第 49 卷第 2 期
七月 2025
*Diqiu Kexue - Zhongguo Dizhi Daxue Xuebao/Earth Science Journal of China University of Geosciences*
Vol. 50 No. 2
July - Dec 2 0 2 5

DOI: 10.5281/zenodo.17934893

# Performance Evaluation of Cavity-Filling and Permeation Grouts for Karst Remediation in Iranian Limestone Formations

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Published: 15 December 2025
Accepted: 19 November 2025
Received: 08 October 2025

**Abstract:** A series of large sinkholes developed within a residential suburb in southwestern Iran, causing significant damage to properties and necessitating partial evacuation of the area. A comprehensive investigation program revealed that the primary cause of these incidents was the presence and progressive enlargement of karstic cavities within the limestone bedrock of the Asmari Formation. The overburden consists of a thick layer of dense to very dense quartz sand, which gradually ravelled into the underlying cavities, triggering ground surface subsidence and collapse. To mitigate the risk of future sinkholes, an extensive treatment program was implemented with the aim of stabilizing the upper-level cavities and reducing the likelihood of further collapse. The adopted solution relied on cement-based grouting to fill and seal the karst voids. Two distinct grout systems were developed and applied: (i) a sand-rich cavity-filling mortar grout and (ii) a cement–bentonite permeation grout. The performance of these mixes was evaluated through systematic testing of compressive strength, workability (slump and flow), thermal conductivity, thermal resistance, bleeding, air content, and setting time. Following the treatment, a control program involving drilling of verification boreholes and coring of hardened grout was carried out to assess in-situ grout properties and compare them with laboratory specimens. The results confirmed that the selected grout mixes satisfied the specified performance criteria and provided effective stabilization of the treated karst cavities, offering a practical framework for similar ground improvement projects in karstic regions of Iran.

**Keywords:** *Karst; Sinkholes; Cement Grouting; Cavity Treatment; Permeation Grout; Ground Improvement; Iran.*

## 1. Introduction

Sinkholes and subsidence phenomena represent one of the major geohazards affecting karst regions worldwide, frequently resulting from dissolution processes within carbonate bedrock and the subsequent migration of overburden materials into developing voids. In several areas of southwestern Iran—particularly regions underlain by the Asmari limestone—numerous cases of localized collapses and subsurface instability have been reported, highlighting the vulnerability of residential and infrastructure zones to karst-induced hazards (Jamshidi et al., 2019; Karami et al., 2021). Karst development in Iran is strongly influenced by the tectonic and hydrogeological evolution of the Zagros Basin. The Asmari Formation, characterized by fractured and cavernous limestone, is particularly susceptible to dissolution-enlarged voids and conduit formation. Overburden soil, often composed of dense to very dense aeolian and fluvial sands, gradually ravels into these cavities, reducing ground support and initiating sinkhole collapses—an issue documented in multiple Iranian case studies involving roadways, pipelines, and residential zones (Rezaei & Karimpour, 2022). Given the complexity and unpredictability of karst environments, engineering interventions typically require an integrated approach consisting of geological mapping, geophysical surveys, borehole investigation, and numerical modelling to delineate subsurface voids and assess collapse potential. In recent years, advances in geophysical imaging—such as electrical resistivity tomography (ERT), microgravity, and ground-penetrating radar—have improved the ability to identify hidden karst features prior to failure (Feng et al., 2020; Mahmoodzadeh et al., 2023).

Among available remediation strategies, cement-based grouting remains one of the most widely adopted techniques for stabilizing karst cavities, enhancing rock mass integrity, and reducing the pathways for soil migration. Grouting has been effectively applied in numerous international and regional projects involving tunnel construction, foundation stabilization, and mitigation of collapse-prone zones (Mayer et al., 2022; Zhang & Chen, 2023). Its effectiveness depends strongly on grout rheology, penetration capacity, durability, and the ability to adapt mix designs for both large voids and fine fracture networks. Recent studies emphasize the use of hybrid cement–bentonite and ultra-fine cements to enhance penetration and long-term performance in karstified limestone formations similar to those in Iran (Li et al., 2023; Torabi & Miri, 2024). In the present study, a large-scale grouting program was implemented in a residential district in southwestern Iran where repeated sinkhole incidents raised significant safety concerns. The project employed two grout systems—a sand-rich cavity-filling mortar and a cement–bentonite permeation grout—each designed to address specific subsurface conditions. This paper presents the methodology, performance assessment, and post-treatment evaluation of these grout systems, contributing to the growing body of knowledge on karst remediation practices suitable for Iranian geological settings

