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Laboratory investigation into the stabilization of dispersive clay using ionized material: engineering performance and environmental efficiency

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ABSTRACT

Dispersive clays present significant challenges in civil engineering due to their high erodibility and poor structural stability. In recent years, chemical stabilization has emerged as an effective, economical, and environmentally sustainable method for improving the behavior of such problematic soils. This study investigates the effectiveness of an eco-friendly stabilizer, referred to as Ionized Material (IM), commercially known as Royal Road Product, in enhancing the engineering properties of dispersive clay. Initially, the physical and chemical characteristics of the untreated soil were assessed. Subsequently, a series of laboratory experiments, including the pinhole test, standard Proctor compaction test, and unconfined compressive strength (UCS) test, were conducted to evaluate the influence of varying IM dosages and curing periods on soil performance. The results indicate that a 0.0345% concentration of IM eliminated the soil's dispersivity after seven days of curing. Moreover, the maximum dry density increased, while the optimum moisture content decreased with higher IM concentrations. The UCS also exhibited substantial improvement: at an IM concentration of 0.0498%, UCS increased from 0.73 kg/cm² in the untreated sample to 0.905 kg/cm² without curing (a 24% increase), and to 2.32 kg/cm² after seven days of curing (a 47% increase).

Highlights

- The effectiveness of Ionized Material (IM) in stabilizing dispersive clay soils was demonstrated.
- Improvements in compaction characteristics and strength behavior of treated soils were observed.
- The dispersivity of clay soils was reduced through physicochemical mechanisms induced by IM.
- A sustainable and environmentally compatible alternative to conventional stabilizers was proposed.

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1. Introduction

Due to dispersive soils, many earth dams, hydraulic structures, and other constructions, such as roads and embankments, have suffered severe erosion and collapsed. Although the problem has only recently been recognized in many parts of the world, technological preventative measures and design improvements have not yet been fully developed or implemented. Preventing failures caused by soil dispersibility has become a primary concern for geotechnical engineers, given the broad range and scale of issues that can arise from dispersive soils (Van Baars, 2016; Das, 2019). Over the past decade, many experimental studies have been carried out to develop environmentally sustainable and mechanically effective stabilization methods for problematic soils.

Vakili et al. (2017) investigated the use of a new chemical additive called ZELIAC to stabilize Malaysian dispersive clays. Adding 8% ZELIAC and curing for 90 days transformed the soil from highly dispersive to non-dispersive. This treatment resulted in a 7.3-fold increase in unconfined compression strength (UCS), along with reductions in plasticity index and fines content. Türköz et al. (2021) examined the effect of silica fume (SF), a waste material, on dispersive soil stabilization. Their results indicated that incorporating up to 30% SF significantly improved dynamic properties and decreased dispersivity, confirmed through pinhole and resonant column tests. Liu et al. (2022) introduced hydroxyl aluminum, a positively charged aluminum hydroxide, to modify dispersive soils. Their findings demonstrated a strong agglomeration and cementation effect, reducing dispersion and stabilizing the clay structure. Hassan et al. (2023) proposed Potassium-Rich Wood Ash (KRWA) as a sustainable, non-calcium stabilizer. Their results suggested that adding 10% KRWA decreased dispersion and sodium content by 82% and 57%, respectively, after 28 days. Microstructural and XRD analyses showed gel formation from pozzolanic reactions, which improved soil integrity. Economically, KRWA proved more viable than traditional stabilizers. Pouraziz et al. (2023) conducted tests using wollastonite powder at varying contents (2%–10%) and curing periods (3–7 days). They observed significant reductions in plasticity index (up to 30.76%) and increases in CBR strength of up to 141% (dry samples), along with UCS improvements of 181% with 8% wollastonite. Soltanian et al. (2024) examined the combined effect of metakaolin and zeolite on Iranian dispersive soils. The optimal mixture (6–8% metakaolin + 2% zeolite) reduced dispersion by 70% and increased UCS by up to 1.8 times after 7 days. Pouraziz et al. (2024) continued their research on wollastonite powder, confirming earlier findings. They reported improvements in mechanical strength and reductions in dispersive potential. At 10% wollastonite, CBR strength increased by 89% (saturated) and 141% (dry), with UCS rising by 181% after 7 days. This reaffirmed wollastonite's effectiveness as a sustainable geotechnical and environmental stabilizer. Geopolymerization has proven to be an effective technique for stabilizing carbonate-rich marl soils. Dibamehr et al. (2024) investigated the enhancement of Tabriz green marl using alkali-activated zeolite and meta clay. Their results showed that increasing curing time, alkaline solution molarity, and aluminosilicate content significantly enhanced unconfined compressive strength (UCS) while decreasing deformation. Building on this work, Dibamehr et al. (2025) studied both green and yellow marl types with varying dosages of zeolite and meta clay (5–20%) and sodium hydroxide concentrations (4–16 molarity). The results demonstrated substantial improvements in strength, with up to 26 times higher strength in optimally treated yellow marl with zeolite, and a consistent reduction in failure strain as aluminosilicate content increased. Overall, zeolite outperformed meta clay, especially at higher alkaline concentrations. Soltnanian et al. (2025) performed a long-term study assessing the combined effects of zeolite and metakaolin over 28 days. The optimal blend of 2% zeolite and 8% metakaolin yielded significant gains in UCS and shear strength. These results supported earlier short-term findings and validated long-term strength improvements. Ren et al. (2025) focused on using thermal-activated bauxite residue (BR), a by-product of aluminum production, for dispersive soil stabilization. Adding 2% BR resulted in a 426% increase in UCS and a 167% rise in Brazilian Tensile Strength (BTS). The stabilization mechanism involved initial void filling and water film reduction, followed by calcium carbonate formation through carbonation and hydration reactions. This process caused fine particles to agglomerate into sand-sized particles, leading to significant improvements in water stability and strength. Yin et al. (2025) investigated the effects of non-traditional additives on the early strength of lean clay stabilized with a compound calcium-based stabilizer. Their results showed that specific sodium salt combinations, particularly sodium carbonate with sodium silicate, significantly enhanced the 7-day unconfined compressive strength. In contrast, nano-materials and certain iron and aluminum salts had minimal or adverse effects. Mikofsky et al. (2025) examined the physicochemical interactions between five polysaccharide biopolymers and two common clays to advance sustainable, high-performance biopolymer-stabilized earthen materials. They found that despite nonbinding behavior, anionic biopolymers like sodium alginate significantly enhanced compressive strength, particularly in bentonite, due to their plasticizing effects. Moazzami (2025) investigated the improvement of mechanical properties in wind-blown, erosion-prone sandy soils by synthesizing a geopolymer using diatomite, mica, and fly ash. The study revealed that the untreated soil, classified as poorly graded coarse-grained sand with a permeability coefficient of 1×10^{-3} cm/s, sand equivalent of 79%, and pH of 7.7, exhibited zero compressive strength; however, the geopolymer sample containing diatomite achieved the highest strength, highlighting its potential as a sustainable alternative to cement-based stabilization.

