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Experimental Study on the Effect of Hydroxyethyl Cellulose on the Friction-Reducing Performance of Thixotropic Slurries in Pipe Jacking Construction

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Abstract: In pipe jacking construction, thixotropic slurry critically governs lubrication, friction reduction, and ground support. This study evaluated slurry performance through six parameters: specific gravity (SG), pH, fluid loss (FL), water separation rate (WSR), filter cake thickness (FCT), and funnel viscosity (FV). Orthogonal experiments optimizing bentonite, carboxymethyl cellulose (CMC), and sodium carbonate (Na_2CO_3) ratios established 10 wt.% bentonite, 0.4 wt.% CMC, and 0.3 wt.% Na_2CO_3 as the optimal formulation. Subsequently, to address performance limitations in challenging conditions, this study introduces hydroxyethyl cellulose (HEC) as a novel additive, with potential advantages under high-salinity and variable pH conditions. Comparative experiments demonstrated that HEC, as a non-ionic water-soluble cellulose, not only significantly increases FV and reduces FL while maintaining SG, FCT, and WSR within acceptable thresholds, but also exhibits superior pH stability compared to CMC. The microstructures of the three thixotropic slurries with distinct compositions were examined using scanning electron microscopy (SEM) based on the aforementioned results, leading to systematic analysis of their structural characteristics and friction-reduction mechanisms that microscopically demonstrated the good compatibility between HEC and bentonite.These findings highlight HEC's potential as an effective alternative in pipe jacking, particularly in demanding geological environments.

Keywords: pipe jacking construction; thixotropic slurry mix design; orthogonal experiment; hydroxyethyl cellulose

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1. Introduction

Pipe jacking technology, as an advanced trenchless technology for underground pipeline installation, has seen extensive application in urban utility networks and major infrastructure projects—including transport tunnels, hydraulic systems, and utility corridors—due to its minimal surface disruption and ecological benefits [1,2]. The technique operates by hydraulically or mechanically thrusting prefabricated pipe segments through the ground while excavating the tunnel face. Nevertheless, substantial technical challenges persist, particularly with interfacial friction between pipes and surrounding strata. As projects encounter longer distances, larger diameters [3–8] or complex geologies [9–15], frictional resistance exhibits nonlinear escalation. This not only demands higher jacking forces but also risks construction defects (e.g., pipe misalignment) and geohazards (e.g., ground settlement), especially in high-water-table or soft-soil conditions. In practical engineering, various engineering measures have been adopted to reduce the jacking force, such as grouting with thixotropic slurry and installation of intermediate jacking stations[16,17].

The thixotropic slurry friction-reduction technique addresses this challenge by forming interfacial lubricating films. Injection of the slurry into the pipe-strata annular gap establishes a stable lubricating layer that significantly reduces friction coefficients and enhances jacking performance - with formulation quality being the primary determinant of effectiveness [18–22]. Conventional

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thixotropic slurries typically contain bentonite, carboxymethyl cellulose (CMC), sodium carbonate (Na_2CO_3), and water. As the key thickening agent, CMC enables stable lubricating film formation through its combined shear-thinning behavior and water retention capabilities.

Recent research on thixotropic slurry technology for complex geological applications has evolved along two parallel tracks: performance enhancement through multicomponent additives and the development of environmentally sustainable formulations. Microbial-induced calcium carbonate precipitation (MICP) technology has emerged as a particularly promising approach, demonstrating the ability to simultaneously reduce interfacial friction coefficients and reinforce adjacent strata through bacterially-mediated calcification processes [23]. In parallel, boronic acid-crosslinked polymer systems have been successfully incorporated into polyacrylamide-bentonite slurries, effectively addressing the biodegradation limitations characteristic of conventional materials [24]. The strategic combination of plant-derived additives (gums and potassium humate) with synthetic components (sodium carboxymethyl cellulose and graphite powder) has yielded measurable improvements in overall slurry performance [8] , while nanomaterial additives have shown particular efficacy in enhancing both thixotropic behavior and rheological properties [17]. Furthermore, the technological synergy with drilling fluid systems, which share fundamental compositional and functional characteristics with thixotropic slurries, has generated several significant innovations, including core-shell nano acrylic resin/SiO_2 composites for enhanced wellbore stability in shale gas applications [25],laponite nanoparticles for improved thermal stability [26], and specialized cellulose derivatives for precise rheological modification [27].

In addition, cellulose ether modification research [28–31] offers new avenues for slurry enhancement. Hydroxyethyl cellulose (HEC), sharing water-soluble cellulose ether characteristics with CMC, demonstrates superior thickening, water retention, and rheological performance [27,32–37], with established applications in food [38], pharmaceuticals [39,40], 3D printing, and oilfields. Compared to CMC, HEC's non-ionic nature confers enhanced acid stability and salt tolerance, particularly advantageous in pH-fluctuating or high-salinity strata. These attributes position HEC as a promising candidate for thixotropic slurry optimization in geologically challenging environments.

While HEC has demonstrated efficacy in conventional drilling fluids, its performance in pipe jacking slurry applications remains insufficiently characterized. This study first employed orthogonal experimental design to systematically investigate bentonite-CMC-Na_2CO_3 formulations, quantitatively determining the hierarchical influence of constituent components. Subsequently, through the innovative incorporation of HEC as a novel thickener, comparative experiments revealed HEC’s exceptional capability in enhancing thixotropic slurry performance metrics. Microstructural characterization via scanning electron microscopy (SEM) was conducted on three distinct formulations—bentonite-CMC- Na_2CO_3, bentonite-CMC, and bentonite-HEC—to elucidate structural configurations and their correlation with drag reduction mechanisms. This paper establishes a new technical pathway for slurry material optimization, offering both theoretical significance and engineering application potential.

2. Materials and Methods

2.1. Materials and Slurry Preparation

Figure 1 displays the four materials used in the thixotropic slurry, whose complete specifications are provided in Table 1.

Table 1. Specifications of raw materials.

Name	Specification
Sodium bentonite	Montmorillonite content ≥75%
	Gel yield (swelling capacity): 100.2 mL/15g
Na_2CO_3	Manufacturer: Shanghai Xilong Scientific Co., Ltd.
	Purity ≥99.8% (chemically pure grade)

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HEC	Viscosity of 2% aqueous solution: 5,000–6,000 mPa·s at 20°C
CMC	Viscosity of 20 g/L solution: 800–1,200 mPa·s at 25°C
Water	Municipal tap water

Figure 1. Raw materials.

