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Investigating the Effect of Silica Fume on the Engineering Behavior and Microstructure of Clay Liners

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ABSTRACT

Clay liners are widely used in landfill systems to prevent the migration of contaminants into the surrounding soil and groundwater by providing low permeability and adequate mechanical stability. Various stabilizing agents have been investigated to enhance the engineering performance of these clayey soils, particularly materials that are economical, readily available, and capable of participating in pozzolanic reactions. Limited attention has been given to the application of silica fume, a highly fine amorphous silica produced as a by-product of silicon or ferrosilicon alloy manufacturing, in clay liner systems. In this study, the influence of silica fume contents of 5%, 10%, and 15% (by dry weight of soil) on the behavior of high-plasticity clay was evaluated through standard compaction, unconfined compressive strength, free swell, and permeability tests. The experimental results showed that increasing silica fume content decreased maximum dry density, permeability, swelling percentage, and swelling pressure, while increasing optimum moisture content and unconfined compressive strength. The specimen containing 15% silica fume exhibited more than a 50% reduction in permeability and achieved compressive strength values exceeding the minimum recommended for clay liner materials. In addition, swelling pressure decreased by more than 30% at this dosage. Microstructural observations obtained from scanning electron microscopy confirmed the development of a denser and more compact soil matrix following silica fume treatment.

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1. Introduction

In many cases, the soils at sites considered for landfill development do not possess the required engineering properties. Because the primary objective of landfill design is to isolate waste from the surrounding environment and groundwater [1], the engineering characteristics of the on-site soil are critically important. Ideally, the soil should have very low permeability, high pollutant adsorption capacity, adequate flexibility to accommodate moisture variations, minimal settlement, and sufficient strength to withstand imposed loads [2]. Clay soils are commonly used as liners and base layers in landfills because of their low permeability. When the clay available at a site does not possess the required properties for use as a liner, and the cost of transporting large volumes of suitable soil is high, a cost-effective alternative is to chemically stabilize the existing soil using appropriate additives [3]. Today, in order to reduce environmental pollution and the consumption of energy and natural resources, there is growing interest in environmentally friendly methods for soil improvement [4-7], including the use of industrial by-products such as silica fume in chemical soil stabilization [8, 9].

According to ACI 116R [10], silica fume is an extremely fine, amorphous silica produced in electric arc furnaces and is a by-

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product of the silicon metal and ferrosilicon alloy industries. During the production of 1 ton of ferrosilicon, approximately 200-400 kg of silica fume is generated as a by-product [11]. The silica fume production process is illustrated in Fig. 1.

The amorphous structure and high specific surface area of silica fume particles enhance its reactivity. The use of silica fume as a supplementary or alternative material to Portland cement in concrete production has increased significantly [12]. In recent years, considerable research has focused on the application of silica fume for soil improvement and stabilization. Kalkan [13] demonstrated that the addition of silica fume significantly reduces shrinkage cracks in clay soils, and similar findings were reported by A. Al-Azzawi et al. [14]. Moradi et al. [15] studied marl soil-lime mixtures and found that adding silica fume increased the plastic limit, reduced the plasticity index, enhanced soil strength, and improved bearing capacity. Mostafa et al. [16] also observed that combining lime and silica fume increased the compressive strength, CBR, cohesion, and internal friction angle of the soil while reducing its free swelling. Goodarzi et al. [17] reported that partially replacing Portland cement with silica fume decreased the soil's swelling potential, increased its strength, and accelerated the stabilization process. taghdisi et al. [18] documented similar effects on enhancing soil hardness and strength. Studies by Badv and Emdadi [19] on silty clay soil further confirmed that increasing the silica fume content improves cohesion and strength while reducing soil permeability. In another study, a 50% reduction in collapse potential and a 348% increase in unconfined compressive strength were observed in collapsible soil after the addition of 5% silica fume [20].Türköz et al. [21] indicated that the incorporation of silica fume can enhance the dynamic behavior of clay soils by increasing the initial shear modulus under different effective confining pressures. The positive effect of silica fume on reducing the swelling and swelling pressure of expansive soil was observed by Al-Gharbawi et al. [22]. Waleed and Alshawmar [9] found that the addition of silica fume at an optimum content of 9% improved the shear strength parameters of fine-grained soil, increasing the internal friction angle from 23.8° to 24.51° and cohesion from 15.89 kPa to 23.80 kPa.