Ionized Material (IM), commercially known as Royal Road Product (RRP), is a brown liquid additive used in road and pavement construction for the stabilization of clay soils. Studies have demonstrated that IM significantly improves the mechanical strength of treated soils compared to conventional stabilizers such as cement and lime (Ghasemzadeh & Tabaiyan, 2017). IM or RRP operates by disrupting the dual-layer water structure in clay particles, facilitating the release of excess moisture and introducing water-repellent properties through ion exchange. This transformation generally occurs within 8 to 24 hours, depending on the soil type and classification (Gaspar & Jr., 1995; Zareh et al.,2023). In addition, IM or RRP reduces the thickness of the diffuse double layer, enhances soil plasticity and swelling characteristics, and alters water viscosity to improve compaction efficiency (Ghorbani Dolama et al. 2022). Due to its versatile properties, IM is widely utilized in transportation and geotechnical projects worldwide. Unlike traditional stabilizers, IM or RRP possesses a re-stabilization capability, ensuring long-term durability, improved soil strength, and minimal environmental impact (Ghorbani Dolama, 2023; Farajniya et al., 2024; Farajniya et al., 2025).

Despite significant advancements in stabilizing dispersive clay soils, investigations into the performance of emerging additives with physicochemical mechanisms distinct from conventional stabilizers remain limited. Compared to conventional additives like lime and cement, IM acts through unique physicochemical mechanisms, including the reduction of diffuse double layers, moisture repellency, and structural densification at the micro level. This mechanism makes IM an innovative alternative for stabilizing dispersive soils with a minimal environmental footprint. However, comprehensive experimental studies specifically evaluating the effects of this additive on the dispersive behavior and mechanical properties of dispersive clay soils remain insufficient. Therefore, the objective of this study is to address this research gap through a laboratory investigation into the influence of IM on the strength characteristics of dispersive clay soils.

2. Materials and Methods

2.1 Materials

2.1.1 Soil

Dispersive clay soil, whose parameters are given in Table 1, was obtained from the southeast of Urmia city, Iran, for the current investigation. The soil in question falls under the category of clay soils with low plasticity (CL) in accordance with the Unified Soil Classification System (Pouraziz et al. 2024). Figure 1 shows the location of the soil resource.

Table 1 Specifications of the dispersive clay soil used in the present research

Parameter	Value
Soil type	clay
Soil colour	Light brown
Classification (USCS)	CL
Maximum dry density (gr/cm^3)	1.72
Optimum water content (%)	18
Specific gravity (Gs)	2.67
Plasticity index (%)	11.2
Dispersivity percentage	41

