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Assessment Of Collapse Potential Of Nanomaterial Improved Collapsible Soils

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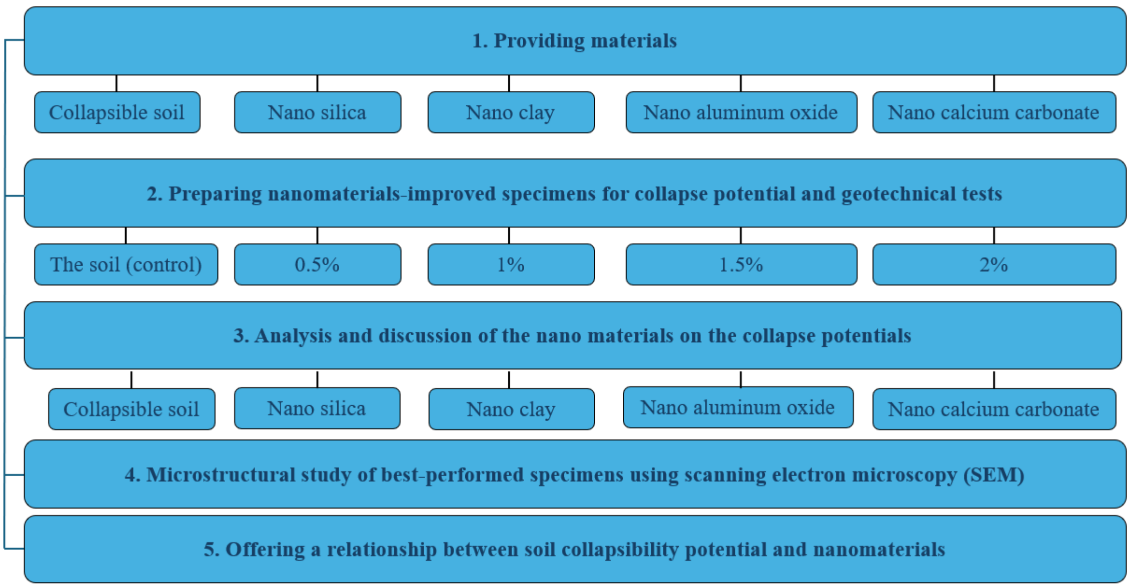
Abstract: Collapsibility refers to the sudden failure of soil due to the loss of cohesive forces between its particles. Collapsibility has significant challenges in construction, making it essential to analyze and enhance soil behavior. In this study, the impact of nanomaterials on collapsibility potential was investigated. A soil with high collapsibility potential from the Allahabad region in Kerman was selected, and the effects of adding Nano silica, Nano Clay, Nano Aluminum Oxide, and Nano Calcium Carbonate at different percentages on the soil's volume change, collapsibility potential and shear strength were examined. The results indicated that adding nano-silica and nano-clay significantly reduced the soil's potential for collapsibility by modifying its structure. Nano Calcium Carbonate and Nano Aluminum Oxide had a smaller impact on reducing collapsibility. Nano silica and Nano Clay increased the Adhesion Coefficient, while Nano Calcium Carbonate and Nano Aluminum Oxide had the most significant impact on the soil's Angle of Internal Friction. Scanning electron microscope (SEM) images revealed that the collapsible soil contained microscopic pores, which decreased with the addition of nanomaterials, resulting in a denser structure and reduced collapsibility potential.

Keywords: Soil collapsibility, Nanomaterials, Soil behavior, Problematic soils, Soil Improvement

Graphical Abstract



1. INTRODUCTION

In the field of geotechnical engineering, soils that are unsuitable for construction are known as problematic soils. There are various types of problematic soils, including swelling, dispersive, and collapsible soils (Ohadian et al. 2024, Ayadat and Hanna 2012). Three main approaches are considered when addressing problematic soils: relocating the construction site, replacing unsuitable soil with appropriate materials, and enhancing the existing soil. (Rollins, Kim and Engineering 2010, Khaleghi, Rowshanzamir and Engineering 2023, Lin and Wang 1988). Collapsible soils are a type of problematic soils that undergo volume reduction due to the sudden loosening of intergranular bonds when humidity increases, approaching a saturated state (Evstatiev 1988, Jalali et al. 2023, Al-Gharbawi, Fattah and Mahmood 2022).

