

# EVALUATION OF THE IMPACT OF A MODIFIED ADDITIVE IN INJECTION SOLUTION ON ITS PHYSICAL AND MECHANICAL PROPERTIES

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**ABSTRACT:** The stabilization of weak soils is a critical challenge in geotechnical engineering, particularly in regions with complex geological conditions. This study addresses the problem of limited performance in traditional cement-sand injection grouts used for soil stabilization. A modified additive was developed to enhance the mobility and physical-mechanical properties of such grouts. The proposed additive, composed of paraffin, cement, sulfuric acid, and water, aims to increase the mobility of the injection mixture and improve its penetration into the soil while maintaining or enhancing strength properties. The research evaluates the effects of varying additive concentrations (0.2–1.0% by mass) on compressive strength, flexural strength, and bleeding properties. The experimental results reveal that the additive improves compressive strength by 6–9% and flexural strength by 6–8% at an optimal concentration of 0.6–0.8%, with further increases showing diminishing returns. Bleeding values decreased progressively with additive inclusion, transitioning the grout from conditionally stable (8–16%) to stable (<8%) at 0.6% concentration. Statistical analysis confirmed the consistency and reliability of the results, with variation coefficients below 2%. The study concludes that the additive effectively enhances the performance of injection grouts for soil stabilization, achieving optimal results at 0.6% concentration. These findings provide a cost-effective and efficient solution for improving soil stabilization techniques in geotechnical engineering. Future work will explore long-term durability and environmental impacts of the modified additive.

*Keywords: Modified additive, Soil stabilization, Cement-sand, Paraffin*

## 1. INTRODUCTION

“This article examines deep cementation—a widely adopted technique for stabilizing weak soils—based on injecting cement slurry to improve soil strength and durability under complex geological conditions [1].

The history of deep cementation dates back to the early 20th century when engineers first encountered challenges with unstable soils during large-scale infrastructure projects [2]. Early cement slurries often lacked sufficient strength, prompting mid-20th-century research into polymer additives that significantly improved cement properties and led to modern, more effective deep cementation methods [3].

The stabilization of weak soils remains one of the most pressing challenges in geotechnical engineering. Deep cementation, involving the injection of cementitious slurries into soil, has been widely adopted across the globe to improve soil bearing capacity and structural durability. Historical developments from the early 20th century demonstrated the limitations of pure cement slurries, which often failed to meet durability standards. Subsequent introduction of polymer-based additives

in the mid-20th century significantly improved performance. Recent decades have seen research into nanomaterials and bioactive additives for improved hydration and microstructural enhancement. However, despite these advances, knowledge gaps remain in terms of cost efficiency, sustainability, and applicability in diverse geological conditions such as those in Kazakhstan.

Deep cementation plays a pivotal role in modern construction technologies, especially in urbanization and complex geological settings. This method is highly relevant in seismically active regions, where soil stabilization is crucial for preventing structural damage during earthquakes. The technique ensures the stability and durability of structures, particularly under challenging conditions. Recent developments focus on using polymer additives, nanomaterials, and bioactive compounds to enhance the interaction between cement matrices and natural soils [4].

The relevance of this study stems from the critical importance of weak soil stabilization in contemporary geotechnical engineering. Urban expansion, infrastructure development, and increasing ground loads necessitate effective methods for ensuring stability and durability. Although deep cementation has proven effective, new materials and technologies

drive the need for improved approaches and innovative solutions to enhance cement slurry properties [5].

For high-rise construction, polymer additives and nanomaterials are recommended to increase soil bearing capacity and structural stability. In metro construction, nanomaterials and chemical additives ensure high strength and water resistance of stabilized soils, protecting underground structures from water-saturated layers [6]. Furthermore, bioactive additives are gaining attention for their ability to improve the microstructure and hydration process of cementitious materials, enhancing their strength and durability [7].

A significant challenge in this context is the lack of long-term data on the effectiveness of modified additives under varying conditions. While current studies provide promising results, additional research and monitoring are necessary to validate the durability and strength of stabilized soils.

