8794

Table 4. Optimal preparation ratio test results

Influencing factors	Content	Target		Predicted value	Actual value
R·SAC425, %	12.48	Gel time, s		717.78	724.19
		Water separation rate, %		3.01	2.87
PCE, %	0.91	Viscosity, mpa.s		2000.00	2064.00
		Compressive strength, MPa	3d	18.72	19.13
CLS, ‰	3.03		7d	15.97	16.05
			28d	11.39	11.25
KMCE, ‰	1.00	Flexural strength, MPa	3d	4.42	4.53
			7d	4.35	4.41
–	–		28d	2.31	2.38

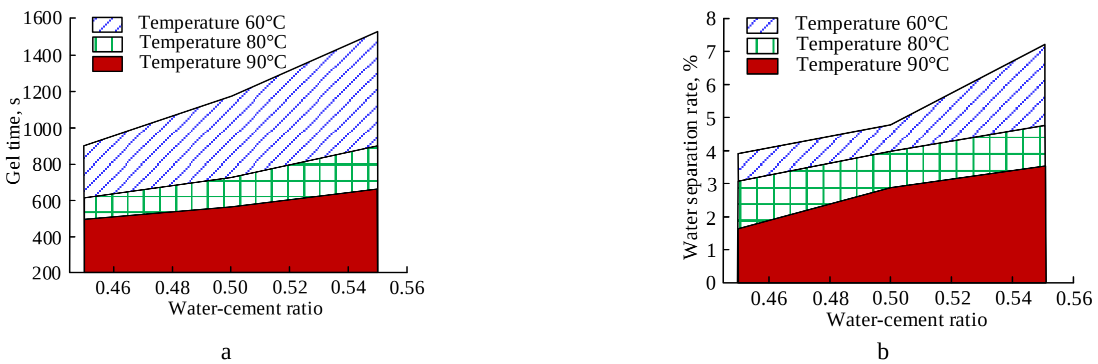
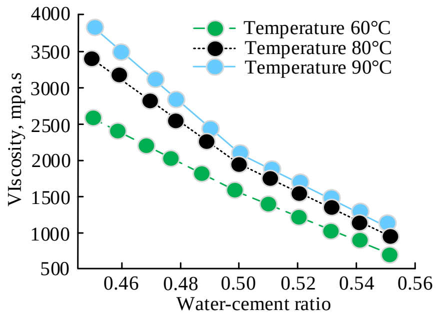


Fig. 7. Changes in grouting gel time and water precipitation rate under the optimal formulation scheme: a – effect of varying water-cement ratios and water bath temperatures on grouting gel time; b – effect of varying water-cement ratios and water bath temperatures on grouting water separation rate



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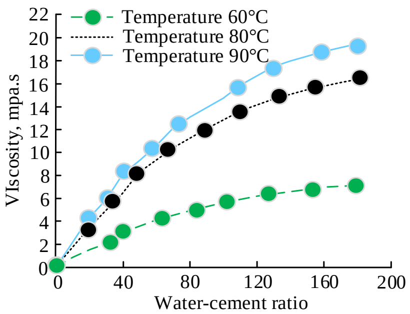

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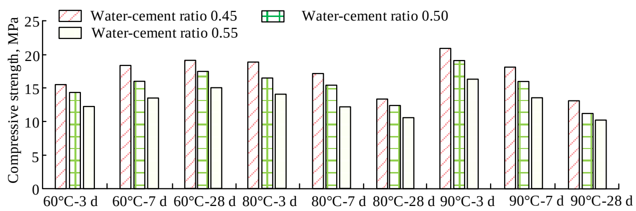
Fig. 8. Influence of different WCRs and water bath temperatures on grouting viscosity: a – effect of varying water-cement ratios and water bath temperatures on grouting viscosity; b – grouting viscosity fitting curve

Based on Fig. 8 b, the prepared grouting can be divided into a growth period (0 s – 60 s), a stable period (60 s – 120 s), and a fixed period (120 s – 180 s) in terms of time, with an increase in temperature and a decrease in WCR. After grouting and mixing, its viscosity significantly increased and entered a stable stage, with no significant change in viscosity. With the increase of time, the viscosity rose again and solidified and hardened. The changes in grouting mechanical properties under different conditions are displayed in Fig. 9.



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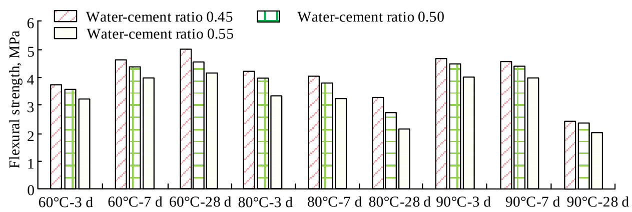

b

Fig. 9. Changes in mechanical properties of grouting under different ratios and water bath temperatures: a – compressive strength of grouting under varying water-cement ratios and temperatures; b – flexural strength of grouting under varying water-cement ratios and temperatures

Combining Fig. 9 a and b, when the ratio was fixed, the higher the water bath temperature, the higher the compressive and flexural strength after 3d grouting. The higher water bath temperature reduced the strength of grouting after 7 and 28 days. When the temperature was 90 °C, the compressive strength of grouting with a WCR of 0.55 at 3d, 7d, and 28d was reduced by 47.32 %, 47.45 %, and 49.38 %, respectively in contrast with ratio of 0.45. In contrast with the effect of water bath temperature changes on the compressive and flexural strength of grouting, the effect of WCR changes was smaller. This indicates that under the optimal configuration scheme, the water bath temperature has obvious impacts on the mechanical properties of grouting.