## 2. Background

### 2.1 Treatment Techniques

Karst-related subsidence and sinkhole formation pose significant engineering challenges, particularly in regions underlain by soluble carbonate formations. A wide range of remediation techniques has been developed globally, including full excavation and replacement, compaction grouting, deep foundations, polymer injection, and cement-based grouting. The choice of method depends on cavity geometry, depth, groundwater conditions, and the sensitivity of overlying structures (Gutiérrez et al., 2020; Parise & Gunn, 2019). Excavation and replacement are effective for shallow collapses but become impractical and costly when cavities occur at depths greater than 20–30 m. Deep foundations and micropiles provide structural bypassing of unstable zones but do not address void migration pathways, limiting their applicability in sandy overburden typical of many Iranian karst regions (Jamshidi et al., 2019). In contrast, cementitious grouting has emerged as one of the most versatile and widely applied approaches for stabilizing subsurface cavities. It allows void filling, fracture sealing, and local reinforcement of weak rock masses while minimizing surface disruption. Case histories from Europe, China, and the Middle East demonstrate that grouting is particularly suitable for large-scale karst mitigation beneath urban and infrastructure environments (Mayer et al., 2022; Fang et al., 2020). Its advantages include adaptability to different geological settings, controllability of injection parameters, and the ability to tailor grout mixes for varying cavity conditions. However, successful implementation requires careful planning of injection pressures, borehole spacing, mix rheology, and verification measures. Failure to understand cavity connectivity or groutability may result in insufficient filling, undesirable hydraulic fracturing, or excessive consumption of materials (Li et al., 2023).

### 2.2 Grouting Methods

Grouting in karst terrain involves injecting a cementitious or chemical slurry into voids and fractured rock to enhance stability and block pathways of soil migration. Cement-based grouts remain the most widely used due to their availability, cost-effectiveness, and long-term durability. Modern grouting practice distinguishes between two primary categories: cavity-filling grouts and permeation grouts, each designed for different geological conditions (Zhang & Chen, 2023). Cavity-filling grouts are typically mortar-like mixtures incorporating sand, cement, water, bentonite, and chemical admixtures. These mixes are optimized for low bleeding, high stability, and controlled workability, enabling them to fill large voids without segregation. Their mechanical performance depends on aggregate grading, cement content, and hydration behavior. Recent studies emphasize enhancing stability using bentonite and viscosity-modifying agents to reduce washout and improve consistency in groundwater-influenced environments (Torabi & Miri, 2024).

Permeation grouting, on the other hand, targets networks of fine fractures and small karst features within the bedrock. These grouts require low viscosity, appropriate flow time (e.g., Marsh funnel), and minimal bleeding to ensure penetration without causing hydraulic fracturing. Advances in ultra-fine cements, nano-modified additives, and bentonite-enhanced suspensions have significantly improved grout penetrability in highly fractured limestone typical of the Asmari Formation in Iran (Mahmoodzadeh et al., 2023). The effectiveness of any grouting method depends on a combination of laboratory characterization, field monitoring, and verification drilling. Proper selection of mix design, injection pressures, and stage sequencing is crucial to achieving durable cavity stabilization and preventing future sinkhole development. High-resolution geophysics, real-time pressure monitoring, and post-treatment coring provide essential feedback to validate treatment success (Feng et al., 2020; Rezaei & Karimpour, 2022).

## 3. Method

The main objective of the treatment program in this study was to reduce the likelihood of sinkhole recurrence by stabilizing the upper-level cavities within the limestone bedrock. The treatment focused on filling the shallow cavities located between 30 and 50 m depth—those closest to the overlying dense sand layer—using a stable cement-mortar grout injected from the ground surface. The work was carried out in a pilot area of approximately 62,000 m² within the affected residential zone. As shown in Figure 1, this area was divided into six zones based on their risk level, determined through earlier geophysical investigations (Kamal et al., 2007).

