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Feasibility Study to Evaluate the Application of Microsilica in Enhancing the Mechanical and Physical Characteristics of an Oil-Contaminated Silty Soil

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ABSTRACT

This study investigates the modification of oil-contaminated soils using microsilica, a pozzolanic material. Laboratory tests, including compaction, Atterberg limits, direct shear, consolidation, and unconfined compression, were conducted. The results show that adding an optimal dosage of 15% microsilica improved soil mechanical properties: it reduced the compression index, decreased void ratio over time, and lowered plasticity. These improvements are attributed to particle agglomeration, flocculation, and long-term pozzolanic reactions between microsilica and soil minerals. Overall, 15% microsilica effectively enhanced the strength and consolidation behavior of oil-contaminated soils after 28 days of curing.

1. Introduction

The accelerated pace of urban development has contributed to a considerable growth in the construction of expansive, tightly clustered structures. Such extensive and dense construction activities necessitate a stable and robust foundation soil capable of supporting the imposed loads. Consequently, evaluating the strength and stability of the underlying soil becomes a critical step in selecting suitable sites before initiating structural design [1]. To put it differently, the soil's bearing capacity plays a critical role in determining a structure's ability to bear loads, making its assessment essential during initial studies. The behavior of soils is primarily influenced by their inherent properties and, secondarily, by environmental conditions and the detrimental impacts caused by human activities [2, 3].

A significant issue impacting various regions globally is the infiltration of oil into urban soils, resulting in contamination and alterations to the soil's fundamental properties [4-6]. This pollution may originate from multiple sources, including oil leaks near petroleum refineries, damaged pipelines and storage reservoirs, as well as the incorrect disposal of used engine oil [7, 8]. Crude oil is a type of hydrocarbon contaminant that disrupts the soil's structure and has harmful impacts on its physical, chemical, and mechanical characteristics [9-12].

Oil contamination significantly alters soil fabric and interparticle bonding mechanisms by coating soil particles with hydrocarbons, which disrupts direct particle-to-particle contact and reduces interparticle friction. This coating promotes a more porous, agglomerated, and loose structure, increasing void spaces, eccentricity, and overall porosity while decreasing density. In fine-grained soils, oil may enhance cohesion temporarily through viscous bridging, but it generally weakens van der Waals forces, cation exchange capacity, and frictional interactions, leading to reduced shear strength, unconfined compressive strength (UCS), internal friction angle, and load-bearing capacity. Permeability also decreases as oil blocks interparticle gaps, further compromising mechanical integrity and stability for foundations or slopes [13].

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Addressing these issues is a key priority for geotechnical engineers, who aim to render oil-contaminated soils suitable for civil engineering operations. Given that soil contamination remediation is both costly and time-intensive, identifying effective solutions for improving such soils has consistently garnered attention. If the soil's strength is insufficient to support the imposed loads, relocating the project may be considered. However, site-specific constraints and limited availability of alternative land often compel engineers to focus on soil improvement. Chemical stabilization is one method that effectively enhances soil behavior, especially in soils polluted with crude oil, where a sequence of chemical reactions plays a key role [14-16]. Earlier studies have shown that additives like lime and cement are crucial in stabilizing and restoring soils affected by contamination [5, 8, 17]. However, the use of these conventional materials, while potentially imposing significant costs on the project, may also present limitations, such as increased soil brittleness [18, 19]. Furthermore, the production of these additives is linked to the release of greenhouse gases, such as carbon dioxide, which result in significant and irreversible environmental harm [20]. Consequently, researchers continuously seek alternative materials to minimize the reliance on conventional binders. Microsilica, a largely spherical silica substance, emerges as a by-product of silicon alloy manufacturing and is produced in substantial quantities globally [21, 22]. Due to the adverse health effects associated with the release of this material as industrial waste into the environment, researchers are actively exploring its utilization in the construction sector. Its significant pozzolanic properties, coupled with its high reactivity, have rendered this industrial by-product a valuable substitute for traditional additives [23]. Furthermore, the amorphous structure of microsilica particles with their high Specific Surface Area (SSA) makes it a highly reactive substance [24]. Notably, microsilica particles are significantly smaller than conventional additives like cement, being 100 to 150 times smaller. This characteristic enables them to effectively fill the micro-pores between soil particles, resulting in a substantially denser composition. This distinctive attribute, known as the "filling/packing effect," markedly enhances the soil's physical and mechanical properties [21, 25].

The addition of microsilica (including precipitated silica, nanosilica, or silica fume) modifies these mechanisms by filling voids, promoting pozzolanic reactions with available calcium sources to form calcium silicate hydrate (C-S-H) gels, and creating cementitious bridges between particles. This results in a denser, more uniform, and isotropic fabric, with reductions in pore area, eccentricity, and porosity, while enhancing cohesion (e.g., doubling in some cases), friction angle, and shear strength. Consequently, UCS and load-bearing capacity are restored or even enhanced beyond that of untreated clean soil in many instances, depending on dosage, curing time, and soil type/contamination level [26, 27].

Previous studies have shown that the incorporation of microsilica can improve the strength characteristics of different soil types. However, most existing research has primarily focused on the use of microsilica in combination with calcium-based binders such as cement or lime, or on its application in uncontaminated soils. Consequently, there remains a significant lack of knowledge regarding the effectiveness of microsilica used alone for the stabilization of oil-contaminated fine-grained soils, particularly with respect to both strength and consolidation behavior. Therefore, this study aims to systematically evaluate the feasibility of using microsilica as a standalone stabilizing agent for oil-contaminated silty soil. Soil specimens were treated with microsilica contents of up to 20% and cured for designated periods. Subsequently, a comprehensive laboratory testing program—including compaction, Atterberg limits, direct shear, unconfined compressive strength (UCS), and one-dimensional consolidation tests—was conducted to assess the mechanical and physical performance of the treated soils.

2. Materials and method

2.1. Based soil and stabilizer

In this study, soil samples were sourced from a depth of 20 cm in proximity to an oil refinery located in Ahvaz in which the precise sampling location is depicted in Fig. 1. To characterize the soil, wet sieving and hydrometer tests were done in accordance with ASTM D422, and the results are presented in Fig. 2. Based on the test results, with over 50% passing through the #200 sieve, the soil was classified as fine-grained. The determination of Atterberg limits for the untreated soil further revealed that based on Unified Soil Classification System (USCS) it was silt with low plasticity (ML).