The relevance of this article is further underscored by the need to ensure reliable and safe construction on weak soils while reducing maintenance costs for infrastructure projects. The introduction of novel modifiers and complex additives into cement slurries creates more efficient and cost-effective solutions, promoting sustainable development and environmental protection.

This study focuses on the modification of injection slurries using ordinary construction-grade cement. The choice of materials is justified by the high demand for standard M500 cement in the construction market and in the engineering-geological conditions of the research region (central Kazakhstan) [8].

The aim of this research was to develop a composition and production technology for a modifying additive for injection slurries based on general-purpose cement for the deep cementation method in soil stabilization. This article presents the findings on the influence of the developed modified additive on the physical and mechanical properties of the injection slurry, contributing to the improved efficiency and reliability of soil stabilization methods in diverse conditions.

The novelty of this study lies not only in proposing a paraffin–sulfuric acid combination for grout modification, but also in demonstrating its dual functionality: enhancing the mobility of injection mixtures while simultaneously reducing bleeding without compromising strength. Unlike polymer- or nanomaterial-based additives, the proposed formulation is cost-effective, utilizes locally available materials (ordinary Portland cement M500 and paraffin common in Kazakhstan), and generates environmentally benign by-products ( $\text{CaSO}_4$ ). These aspects provide a new, practical, and sustainable alternative for soil stabilization, particularly under the geological conditions of Central Asia [9].

## **2. RESEARCH SIGNIFICANCE**

This study introduces a novel paraffin–sulfuric acid additive system for injection grouts, which demonstrates dual functionality: improving mixture mobility while simultaneously reducing bleeding without compromising strength. Unlike conventional polymer- or nanomaterial-based additives, the proposed formulation is cost-effective, based on locally available materials, and produces environmentally benign by-products such as  $\text{CaSO}_4$ . The originality lies in combining hydrophobic modification and chemical stabilization within a single additive, offering both technical efficiency and sustainability. This approach addresses existing gaps in grout technology, particularly in regions with weak and water-saturated soils, and provides a practical solution for cost reduction and ecological safety [10].

## **3. MATERIALS AND METHODS**

Earlier studies on polymer- and nanomaterial-based additives typically improved either grout workability or mechanical strength, but seldom achieved both simultaneously. These approaches were also limited by higher costs, environmental concerns, and empirical dosage selection. The present study introduces a paraffin–sulfuric acid system that demonstrates dual functionality: enhancing mobility and reducing bleeding while maintaining strength. Unlike previous works, the dosage interval was systematically tested (0.2–1.0%) and an optimal range identified (0.6–0.8%). Bleeding was evaluated using both absolute and relative indicators, and replicate variability was quantified with coefficients of variation. These methodological improvements ensure more accurate, reproducible, and practically relevant results. The preparation of the modified additive involves completely dissolving paraffin in the cement mixture while carefully controlling the water content. This is necessary due to the exothermic reaction that occurs when sulfuric acid neutralizes the alkaline environment of the mixture, leading to water evaporation. Through multiple iterations of mixture preparation, an optimal component ratio was determined to account for water evaporation: 1000 g of cement, 200 g of paraffin, 100 g of sulfuric acid, and 1000 g of water. This proportion yields a balanced and mobile mixture that can be easily incorporated into the injection grout.

The concentration interval of 0.2–1.0% by mass of cement was selected based on preliminary trials and literature data [11]. Concentrations below 0.2% were found to have negligible influence on mixture mobility, while values exceeding 1.0% introduced risks of excessive heat release during neutralization and provided diminishing improvements in strength and bleeding resistance. Thus, the chosen range ensures both safety and economic feasibility while

enabling the identification of an optimal dosage.

The control injection grout consisted of the following components: 500 g of cement, 1500 g of sand, and 250 ml of water. The modified additive was variably included in the control grout at concentrations of 0.2, 0.4, 0.6, 0.8, and 1% by mass of the grout.

For strength tests under compression and bending, three samples were prepared for each mixture, denoted in the results as Mix 1, Mix 2, and Mix 3. To indicate the corresponding additive concentration, the samples were labeled as Mix(R)1-3, Mix(0.2)1-3, Mix(1.0)1-3, where "R" stands for the reference sample, and "0.2-1.0" indicates the percentage of the additive in the sample composition. In total, 18 mixtures were prepared, each containing three specimens. The composition of each mixture is detailed in Table 1.