This study established standardized preparation procedures for the following two distinct formulation systems.

For the Na_2CO_3-containing system, preparation commenced with precise weighing of components according to formulated ratios. The standardized protocol consisted of four consecutive stages: (i) 2-minute dry blending of bentonite and CMC, (ii) incremental addition of 5% Na_2CO_3 solution in three aliquots with continuous 3-minute mixing, (iii) incorporation of remaining water accompanied by 5-minute wet mixing, and (iv) final 24-hour temperature-controlled hydration in sealed containers.

For the Na_2CO_3-free system, preparation commenced with precision weighing of bentonite and selected cellulose (CMC or HEC), progressing through sequential phases: (i) initial 2-minute dry mixing of bentonite with selected cellulose (CMC or HEC), (ii) transfer to mixing tank and subsequent 8-minute aqueous mixing for complete dispersion, (iii) application of the identical temperature-controlled curing protocol as the Na_2CO_3 system, and (iv) concluding 24-hour sealed hydration phase.

All specimens were prepared in triplicate (n=3). Experimental data underwent outlier removal via Grubbs' criterion prior to calculating arithmetic means as final results.

2.2. Experimental Methods

This study developed a comprehensive performance evaluation system based on six critical parameters: specific gravity, Marsh funnel viscosity, pH, fluid loss, filter cake thickness, water separation rate, and Marsh funnel viscosity. The detailed experimental methods are as follows: Specific gravity (SG) determined using an NB-1 mud balance (Figure 2a); Marsh funnel viscosity (FV) measured with standardized Marsh funnels (Figure 2b); pH value measured by PHB-4 portable pH meters (Figure 2c); Fluid loss (FL) and filter cake thickness (FCT) assessed via ZNS-2A filter press

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(Figure 2d, Figure 2e); Water separation rate (WSR), quantified using a 1000 mL graduated cylinder (Figure 2f) after 24 h static sedimentation.

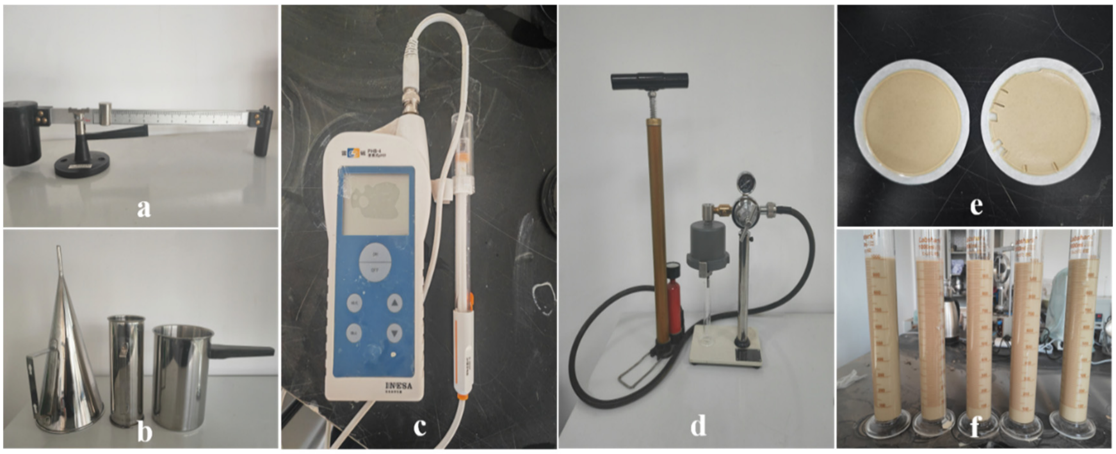

Figure 2. Experimental instruments.

2.3. Experimental Design

2.3.1. Orthogonal Experimental Design and Range Analysis

Orthogonal experimental design is an efficient, rapid, and economical methodology for investigating multi-factor and multi-level systems. In this study, an orthogonal design was employed to examine the synergistic effects of sodium bentonite content, CMC concentration, and Na_2CO_3 dosage on slurry performance. Based on the multi-factor, multi-level orthogonal design principle, a three-factor, four-level orthogonal array ($L_{16}(4^3)$) was implemented to systematically analyze the interaction mechanisms among these components [17]. The experimental factor-level configuration is presented in Table 2.

Table 2. Factors and levels of the orthogonal experiment.

No.	Factors	Level 1	Level 2	Level 3	Level 4
A	Bentonite content (%)	6.0	8.0	10.0	12.0
B	CMC content (%)	0.1	0.2	0.3	0.4
C	Na_2CO_3 content (%)	0.1	0.2	0.3	0.4

The experimental results were analyzed using the range analysis method [41]. Range analysis determines the influence intensity of factors by calculating the average values (K) of the corresponding indicators at different levels of each factor. The range value ($R = K_{max} - K_{min}$) is used to assess the significance of each factor: a larger range indicates a more significant influence of the factor on the performance indicator. The ranking of range values determines the primary and secondary relationships among factors, guiding the optimization direction of the formulation.

2.3.2. Comparative Experimental Design

Building upon the orthogonal experimental investigation of CMC's influence on thixotropic slurry performance, this study established a binary control system to systematically evaluate the feasibility of substituting CMC with HEC as the thickening agent. The experimental design incorporated parallel formulations: an experimental group combining 8 wt.% sodium bentonite with HEC (0.2–1.0 wt.%) and a control group maintaining 8 wt.% sodium bentonite with CMC (0.2–1.0 wt.%) for direct performance comparison.

The detailed mix proportion parameters for each group are presented in Table 3. Through systematic comparative analysis of the effects of HEC and CMC on key slurry performance

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indicators—including SG, pH, FL, WSR, FCT, and FV—this study evaluates the performance enhancement effects of HEC across varying dosage gradients (0.2–1.0 wt.%) relative to CMC. This analysis aims to demonstrate the potential application of HEC in thixotropic slurry systems.

Table 3. Slurry formulations in the comparative experiment.