The hydrocarbon contamination in this study deposit was quantified using the conventional Soxhlet extraction method. Organic solvents such as dichloromethane were employed to extract petroleum compounds, and the contamination level was measured by comparing the original soil mass to the mass of the extracted hydrocarbons. The analysis showed that the soil contained 10% oil contamination by dry mass. The geotechnical characteristics of the contaminated soil such as liquid limit(LL), plasticity index(PI), specific gravity (Gs), maximum dty density (MDD), optimum moisture content (OMC) and unconfined compressive strength (UCS) are presented in Table 1. The oil-contaminated soil was dark brown in color and exhibited an unconfined compressive strength (UCS) of approximately 886 kPa.

The chemical structure of the soil was investigated through X-ray fluorescence (XRF) analysis, and the findings are provided in Table 2. Additionally, X-ray diffraction (XRD) analysis indicated that the soil primarily comprises quartz, calcite, dolomite, biotite, palygorskite, and gypsum. Microsilica used as a stabilizer in this research was sourced from the Iran Ferroalloy Industries Company. Its chemical and physical properties are outlined in Tables 2 and 3, respectively.

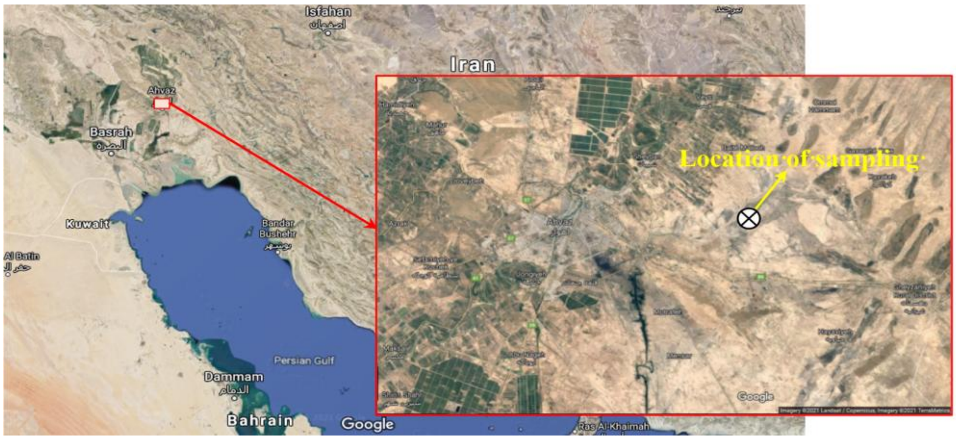


Fig. 1. Location of oil-contaminated soil used in this study.

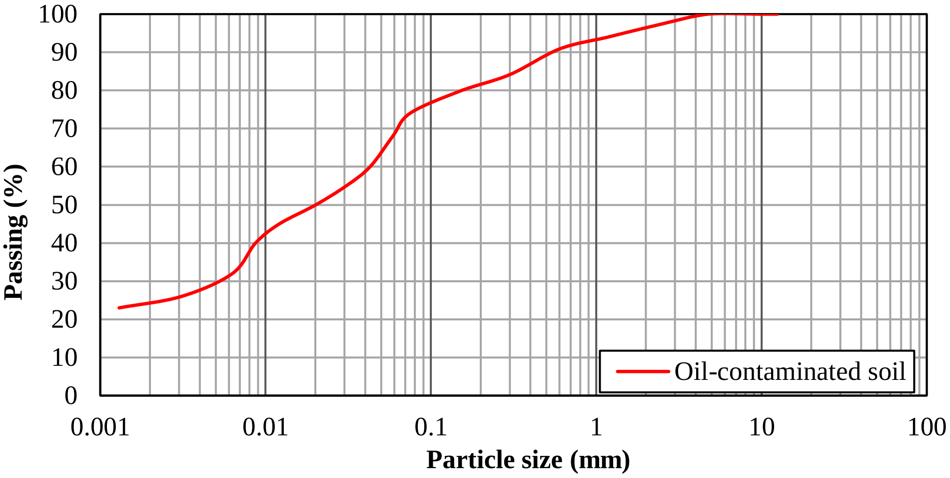


Fig. 2. Particle size distribution of the studied oil-contaminated soil.

Table 1. Oil-contaminated soil index.

Characteristics	Value	ASTM Standard
LL (%)	38.13	ASTM D4318
PI (%)	26.70	ASTM D4318
G_S	2.62	ASTM D854
MDD (g/cm^3)	1.9	ASTM D698
OMC (%)	13.2	ASTM D698
UCS untreated sample in OMC and MDD (kPa)	886	ASTM D2166
Color	Dark brown	-

Table 2. Chemical compositions (percentage in weight (%)) of materials used in this study.

Chemical composition	Material	
	Soil	Microsilica
SiO_2	66.31	91.7
Al_2O_3	25.42	1.13
Fe_2O_3	1.12	1.42
CaO	1.23	1.52
MgO	0.21	0.29
Na_2O	0.12	0.51
K_2O	0.1	1.21
MnO	-	0.7
SO_3	-	0.33
TiO_2	-	-
LOI	5.49	1.19

[*] Loss on ignition

Table 3. Physical properties of microsilica used in this study.

Microsilica properties	Value
Structure	Amorphous
Size, µ	0.2-0.3
Physical form	Powder
Color	White
Bulk density, kg/m^3	200
Specific gravity (G_S)	2.64

2.2. Sample preparation and methodology

To improve the strength characteristics and stabilize the oil-contaminated soil, microsilica was added at contents of 5%, 10%, 15%, and 20% by dry weight of soil. For each microsilica dosage, a comprehensive experimental program was implemented to evaluate its effectiveness. First, standard Proctor compaction tests were performed on untreated and treated samples to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) required for specimen preparation. Dry microsilica powder was initially mixed thoroughly with the soil, after which water was added to achieve a uniform mixture. Compaction tests were conducted in accordance with ASTM D698.

Cylindrical specimens with a diameter of 3.5 cm and a height of 10 cm were prepared at their respective OMC and MDD values for Unconfined Compressive Strength (UCS) testing. The specimens were sealed in airtight plastic containers and cured at room temperature for 28 days before being tested according to ASTM D2166.

Direct shear tests were also conducted following ASTM D3080. The soil–microsilica mixtures were compacted into square shear boxes with a side length of 5 cm in three layers, each 2 cm thick, at their corresponding OMC and MDD. After 28 days of curing, vertical normal stresses of 50, 100, and 150 kPa were applied to determine shear strength parameters, including cohesion (C) and internal friction angle (ϕ).