A low-pressure injection method was adopted to ensure controlled filling of underground cavities without causing fracturing of the surrounding rock. The aim of the treatment was not to improve the strength of the limestone, but to seal voids and prevent downward migration of sand from the overburden. Once these pathways are closed, the dense sand layer provides adequate support for the ground surface.

Two grouting methods were used:

Cavity-filling grout: A cement–sand mortar with water and additives, applied where open cavities were encountered.

Permeation grout: A cement–water slurry without aggregates, used in areas where no large cavities existed but the upper limestone was highly permeable due to fissures or small karst features. This grout was injected under controlled pressure using packers.

The treatment process began with an exploratory drilling program, including in-situ testing and sampling to determine soil and rock properties. Based on these findings, suitable grout mixes were designed and a strict quality-control plan was implemented. Extensive borehole drilling was required to inject both grout types into the rock mass.

After completion of the grouting works, a verification program consisting of additional borehole drilling, in-situ measurements, and laboratory testing was carried out to confirm the effectiveness of the treatment (Kamal et al., 2007). A detailed dilapidation survey was also conducted before, during, and after construction to monitor the condition of existing structures.

## 4. Results and Discussions

### 4.1 Grout Types and Material Properties

Two grout systems were developed and applied across the treatment zones:

(1) a cavity-filling mortar grout, and

(2) a cement–bentonite permeation slurry.

Both mixes underwent laboratory characterization prior to field application, including testing for strength, stability, workability, density, and setting behavior. These parameters were selected in accordance with current best practices for karst remediation in carbonate formations (Zhang & Chen, 2023; Torabi & Miri, 2024).

The cavity-filling grout demonstrated high stability and minimal bleeding (<2%), attributed to bentonite addition, which helps maintain suspension uniformity and reduce segregation in irregular cavity geometries. Similarly, the permeation grout exhibited low viscosity and controlled funnel flow times appropriate for penetration through small fractures within the Asmari limestone.

Such performance characteristics closely match findings reported for grouting operations in other karstic regions, such as southwest China and European limestone belts, where mix stability is considered essential for successful void filling (Li et al., 2023; Fang et al., 2020).

### 4.2 Cavity-Filling Grout Performance

The cavity-filling grout used in the Iranian karst-remediation project was formulated to limit decantation to less than 2% after two hours and to achieve a minimum cylindrical compressive strength of 1 MPa at the specified testing age. All performance requirements were evaluated in accordance with the relevant ASTM standards, and quality control procedures were carried out continuously throughout grout production. For every 500 m$^3$ of grout produced, at least one set of three test specimens was prepared, and in no case was the sampling frequency allowed to exceed a 10-day interval.

The adopted grout mixture, proportioned per cubic metre, consisted of approximately 1,500 kg of natural sand sourced from Iranian quarry deposits, 150 kg of Type I Portland cement in accordance with ISIRI/EN 197-1, 300 L of potable water, 1.5 L of retarding admixture suitable for warm climatic conditions, and 15 kg of bentonite to enhance mix stability and reduce bleeding. The target slump range of 200–220 mm provided sufficient workability for pumping while ensuring resistance to segregation during transportation and placement. Grout production was performed at an off-site batching facility and delivered to the treatment area using truck mixers. Test results demonstrated compressive strength values between 1 MPa and 4 MPa, with an average of approximately 1.64 MPa, thereby satisfying the minimum strength criterion. The saturated unit weight of the grout ranged from 15.05 to 19.86 kN/m³, with an overall average of about 18.77 kN/m³. These values are consistent with typical dense cement-sand mortars used in ground-improvement projects across Iran.

***Table 1.*** *Representative properties of the cavity-filling mortar grout.*

| Property | Sample Test Results | Average Value |
|---|---|---|
| Compressive strength | (1.12, 1.09, 1.05) MPa | 1.09 MPa (> 1 MPa) |
| Bleeding | 1.00%, 0.90%, 0.95% | 0.95% (< 2%) |
| Air content | (2.0%, 2.0%, 2.1%, 2.0%) | 2% |
| Setting time | Within 10–24 hours | Complies with project specification |

Thermal conductivity and thermal resistance of the grout were also measured, yielding typical values of approximately 0.49 W/m·K and 0.163 m²·K/W, respectively. Although these thermal parameters were not central to the design requirements, they provide useful supplemental information regarding grout performance under temperature-sensitive conditions, which may be relevant in deep karst environments in Iran.