No.	Bentonite content (%)	HEC content (%)	CMC content (%)	Water content (%)
HEC-0.05	8	0.05	-	91.95
HEC-0.10	8	0.10	-	91.90
HEC-0.15	8	0.15	-	91.85
HEC-0.20	8	0.20	-	91.80
HEC-0.25	8	0.25	-	91.75
CMC-0.05	8	-	0.05	91.95
CMC-0.10	8	-	0.10	91.90
CMC-0.15	8	-	0.15	91.85
CMC-0.20	8	-	0.20	91.80
CMC-0.25	8	-	0.25	91.75

Figure 3 details the workflow of orthogonal experiments and comparative experiments, along with the slurry preparation procedures.

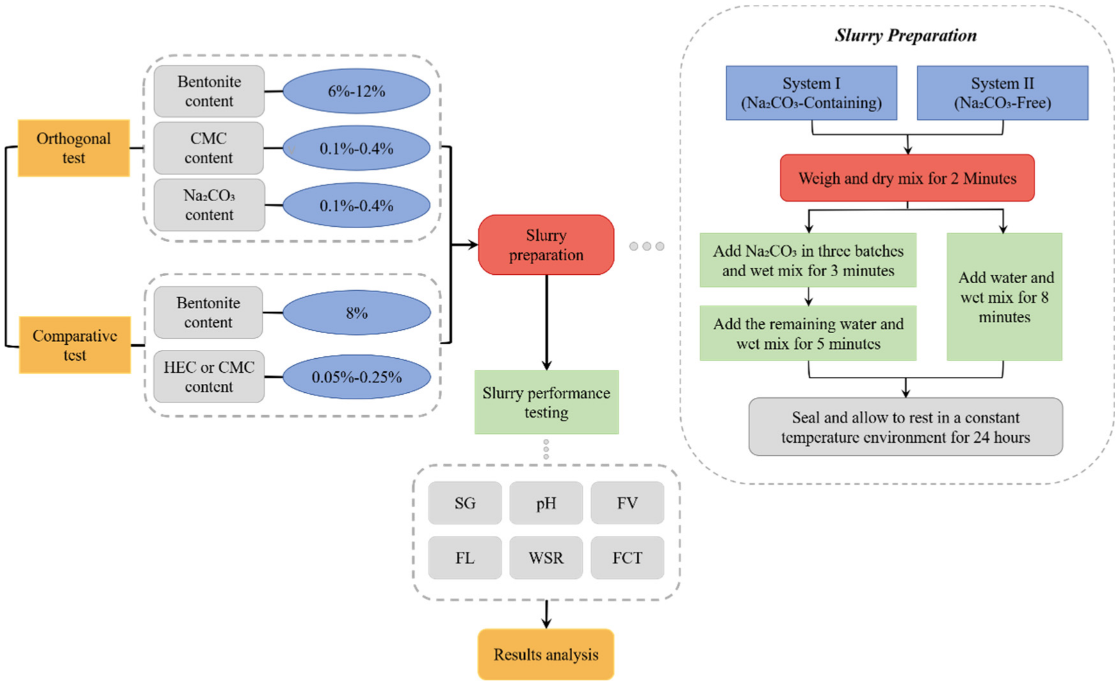

Figure 3. Schematic of experimental procedure and slurry formulation.

2.4. SEM Microstructural Observation

The microstructural characteristics of three slurry systems—bentonite-CMC-Na_2CO_3, bentonite-CMC, and bentonite-HEC—were systematically investigated using a Hitachi SU3500 field-emission scanning electron microscope (Figure 4). Sample preparation involved oven-drying at 55°C for 6 hours to constant weight, followed by ion-sputter gold coating to ensure adequate conductivity. High-resolution imaging was conducted in secondary electron imaging (SEI) mode at progressively increasing magnifications of 400× for macrostructural evaluation, 1500× for interfacial characterization, and 3000× for microstructural examination.

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Figure 4. Hitachi SU3500 field-emission SEM system.

4. Results and Discussion

4.1. Analysis of Orthogonal Experimental Results

The orthogonal experimental results are presented in Table 4. Based on the experimental data, the mean (K) and range (R) for each influencing factor were calculated to quantify their impacts on the thixotropic slurry performance. Through range analysis, the factors were then ranked by significance, and the optimal combination within the three-factor concentration range was determined.

Table 4. Results of the orthogonal experiment.

No.	A (%)	B (%)	C (%)	SG	pH	FV (s)	WSR (%)	FL (mL/30min)	FCT (mm)
1	6	0.1	0.1	1.020	10.68	36	0	13.7	0.7
2	6	0.2	0.2	1.023	10.80	43	0	11.0	0.5
3	6	0.3	0.3	1.030	10.98	56	0	9.0	0.6
4	6	0.4	0.4	1.031	11.11	72	0	8.4	0.8
5	8	0.1	0.4	1.038	10.70	183	0	8.0	1.0
6	8	0.2	0.3	1.040	10.89	82	0	8.9	1.1
7	8	0.3	0.2	1.038	11.02	49	0	8.2	0.7
8	8	0.4	0.1	1.037	11.11	38	0	11.4	0.9
9	10	0.1	0.2	1.053	10.57	154	0	8.3	0.9
10	10	0.2	0.1	1.050	10.77	62	0	11.4	1.1
11	10	0.3	0.4	1.051	10.93	225	0	7.0	1.0
12	10	0.4	0.3	1.058	11.09	119	0	7.5	0.9
13	12	0.1	0.3	1.068	10.68	803	0	7.6	1.1
14	12	0.2	0.4	1.070	10.80	601	0	6.4	1.5
15	12	0.3	0.1	1.069	10.96	83	0	10.4	1.1
16	12	0.4	0.2	1.068	11.11	95	0	8.5	1.1

The contribution effects of three factors on FL are illustrated in Figure 5, where the four level values of each factor are represented on the x-axis and the FL values are indicated on the y-axis. The analysis results demonstrate that the degree of influence of each factor on slurry FL follows the order: CMC > bentonite > Na_2CO_3. Specifically, FL shows a significant decreasing trend with increasing CMC and bentonite content, while it initially decreases and then increases with rising Na_2CO_3 content. The range analysis in Table 5 further confirms this conclusion, with the range values ranking as: CMC (R=4.275) > bentonite (R=2.3) > Na_2CO_3 (R=0.775). Notably, FL exhibits a negative correlation with slurry performance, meaning that lower FL corresponds to better slurry performance. Therefore, when optimizing the slurry formulation, priority should be given to increasing the dosage of CMC and bentonite, while the Na_2CO_3 content needs to be controlled within an optimal range to achieve the best slurry performance. Ultimately, the optimal combination for minimizing slurry fluid loss was determined to be $A_4B_4C_3$.