Atterberg limits tests were performed on untreated and treated soils in accordance with ASTM D4318 to evaluate changes in soil plasticity due to microsilica addition. After mixing soil, microsilica, and water, the samples were cured for 28 days, and Liquid Limit (LL) and Plastic Limit (PL) were determined. The Plasticity Index (PI) was then calculated as the difference between LL and PL.

One-dimensional consolidation tests were carried out in accordance with ASTM D2435 to assess compressibility and consolidation characteristics. Soil–microsilica mixtures prepared at their respective OMC and MDD were placed into molds with a diameter of 50 mm and a height of 20 mm and tested in an oedometer after curing periods of 7 and 28 days. These tests provided key parameters such as compression index, coefficient of consolidation, and void ratio for evaluating the settlement behavior of stabilized soils.

3. Result and discussion

3.1. Effect of microsilica on MDD and OMC of the contaminated soil

In this study, standard Proctor tests were performed on all samples, including parent oil-contaminated soil and microsilica-stabilized ones, to determine the OMC and MDD values. Figs. 3 and 4 show the results of the compaction test in full. As can be seen, the addition of microsilica to oil-contaminated soil increased the OMC as well as decreased the MDD. The inclusion of microsilica into the soil caused a change in the particle size distribution and increased the particle surface of the blends compared to that of the oil-contaminated soil sample. The amount of these changes was directly related to the amount of microsilica in the compounds. Adding 20% of microsilica content to contaminated soil increased OMC from 13.18% to 16.3%. In addition, as the OMC increased, the MDD of the composites gradually decreased. This effect can be attributed to the additional microsilica filling the voids between the particles of the samples [28, 29]. As can be seen in Fig. 4, the addition of 5% microsilica had little effect on MDD changes. The most significant increase in performance was observed with the addition of 15% microsilica to the contaminated soil. This specific microsilica content reduced the soil's Maximum Dry Density (MDD) from 1.92 to 1.88 g/cm^3. According to previous studies, [28, 29], a similar behavior was observed for soils without oil-contaminants stabilized with microsilica.

3.2. Effect of microsilica on consistency limits of the contaminated soil

To determine the liquid limit (LL), plastic limit (PL), and Plasticity Index (PI) of oil-contaminated soil, the Atterberg limits tests were performed on the samples, the results of which are shown in Figs. 5 and 6. As shown in Fig. 5, as the amount of microsilica increased, the LL and PL of the soil decreased. The trend of changing these two parameters was such that their differences (PI) also showed a downward behavior. The incorporation of microsilica into the soil particles can induce particle flocculation over time, which in turn reduces the Liquid Limit (LL) and, consequently, decreases the soil's plasticity [30, 31].

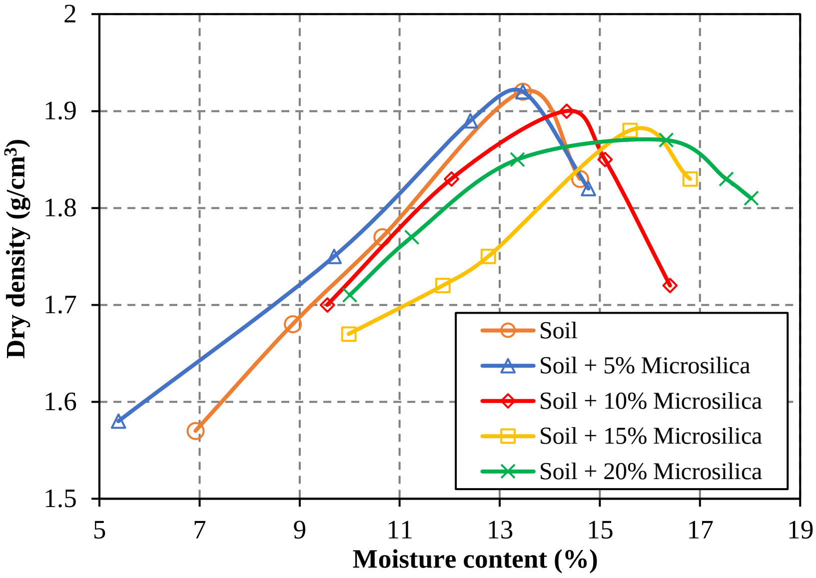


Fig. 3. Results of compaction tests on microsilica-stabilized oil-contaminated soil samples.

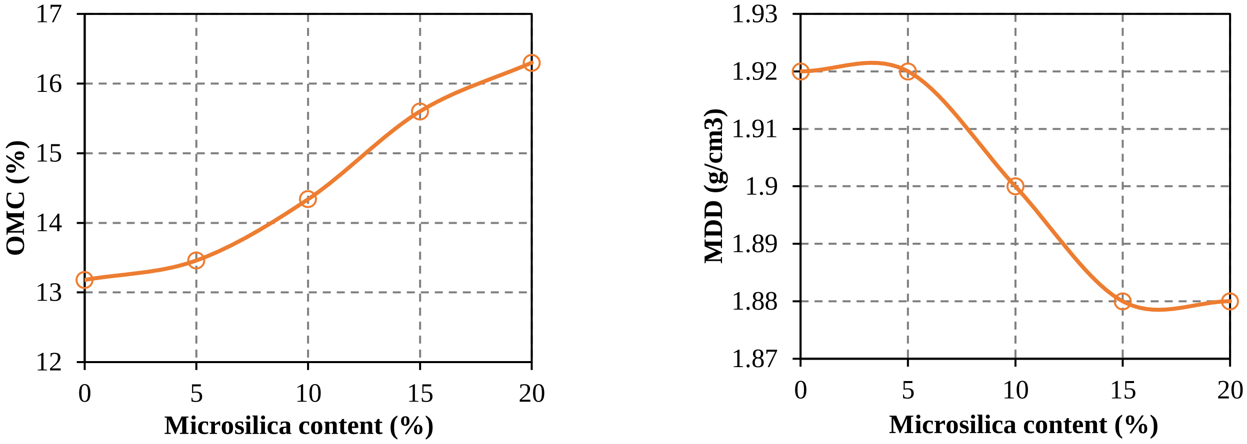


Fig. 4. Variation of OMC and MDD of microsilica-stabilized oil-contaminated soil samples.

The amount of 20% microsilica was able to reduce the LL from 38.13% to about 31%. This amount of additive was also able to reduce the PI by about 15%. It should be noted that this decrease in the PI and LL could change the USCS classification from ML to CL, as shown in Fig. 6. This can be due to the simultaneous reduction of PL and LL with the addition of microsilica, which changes the soil group.