Table 1. Mixture compositions

Sample ID	Sand, (g)	Cement, (g)	Water, (g)	Additive, (g)
0	1500	500	250	Reference sample
1	1500	499	250	Mix(0.2)
2	1500	498	250	Mix(0.4)
3	1500	497	250	Mix(0.6)
4	1500	496	250	Mix(0.8)
5	1500	495	250	Mix(1.0)

The strength tests for compression and bending were conducted in accordance with GOST 310.4 (Figure 1), which are standard methods for evaluating the performance of injection grouts. The comparison of the strength of specimens with varying compositions was performed to determine the optimal formulation of the modified additive and assess its effectiveness. By comparing the strength parameters of samples with and without the additive, the study evaluates the impact of additive components on the modification of the injection grout and its transformation in terms of enhanced strength.

Bleeding tests, essential for evaluating injection grouts, were conducted following GOST 310.6 (Figure 2). According to the standards, the acceptable bleeding range for solutions based on ordinary construction-grade cement with a specific surface area of up to 5000 cm<sup>2</sup>/g is 2-10% [Methodology]. Bleeding levels are categorized as follows: Stable grout: bleeding within 2-8%,

Conditionally stable grout: bleeding within 8-16%. Unstable grout: bleeding exceeding 16%.

These tests provide critical insights into the stability and suitability of injection grouts for practical applications, particularly in the context of modified formulations.

In this study, variation coefficients (CV) were calculated to assess reproducibility. However, no

statistical hypothesis testing (e.g., ANOVA, Student's t-test) was applied to confirm the significance of observed changes between reference and modified samples. This limitation is acknowledged, and future work will incorporate such statistical methods to ensure rigorous verification of differences in strength and bleeding performance.

For each composition, three replicate specimens were tested (n = 3). Mean values are reported in the results, while coefficients of variation (CV) were calculated to reflect reproducibility. Although replicates were considered in the analysis, no formal hypothesis testing (e.g., ANOVA or t-tests) was applied to determine statistical significance between mixtures.

Equipment: compressive and flexural strength were measured using an automatic testing press with a maximum capacity of 500 kN, accuracy ±1%. Bleeding tests were performed using standardized graduated cylinders, following GOST 310.6. Ambient laboratory conditions were maintained at 20 ± 2 °C and relative humidity 60 ± 5%. These parameters ensured compliance with GOST 310.4 and ASTM standards.

Definitions: 'Decrement in bleeding' refers to the absolute reduction in water separation relative to the control mixture, while 'Reduction in bleeding' represents the relative percentage decrease. This dual evaluation provides both absolute and comparative perspectives on additive efficiency



Fig. 1 Laboratory testing of concrete samples



Fig. 2 Laboratory testing of concrete samples

## 4. RESULTS AND DISCUSSION

### 4.1 Compressive Strength Testing

Figure 3 illustrates diagrams representing the variations in strength characteristics depending on the additive content. Figure 3A shows the absolute strength values, where the x-axis indicates the sample type by ordinal number. Figure 3B presents the percentage changes in strength relative to the reference samples, along with the maximum and minimum values of variation coefficients for individual strength measurements.

These visualizations highlight the effects of the modified additive on the compressive strength of the injection grout, providing a comprehensive comparison between different formulations and their performance.

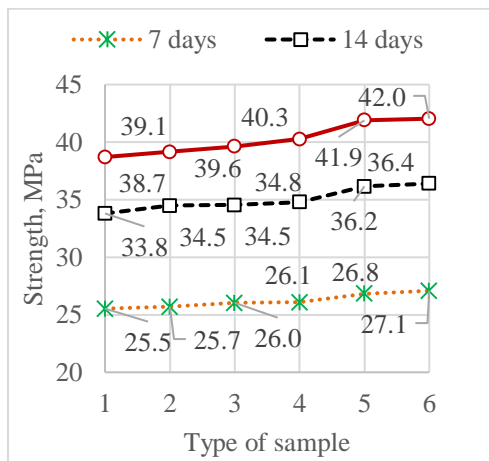


Fig. 3 Compressive strength of injection grouts with different additive concentrations (Reference sample = 0%).