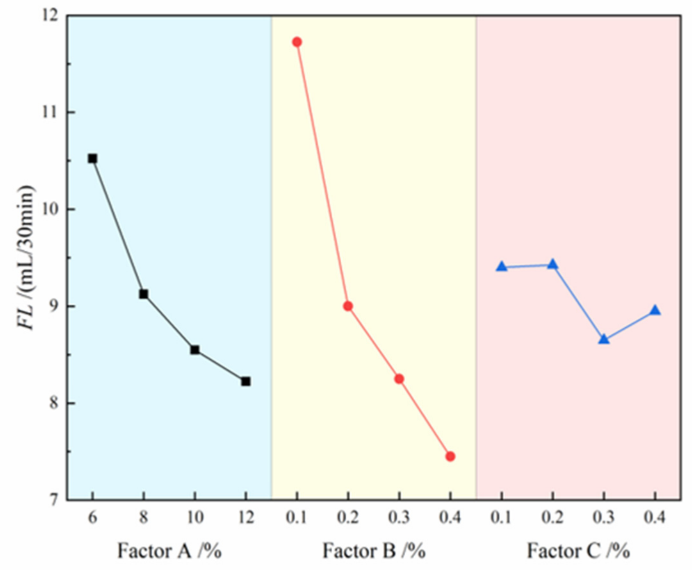

Figure 5. Effects of three factors on FL.

Table 5. Results of range analysis for FL.

Factors	Mean FL values (K_1) across experimental levels (mL/30 min)						
	Level 1	Level 2	Level 3	Level 4	R	Priority order	Optimal combination
A	10.525	9.125	8.550	8.225	2.300		
B	11.725	9.000	8.250	7.450	4.275	B-A-C	$A_4B_4C_3$
C	9.400	9.425	8.650	8.950	0.775		

The contribution effects of three factors on FV are illustrated in Figure 6, where the four level values of each factor are represented on the x-axis and the FV values are indicated on the y-axis.The analysis results reveal that the degree of influence of each factor on slurry FV follows the order: bentonite > CMC > Na_2CO_3. Specifically, FV shows a significant increasing trend with rising bentonite and CMC content, while it exhibits a clear decreasing trend with increasing Na_2CO_3 content. The range analysis in Table 6 further confirms this conclusion, with the range values ranking as: bentonite (R=343.75) > CMC (R=215.5) > Na_2CO_3 (R=213). Notably, bentonite demonstrates the most pronounced effect on FV enhancement, as evidenced by its significantly higher range value compared to other factors, indicating its dominant role in regulating slurry viscosity. Although CMC and Na_2CO_3 show relatively smaller effects, their influence remains non-negligible. Ultimately, the $A_3B_2C_3$ formulation was identified as the optimal composition for maintaining slurry FV within the target range of 100-120 s, achieving balanced rheological properties and stability.

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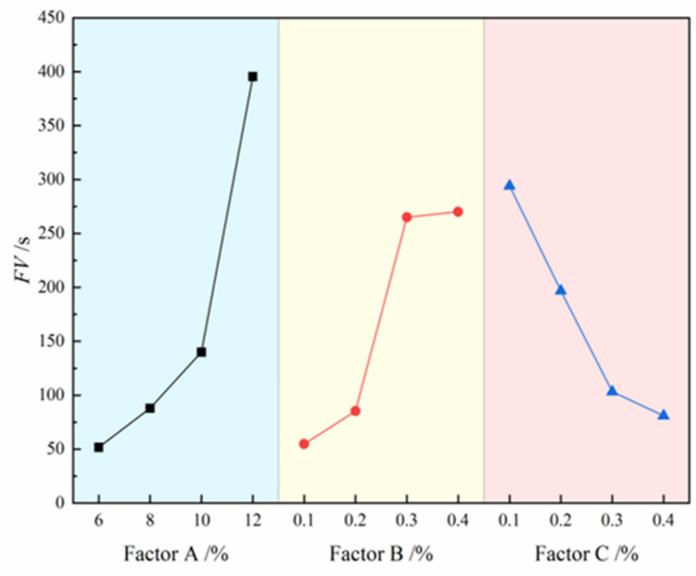

Figure 6. Effects of three factors on FV.

Table 6. Results of range analysis for FV.

Factors	Mean FV values (K_2) across experimental levels (s)						
	Level 1	Level 2	Level 3	Level 4	R	Priority order	Optimal combination
A	51.750	88.000	140.000	395.500	343.750	A-B-C	$A_3B_2C_3$
B	54.750	85.250	265.000	270.250	215.500		
C	294.000	197.000	103.250	81.000	213.000		

The contribution effects of three factors on FCT are illustrated in Figure 7, where the four level values of each factor are represented on the x-axis and the FCT values are indicated on the y-axis.The analysis results demonstrate that the degree of influence of each factor on FCT follows the order: bentonite > CMC > Na_2CO_3. Specifically, FCT shows a significant increasing trend with rising bentonite content, while it exhibits a fluctuating pattern of initial decrease followed by increase with increasing CMC content. For Na_2CO_3, the FCT displays a more complex trend of increase, decrease, and subsequent increase. The range analysis in Table 7 further confirms this conclusion, with the range values ranking as: bentonite (R=0.55) > CMC (R=0.275) > Na_2CO_3 (R=0.2). The range values indicate that bentonite has the most pronounced effect on FCT, with its range value approximately twice that of CMC and 2.75 times that of Na_2CO_3, highlighting its dominant role in regulating FCT. Although both CMC and Na_2CO_3 exhibit relatively minor overall effects, their complex variation trends suggest potentially significant impacts on FCT within specific concentration ranges. Ultimately, through comprehensive analysis of optimal FL and FV combinations, the $A_3B_2C_3$ formulation was identified as maintaining the filter cake within the target thickness range, despite multiple formulations meeting the basic FCT engineering requirements.