Engineers are always looking for proper methods for stabilizing collapsible soils due to the challenges they present in construction. Various methods have been proposed to improve these types of soils, depending on the severity of collapsibility and economic factors (Sheikhhosseini Lori, Toufigh and Toufigh 2021, Toufigh et al. 2023). Wet compaction is effective for stabilizing the surface layers of the soil affected by light structures, while deep injection is more suitable for deep structures. Another approach to managing collapsible soils involves using deep foundations to transfer the structural load to deeper stable soil layers. Additionally, chemical stabilization is a commonly used method for improving collapsible soils (Ayeldeen et al. 2017, AlShaba, Abdelaziz and Ragheb 2018).

In a study conducted by Buhler et al. (2007) on expansive soils modified with lime and fly ash, the findings indicated that both substances effectively reduced soil collapsibility and swelling. Notably, lime had a more pronounced effect at the same weight percentage . Researchers conducted studies on collapsible soils by adding mineral salts such as ammonium sulfate and potassium chloride at concentrations of 0.5, 1, 1.5, and 2 moles per liter. The results indicated a significant reduction in soil collapse when these mineral salts were used with collapsible soils. Additionally, reconstructed samples with higher compacted energy demonstrated a lower potential for collapsibility (Abbeche et al. 2010).

Research investigated chemical stabilization using sodium silicate, activating it with formamide and ammonium persulfate. The uniaxial tests showed that substituting formamide with ammonium persulfate increased the uniaxial strength from 0.3 MPa to 0.7 MPa and improved the elastic modulus from 22 MPa to 47 MPa (Mohamed and El Gamal 2012). Studies on mixing collapsible soil with fly ash and sulfur at various curing temperatures and periods demonstrated that the strength of these samples was three times greater than that of samples stabilized with Portland cement (Alizadeh Rafiei 2009).

In the improvement of collapsible soil using the injection method with cement, gypsum, and Nano silica, the Lime showed the most significant reduction in collapsibility potential, achieving a 70% decrease. In comparison, cement and micro silica reduced the collapsibility of the local soil by 60% and 40%, respectively (Fattah et al. 2014). The analysis of strength and collapsibility parameters in soil during the injection of different volumes of liquid acrylate chemical slurry showed that increasing the amount of liquid acrylate reduced the soil's collapsibility. However, when the injection volume was high, the characteristics of the soil were negatively affected, ultimately influencing the behavior

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of the slurry. As a result, the potential for collapsibility remained relatively unchanged and did not exhibit significant variation (Nik Iqbal Sanikht 2013).

Abbas et al. (2021) explored the use of textile waste to improve collapsible soils. Mixing 4% to 24% of this waste with soil showed that the collapsibility potential significantly decreased from about 11% to 2.6% at a 24% concentration. Shear tests showed increased adhesion and reduced internal friction, while Atterberg limit tests indicated a higher plasticity limit. Compaction tests revealed lower maximum dry density and increased optimum moisture content. The California Bearing Ratio (CBR) values suggest that soil-sludge mixtures are suitable only for the lower layers of pavement construction (Abbas et al. 2021). Bahrami and Marandi (2021) conducted a large-scale experiment to investigate the improvement of collapsible soil using a stone pillar. They found that using a stone pillar surrounded by geogrid can reduce the collapsibility potential of low-plasticity clay soil by up to 80% (Bahrami and Marandi 2021).

Nanomaterials are increasingly being used for the chemical stabilization of problematic soils, alongside traditional materials like cement and lime. Nanotechnology involves advanced techniques that operate at the nanoscale, which ranges from approximately 1 to 100 nanometers. This technology aims to create materials with unique properties(Johari et al. 2022, C. Bréchignac 2008, Martin 1994) The most commonly used nanomaterials for improving problematic soils include nano lime, nano silica, nano bentonite, nano zeolite, nano montmorillonite, and nano aluminum (Haeri et al. 2015). Research conducted by Khan Abadi et al. (2018) demonstrated that the effectiveness of improving collapsible soil using nano montmorillonite was influenced by the size of the land and the depth of the improvement. Consequently, this method may not be cost-effective as the size or depth of the area increases(Mohammadi Khan Abadi 2018).