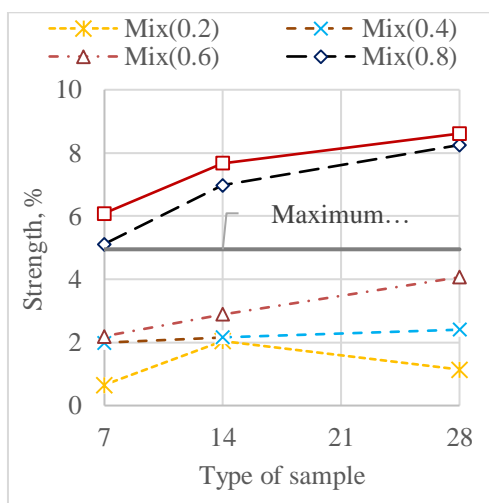


Fig. 4 Compressive strength of injection grouts with different additive concentrations, maximum variation.

According to Figure 3, there is a noticeable trend of increasing strength with a higher additive concentration. The numerical changes in strength for different sample compositions are as follows:

- Mix(0.2): 0.65% to 2.04%,
- Mix(0.4): 1.98% to 2.40%,
- Mix(0.6): 2.19% to 4.07%,
- Mix(0.8): 5.10% to 8.25%,
- Mix(1.0): 6.08% to 8.61%.

Figure 4 shows the maximum variation coefficient values at 4.95%, which suggests that an increase in strength exceeding this threshold (with 95% confidence) can be attributed to the additive's potential influence. Curves above the maximum variation line indicate significant changes in strength, while curves below this line can be attributed to statistical errors in individual strength values. For concentrations of 0.8% and above, there is a slight increase in concrete strength, with a maximum of 8.25% for 0.8% and 8.61% for 1.0% compared to the reference samples. In 28-day samples, where concrete's structural strength is fully developed, the variation coefficient threshold is 3.01%.

Based on this criterion, the additive's impact on maximum strength becomes observable at concentrations above 0.6%. While the additive's effect on concrete strength is relatively minor, maintaining strength levels after the additive's inclusion can still be considered a positive outcome. The primary objective of the additive is not strength enhancement but increased mobility of the injection mixture, thereby improving its penetration capability into the soil when using ordinary construction-grade cement.

The inclusion of the additive improved compressive strength by 6–9% at 1.0% concentration compared to the control mixture. Significant gains were observed up to 0.8%, beyond which improvements diminished, reflecting a saturation effect. These findings align with previous studies on polymer additives but demonstrate a more cost-efficient solution.

### 4.2 Flexural Strength Testing

Figure 5 depicts diagrams illustrating changes in flexural strength depending on the additive concentration. Figure 5 shows absolute strength values, with the x-axis representing the ordinal number corresponding to the sample type. Figure 4B displays the percentage changes in flexural strength relative to the reference samples, along with the maximum variation coefficients of individual strength values.

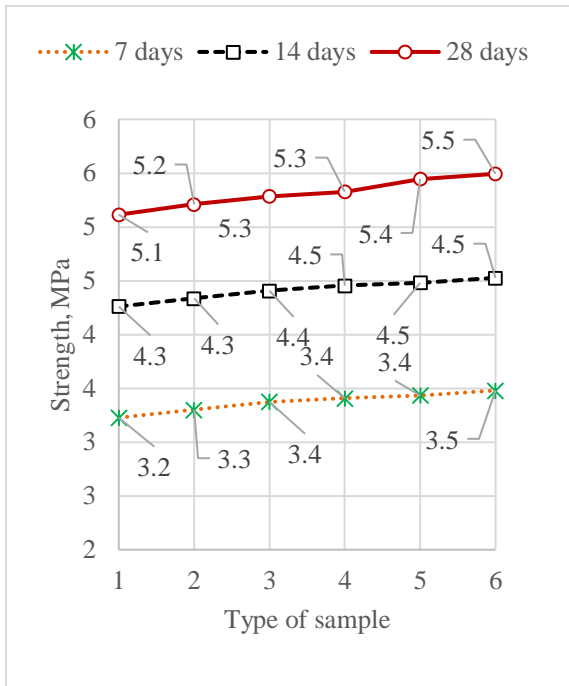


Fig. 5 - Flexural strength of injection grouts with different additive concentrations. Changing the MPA force