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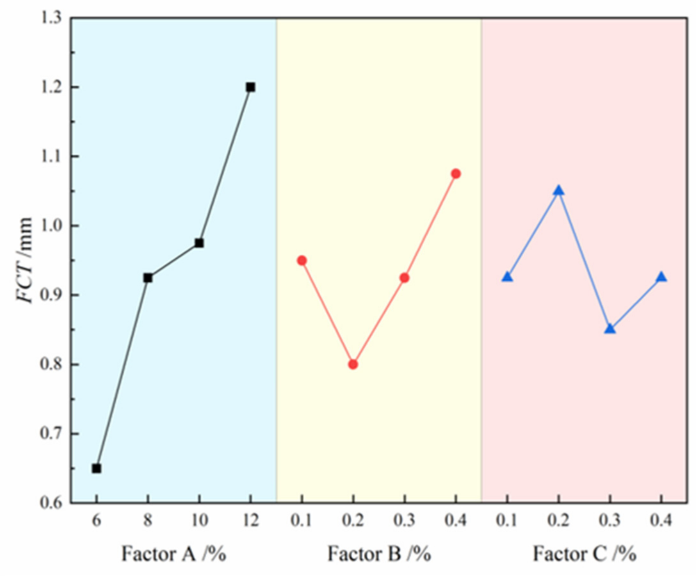

Figure 7. Effects of three factors on FCT.

Table 7. Results of range analysis for FCT.

Factors	Mean FCT values (K_3) across experimental levels (mm)						
	Level 1	Level 2	Level 3	Level 4	R	Priority order	Optimal combination
A	0.650	0.925	0.975	1.200	0.550	A-B-C	$A_3B_2C_3$
B	0.950	0.800	0.925	1.075	0.275		
C	0.925	1.050	0.850	0.925	0.200		

Based on the orthogonal experimental results and cost-benefit analysis, the optimal thixotropic slurry formulation was determined to be $A_3B_4C_3$ (10 wt.% bentonite, 0.4 wt.% CMC, and 0.3 wt.% Na_2CO_3) after comprehensive evaluation of multiple performance indicators. Figure 8 shows the prepared slurry under this formulation. Notably, range analysis revealed that none of the three factors exhibited statistically significant effects on either slurry SG or pH, and all 16 experimental groups achieved zero WSR, demonstrating that all formulations met the fundamental stability requirements. Consequently, these parameters were not subjected to further detailed analysis in this study.

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Figure 8. Photograph of the prepared optimal thixotropic slurry ($A_3B_4C_3$).

4.2. Analysis of Comparative Experimental Results

4.2.1. Effect of HEC Content on Slurry Performance

According to the experimental data on the performance of thixotropic slurry with varying HEC dosages in Table 8, the incorporation of HEC exerts a significant regulatory effect on the rheological properties and stability of the system. The experimental results reveal that as the HEC dosage increases from 0.2% to 1%, the slurry SG exhibits a linear growth from 1.035 to 1.041, while the FV simultaneously rises from 43 s to 121 s, demonstrating a significant positive correlation. Notably, within this dosage range, the WSR of the slurry remains consistently at 0%, and the FCT is maintained within the ideal range of 0.8 to 1 mm, indicating excellent suspension stability and dense film-forming capability. Simultaneously, the evolution of the system's pH value displays a non-linear characteristic of initially decreasing, then increasing, and finally decreasing again, which is primarily attributed to the dynamic influence of polar groups in HEC molecules on the double electric layer structure of the slurry colloid.

Table 8. Results of the comparative experiment (HEC).

No.	Key performance indicators of thixotropic slurry					
	SG	FV (s)	WSR (%)	FCT (mm)	FL (mL/30min)	pH
HEC-0.05	1.035	43	0	1.0	15.5	10.17
HEC-0.10	1.039	54	0	1.0	12.1	9.98
HEC-0.15	1.039	83	0	1.0	10.8	9.98
HEC-0.20	1.040	90	0	0.8	9.8	10.22
HEC-0.25	1.041	121	0	1.0	9.5	10.20

Regarding key performance parameters, the FL exhibits an exponential decline with increasing HEC dosage, significantly decreasing from 15.5 mL in the 0.2% dosage group to 9.5 mL in the 1% dosage group (a reduction of 38.7%). This is closely related to the molecular structure characteristics of HEC. As a non-ionic water-soluble cellulose ether, the numerous hydroxyl (-OH) and hydroxyethyl ($-CH_2CH_2OH$) groups in its molecular chains form a three-dimensional hydration network through hydrogen bonding: (i) Hydrophilic groups strongly associate with water molecules, significantly enhancing the water retention capacity of the system; (ii) Long-chain molecules entangle to create spatial steric hindrance, effectively inhibiting the sedimentation and separation of solid particles; (iii) The formation of hydration films effectively seals filtration channels, reducing permeability. These multiple mechanisms synergistically improve the fluid loss control performance of the slurry.

Experimental analysis confirms that HEC significantly enhances the rheological properties and stability of the slurry through its unique molecular structure and hydration mechanisms. Its thickening effect, fluid loss reduction characteristics, and colloidal stability advantages provide potential applications for thixotropic slurries in complex engineering environments.

4.2.2. Effect of CMC Content on Slurry Performance

According to the experimental data on the performance parameters of thixotropic slurry with varying CMC dosages in Table 9, as the CMC dosage increases from 0.2% to 1%, the SG of the slurry rises from 1.036 to 1.041, and the FV significantly increases from 45 s to 112 s. This phenomenon indicates that CMC effectively enhances the structural strength of the slurry through molecular chain entanglement, thereby significantly improving the rheological properties of the slurry. The increase in FV further validates the thickening effect of CMC in the thixotropic slurry, providing essential assurance for the stability and fluidity of the slurry during construction.

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Table 9. Results of the comparative experiment (CMC).

No.	Key performance indicators of thixotropic slurry					
	SG	FV (s)	WSR (%)	FCT (mm)	FL (mL/30min)	pH
CMC-0.05	1.036	45	0	1.0	14.6	10.43
CMC-0.10	1.038	53	0	1.0	12.0	10.37
CMC-0.15	1.040	66	0	1.0	10.6	10.37
CMC-0.20	1.041	91	0	1.0	10.0	10.35
CMC-0.25	1.041	112	0	1.0	9.2	10.35

Regarding the key performance parameters, the FL shows a clear negative correlation with increasing CMC dosage, decreasing from 14.6 mL at a 0.2% dosage to 9.2 mL at a 1% dosage (a reduction of 37.0%). This result confirms the adsorption and stabilization effects of the hydroxyl and carboxyl groups in CMC molecules on bentonite particles, significantly reducing the fluid loss of the slurry. Additionally, the pH value gradually decreases from 10.43 to 10.35, indicating that as an anionic cellulose ether, CMC dosage has a certain influence on the pH value of the thixotropic slurry. Notably, under all formulations, the WSR remains stable at 0%, and the FCT stays consistent at 1 mm. This demonstrates that the three-dimensional network structure formed by CMC and bentonite particles exhibits excellent anti-segregation stability and interfacial sealing properties. This stable structure not only effectively prevents stratification and water separation in the slurry but also provides reliable support for the long-term stability of the slurry during construction.