Despite numerous studies on the stabilization of clay soils using silica fume, most previous research has mainly focused on general geotechnical applications such as subgrade improvement or soil stabilization for construction purposes. Limited attention has been given to the application of silica fume in clay liner systems used in landfills, where both low permeability and sufficient mechanical strength are required. In addition, the geotechnical behavior of the clayey soils located near the landfill in Varamin city (southeast of Tehran province, Iran) has not been previously investigated. Therefore, this study examines the influence of silica fume on the engineering behavior and microstructure of this local clay soil. Different percentages of silica fume were incorporated into the soil, and its compaction characteristics, strength, swelling potential, and hydraulic properties were evaluated. Furthermore, scanning electron microscopy (SEM) was used to investigate the microstructural changes associated with silica fume addition. The findings contribute to a better understanding of the mechanisms governing the performance of silica fume-stabilized clay liners and their potential use as sustainable landfill barrier materials.

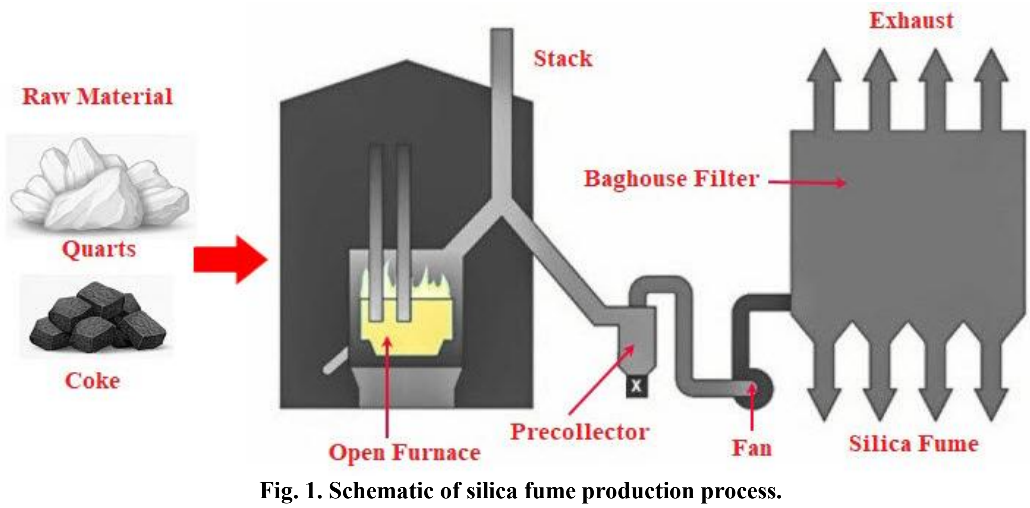


Fig. 1. Schematic of silica fume production process.

2. Materials and methods

The soil investigated in this study was collected from an area in Varamin city, located in the southeast of Tehran province. Bentonite is widely used as an additive to improve on-site soils that do not satisfy the hydraulic conductivity requirements for liner materials [1, 23, 24]. The required bentonite content depends on the type and gradation of the host soil and typically ranges from 10% to 30% by weight [25-27]. Since no standard engineering guideline has yet been established for determining the optimum bentonite content based on soil type, a bentonite content of 20% was selected in this study as a representative value within the commonly reported range for liner materials. The local soil was mixed with 20% bentonite supplied by Semnan Negin Powder Company. Hereafter, the term soil in this article refers to this prepared mixture. To determine the engineering properties of the studied soil, basic soil mechanics tests were conducted in accordance with ASTM standards. The geotechnical properties of the local soil and the local soil mixed with 20% bentonite are presented in Table 1. The grain size distribution curve of the soil (Local Soil+20% Bentonite), determined based on ASTM D422 [28], is presented in Fig. 2. According to the Unified Soil Classification System (USCS) [29], this soil is classified as high-plasticity clay (CH). The chemical compositions of the soils obtained from the X-ray fluorescence (XRF) analysis are presented in Table 2. Silica fume produced by Iran Ferroalloy Industries Company, in compliance with Iranian National Standard No. 13278 [30], was used in this study, and its physical and chemical properties are provided in Table 3. Fig. 3 shows the materials used in this study.

For soil stabilization, the recommended dosage of silica fume is usually between 5% and 15%, depending on the soil type and the targeted engineering properties. For example, Türköz et al. [21] observed the highest shear modulus in a soil mixture containing 15% silica fume. Experiments conducted by Waleed and Alshawmar [9] showed that the optimal amount of silica fume to increase soil strength was 9%. Accordingly, in this study, silica fume contents ranging from 0% to 15% were investigated. To prepare the specimens, silica fume was added to the soil at contents of 5%, 10%, and 15% by dry weight of the soil. After adding water at the target moisture content, the mixture was manually blended until a homogeneous specimen was obtained.