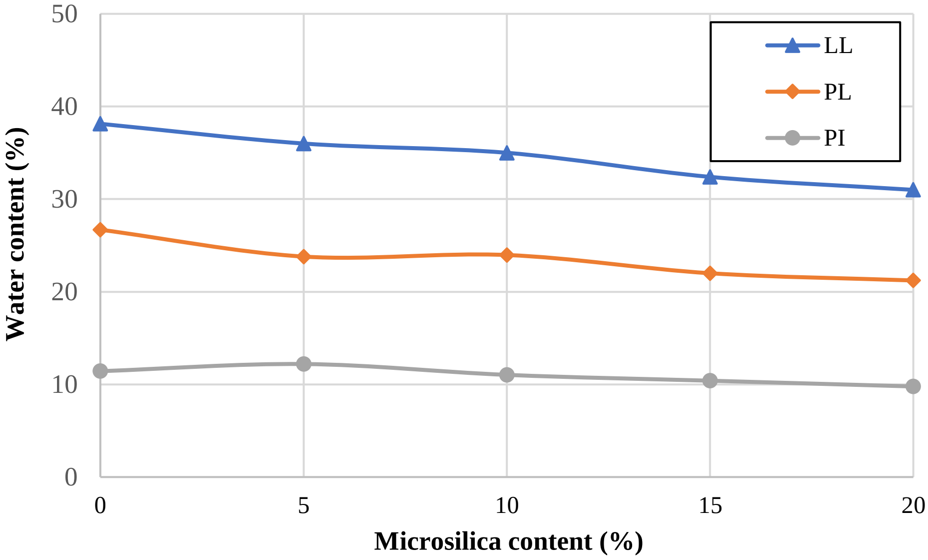


Fig. 5. Variation of Atterberg limits of microsilica-stabilized oil-contaminated soil samples.

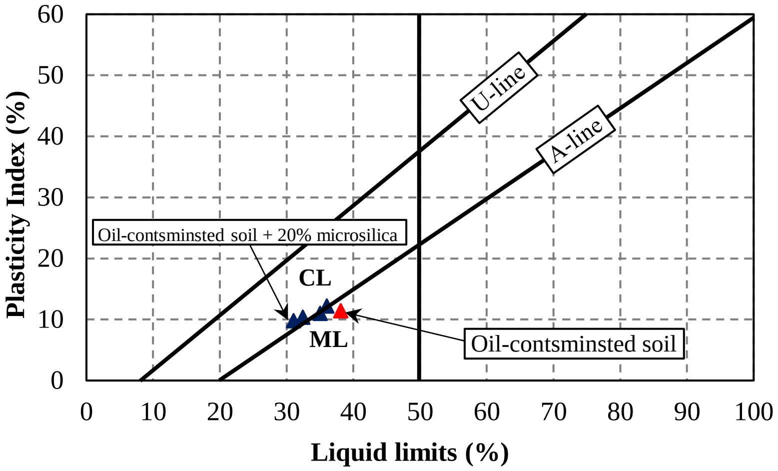


Fig. 6. Plasticity chart for microsilica-stabilized oil-contaminated soil samples.

3.3. Effect of microsilica on shear properties of the contaminated soil

In this study, direct shear tests were performed on the samples under fully saturated conditions, representing the critical state of fuel oil-contaminated soils after microsilica stabilization and curing. Saturation ensured uniform pore water distribution and accounted for the effects of moisture on interparticle friction and adhesion. Testing under these conditions provides a realistic and reliable assessment of shear strength across different microsilica dosages while reflecting the potential impact of oil contamination. Fig. 7 presents the shear strength changes for oil-contaminated soils stabilized with different amounts of microsilica. For this purpose, three different vertical confining pressures of 50, 100 and 150 kPa were considered to be able to determine the changes in cohesion (C) and friction angle (φ), the results of which are shown in Fig. 8. According to Fig. 7, it can be seen that the addition of microsilica up to 15% to oil-contaminated soil increased the shear strength of the soil. The shear strength of oil-contaminated soil at a vertical confining pressure of 50 kPa was approximately 33 kPa. In contrast, the sample containing 15% microsilica under similar conditions exhibited a shear strength of around 55 kPa. Additionally, as the vertical confining pressure increased, the shear strength also increased. Specifically, the shear strength of the 15% microsilica sample at vertical confining pressures of 100 kPa and 150 kPa rose by approximately 20% and 111%, respectively, compared to the strength at 50 kPa.It should be noted that the incorporation of more microsilica (20%) reduced shear strength. The reduction in shear strength at 150 kPa is more pronounced than at lower stresses. Although minor experimental errors cannot be entirely ruled out, repeated tests confirmed the trend. This stress-dependent behavior likely arises from increased particle rearrangement and localized brittleness at higher microsilica contents, which reduces interparticle contacts and shear resistance.

As shown in Fig. 8, with the addition of 15% microsilica to the oil-contaminated soil, the amount of internal friction angle increased from 24.65° to 31.38°. However, with the addition of 20% microsilica, despite increasing the cohesion to about 19.66 kPa, the internal friction angle and the value of shear strength decreased. It is important to note that the value of cohesion, as well as the internal friction angle of the soil, was very low due to the coating of soil particles with petroleum products which results in reduced interaction between particles. As the dosage of microsilica in the oil-contaminated soil composition increased, the value of cohesion and friction angle increased. The observed effect can be attributed to the increase in Optimum Moisture Content (OMC) corresponding to the stabilized samples, which in turn enhances the adhesion between the soil particles [28]. Additionally, the increase in the friction angle of the samples is attributed to the fact that, in the absence of microsilica, oil acts as a lubricant, allowing the particles and soil grains to slide past one another. This reduces the interaction and friction between the particles [32, 33].

The observed decrease in friction angle when microsilica content increases from 15 to 20 % can be attributed to over-saturation of the soil matrix with fine particles, which reduces interparticle friction and promotes a more brittle structure. At higher microsilica dosages, excessive gel formation and filling of voids can partially disrupt the natural particle contacts, leading to a reduction in the soil’s internal resistance to shear. This explains why, despite small changes in unconfined compressive strength, the friction angle declines beyond the optimal 15 % dosage, highlighting the importance of identifying an optimal microsilica content for balancing strength gain and shear stability.