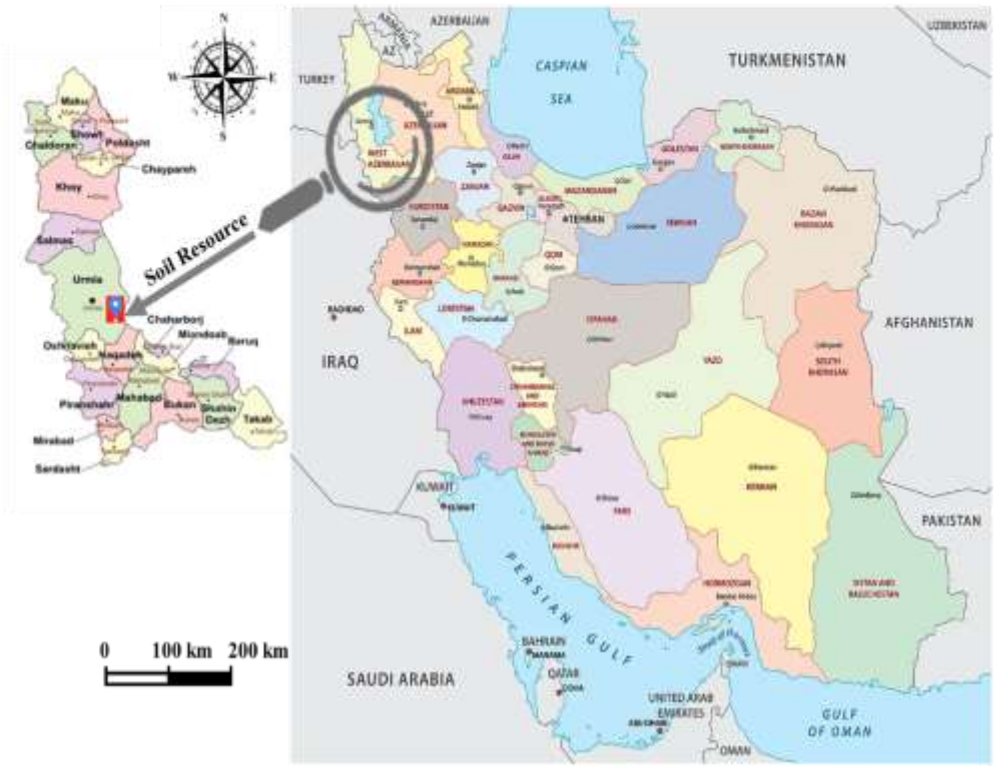


Fig. 1 Location of the soil resource

Several experiments, including the sieve analysis test, the standard Proctor compaction test, and the double hydrometer test to assess the soil's percentage dispersivity, were conducted in the current study to identify the kind of soil. Fig. 2 shows the particle size distribution of the used clay, and Table 2 suggests the standards for the aforementioned studies.

On the soil under study, a double hydrometer test was conducted in two modes: with and without a stirrer and a dispersion chemical. Eq.1 was used to calculate the soil's dispersivity percentage:

$$Dispersivity\ percentage = \left(\frac{A}{B}\right) \times 100 \qquad (1)$$

where A represents the weight percentage of particles with a diameter less than 5 μm in the former mode, and B represents the related value in the latter. By determining the percentage of particles smaller than 5 μm and plotting the grain size curve, the dispersivity percentage was determined as 41%. Based on the soil classification standards provided by the Soil Conservation Organization (SCO), the soil used in this study is classified as a soil with a medium dispersiveness ratio.

Fig. 2 Particle size distribution of the soil sample

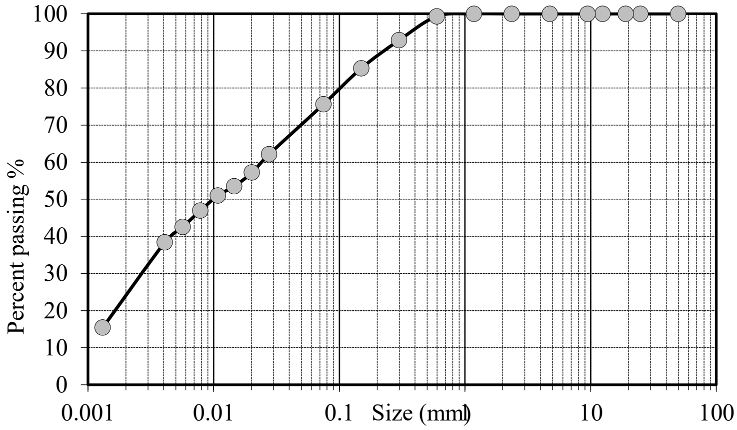


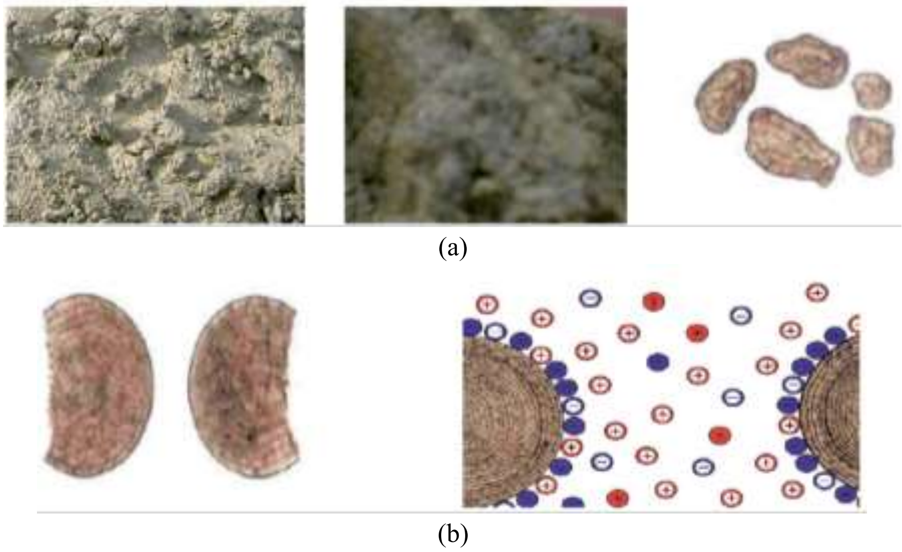
Table 2 Standard codes used in the experiments

Standard code	Test name
ASTM D422	Particle-Size Analysis test
ASTM D1557	Compaction test
ASTM D2166	Unconfined compressive strength test
ASTM D4647	Pinhole test

2.1.2 Ionized Material (IM)

Ionized Material (IM), commercially known as Royal Road Product (RRP), is a chemical-physical substance used for soil stabilization in clayey soils. It focuses on water repellency and density preservation. IM is widely used in road and transportation infrastructures, while its application in railway infrastructure and subgrades remains limited. IM stabilizes compacted clay soils by creating water-repellent properties and reducing malleability. The chemical reaction between IM and soil fine particles is crucial for permanent stabilization (Ghorbani Dolama, 2023). Fig. 3 illustrates the conceptual mechanism of soil stabilization using the IM additive. Within the colloidal and interstitial spaces of the soil, various elements exist in the form of both free and bound ions. The stabilization process facilitated by IM comprises three sequential stages: dispersion, ion exchange, and neutralization. The core mechanism of IM is centered on inducing water repellency within the soil matrix, while maintaining sufficient density to ensure the mechanical integrity of the stabilized layer. For long-term stabilization to be achieved, a chemical interaction must occur between IM and the fine soil particles, during which the additive bonds to the soil structure, contributing to lasting improvements in soil behavior.