Table 1. Geotechnical properties of soils.

Standard	Local soil	Local soil + 20% bentonite	Standard
Liquid limit, %	37	52	ASTM D4318 [31]
Plastic limit, %	22	28	ASTM D4318 [31]
Plasticity index, %	15	24	ASTM D4318 [31]
Specific gravity (G_s)	2.69	2.67	ASTM D854 [32]
Maximum dry density, kN/m^3	14.8	14.2	ASTM D698 [33]
Optimum moisture content, %	18.2	20.1	ASTM D698 [33]
Unconfined compressive strength, kPa	76.1	86.5	ASTM D2166 [34]
Permeability, cm/s	1.03×10^{-6}	3.1×10^{-7}	ASTM D5084 [35]
Swelling pressure, kPa	91	120	ASTM D4546 [36]

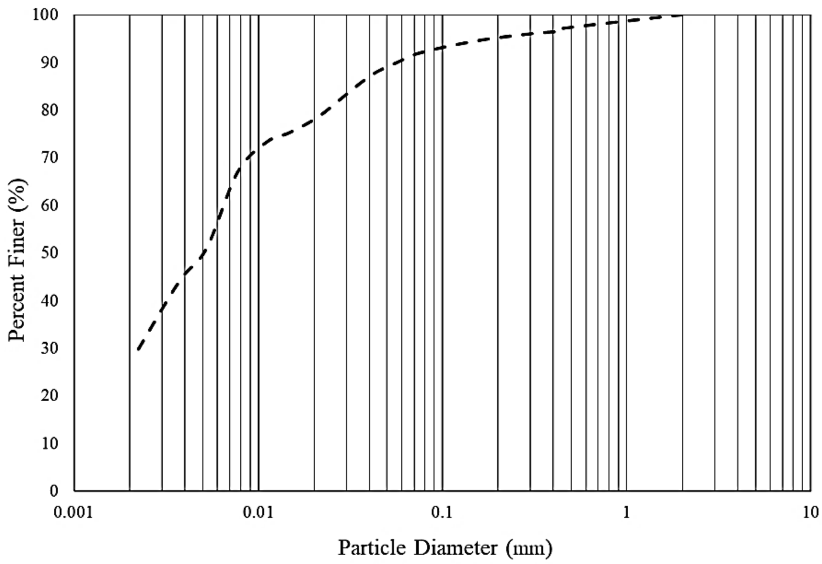


Fig. 2. Grain-size distribution curve of the soil (local soil+20% bentonite).

Table 2. Chemical compositions of the soils.

Compound	Local soil	Bentonite
SiO_2	57.9	60.05
Al_2O_3	16.1	15.48
Fe_2O_3	5.24	4.1
CaO	7.08	3.25
MgO	2.74	2.2
SO_3	1.03	0.41
K_2O	1.35	1.78
Na_2O	1.68	2.84
Other	3.6	5.83
Loss on ignition	3.28	4.06

Table 3. Physical and chemical properties of silica fume.

Chemical properties	Value	Physical properties	Value
90-95	SiO_2 (%)	Color	Grey
0.8-3	C (%)	Diameter (μm)	<1μm
Loss on ignition (%)	1.5-2.5	Specific gravity	2.2
		Surface area (m^2/g)	15-30