3.4. Effect of microsilica on UCS of the contaminated soil

Fig. 9 demonstrates the results of the UCS test in terms of stress-strain changes. As observed, the addition of microsilica has positively impacted the compressive strength of oil-contaminated soil. As the strain in the microsilica-treated samples increased, it led to a shift in the soil's behavior from a brittle state to a more ductile state. The ultimate strength for each sample is shown in Fig. 10. The addition of 15% microsilica to the oil-contaminated soil significantly improved its structure and increased the sample's strength by approximately 158% compared to the unstabilized soil, achieving a maximum Unconfined Compressive Strength (UCS) of 2288 kPa. Notably, the strain at fracture for this sample was 12.38%, much higher than the 5.1% strain observed in the unstabilized contaminated soil. However, further increases in microsilica content not only led to a slight reduction in compressive strength but also decreased the strain by about 10.92%.

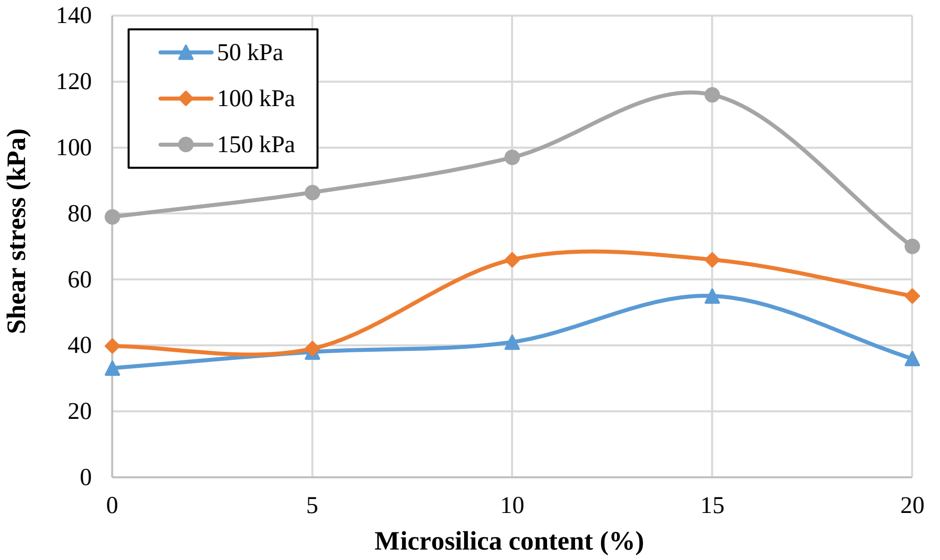


Fig. 7. Variation of shear strength for microsilica-stabilized oil-contaminated soil samples.

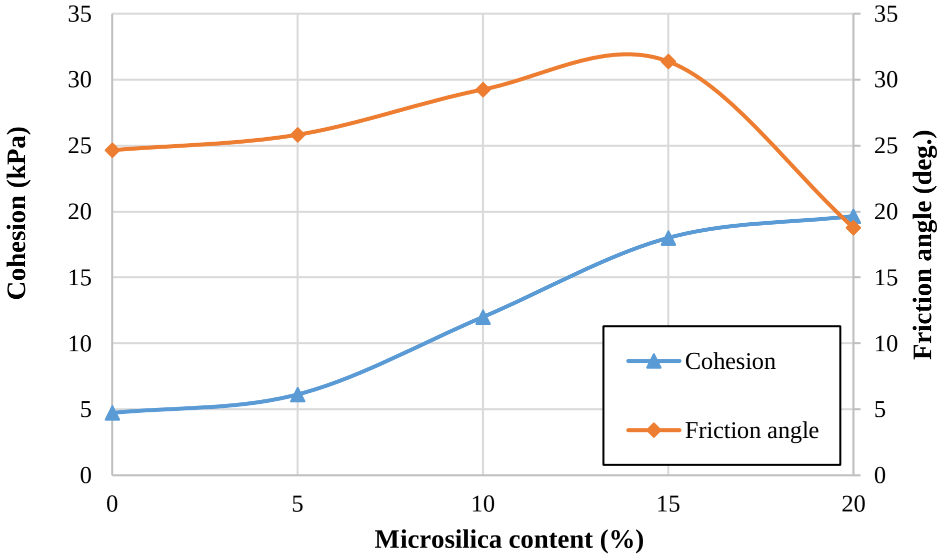


Fig. 8. Variation of cohesion and friction angle for microsilica-stabilized oil-contaminated soil samples.

These results align well with the shear strength test outcomes, indicating that the optimal microsilica content for oil-contaminated soil is 15%. The observed increase in compressive strength can be attributed to the pozzolanic reaction between the silica and soil particles in the presence of water, which occurs over time, enhancing the mechanical properties of the soil. The soil contains clay minerals, which provide a limited amount of naturally occurring calcium (e.g., in carbonates or clay lattice structures). While classical pozzolanic reactions typically require additional calcium sources such as lime or cement, the observed improvements in soil properties are primarily attributed to surface interactions between microsilica and clay particles, particle agglomeration, and flocculation. Therefore, even in the absence of added calcium, microsilica can effectively modify the mechanical behavior of clay-rich soils. This point has been clarified in the manuscript, moderating claims related to classical pozzolanic reactions and emphasizing the combined mechanical and surface-interaction effects of microsilica. Additionally, the internal friction of microsilica particles plays a crucial role in strengthening the oil-contaminated samples. Microsilica reacts with the soil particles, improving both internal friction and cohesion. This reaction counters the lubricating effect of the oil surrounding the soil particles, allowing the formation of a more cohesive and integrated structure, ultimately leading to increased strength.

3.5. Effect of microsilica on consolidation behavior of the contaminated soil

One of the key parameters in foundation design on soil is the compression index (Cc), as it provides valuable insight into soil settlement when subjected to increased loads. The compression index is determined from the slope of the linear portion of the e-log p curve, which represents the relationship between the void ratio (e) and the logarithm of the applied pressure (p) [34]. In this study, one-dimensional consolidation test was performed on all samples after 7 and 28 days of curing, during which the compression index, coefficient of consolidation and void ratio were determined, the results of which are shown in Fig. 11. The results of the one-dimensional consolidation test indicate that the addition of microsilica to the soil led to a reduction in the compression index of the oil-contaminated soil after 7 and 28 days of curing.