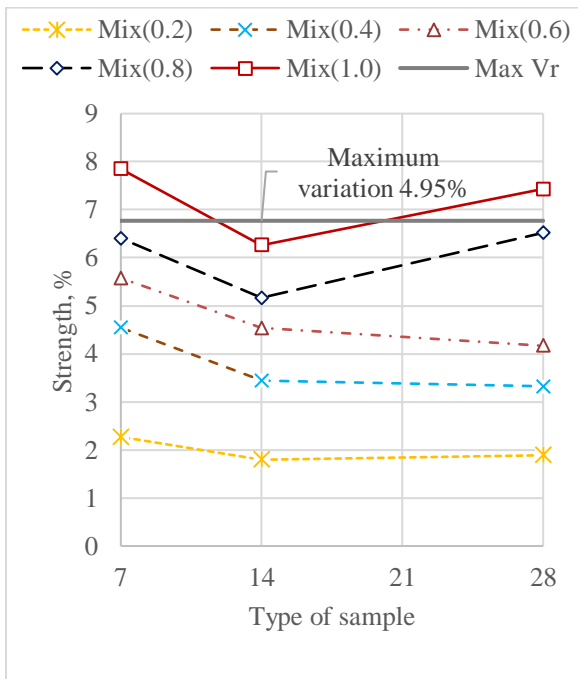


Fig. 6 - Flexural strength of injection grouts with different additive concentrations. Strength change in % .

According to Figure 5, an upward trend in flexural strength is observed with increasing additive concentration. The numerical changes in strength for various sample compositions are as follows:

- Mix(0.2): 1.80% to 2.27%,
- Mix(0.4): 3.32% to 4.55%,
- Mix(0.6): 4.17% to 5.58%,
- Mix(0.8): 5.16% to 6.52%,
- Mix(1.0): 6.26% to 7.85%.

Figure 6 demonstrates that the maximum coefficient of variation is 6.77%, while for 28-day samples, where structural strength is fully developed, the coefficient does not exceed 3.95%. Based on this criterion, the additive begins to influence the strength of concrete at concentrations above 0.4%, with 95% confidence.

Average flexural strength values exceeding 3.95% of the reference samples can be attributed to genuine changes in concrete strength, while lower values fall within the range of statistical error. Although the additive's impact on concrete strength is relatively minor, this metric is not the primary focus.

The main goal of the additive is to enhance the mobility of the injection mixture, thereby improving its penetration capability into soil when using ordinary construction-grade cement. Even maintaining flexural strength levels after the additive's inclusion is considered a positive outcome, aligning with its intended purpose of optimizing grout performance for soil stabilization.

Flexural strength increased by 6–8% at 1.0% concentration. The additive preserved or enhanced performance without negatively impacting durability, fulfilling the primary objective of improving mobility without strength loss.

### 4.3 Bleeding Tests

Figure 7 presents the results of bleeding tests conducted on cement samples.

Figure 7 illustrates the bleeding values and the coefficients of variation for each series of tests at different additive concentrations. The x-axis represents the percentage of additive in the mixture, while the y-axis shows the bleeding values and their corresponding variation coefficients.

Figure 8 depicts the decrement in bleeding values as the additive concentration increases stepwise. Additionally, it shows the percentage reduction in bleeding compared to the reference sample (mixture without additive).

The results highlight the influence of the additive on the bleeding properties of the injection grout. Stepwise increments in additive concentration lead to noticeable reductions in bleeding, showcasing the additive's role in improving the stability of the grout mixture. The percentage reduction relative to the reference sample provides a quantitative measure of the additive's effectiveness in minimizing water separation, which is critical for maintaining grout performance during application.