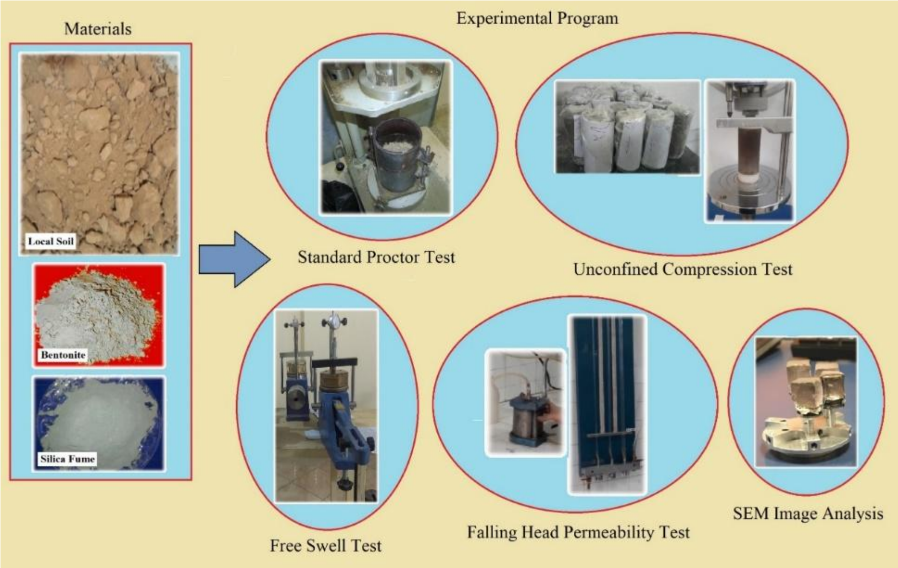


Fig. 3. Materials used and experimental program in this study.

To determine the compaction characteristics of the specimens, including the maximum dry density (MDD) and optimum moisture content (OMC), the Standard Proctor compaction test was conducted. After the addition of silica fume, the soil mixture was stored in a plastic container for 24 hours to allow chemical reactions to take place. The compaction test was then performed on the treated soil. According to ASTM D698 [33], the Standard Proctor test involved compacting the soil in three layers, with 25 blows per layer, corresponding to a compaction energy of 600 kN·m/m³. The compaction was carried out in a mold with a diameter of 101.6 mm using a hammer weighing 24.4 N, dropped from a height of 305 mm.

To perform the unconfined compressive strength (UCS) test in accordance with ASTM D2166 [34], soil and silica fume were mixed at the optimum moisture content, and the specimens were compacted to 100% of the maximum dry density in a mold with a diameter of 38 mm and a height of 76 mm. After removal from the mold, the cylindrical specimens were wrapped in a layer of plastic film, placed in plastic bags, and stored at 23 ± 1.7 °C for 7 days (Fig. 3). Following the curing period, the specimens were subjected to axial loading using a uniaxial testing machine.

To evaluate the swelling characteristics of both untreated and stabilized soils, the free swell test was conducted on the specimens in accordance with ASTM D4546 [36]. Initially, a surcharge pressure was applied to the specimen to achieve the desired void ratio. The surcharge was then removed, and the specimen was inundated to allow free swelling. After the specimen attained full swell, it was reloaded to its initial height, and the swelling pressure was determined accordingly.

Permeability is the ability of water to flow through saturated soil and is commonly measured for fine-grained soils using the falling-head permeability test. In this test, the soil specimen is placed inside a permeameter, and water is allowed to flow through it. The initial hydraulic head difference at time $t = t_1$ is recorded as h_1, and as water flows through the soil, the hydraulic head difference at time $t = t_2$ is recorded as h_2. The coefficient of permeability, k, is calculated using Eq. 1:

$$k = 2.303 \frac{a \cdot L}{A \cdot \Delta t} log \frac{h_1}{h_2} \quad (1)$$

where h is the hydraulic head difference (cm) at time t, A is the cross-sectional area of the soil specimen (cm²), a is the cross-sectional area of the standpipe (cm²), and L is the length of the soil specimen (cm). The permeability of the specimens was determined using the falling-head permeability test in accordance with ASTM D5084 [35].

To investigate the mechanism of the additive's effect on the soil, scanning electron microscopy (SEM) analysis was conducted using a VEGA\\TESCAN-LMU microscope at 10000x magnification at the Razi Metallurgical Research Center. The selected specimens for SEM analysis were untreated soil and soil treated with 15% silica fume. After curing the stabilized specimen, a small portion was extracted for analysis to examine the pores and evaluate the effect of silica fume on the soil structure. The samples were then analyzed using the scanning electron microscope. The experimental tests conducted in this study are presented in Fig. 3.

3. Results and discussion

Fig. 4 presents the compaction curves for the untreated soil and specimens stabilized with varying percentages of silica fume. For each mix design, five specimens were tested, and the compaction curves were generated based on the measured moisture content and dry density of each specimen. As observed, the addition of silica fume to the soil reduces the MDD while increasing the OMC of the specimens. Specifically, incorporating 15% silica fume decreases the MDD from 14.2 to 13.7 kN/m³ and increases the OMC from 20.1% to 21.7% (Table 4). The reduction in MDD for the silica fume-containing specimens can be attributed to the replacement of soil particles with a higher specific gravity (G_s) by silica fume with a lower density. The increase in OMC is likely due to the presence of silica fume, which increases the specific surface area of the soil, thereby requiring more water for proper compaction of the clayey soil. A similar trend in the variation of compaction parameters with the addition of silica fume to different soils has been reported by Badv and Emdadi [19] and Fattah et al. [37].