Fig. 3 Stages of soil stabilization: a) Microscopic image of soil's fine-grained part, and b) Soil colloids and elements between them



2.2 Laboratory testing program

Using a modified Proctor method, the compaction test was performed on the soil samples with and without additives in compliance with ASTM D1557. To determine the ideal moisture content and dry density, this test was run on every soil-additive combination. Table 3 lists the mold's characteristics, the number of layers, and additional test information. The UCS test in this study was carried out with a loading rate of 1 mm/min utilizing a specific apparatus based on ASTM D2166. Following the conclusion of the curing time, the cylindrical samples, which had dimensions of 38 mm in diameter and 76 mm in height, were manufactured and evaluated right away. The soil erodibility potential is assessed using the pinhole test, which replicates concentrated leak erosion in the furrow. This test was performed to determine the erodibility and dispersivity of specimens by assessing the effects of adding IM to soil samples. The soil sample used in this investigation was cylindrical in shape, measuring 33 mm in diameter and 38 mm in length (Fig. 4).

Table 3 Compaction test specifications

Parameter	Value
Mold volume	943.9 cm^3
Mold Diameter	15.2 cm
Mold height	11.62 cm
Falling height	45 cm
Hammer weight	10 lb
Number of layers	5
Number of strokes per layer	56

Using technique A in ASTM D4647, water flow is passed through an orifice with a diameter of 1 mm under head flows of 50, 180, and 380 mm. Table 4 shows the pinhole test criteria summary based on technique A. The device compresses soil samples of a given size using a cylindrical tube that is 100 mm long, 38 mm in diameter, and has a wall that is 3 mm thick. For soil samples with a particular particle size, a coarse sand filter is positioned at both the top and bottom. Then, using a specialized needle, a hole with a diameter of 1 mm is made inside the sample at pressures of 50, 180, and 380 mm. The three techniques for classifying soil dispersivity are A, B, and C. In the A and C approaches, soils are classified into six groups according to their dispersivity: non-dispersive (ND2 and ND1), slightly and moderately dispersive (ND3 and ND4), and dispersive (D1 and D2). According to Mohanalakshmi (2016), method B divides soils into three categories: dispersive (D), slightly dispersive (SD), and non-dispersive (ND) (Mohanalakshmi 2016). The soil dispersivity potential was assessed in this investigation using technique A.

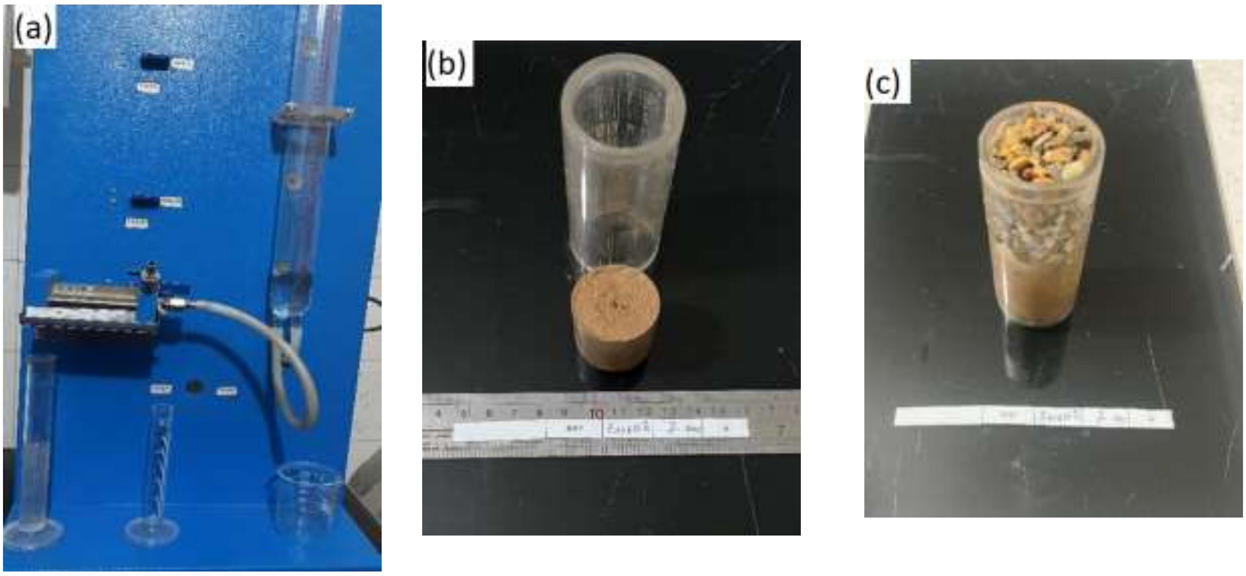


Fig. 4: a) Pinhole test apparatus, b & c) Preparation of dispersive soil in the cylindrical tube for testing

Table 4 Dispersive classified samples with different additive contents

Additive percentage	Without additive	3 days	7 days
0	D2	D2	D2
0.0115	D2	ND3	ND3
0.0192	ND3	ND3	ND3
0.0268	ND3	ND4	ND4
0.0345	ND3	ND4	ND4
0.0421	ND3	ND4	ND4

The dry soil and IM at the six specified percentages were first diluted with water and well mixed in order to prepare test samples. Second, to attain the ideal moisture content, water was added separately to each mix. The mixtures were then tightly packed into plastic bags for a full day to ensure that the moisture was evenly distributed throughout the soil (Mahmudi et al., 2021). Molds were used to create the necessary samples, and each specimen was given the ideal amount of water to get the corresponding maximum dry density. The samples were then sealed in cellophane and stored until the curing period was over. The cellophane was removed from the samples after the curing period, allowing them to be examined before their moisture content changed (Behboudi, 2023; Pouraziz et al. 2024; Zhao, 2023). Room temperature was used as the ambient temperature during the preparation period, and the samples were evaluated at 0, 3, and 7 days after preparation. All tests were repeated at least three times, and the results are presented as averages.