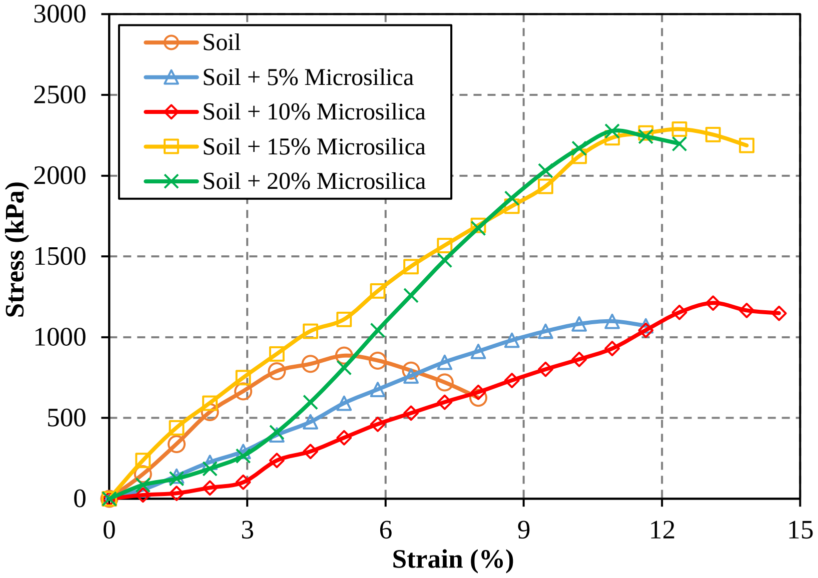


Fig. 9. Stress-strain curves for microsilica-stabilized oil-contaminated soil samples.

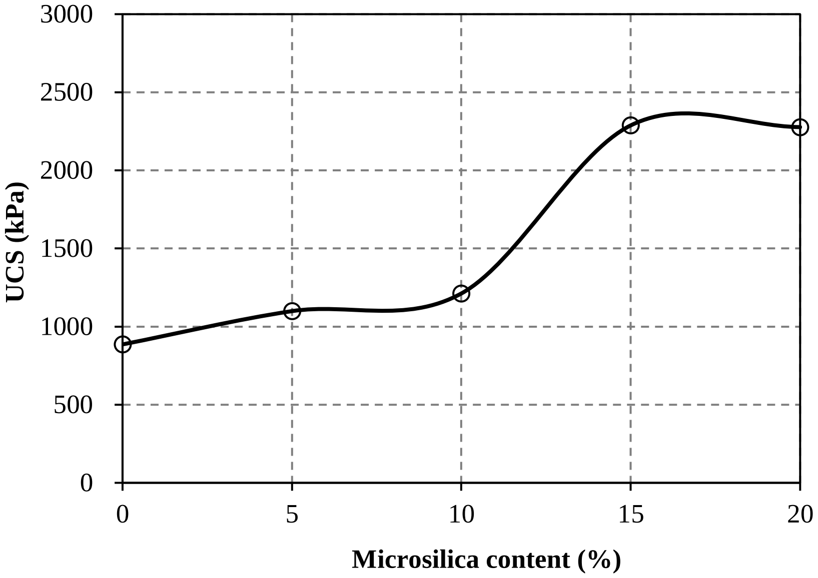
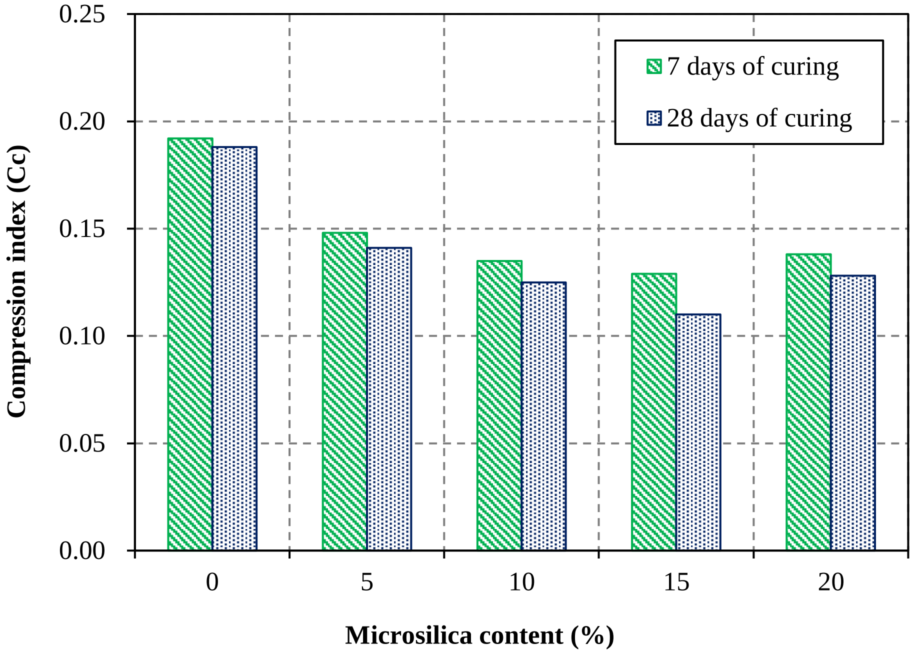


Fig. 10. Variation of the UCS for microsilica-stabilized oil-contaminated soil samples.

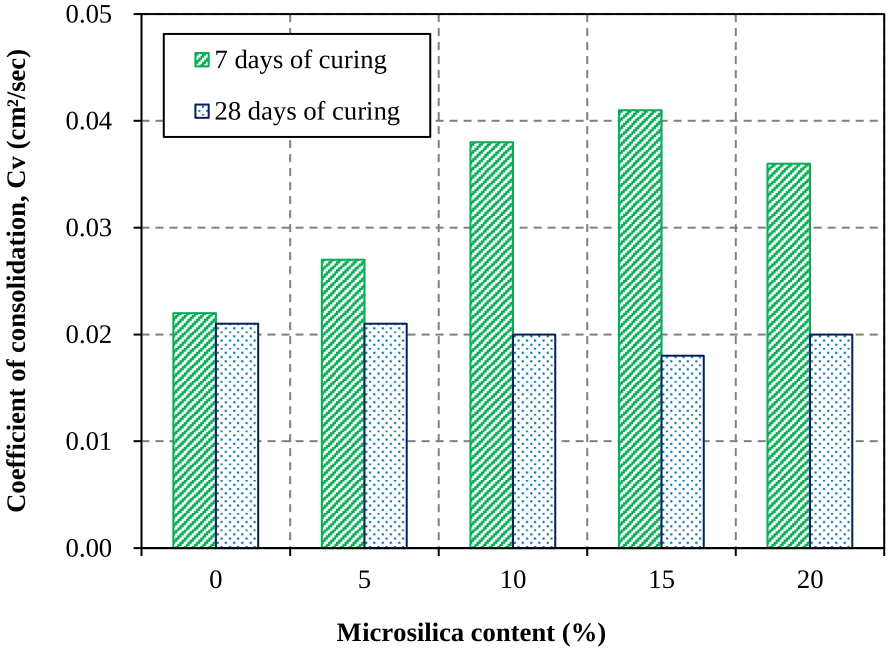
Initially, the compression index for the contaminated soil was 0.192. However, with the incorporation of microsilica, this value decreased by 15%, reaching approximately 0.129 after 7 days of curing (Fig. 11a). Furthermore, the compression index continued to decrease over the curing period, reaching approximately 0.11 after 28 days. This significant reduction in the compression index can be attributed to the reaction between microsilica and the oil-contaminated soil particles. During these chemical reactions, a cementitious gel is formed, which enhances the resistance of the samples to external loads, thereby improving the soil's overall structural integrity [35]. However, with the increase of microsilica, the compression index increased again and reached 0.138.