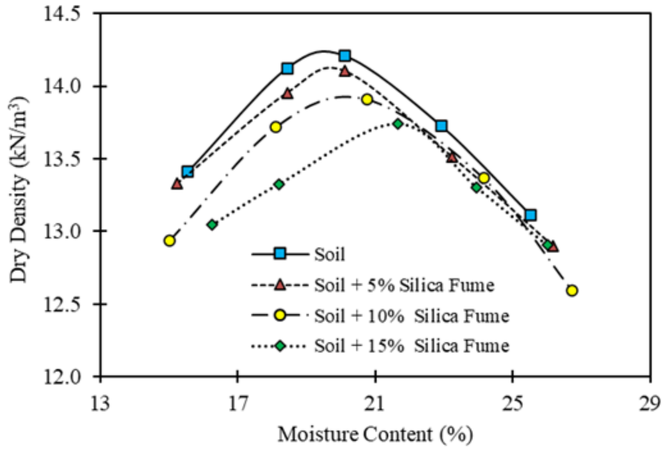


Fig. 4. Compaction curves of the specimens.

Table 4. Changes in the geotechnical properties of the samples.

Properties	Local soil	Local soil + 20% bentonite	Soil + 5% silica fume	Soil + 10% silica fume	Soil + 15% silica fume
MDD, kN/m^3	14.8	14.2	14.1	13.9	13.7
OMC, %	18.2	20.1	20.2	20.8	21.7
UCS, kPa	76.1	86.5	97.5	112.9	121.9
Permeability, cm/s	1.03×10^{-6}	3.1×10^{-7}	2.7×10^{-7}	1.9×10^{-7}	1.4×10^{-7}
Swelling pressure, kPa	91	120	—	—	80

The UCS of the soil was 86.5 kPa, indicating its low strength and limited bearing capacity. As shown in Fig. 5, the addition of silica fume significantly increased the compressive strength. Specifically, specimens containing 5%, 10%, and 15% silica fume exhibited strength increases of approximately 13%, 30%, and 40%, reaching 97.5, 112.9, and 121.9 kPa, respectively. The observed trend suggests that further increases in silica fume content would result in diminishing gains in strength. In the chemical stabilization of clayey soils, the chemical compositions of both the soil and the additive play a crucial role. The soil used in this study contains calcium oxide, which reacts with water molecules to produce Ca^{2+} ions and hydroxyl ions. The active silica present in silica fume reacts with calcium hydroxide to form Calcium Silicate Hydrate (C-S-H) gels. As these gels fill the pore spaces within the soil matrix, a denser structure is formed. Consequently, the soil becomes stiffer, and its strength increases. Other studies have also reported the production of cement products in the presence of silica fume [20, 38, 39]. Another contributing mechanism is the reduction in particle spacing caused by the presence of silica fume, which further increases interparticle friction. The UK Environment Agency [40] stated that a clay liner material should have a minimum remolded undrained shear strength greater than 50 kPa (equivalent to an unconfined compressive strength of 100 kPa). The results of the present study showed that the soils stabilized with 10% and 15% silica fume exhibited strength values higher than this recommended criterion. As seen in the stress-strain curves in Fig. 5, the behavior of the specimens becomes more brittle with increasing silica fume content, and the maximum stress is achieved at lower strains. The strain at peak stress for the untreated soil and soils stabilized with 5%, 10%, and 15% silica fume were 0.043, 0.039, 0.032, and 0.029, respectively. The more brittle behavior observed in the silica fume-treated samples can be attributed to the fact that when the initial soil porosity is high, strength increases due to cementation; however, with increasing stress, the sudden breakdown of these cementitious products leads to a rapid reduction in strength [41].