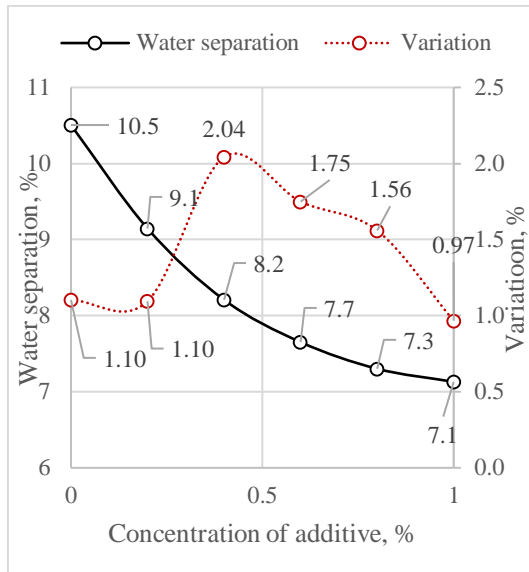


Fig. 7 Results of compression strength of the samples. Reference samples

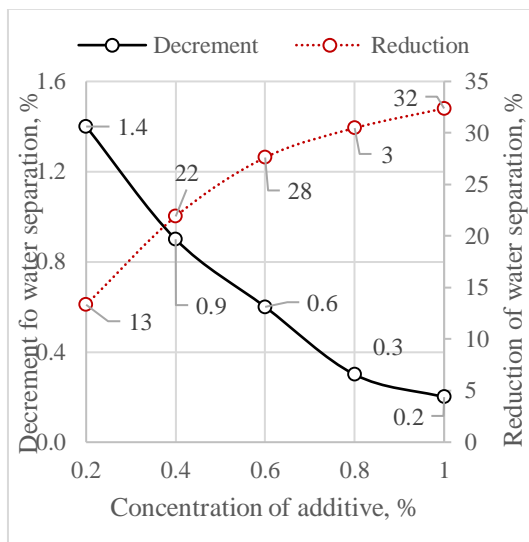


Fig. 8 Results of compression strength of the samples. Mixture 0.2% additive

The average bleeding value of the reference sample is 10.5%, with individual values ranging from 10.39% to 10.67% and a variation coefficient of 1.1%. According to regulatory requirements, the grout is categorized as conditionally stable, as its bleeding falls within the 8-16% range.

Mix(0.2): Average bleeding: 9.1% (range: 9.01–9.29%, variation coefficient: 1.1%).

Decrement: 1.4%, reduction: 13% compared to the reference sample. The grout remains conditionally stable.

Mix(0.4): Average bleeding: 8.2% (range: 8.03–8.42%, variation coefficient: 2.04%). Decrement: 0.9%, reduction: 22% compared to the reference sample. The grout is categorized at the lower limit of

conditionally stable grouts.

Mix(0.6): Average bleeding: 7.7% (range: 7.49–7.84%, variation coefficient: 1.75%). Decrement: 0.6%, reduction: 28% compared to the reference sample. The grout transitions to being stable as bleeding does not exceed 8%.

Mix(0.8): Average bleeding: 7.3% (range: 7.19–7.47%, variation coefficient: 1.56%). Decrement: 0.3%, reduction: 30% compared to the reference sample. The grout remains stable.

Mix(1.0): Average bleeding: 7.1% (range: 7.05–7.21%, variation coefficient: 0.97%). Decrement: 0.2%, reduction: 32% compared to the reference sample.

The grout is categorized as stable. All data points exhibit a high degree of consistency, with variation coefficients indicating that deviations from the mean do not exceed 1%, meeting the requirements of GOST 310.6. Figure 8 shows that with each incremental increase in additive concentration, the bleeding decrement diminishes, indicating a reduced rate of influence. Stability is achieved at a concentration of 0.6% or higher, with subsequent increases in additive concentration yielding negligible effects. Thus, for bleeding optimization, an additive concentration of 0.6% is deemed optimal.

Although variation coefficients indicated consistent trends across additive concentrations, the absence of statistical significance testing (ANOVA, t-tests) restricts the robustness of the conclusions. Future studies should apply hypothesis testing with larger sample sizes to confirm whether the observed improvements are statistically meaningful and not solely attributed to experimental variability.