The studies referenced highlight the importance of using novel materials to enhance soil collapsibility despite numerous theoretical and laboratory investigations already conducted. It is crucial to perform comparative studies on the effects of nano additives at various concentrations to obtain new insights and data for geotechnical engineers. Therefore, this research was conducted to examine the impact of four nanomaterials nano silica, nano clay, nano aluminum oxide, and nano calcium carbonate on soil collapsibility. The main criteria for assessing the performance of these nanomaterials included tests for collapsibility potential and direct shear strength. Additionally, scanning electron microscopy (SEM) was utilized to gain a better understanding of the microstructure of the selected samples.

2. MATERIALS

2. 1. Soil

The studied soil was extracted from a depth of 1.5-2 meters with a moisture content of 3.2% from the Allah Abad region, Kerman, Iran. To determine the soil type, particle size distribution was conducted according to the ASTM D422-63 standard. Atterberg limits were determined by ASTM D4318, and the Proctor compaction test was carried out following ASTM D698. Figure 1 shows the particle size distribution, and Table 1 provides an overview of the soil characteristics. Based on the the unified classification system, the studied soil was identified as clay with low plasticity properties (CL). In

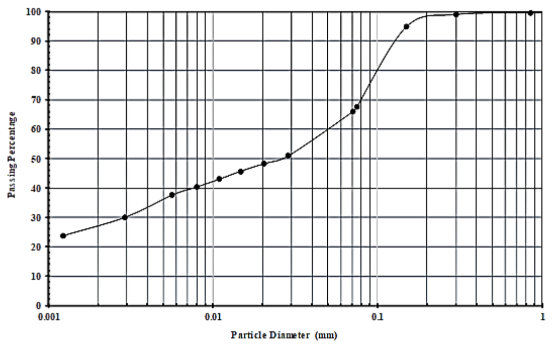

Figure 1. Particle size distribution of the soil

addition, the density of the soil at the site was determined 1.4 grams per cubic centimeter using the bulk specific density based on ASTM D1188-96.

2. 2. Nano Silica (Nano SiO_2)

Nano silica is simply silicon dioxide (SiO_2) with particle sizes in the nanometer range. The amorphous nano-silica used in this study was obtained from US Research Nanomaterials Inc. The specifications of the nano silica are detailed in Table 2, based on the data provided by the manufacturing company.

2. 3. Nano Clay (Montmorillonite)

The nano clay used in this study is of the montmorillonite type procured from Sigma-Aldrich. The specifications of the nano clay are detailed in Table 3, based on the data provided by the manufacturing company.

TABLE 1. Properties of the studied soil

Maximum Dry Density (g/cm^3)	3
Optimal water content (%)	15.5
Liquid Limit (%)	30
Plasticity Limit (%)	19
Plasticity Index (%)	11
Specific Gravity, G_s	2.7
Internal Friction angle, ø (˚)	36
Adhesion, *c* (kg/cm^2)	0.09

TABLE 2. Properties of used nano silica

Particles Size (nm)	20-30
Specific Surface Area (m^2/g)	180-160
Bulk Density (g/cm^3)	<0.1
True Density (g/cm^3)	2.4
Color	white

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Purity (%)	>99
Morphology	spherical

TABLE 3. Properties of used nano clay

Particles Size (nm)	1-2
Specific Surface Area (m^2/g)	220-270
Bulk Density (g/cm^3)	0.5-0.7
True Density (g/cm^3)	1.98
Color	Light yellow
Purity (%)	>99%
Morphology	oligomeric and almost planar

2. 4. Nano Aluminum Oxide (Nano Al_2O_3)

Alpha-phase nano aluminum oxide, with a chemical formula of Al_2O_3 and 99% purity, was obtained from US Research Nanomaterials. The specifications for the nano aluminum oxide are outlined in Table 4, based on the information provided by the manufacturer.

TABLE 4. Properties of used nano aluminum oxide

Particles Size (nm)	50
Specific Surface Area (m^2/g)	>19
Bulk Density (g/cm^3)	0.19
True Density (g/cm^3)	2.7
Color	white
Purity (%)	>99
Morphology	almost spherical

2. 5. Nano Calcium Carbonate (Nano $CaCO_3$)

Nano calcium carbonate was obtained from American Elements. According to the manufacturer's information, the specifications for the Nano calcium carbonate are outlined in Table 5.