Workability was assessed as a major operational parameter. Due to the incorporation of a retarding admixture particularly important in the elevated temperatures typical of many Iranian regions the grout retained pumpable consistency for several hours after batching. Slump tests indicated that even after five hours, the mortar exhibited a slump exceeding 100 mm, confirming that it remained workable for the duration of field operations. Flow-table results further showed that the decrease in workability occurred gradually rather than abruptly, which is advantageous for large-scale cavity treatment projects requiring extended handling and placement time.

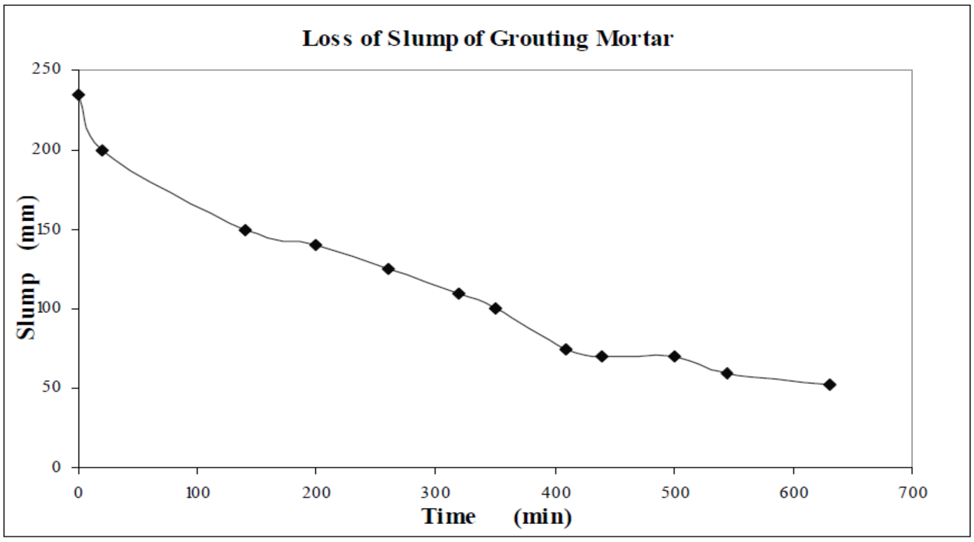


***Fig1.*** *Slump of the cavity filling mortar*

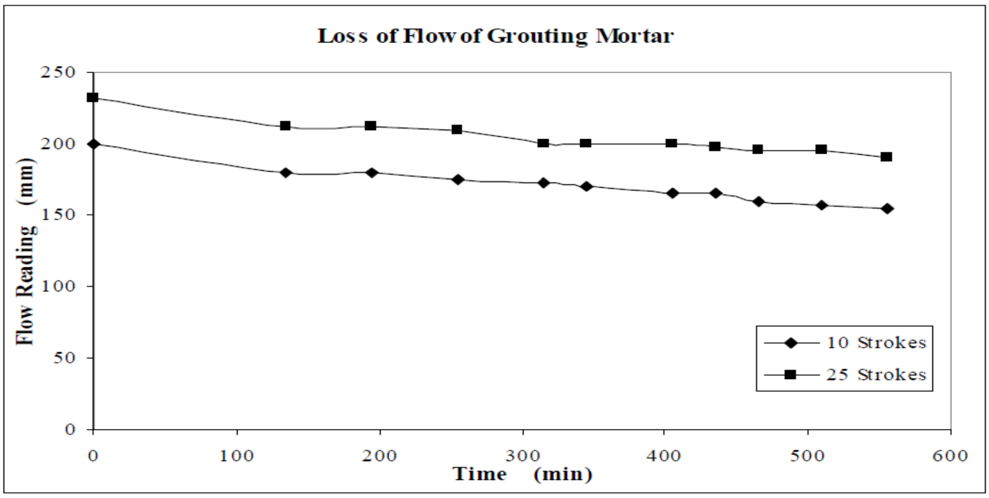


***Fig 2.*** *Flow table results of the cavity filling mortar*

### 4.3 Permeation Grout Performance

The permeation grout was designed as a cement–bentonite slurry with a water-to-cement ratio of less than one. The target average compressive strength was at least 5 MPa, with bleeding at two hours after mixing limited to less than 3% and a March funnel flow time of less than 50 seconds. These parameters were selected to ensure sufficient mechanical strength, stability against segregation and washout, and appropriate viscosity and penetrability.