Bleeding values decreased progressively with additive inclusion: 13% reduction at 0.2% and 32% reduction at 1.0%. A transition from conditionally stable to stable mixtures occurred at 0.6%, confirming this as the optimal concentration

Table 2 compares paraffin-based additives with polymer-based alternatives. Results indicate 20–25% lower costs and improved sustainability for the paraffin-based system, alongside comparable strength improvements.

Table 2. Comparison of paraffin, nanomaterials and polymer-based additives

Additive Type	Compressive Strength (%)	Flexural Strength (%)	Relative Cost / Environmental Impact
Paraffin-based	6–9	6–8	75–80% cost, lower CO <sub>2</sub> , inert by-products
Polymer-based	5–7	5–6	100% cost, higher CO <sub>2</sub> , synthetic residues
Nanomaterials	7–10	6–9	High cost, high energy input

## 5. CONCLUSION

The experimental investigation demonstrated that the introduction of paraffin-based additives into cement-sand mixtures leads to improved performance of injection grouts. The main advantage of the proposed modifier is its ability to increase mixture mobility and reduce water bleeding while maintaining mechanical strength at a level comparable to or exceeding that of the reference specimens. This dual functionality makes it suitable for practical application in geotechnical engineering.

The most efficient additive dosage was found within the range of 0.6–0.8%, which ensured stable grout performance with enhanced workability. At higher concentrations, such as 1.0%, the mixtures exhibited measurable improvements in compressive (6–9%) and flexural (6–8%) strength, accompanied by a significant decrease in bleeding of up to 32%. Importantly, the transition from conditionally stable to stable grout occurred at 0.6%, highlighting this dosage as optimal for balancing strength and stability with mobility.

Despite these encouraging results, the study has certain limitations. The experiments were restricted to laboratory-scale conditions, without validation under real construction environments. The potential long-term environmental impact, particularly the possibility of paraffin or acid residues leaching into groundwater, requires additional investigation. Furthermore, rheological parameters such as slump flow and viscosity were not directly measured but inferred from the behavior of the mixtures. The absence of statistical hypothesis testing (ANOVA, t-tests) also limits the certainty of the conclusions, even though variation coefficients for all tested properties remained within acceptable limits (<5%), confirming consistency of the data. Future studies should therefore focus on comprehensive statistical analyses, larger sample sizes, and field trials to provide more definitive evidence.

From a practical perspective, paraffin-based additives in the range of 0.6–0.8% are recommended for soil stabilization projects, particularly in areas with weak or water-saturated soils. In addition to technical benefits, the additive offers 20–25% cost savings compared to polymer-based alternatives and produces environmentally benign by-products, contributing to a lower carbon footprint. Its application thus supports not only economic efficiency but also sustainability goals in construction.

In summary, the developed additive provides engineers with a reliable and eco-friendly tool for improving grout performance under complex geological conditions. Its implementation has the potential to enhance construction reliability, reduce maintenance costs, and promote long-term infrastructure resilience.

From an environmental perspective, the paraffin–sulfuric acid system demonstrates distinct advantages. The neutralization reaction produces calcium sulfate ( $\text{CaSO}_4$ ), which is environmentally benign and widely used in construction. Unlike polymeric residues, which may persist in the environment, paraffin is chemically inert and stable within the cementitious matrix. In addition, cost savings of 20–25% translate into reduced resource use and a lower carbon footprint, supporting sustainable construction practices in Kazakhstan and beyond.

Accordingly, this study investigates the impact of a paraffin–sulfuric acid additive system on the physical and mechanical properties of injection grouts. The research design includes a systematic evaluation of dosage intervals (0.2–1.0%), laboratory testing of compressive and flexural strength, and bleeding performance with replicate validation. Special emphasis is placed on identifying the optimal concentration range, refining bleeding assessment methods, and comparing results with polymer- and nanomaterial-based additives. The following sections present the adopted methodology, experimental results, comparative discussion, limitations, and practical implications, culminating in conclusions and recommendations for engineering practice.

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