Another important parameter derived from the one-dimensional consolidation test is the coefficient of consolidation (Cv), which is usually obtained through the graphical method (i.e., logarithm of time) introduced by Casagrande and Fadum [36]. The coefficient of consolidation is a measure of the rate at which consolidation occurs in soil under a given load. It indicates the time required for a certain degree of consolidation to take place, reflecting the soil's ability to undergo compression over time when subjected to increasing pressure [37]. It should be noted that two factors can affect this parameter, including the amount of compressed water and the flow rate of that water. Fig. 11b shows the results obtained for the coefficient of consolidation. As can be seen, the addition of microsilica to the oil-contaminated soil increased this coefficient at an early age. So that with the addition of 15% microsilica, Cv increased from 0.015 cm2/sec for untreated soil to 0.041 cm2/sec. But with the addition of microsilica up to about 20%, it was observed that the Cv value was reduced to 0.036 cm^2/sec. It should be noted that the addition of microsilica to the soil after 7-day curing caused chemical reactions in the samples. Short-term reactions, such as cation exchange, cause the structure of the contaminated soil to flocculate, leading to an increase in the size of the soil particles. This, in turn, results in an increased coefficient of consolidation (Cv) as well as higher permeability. In general, it can be stated that after 7 days of curing, attractive forces dominate over repulsive forces due to the increased ion concentration. The replacement of monovalent ions on the surfaces of soil particles with multivalent ions from the additive leads to the particles coming closer together. This process creates a flocculated structure in the soil, which increases the void size within the soil samples [21]. However, over time, as long-term reactions progress, the coefficient of consolidation decreases further, even becoming lower than that of the oil-contaminated soil. This reduction can be attributed to the formation of new cementitious products during the pozzolanic reactions, which fill the voids between the soil particles, thereby reducing the soil's permeability and enhancing its overall stability. As can be seen, the addition of microsilica to the contaminated soil after 28 days of treatment causes the coefficient of consolidation to decrease to about 0.018 cm2/Sec. Therefore, the variations of Cv in the short and long term were different and opposite to each other.

Fig. 11c illustrates the variation in initial void ratios for different oil-contaminated soil compositions. As the microsilica content increased to 15%, the void ratio increased, but then decreased with a further increase in microsilica content to 20% after 7 days of curing. The void ratios for oil-contaminated soil stabilized with 15% and 20% microsilica were 0.55 and 0.49, respectively, compared to 0.47 for the unstabilized contaminated soil. The addition of microsilica to the samples led to a decrease in the density of the samples. This can be attributed to the chemical reactions between the microsilica and soil particles, which result in the agglomeration or flocculation of the particles. This leads to an increase in the void ratio, which consequently decreases the density of the samples, as observed in the density test. However, as previously mentioned, after 28 days of curing, the formation of new cementitious products fills the voids within the soil, reducing the void ratio. Specifically, after adding 15% microsilica to the contaminated soil, the void ratio decreases to approximately 0.35 after 28 days of curing.



(a)



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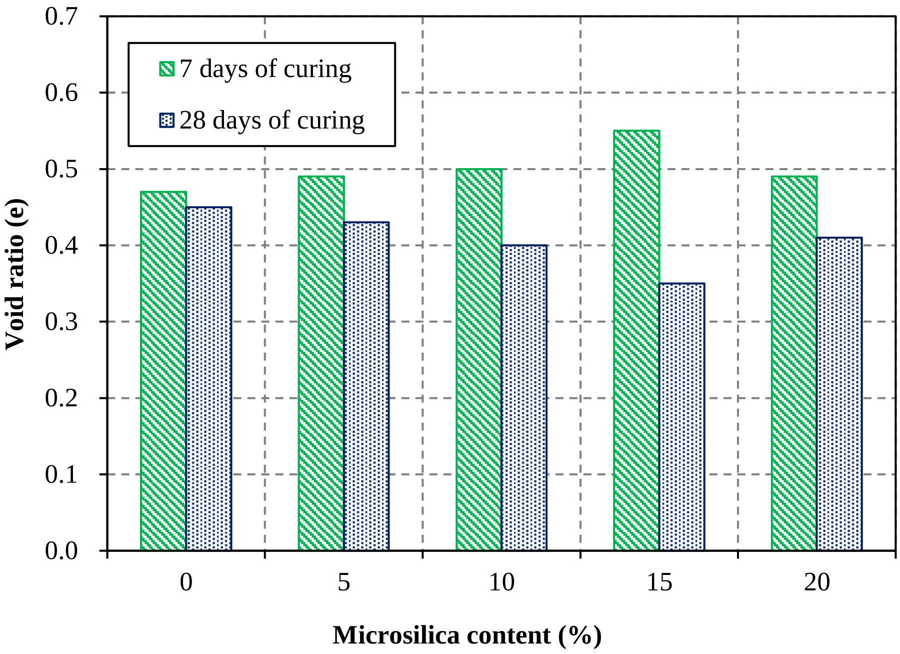

(c)

Fig. 11. Variation of a) compression index, b) coefficient of consolidation, and c) void ratio for microsilica-stabilized oil-contaminated soil samples.