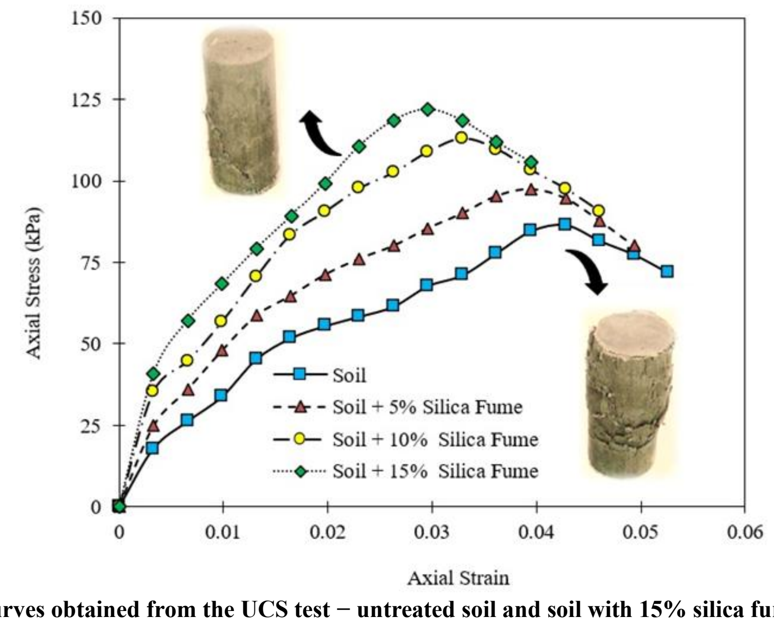
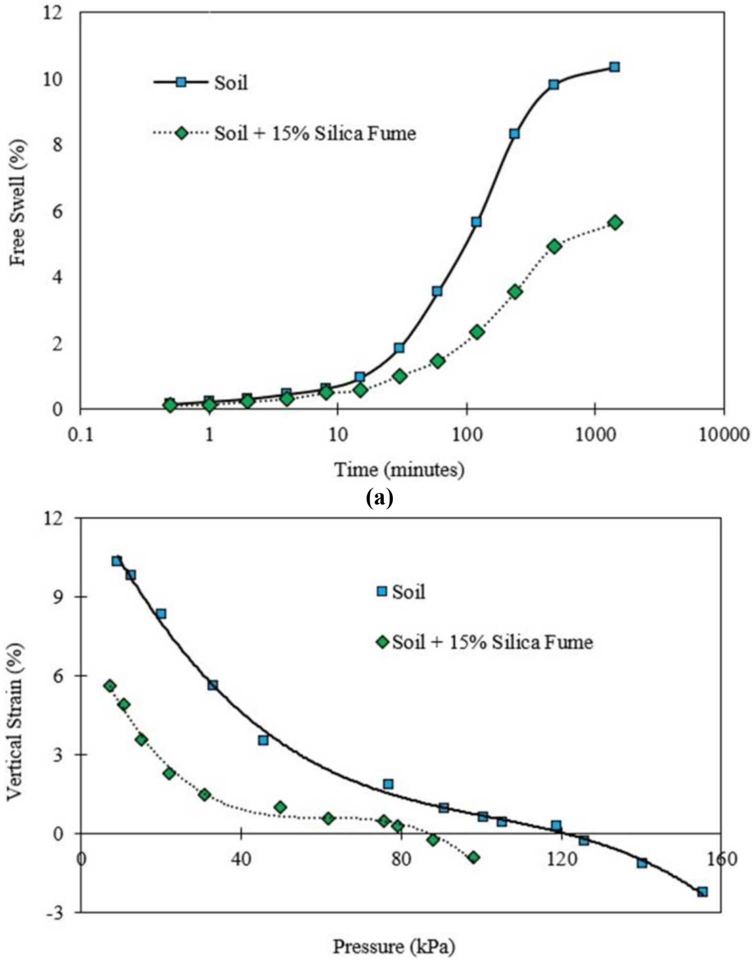


Fig. 5. Stress-strain curves obtained from the UCS test − untreated soil and soil with 15% silica fume, shown after failure.

Fig. 5 also shows that, after loading, the untreated soil and the soil containing 15% silica fume exhibit different failure patterns. The brittle behavior of the silica fume-stabilized specimen results in sudden failure at higher strength, with fewer cracks compared to the untreated soil. Therefore, besides enhancing strength, the incorporation of silica fume is expected to decrease soil permeability by restricting crack development.

The free swell and swelling pressure of the untreated soil and the soil stabilized with 15% silica fume are presented in Fig. 6. The addition of 15% silica fume reduced the swelling percentage from 10.35% to 5.64%, representing a 45% reduction in swelling. The swelling pressure of the untreated soil was measured as 120 kPa, while the soil stabilized with 15% silica fume exhibited a 33% reduction in swelling pressure, decreasing to 80 kPa. The improvement in the swelling behavior of soils due to the addition of silica fume has also been confirmed by other researchers [20, 22, 42]. The formation of bonds between soil particles, as previously discussed, restricts the volumetric expansion of the soil and consequently reduces swelling. Moreover, changes in soil fabric and particle size distribution due to the addition of silica fume reduce the plasticity index of the soil. The reduction in soil plasticity decreases water absorption capacity, which in turn leads to a reduction in percent swell. Several researchers have reported that plasticity is a reliable indicator of the swelling behavior of soils [43].