3. Results and Discussion

IM is the same as RRP, which was subjected to a series of experimental tests to investigate its impact on the physical and mechanical behavior of soil. Fig. 5 illustrates the results of the compaction tests conducted with varying percentages of IM additive. Analysis of the data indicates that increasing the content of IM leads to a reduction in the soil's optimum moisture content, accompanied by an increase in its corresponding maximum dry unit weight. Initially, the optimum moisture content was measured at 19.33%, which decreased to 16.26% following the addition of IM. The influence of the IM additive on the stabilized soil is further depicted in Fig. 6. Furthermore, the dry unit weight of the dispersive soil increased from 1.72 g/cm^3 to 1.80 g/cm^3 with the incorporation of 0.0421 volume percent of IM.

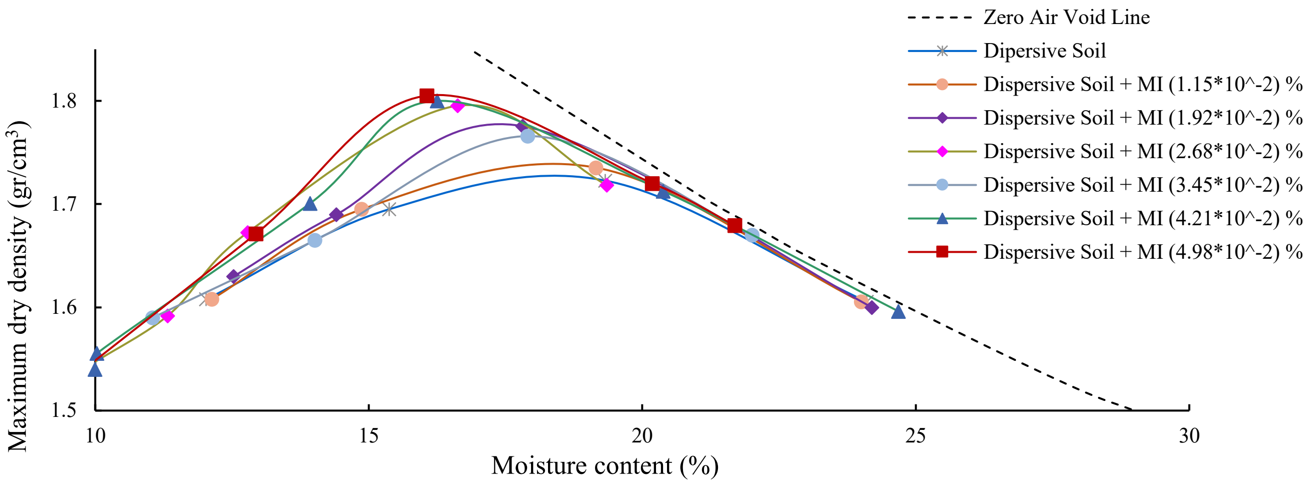


Fig. 5 Modified Proctor test results

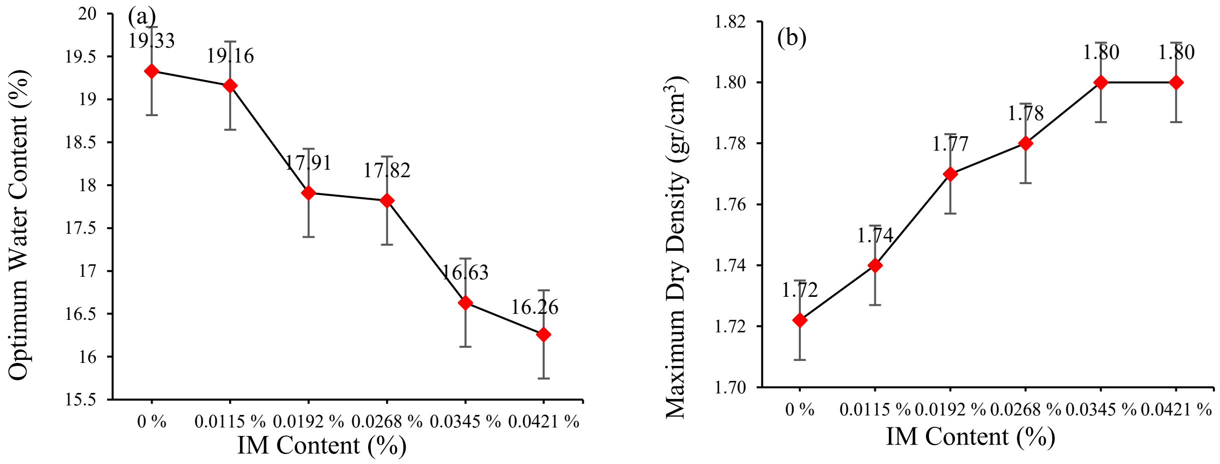


Fig. 6 Effect of IM material on stabilized soil: a) Optimum moisture changes, and b) Maximum dry density changes

Fig. 7 presents the results of unconfined compressive strength (UCS) tests conducted on dispersive soil samples treated with varying percentages of IM. The findings demonstrate a clear enhancement in UCS with increasing IM content. This improvement is also time-dependent. For example, when 0.0498% IM was added, the UCS increased from 0.90 kg/cm² in the uncured state to 2.32 kg/cm² after seven days of curing. As shown in Fig. 8, the addition of 0.0498% IM led to a 29% increase in UCS after three days and a 47% increase after seven days.