The findings highlight that CMC, as an additive for thixotropic slurry, demonstrates significant advantages in thickening, reducing fluid loss, and colloid stability. The three-dimensional network structure formed by CMC and bentonite particles not only enhances the structural strength of the slurry but also improves its rheological properties and construction stability. This conclusion further confirms the widespread applicability of CMC in thixotropic slurries.

4.2.3. Comparison of the Effects of HEC and CMC on Slurry Performance

Marsh funnel viscosity directly correlates with cuttings transport efficiency. As shown in Figure 9, the effects of HEC and CMC content on the FV of thixotropic slurry revel the following trends: both cellulose derivatives exhibit a significant positive correlation between concentration and FV in their thickening effects. At dosages of 2%–4% and 8%, there is no notable difference in FV between HEC and CMC. However, within the dosage ranges of 4%–8% and 8%–10%, HEC demonstrates a more pronounced enhancement in FV compared to CMC, indicating that HEC possesses a more significant thickening capability within certain dosage ranges.

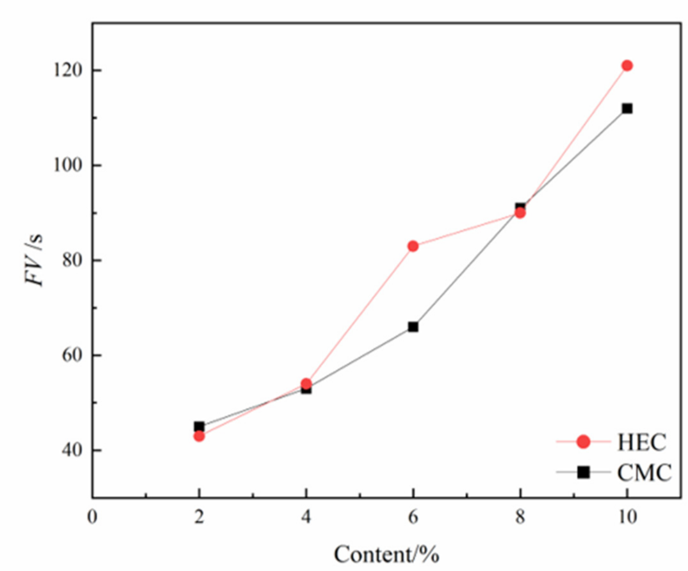

Figure 9. Effects of HEC/CMC content on FV.

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Fluid loss reflects the ability of the thixotropic slurry to maintain liquid - phase stability and control fluid penetration in the subsurface environment. As the dosage of both cellulose-based admixtures gradually increases, the FL of the thixotropic slurry system shows a significant downward trend, and the improvement effects of the two cellulose derivatives on the water retention performance of the slurry are similar (Figure 10). The analysis indicates that the mechanism of action stems from the three-dimensional network structure formed by the polymer segments during the hydration process, which effectively blocks the microporous channels in the slurry system and inhibits the exudation of free water. It is particularly noteworthy that when the dosage exceeds 0.6%, the efficiency of both additives in controlling FL exhibits a diminishing marginal effect. This phenomenon may be attributed to the reduced dispersion uniformity caused by the increased system viscosity. In engineering practice, CMC or HEC can be flexibly selected as water retention enhancers based on material supply conditions and economic indicators.

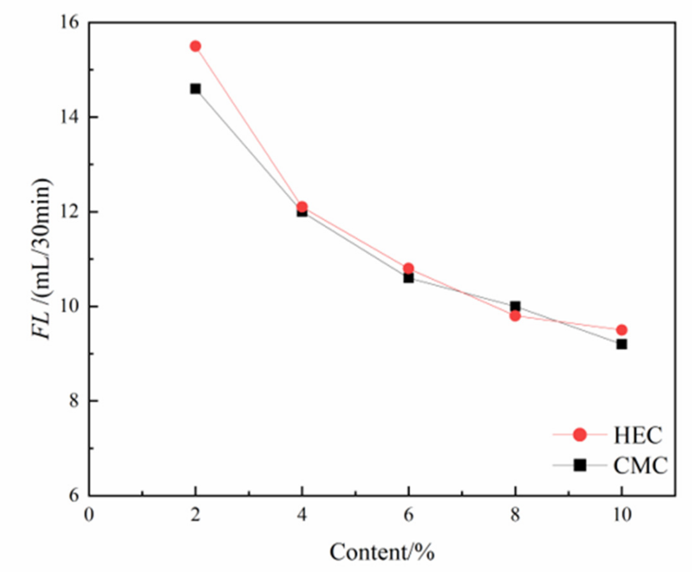

Figure 10. Effects of HEC/CMC content on FL.

Appropriate pH value can maintain the stability of thixotropic slurry and reduce the filtration loss. Under laboratory conditions, pH should be maintained between 8 and 10 to ensure colloidal stability. Under the same dosage conditions, the pH value of the slurry system incorporating CMC is significantly higher than that incorporating HEC. With the increase in CMC dosage, the pH value of the slurry exhibits a linear downward trend, whereas the variation in HEC dosage influences the pH value in a nonlinear manner, characterized by an initial decrease, followed by an increase, and then another decrease (Figure 11). Notably, throughout the entire dosage range, the pH value of the HEC slurry system remains consistently lower than that of the CMC slurry system. This discrepancy in mechanisms primarily stems from the differences in charge response characteristics in solution between non-ionic HEC and anionic CMC.