(b)

Fig. 6. Effect of silica fume on: (a) swelling percentage; and (b) swelling pressure of the soil.

The permeability of the specimens with varying silica fume contents, measured using the falling-head test, is presented in Fig. 7. Permeability decreased with increasing silica fume content. Specifically, the addition of 15% silica fume reduced soil permeability by 55%, lowering it from 3.1×10^{-7} to 1.4×10^{-7} cm/s. Permeability is one of the most critical parameters in the design of landfill liner systems. According to commonly accepted environmental regulations and design guidelines, the permeability of compacted clay liners is generally required to be equal to or lower than 10^{-7} cm/s to effectively control contaminant migration [44, 45]. The results of the present study showed that increasing silica fume content significantly reduced the permeability of the clay liner specimens. This reduction in permeability can be attributed to the filler effect of silica fume and the formation of bonds between soil particles. These findings indicate that silica fume can be considered a suitable additive for improving the sealing efficiency and long-term performance of clay liner systems.

Fig. 8 presents SEM micrographs of the untreated soil and the soil stabilized with 15% silica fume. As shown, the untreated soil exhibits numerous pores and voids, whereas the silica fume-stabilized soil displays a denser structure. The clay particles and plates are coated with a layer of silica fume. Comparison of the two images indicates a significant reduction in pore size in the stabilized soil. Specifically, the pore size decreased from approximately 10 μm in the untreated soil to less than 2 μm in the soil containing silica fume. This behavior can also be attributed to pozzolanic reactions between the reactive silica in silica fume and calcium compounds present in the soil, leading to the formation of cementitious calcium silicate hydrate (C-S-H) products. The generated gels filled the voids between soil particles and enhanced interparticle bonding, resulting in a more compact and integrated structure.

The reduction in pore size and pore connectivity contributed directly to the decrease in hydraulic conductivity observed in the treated specimens. In addition, the improved bonding and cementation between particles increased soil stiffness and load-bearing capacity, which explains the enhancement in unconfined compressive strength. Therefore, the microstructural observations are consistent with the macroscopic improvements in both hydraulic and mechanical behavior of the silica-fume-treated soil. The microstructural changes observed in this study are in agreement with the results reported by Waleed and Alshawmar [9] and Tiwari et al. [42].

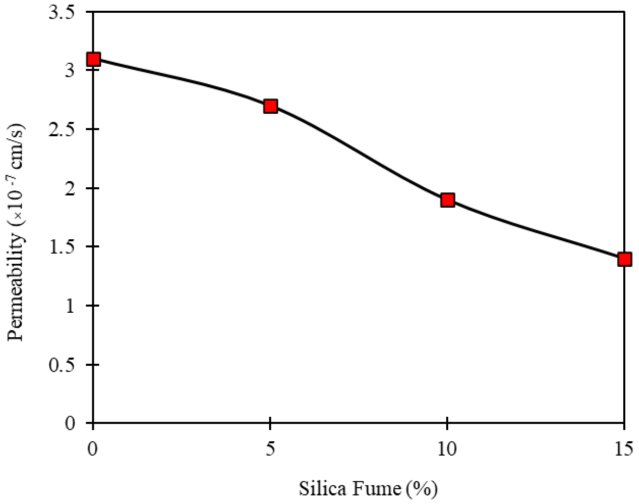


Fig. 7. Permeability variation of specimens with increasing silica fume content.