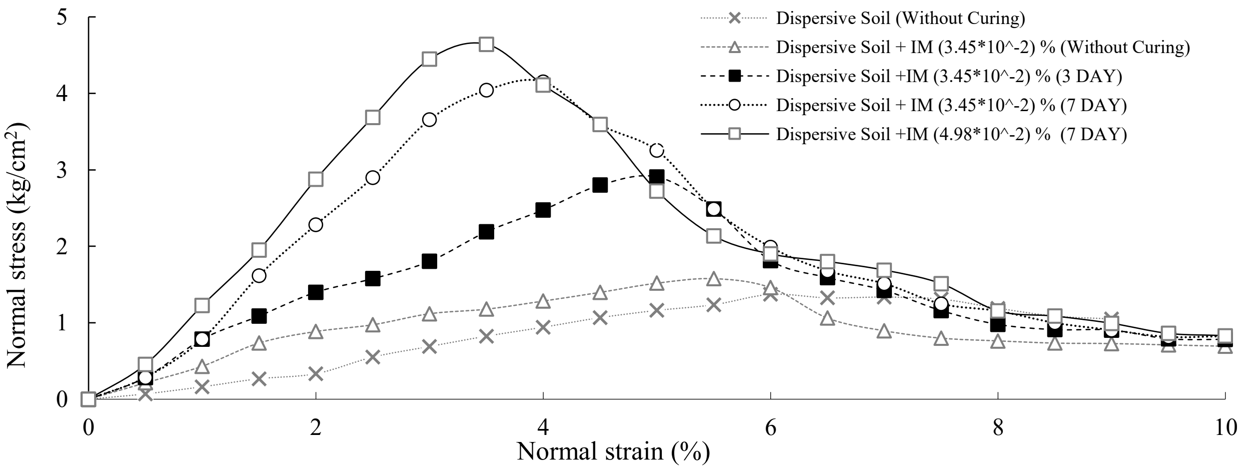
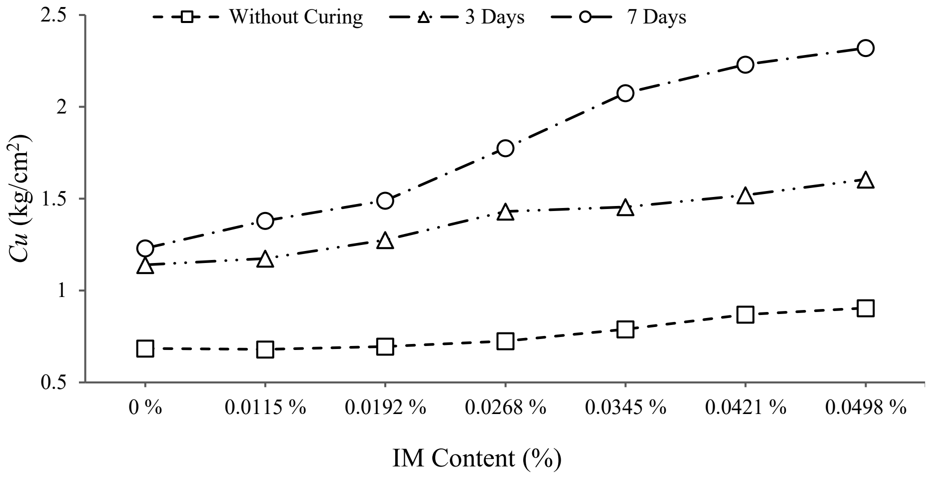


Fig. 7 Stress-strain curve of UCS test of clay with different percentages of IM

Fig. 8 UCS test results considering different percentages of IM



The results indicate that a dosage of 0.0345% IM is the most effective for enhancing compaction and unconfined compressive strength (UCS) parameters. Beyond this dosage (e.g., 0.0421% and 0.0498%), performance gains plateau or slightly decline, suggesting the presence of an optimal threshold. Increasing the dosage further does not yield additional benefits and may reduce cost-effectiveness. The variations in axial strain and elastic modulus (E) associated with different IM contents are illustrated in Figs. 9 and 10, respectively. The data indicate that even without curing, the incorporation of IM significantly enhances soil strength. Specifically, adding 0.0498% IM resulted in a UCS of 0.905 kg/cm², reflecting a 24% improvement compared to the untreated soil. After seven days of curing, this value reached 2.32 kg/cm², corresponding to a 47% increase.