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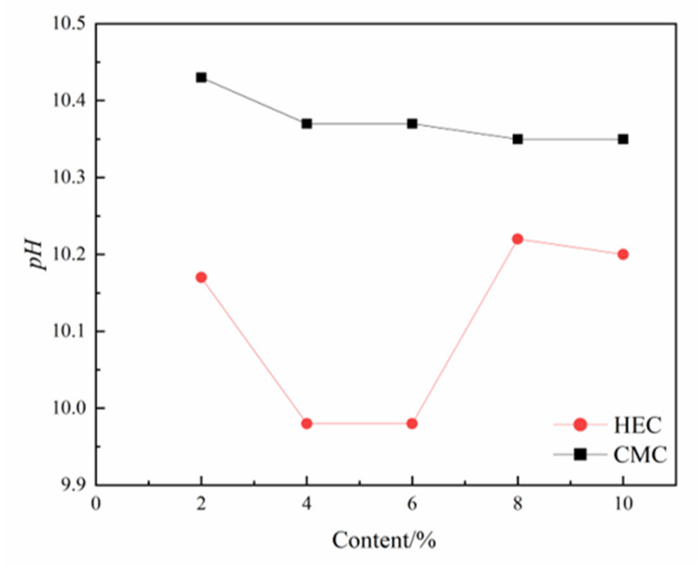

Figure 11. Effects of HEC/CMC content on pH.

Specific gravity (SG) predominantly controls slurry rheological properties and load-bearing capacity. While a lower SG (< 1.05) enhances lubrication, it concurrently reduces suspension capability. Conversely, higher SG values (> 1.08) improve compressive resistance but increase jacking forces. Engineering practice established the optimal range as 1.05-1.08. The incorporation of both cellulose-based admixtures exerts a certain influence on the SG regulation of the slurry system, manifested by an increase in slurry SG with the rising dosage of the admixtures (Figure 12). This phenomenon of SG enhancement is closely related to the molecular structures of the cellulose derivatives: the hydroxyethyl groups (-CH_2CH_2OH) in HEC molecules and the carboxymethyl groups (-CH_2COO^-) in CMC molecules can form stable associations with water molecules through hydrogen bonding. Meanwhile, their long-chain molecules generate steric hindrance effects in the slurry, significantly enhancing the suspension stability of solid particles, thereby inhibiting slurry sedimentation and improving overall compactness, ultimately leading to an increase in SG.

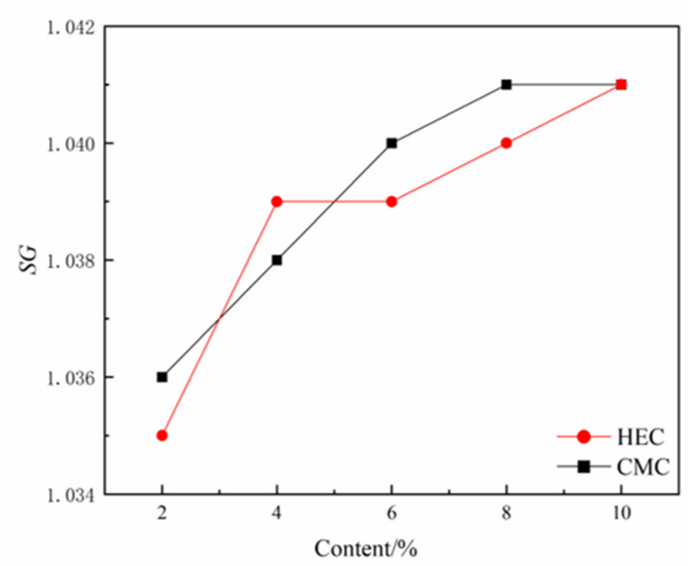

Figure 12. Effects of HEC/CMC content on SG.

In conclusion, HEC and CMC exhibit similar rheological regulation characteristics in thixotropic slurries, but there are certain differences between the two in terms of thickening efficiency, FL control, pH influence, and SG regulation: HEC slightly outperforms CMC in thickening efficiency, while the two show significant differences in their impact on pH; in terms of FL control and SG enhancement, the effects of the two are comparable, effectively improving the construction performance and stability of the slurry. These findings provide an important basis for the selection of cellulose-based admixtures in engineering practice and also lay the foundation for the potential application of HEC in thixotropic slurries for pipe jacking construction.

5.1. Microtructure Analysis

Figure 13 illustratesthe microstructural morphology of the thixotropic slurry in the bentonite-CMC- Na_2CO_3 ternary system. Under 400× magnification (Figure 13a), the sample exhibits a typical montmorillonite lamellar stacking structure, consistent with the morphological characteristics of layered silicate minerals. When magnified to 1500× (Figure 13b), the edges of the montmorillonite lamellae become more distinct. CMC molecules are uniformly coated on the bentonite surface via electrostatic adsorption and hydrogen bonding, while micron-sized crystalline particles, identified as Na_2CO_3 recrystallization products, are observed at partial pores and lamellar edges. Further magnification to 3000× (Figure 13c) reveals clearly distinguishable monolayer montmorillonite structures. CMC forms a continuous wrapping network through molecular chain crosslinking, constructing a uniform organic-inorganic composite interface on the bentonite surface. The regularly distributed pore structures provide effective channels for moisture migration.

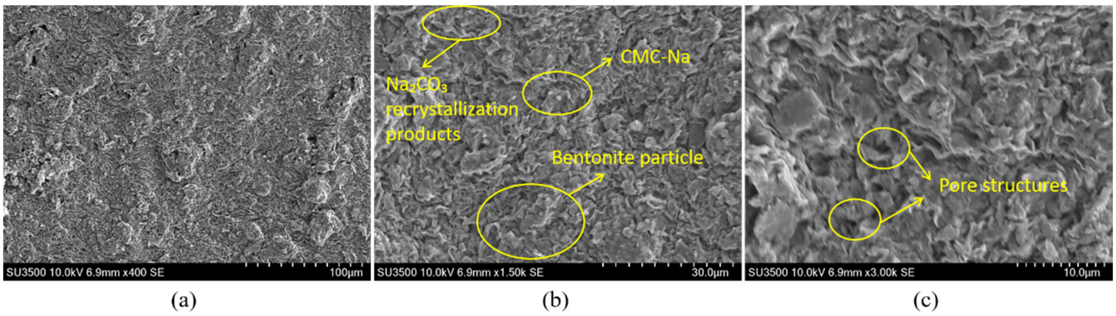

Figure 13. SEM images of the bentonite-CMC- Na_2CO_3 ternary system.

For comparative analysis, Figure 14 shows the microstructural features of the bentonite-CMC binary system for comparison. Under 400× and 1500× magnifications (Figure 14a, Figure 14b), its macroscopic structure remains largely consistent with that of the Na_2CO_3-containing system. However, under 3000× high-resolution imaging (Figure 14c), localized agglomeration phenomena become apparent, accompanied by loosely stacked bentonite lamellae and uneven pore size distribution. This phenomenon can be attributed to the absence of two key mechanisms: (i) insufficient montmorillonite lamellar dispersion due to the lack of ion exchange induced by soda ash, and (ii) disordered entanglement of CMC molecular chains caused by charge imbalance. Such microstructural defects may lead to reduced water retention capacity and impaired thixotropic performance.