4. Discussion

The results of this study indicate that the addition of 15 % microsilica to fuel oil-contaminated soil significantly improves soil plasticity, unconfined compressive strength, shear strength, and consolidation parameters. This dosage was selected as the optimal content under controlled laboratory conditions based on detailed sensitivity analysis, which included microsilica contents up to 20 %. The data show that while the maximum dry density remained almost unchanged between 15 % and 20 %, shear strength decreased beyond 15 %, and unconfined compressive strength showed minimal change, indicating that 15 % represents a balance between mechanical improvement and potential adverse effects. Consolidation parameters after 28 days further confirmed that 15 % microsilica provides an effective balance between strength development and settlement control. The primary mechanisms contributing to these improvements include pozzolanic reactions, flocculation, and cementitious gel formation, as reported in previous studies.

Unlike nanosilica, microsilica is relatively cost-effective and widely available for laboratory and research purposes, allowing for precise and controlled evaluation of its effects. It should be noted that this study focuses on the research and laboratory evaluation phase, and the results cannot be directly generalized to large-scale field applications. For practical implementation, further consideration of optimal dosages, constructability, and economic feasibility is required. With ongoing technological advancements and improvements in production processes, the cost of microsilica and nanosilica is expected to decrease, enhancing their practical applicability and economic viability in engineering projects.

The observed temporal reduction in compression index and void ratio indicates that time-dependent pozzolanic reactions play a significant role in the long-term consolidation behavior of microsilica-stabilized oil-contaminated soils. As curing progresses, the pozzolanic reaction between microsilica and soil minerals promotes the formation of additional cementitious gels, which fill voids, bind soil particles, and increase structural stiffness. This process not only reduces compressibility but also enhances resistance to settlement under sustained loading. While long-term field behavior beyond laboratory conditions remains to be confirmed, these findings highlight the importance of curing time in optimizing the consolidation performance of treated soils and provide a basis for future investigations on long-term settlement under realistic field loads.

In addition to geotechnical performance, the sustainability aspects of microsilica should also be considered. Microsilica, as an industrial by-product from silicon and ferrosilicon alloy production, represents industrial waste valorization, converting a by-product into a value-added material. Its use contributes to resource efficiency, reduces environmental burdens from waste disposal, and aligns with sustainable engineering practices. Compared to traditional stabilizers such as Portland cement or lime, which are energy-intensive and associated with higher carbon footprints, the use of microsilica can lower the overall environmental impact of soil stabilization. Recent studies in the literature have emphasized the importance of evaluating both mechanical performance and environmental compatibility when selecting stabilizing materials, including assessing potential reductions in environmental burden associated with alternative additives such as microsilica and nano-TiO_2 in geotechnical soil stabilization [38].

The observed reduction in soil plasticity and improvement in unconfined compressive strength after 28 days highlight the effectiveness of microsilica stabilization under controlled laboratory conditions. These results suggest that the treated soils can be considered for pavement subbase or road construction applications, where moisture conditions can be controlled, and uniform compaction is achievable. However, for semi-deep or deep soil improvement projects, the variability in moisture content, heterogeneous contamination levels, and scale effects in the field may influence the stabilization efficiency. Therefore, further investigations, including pilot-scale or in-situ trials, are necessary to assess the practical applicability and optimize treatment strategies under real field conditions.

Furthermore, the improved strength and compressibility of microsilica-stabilized oil-contaminated soils have direct implications for deep foundation performance. The modified soil parameters, including reduced plasticity, increased shear strength, and controlled compressibility, can be used as input in both analytical and experimental assessments of helical pile capacity under tension and compression, as demonstrated in previous studies on dense sand. Incorporating these parameters allows the extension of existing models to contaminated and remediated ground conditions, providing valuable guidance for foundation design and performance prediction in areas affected by fuel oil contamination. Further research is recommended to validate these applications under field conditions with variable moisture content and soil heterogeneity.

5. Concluding remark

In this study, an effort was made to explore the potential of using microsilica to stabilize oil-contaminated soils. To achieve this, a series of laboratory tests was conducted on soil samples both with and without microsilica, leading to the following key findings:

- The addition of microsilica to the oil-contaminated soil resulted in an increase in Optimum Moisture Content (OMC) and a decrease in Maximum Dry Density (MDD). The most significant change in MDD was observed with the inclusion of 15% microsilica in the contaminated soil. Furthermore, the incorporation of microsilica altered the particle size distribution and increased the particle surface area of the mixture compared to the untreated oil-contaminated soil sample.
- The inclusion of microsilica in the soil matrix resulted in the flocculation of particles after the curing period, leading to a reduction in both the Liquid Limit (LL) and Plastic Limit (PL), which, in turn, decreased the plasticity of the soil samples. Notably, the reduction in Plasticity Index (PI) and LL could potentially alter the Unified Soil Classification System (USCS) classification from ML (Silt with Low Plasticity) to CL (Clay with Low Plasticity).- The addition of microsilica up to 15%, along with an increase in vertical confining pressure, resulted in an enhancement of the shear strength of the soil samples. Additionally, the incorporation of microsilica into the contaminated soil reduced the lubricating effect, thereby increasing both the cohesion and friction angle of the soil.
- The addition of 15% microsilica to the contaminated soil increased its unconfined compressive strength (UCS) by approximately 158% after 28 days of curing, reaching a maximum value of 2288 kPa. Furthermore, the strain at fracture for this sample was 12.38%, which is significantly higher than the 5.1% observed for the untreated contaminated soil. The increase in UCS in the presence of microsilica can be attributed to the pozzolanic reaction between the silica and soil particles in the presence of water, which enhances the strength of the soil.
- As the microsilica content increased to 15%, the compression index decreased after both 7 and 28 days of curing. Meanwhile, the coefficient of consolidation and void ratio showed an increasing trend in the short term and a decreasing trend in the long term. It is important to note that short-term reactions, such as cation exchange, altered the contaminated soil structure to a flocculated form, resulting in a larger grain size and subsequently increased void ratio and permeability. In contrast, during long-term reactions, the formation of a cementitious gel filled the voids, thereby enhancing the resistance of the samples to external loads.

For future research, it is recommended to perform microstructural analyses, such as scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), Fourier-transform infrared spectroscopy (FTIR), or X-ray diffraction (XRD), to provide direct evidence of mechanisms like pozzolanic reactions, flocculation, and cementitious gel formation, and to further understand and validate the processes involved in soil stabilization.

Statements & Declarations

Author contributions

Arvin Monjezi: Investigation, Formal analysis, Data curation, Software, Writing - Original Draft.

Hamed Ahmadi Chenarboni: Project administration, Resources, Writing - Review & Editing.

Hossein MolaAbasi: Conceptualization, Methodology, Software, Writing - Review & Editing.

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Data availability

The data presented in this study will be available on interested request from the corresponding author.

Declarations

The authors declare no conflict of interest.

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