Fig. 9 Axial strain at failure moment in treated samples

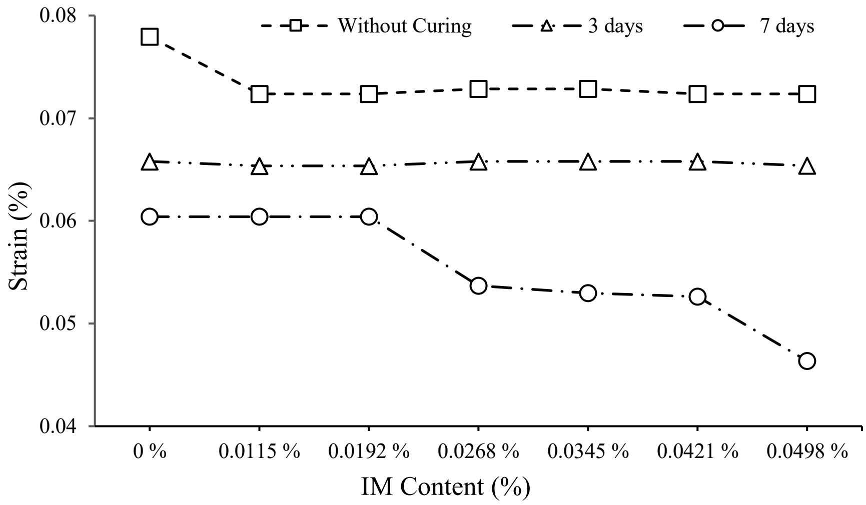


Fig. 10 Elastic Modulus (E) of soil stabilized with different percentages of IM

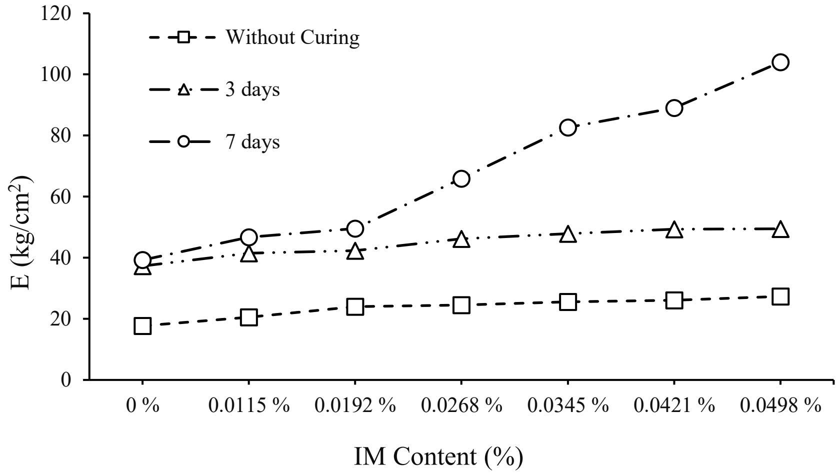


Fig. 11 illustrates the findings of the pinhole test performed on dispersive soil samples treated with various dosages of IM. According to the ASTM D4647 standard, the untreated soil exhibits dispersive behavior. However, incorporating IM into the soil, at specific percentages based on its dry weight, generally leads to a noticeable reduction in its dispersivity. The data suggest that the effectiveness of the additive increases over time, indicating that the longer the treatment period, the lower the soil's dispersive potential becomes. Improvements in dispersivity were evident through decreased flow rates (Q), lighter water coloration, and smaller erosion channels in the treated samples. A visual comparison between the treated and untreated specimens is provided in Fig. 12. Notably, after a seven-day curing period, the sample containing 0.0345% IM demonstrated considerable resistance to internal erosion. In contrast, the untreated sample, after a 10-minute test under a 50 mm hydraulic head, exhibited a flow rate exceeding 1.03 ml/s, murky water, and a final hole diameter of 2.3 mm.

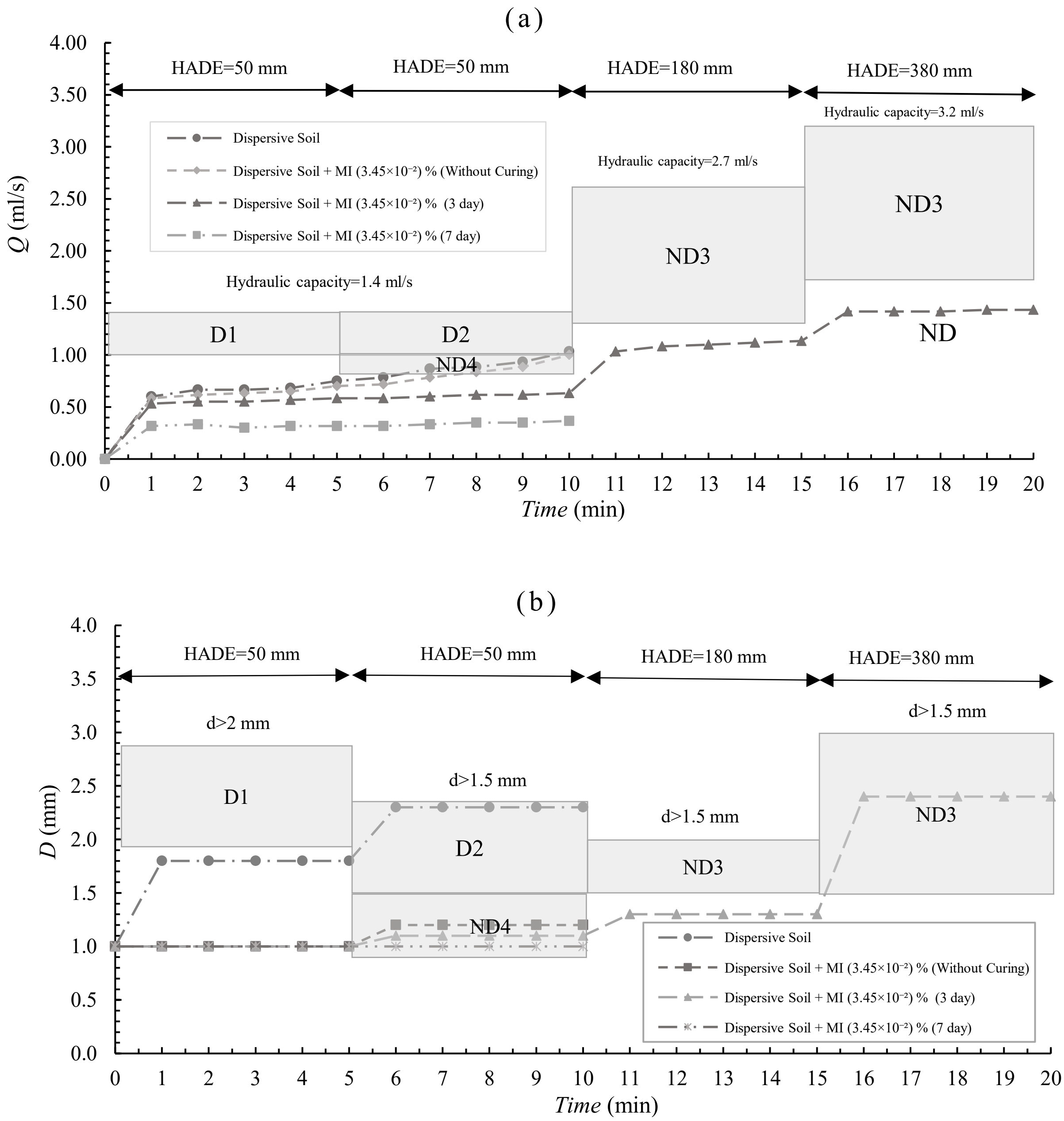
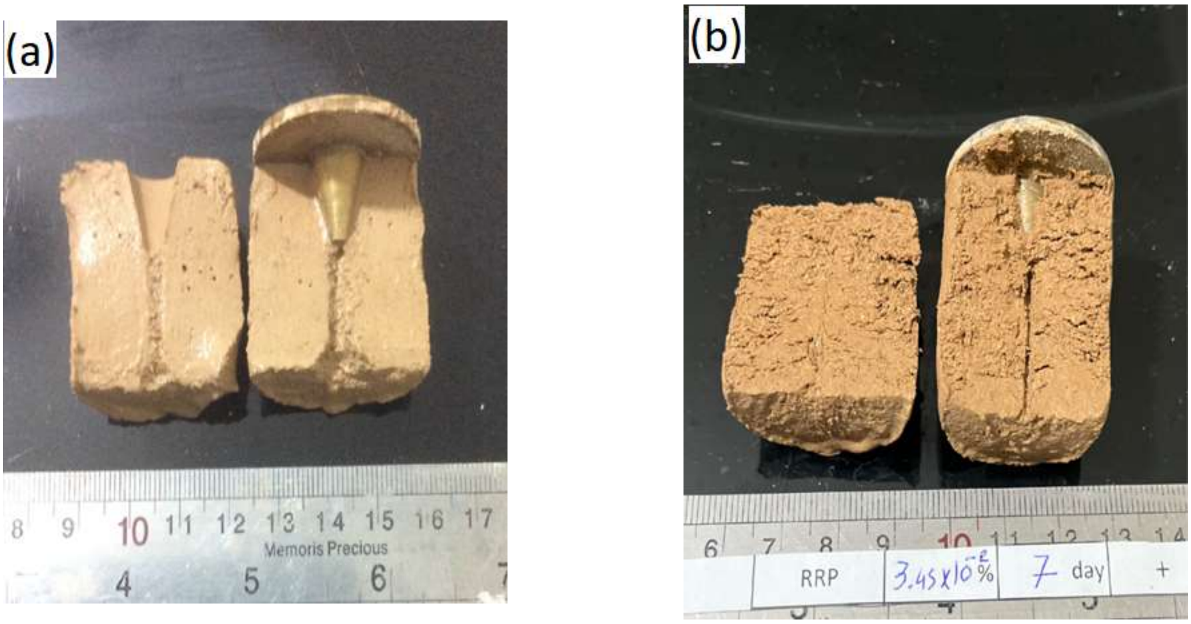