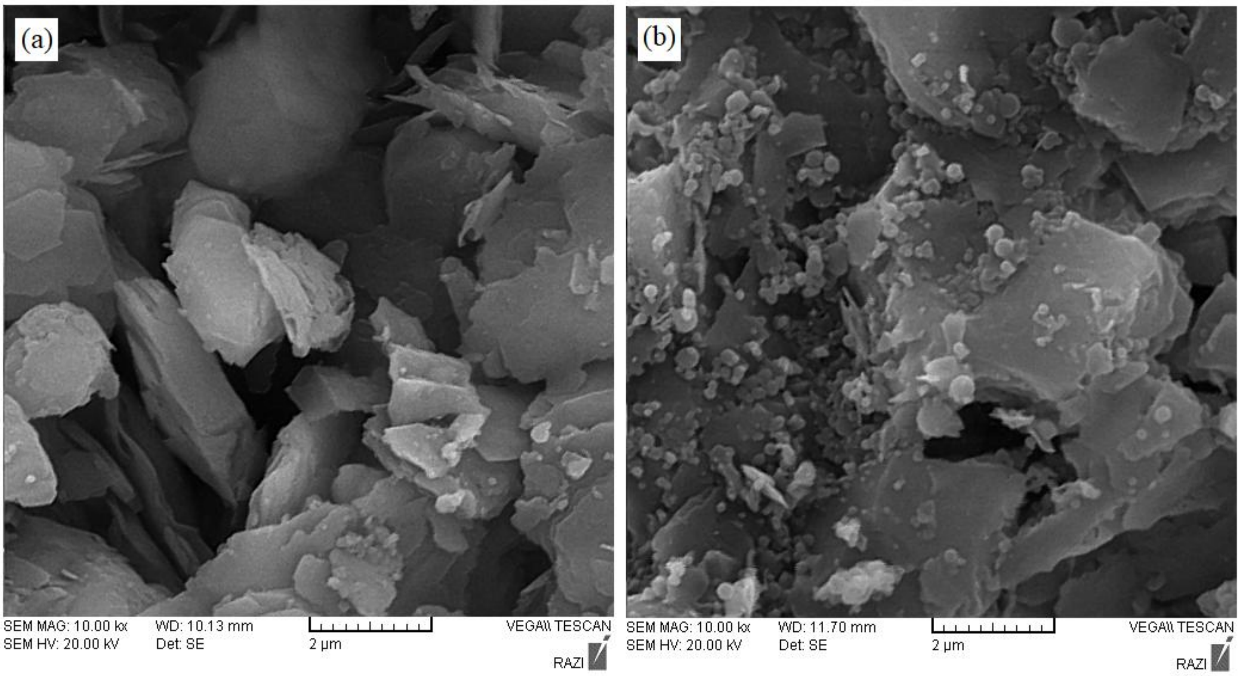


Fig. 8. SEM micrographs of: (a) soil; and (b) soil stabilized with 15% silica fume.

4. Conclusions

This study investigated the effectiveness of silica fume as an environmentally friendly stabilizing additive for improving the geotechnical and microstructural properties of a high-plasticity clay soil intended for landfill liner applications. Based on the experimental results, the following conclusions can be drawn:

- The addition of silica fume led to a reduction in maximum dry density and an increase in optimum moisture content, primarily due to the lower specific gravity and high specific surface area of silica fume particles.
- Unconfined compressive strength increased significantly with increasing silica fume content. The maximum improvement was observed at 15% silica fume, where the strength reached 121.9 kPa, representing an approximately 40% increase compared to the untreated soil and satisfying the minimum strength requirement for landfill liners based on relevant standards. However, the rate of strength gain decreased at higher silica fume contents, indicating diminishing returns. The incorporation of silica fume altered the stress-strain behavior of the soil, making it more brittle and causing peak strength to occur at lower strain levels.
- Swelling characteristics were substantially improved by silica fume stabilization. The free swell percentage and swelling pressure decreased by 45% and 33%, respectively, with the addition of 15% silica fume, mainly due to reduced plasticity and restricted volumetric expansion.

- Permeability decreased markedly with increasing silica fume content. A reduction of approximately 55% was achieved at 15% silica fume, which is attributed to the filler effect and the formation of interparticle bonds. The permeability of the sample containing 15% silica fume was approximately close to the value recommended for clay liner systems (10^{-7} cm/s). Further reduction in permeability may require the use of higher amounts of bentonite or silica fume, while considering the corresponding strength and swelling parameters. The optimum additive contents should be selected by considering both geotechnical performance and practical or economic limitations.
- SEM observations confirmed the densification of the soil structure after stabilization, showing a significant reduction in pore size and a more compact fabric caused by silica fume coating and bonding of clay particles, which is attributed to the formation of C-S-H gels resulting from the reaction between active silica in silica fume and calcium compounds in the soil.

Statements & declarations

Author contributions

Sadegh Ghavami: Investigation, Formal analysis, Supervision, Writing - Review & Editing.

Sina Tahmasebi: Investigation, Methodology, Writing - Original Draft.

Narges Delnavaz: Investigation, Visualization, Writing - Original Draft.

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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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