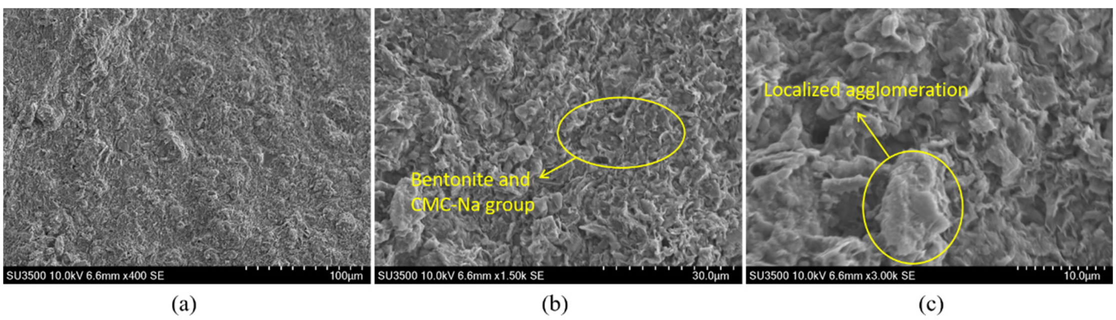

Figure 14. SEM images of the bentonite-CMC binary system.

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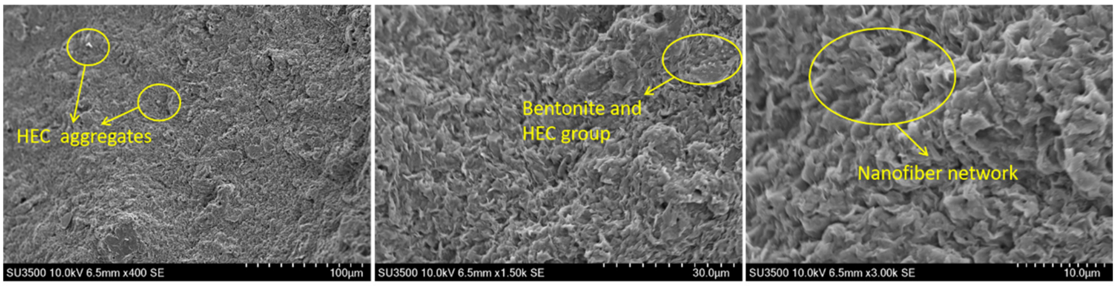
Figure 15 presents the microstructural morphology of the bentonite-HEC binary thixotropic slurry. Under 400× magnification (Figure 15a), bentonite retains its typical lamellar stacking morphology, while HEC molecular chains form localized bright white aggregates due to incomplete dispersion. Under 1500× magnification (Figure 15b), partial exfoliation of bentonite lamellae is observed, with HEC forming a thin film coating on the bentonite surface via intermolecular hydrogen bonding, exhibiting similarities to the CMC systems in Figure 13 and Figure 14. Further magnification to 3000× (Figure 15c) reveals three critical structural features: (i) HEC forming a continuous nanofiber network uniformly coating the bentonite surface and extending into interlayer spaces; and (ii) uniform overall pore distribution interspersed with localized fiber fractures and agglomerations. This composite structure endows the material with pronounced thixotropic properties through synergistic hydrogen-bonded networks and physical entanglement.



(a) (b) (c)

Figure 15. SEM images of the bentonite-HEC binary system.

Further analysis indicates that CMC (existing as CMC-Na), an anionic cellulose ether, adsorbs onto bentonite particles via electrostatic interactions and hydrogen bonding to form a three-dimensional network, enhancing interparticle cohesion and improving slurry thixotropy [42]. In contrast, HEC, a non-ionic cellulose ether, establishes hydrogen bonds between its hydroxyl groups and surface hydroxyls or interlayer cations of bentonite lamellae, strengthening particle adhesion. These distinct properties enable targeted applications of the two cellulose ethers in different engineering scenarios. Additionally, the incorporation of appropriate soda ash facilitates uniform bentonite dispersion and promotes the formation of a more continuous three-dimensional network. This not only enhances slurry stability but also effectively retards the sedimentation rate of solid particles.

6. Conclusions

This study thoroughly investigates the influence mechanisms of bentonite, CMC, and Na_2CO_3 on the key performance parameters of thixotropic slurry through systematic orthogonal experiments and comparative experiments, and for the first time evaluates the potential application of HEC as a new additive in slurry for pipe jacking construction. Based on the experimental results and analysis, the following conclusions are drawn:

1) Utilizing an orthogonal experimental design, this study systematically quantified the effects of bentonite, CMC, and Na_2CO_3 concentrations on thixotropic slurry performance metrics. The results conclusively demonstrate statistically significant influences of each component on all critical parameters, including SG, pH, FL, FCT, WSR, and FV. Through comprehensive range analysis, the relative influence hierarchy of the factors was established, ultimately identifying $A_3B_4C_3$ (10 wt% bentonite, 0.4 wt% CMC, and 0.3 wt% Na_2CO_3) as the performance-optimized formulation.

2)Comparative experimental studies demonstrated that HEC, as an additive, exhibits regulation effects on the rheological properties of the slurry system similar to those of CMC. Its introduction can systematically improve slurry performance, specifically manifested as significant enhancement in FV, effective reduction in FL, and certain control capabilities over key parameters such as WSR and FCT. Notably, the pH regulation mechanism of HEC differs significantly from that of CMC: under equivalent dosage conditions, the pH value of the HEC-based slurry system is significantly lower than that of the CMC-based system. This phenomenon indicates HEC's potential application prospects in high-salinity or acidic complex geological environments.

3)An important innovation of this study lies in the revelation of HEC's potential application value in extreme environments. Based on its excellent pH stability characteristics, it is suggested that subsequent research focus on the following directions: (i) the rheological evolution of HEC-based slurry under high-salinity and highly acidic geological conditions; (ii) the construction of a HEC-CMC composite system to explore synergistic enhancement mechanisms through molecular structure complementarity [43]; (iii) the development of optimized HEC-based thixotropic slurry formulations suitable for special geological conditions.

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