Fig. 11 Pinhole test results: a) changes in flow rate (Q), and b) changes in hole diameter

The experimental results clearly indicate that IM (equivalent to RRP) significantly improves the physical and mechanical properties of dispersive soils, which is in agreement with the findings of Ghorbani Dolama et al. (2023). Compaction tests reveal that increasing the IM content leads to a reduction in the optimum moisture content while simultaneously increasing the maximum dry unit weight, indicating enhanced particle packing and improved soil densification. This observation aligns with previous studies by Pouraziz et al. (2025), who reported similar effects in dispersive soils stabilized using the RRP additive. Such improvements in compaction characteristics suggest that IM contributes to more efficient soil structure formation, which is critical for engineering applications where stability and load-bearing capacity are important. Unconfined compressive strength (UCS) tests further demonstrate that the addition of IM enhances soil strength in a manner dependent on both dosage and curing time. A dosage of 0.0345% was identified as optimal, as higher percentages offered limited additional benefits. The notable increase in UCS and elastic modulus, even without curing, emphasizes the immediate stabilizing effect of IM, while further improvements observed after curing indicate a progressive strengthening of the soil over time. Pinhole tests confirm that IM treatment effectively reduces soil dispersivity, as evidenced by lower flow rates, clearer effluent, and smaller erosion channels. This reduction in dispersivity indicates that IM enhances soil resistance to internal erosion and improves overall stability. These results are in line with the observations of Liu et al. (2024), who reported substantial decreases in soil dispersivity following the application of chemical additives. Collectively, the findings of this study suggest that IM is a highly effective additive for improving compaction, mechanical strength, and erosion resistance of dispersive soils, with an optimal dosage that balances performance and cost-effectiveness.

Fig. 12 Soil samples in 7 days of curing after the pinhole test: a) Dispersive soil, b) Dispersive soil treated with 0.0345% of IM



4. Conclusions

A series of laboratory experiments was carried out to assess how varying the Ionized Material additive content influences the strength characteristics of stabilized dispersive soils. The primary conclusions derived from the tests are as follows:

1. Introducing Ionized Material at up to 0.0345% successfully changed the soil's dispersivity classification from dispersive (D2) to non-dispersive (ND4). Additionally, for a constant Ionized Material dose, increasing the curing time generally reduced the soil's dispersive behavior.

2. Increasing the Ionized Material content up to 0.0345% improved the maximum dry density and decreased the optimum moisture content. However, beyond this point, at 0.0421% and 0.0498%, there were no notable changes in these compaction characteristics, indicating that 0.0345% is the most effective dose.

3. Adding 0.0498% Ionized Material raised the UCS of dispersive soil from 0.73 to 0.905 kg/cm² in the uncured state (a 24% increase) and to 2.32 kg/cm² after 7 days of curing (a 47% increase). These findings confirm that soil strength improvements from Ionized Material depend on both time and dosage.

4. Although using ionized material initially enhances the physical and mechanical properties of dispersive soils, the strength of the treated soil tends to decrease as the curing period lengthens.

Statements and Declarations

Data availability

The data obtained from the experiments conducted in this study are presented in the text of the article.

Conflicts of interest

The authors of this paper declared no conflict of interest regarding the authorship or publication of this paper.

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