The adopted permeation mix, per cubic metre of grout, consisted of approximately 800 kg of cement, 718 L of water, 5 L of retarding admixture, and 15 kg of bentonite. The slurry was batched on site in a dedicated plant and then pumped through packers into the fractured rock zones.

Bleeding, density, and viscosity were checked in the field as part of the routine quality assurance program, typically twice per day. Table 2 provides an example of daily test results for the permeation grout.

***Table 2:*** *Sample daily quality control results for permeation grout.*

| Test | First Test (10:45 am) | Second Test (1:30 pm) |
|---|---|---|
| Bleeding (%) | 1.5 | 1.0 |
| Density (t/m³) | 1.52 | 1.51 |
| Viscosity (sec.) | 36 | 35 |

Laboratory tests on cylinders prepared from the permeation grout indicated compressive strengths ranging from about 5.6 to 16.4 MPa, with an average value of approximately 10.6 MPa, comfortably exceeding the minimum specified strength of 5 MPa. The saturated unit weight of the permeation grout ranged from about 13.11 to 17.75 kN/m³, with an average value around 15.08 kN/m³.

Field measurements of bleeding at two hours and March funnel flow time confirmed that the permeation grout satisfied the design criteria, with bleeding typically between 0.5% and 2.5% (average about 1%) and flow times between 30 s and 39 s (average about 34 s). These values indicate a stable and adequately fluid slurry capable of penetrating the target fracture network under the applied injection pressures.

The results strongly indicate that the grouting strategy—using separate mixes for cavities and fractures—was effective for stabilizing the karstic subsurface conditions in the Iranian case study. This approach aligns with contemporary recommendations emphasizing multi-mix grouting systems for complex karst terrains (Li et al., 2023; Mayer et al., 2022).

## 5. Conclusion

This study explored the use of two cementitious grout systems—a sand-rich cavity-filling mortar and a cement–bentonite permeation slurry—to stabilize karst-induced subsurface instabilities in a residential district in southwestern Iran. The site was underlain by fractured and cavernous limestone of the Asmari Formation, where progressive dissolution and downward migration of dense overburden sands had led to repeated sinkhole occurrences. A multi-stage methodology that included detailed subsurface characterization, zonation of treatment areas, low-pressure grout injection, and post-treatment verification was implemented. Laboratory and field testing demonstrated that both grout systems met or exceeded the required engineering performance criteria. The cavity-filling mortar exhibited high stability, minimal bleeding, and compressive strengths within the expected range for deep-void filling operations. The permeation grout achieved superior penetrability and developed compressive strengths significantly higher than the design minimum, indicating effective hydration and minimal washout during injection. Verification drilling and core sampling confirmed that major cavities and fracture networks were successfully filled, and that the hardened grout displayed uniform density, adequate strength, and continuity throughout the treated zones. These observations suggest that the adopted grouting strategy effectively mitigated the progression of subsurface voids and substantially reduced the risk of future sinkhole formation.

The findings in this Iranian case study align with contemporary international research emphasizing the value of using differentiated grout mixes tailored to geological conditions in complex karst terrains. The demonstrated effectiveness of the dual-system grouting approach highlights its applicability to similar karstic environments across Iran and other regions with comparable subsurface characteristics. Future work may benefit from integrating advanced monitoring technologies—such as real-time pressure tracking, distributed fiber-optic sensing, and high-resolution geophysical imaging—to further improve grout placement accuracy and long-term performance assessment. Additionally, the use of nano-modified or ultra-fine cementitious grouts could enhance penetrability in highly fractured formations, providing a broader.

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