4. DISCUSSION

In order to clarify the effectiveness of using PCE slurry for tunnel water plugging construction, the slurry performance of tunnel water plugging engineering is conducted through RSM and CCD. The content of R·SAC425 had the greatest impact on the gel time, which may be related to the calcium silicate mineral and the aluminum hydroxide gel form formed by R·SAC in the hydration process, which promoted the gel speed of grouting [18, 19]. Secondly, HMCE also had a significant impact on gel time, but its impact was lower than R·SAC425. The long-chain polymer of HMCE may increase the internal structure viscosity of the slurry, thus affecting the gel time [20]. This indicates that the type and content of thickener should be considered when designing grouting materials to achieve the required gel time. With the increase of PCE, the compressive strength of grouting was improved, which may be attributed to the improvement effect of PCE in the later stage of the grouting stone body. On the whole, the influence of R·SAC425, PCE, CLS, and HMCE on grouting gel time was in the order of R·SAC425, CLS, PCE, and HMCE from high to low, the influence on viscosity was in the order of HMCE, R·SAC425, CLS, and PCE, and the influence on stability was in the order of R·SAC425, HMCE, CLS, and PCE. The influence on mechanical performance was in the order of R·SAC425, HMCE, CLS, and PCE. The results showed that the content of R·SAC425 had the greatest influence on grouting performance, which was fitted with the research obtained by Zhou et all [21].

According to the RSM model prediction, the optimal content formulation scheme for R·SAC425, PCE, CLS, and HMCE was obtained, with R·SAC425 content of 12.48 %, PCE content of 0.91 %, CLS content of 3.03 ‰, and HMCE content of 1.00 ‰. In addition, the research found that the WCR and water bath temperature also affected the performance of grouting. Higher water bath temperature and appropriate water cement ratio can improve the early strength of grouting, but may reduce the later strength. This indicates that in actual construction, it is necessary to choose the water bath temperature and WCR reasonably according to the specific requirements and construction conditions of the project. Ruan et al. found that a higher WCR may reduce the slurry stability and improve its flowability [22]. The research results showed that increasing the WCR reduced the compressive and flexural strength of grouting, and shortened the service life of grouting, which was consistent with the conclusion drawn by Jia et al [23].

In summary, the research optimizes the slurry performance of tunnel water plugging engineering integrating PCE through RSM and CCD. The research results not only provide theoretical basis and technical support for tunnel water plugging engineering, but also provide a reference for the selection and application of grouting materials in similar projects.

5. CONCLUSION

Aiming at the optimization of slurry performance in tunnel water plugging engineering, the RSM and CCD methods were used to conduct an in-depth analysis of the slurry performance of tunnel water plugging engineering fused with PCE. The results indicated that increasing the content of R·SAC425 can improve the grouting performance. The content of PCE has a small impact on grouting performance, but can reduce the amount of water required for slurry preparation, ensuring grouting stability and fluidity. The experimental conclusion is as follows:

1. The effect of R·SAC425, PCE, CLS and HMCE on grouting gel time is in the order of R·SAC425, CLS, PCE, and HMCE from high to low;
2. The influence of four materials on grouting flow performance is ranked from high to low as HMCE, R·SAC425, CLS, and PCE;
3. The effect ranking of four materials on grouting stability performance is R·SAC425, HMCE, CLS, and PCE;
4. The effect ranking of four materials on the mechanical properties of grouting is R·SAC425, HMCE, CLS, and PCE;
5. The optimal slurry preparation ratio obtained through the RSM model is R·SAC425 content of 12.48 %, PCE content of 0.91 %, CLS content of 3.03 ‰, and HMCE content of 1.00 ‰;
6. Under the optimal configuration scheme, the WCR and water bath temperature have a significant impact on the grouting performance, with the water bath temperature having a greater influence on the grouting performance. The slurry gel time at 90 °C was reduced by 62.58 % and 30.75 % compared to 60 °C and 80 °C, respectively. The high-temperature environment also affected the stability of the slurry, with the water precipitation rate of the slurry decreasing and stability increasing as the water bath temperature increased. However, the high temperature showed a dual effect on the mechanical properties of the slurry. At the age of 3 days, the slurry prepared under high temperature environment had higher compressive and flexural strengths; however, the strength of the slurry under high temperature environment decreased at the age of 7 and 28 days.

Although the research has achieved ideal optimization results under laboratory conditions, more complex factors may be encountered in practical engineering applications. Therefore, future research should consider more practical engineering conditions, such as the influence of different geological conditions, environmental factors, etc. on the performance of grouting materials, and explore more material and technological innovations to address more complex engineering challenges. At the same time, the RSM model will be optimized to improve its prediction accuracy and reliability for engineering applications.

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