TABLE 5. Properties of used nano calcium carbonate

Particles Size (nm)	10-80
Specific Surface Area (m^2/g)	30-60
Bulk Density (g/cm^3)	0.68
True Density (g/cm^3)	2.93

Color	white
Purity (%)	>98
Morphology	cubic or hexagonal

3. METHODS

Typically, up to 2 percent of soil (by weight) is replaced with nanomaterials for soil improvement, which is considered cost-effective. In this research, the four mentioned nanomaterials were used at 0.5%, 1%, 1.5%, and 2% of soil weight to enhance soil collapsibility. Also, an unstabilized soil specimen was prepared to serve as the control for evaluating the effectiveness of the nanomaterials.

3. 1. Preparation of Specimens

The required amount of dry materials, including soil and nanomaterials, for each composition was measured using a scale with an accuracy of 0.01 grams, based on the specified percentages. The mixture was blended for 10 minutes to ensure uniformity. Next, the appropriate amount of water equivalent to the natural moisture content of the soil was added to the dry mixture. The combined mixture was then mixed for an additional 15 minutes to achieve a homogenous mixture. To mold the samples, the final mixture was poured into the mold in three layers, with each layer compacted to achieve a predetermined fixed volume. For accuracy, two samples were prepared for each composition, and the averages of these samples were reported.

3. 2. Collapsibility Potential Test

The soil collapsibility potential test was conducted according to the ASTM D5333-03 standard. This test was used to measure one-dimensional collapsibility in unsaturated soils as they become saturated with a fluid. The process involves placing a soil specimen inside an oedometer consolidation device. A specified vertical stress is then applied to the sample, and water is added to saturate it, which can lead to collapsibility.

To conduct the test, the soil sample was extracted using the ring of the consolidation apparatus (the oedometer) and positioned within the device. Loading was applied in stages of 0.05, 0.12, 0.5, 1, and 2 kg/cm² for one hour under normal humidity conditions, and the gauge numbers on the oedometer were recorded.

After recording the gauge number at the vertical loading equal to the stress of 2 kg/cm², the sample was submerged in water. Gauge numbers were then recorded at intervals of 0.25, 0.5, 1, 2, 4, 8, 15, and 30 minutes, as well as at 1, 2, 4, and 24 hours. The collapsibility potential (I_c) was subsequently calculated using the following formula (Equation 1):

$$I_c = \left[\frac{d_f - d_0}{h_0} - \frac{d_f - d_i}{h_0}\right] \times 100 = \left[\frac{d_i - d_f}{h_0}\right] \times 100 \quad \textbf{(1)}$$

Where d_i represents the decrease in soil volume before being submerged, d_f represents the decrease in soil volume after being submerged in millimeters, and h_0 represents the initial height of the sample in millimeters.

A collapsibility potential test was performed on an undisturbed sample of used soil. The results indicated a collapsibility potential value of 11.87, suggesting that the soil has a high potential for collapse. Figure 2 illustrates the outcomes of the collapsibility potential test on the undisturbed soil sample.

The soil would inevitably be impacted when nanomaterials were added to the soil. Therefore, reconstructed samples were created through trial and error to match the natural moisture content of the soil (2.3%) with varied densities, aiming to achieve a collapsibility potential nearly equivalent to the soil's natural collapsibility potential. Subsequently, the resulting natural moisture percentage of the soil and the obtained density were used as the basis for creating the samples. Table 6 illustrates the results from the trial and error phase. The table clearly shows that among the three trial and error attempts, the reconstructed samples with 2.3% moisture content and a dry specific weight of 1.4 g/cm^3 closely resemble the undisturbed state.

TABLE 6. Collapsibility test results of undisturbed and disturbed specimens (remolded in 3.2% moisture)

Specimen	I_c
Undisturbed soil (γ_d=1.45 g/cm^3)	11.87
Disturbed soil (γ_d=1.45 g/cm^3)	8.05
Disturbed soil (γ_d=1.40 g/cm^3)	12.9
Disturbed soil (γ_d=1.35 g/cm^3)	16.35

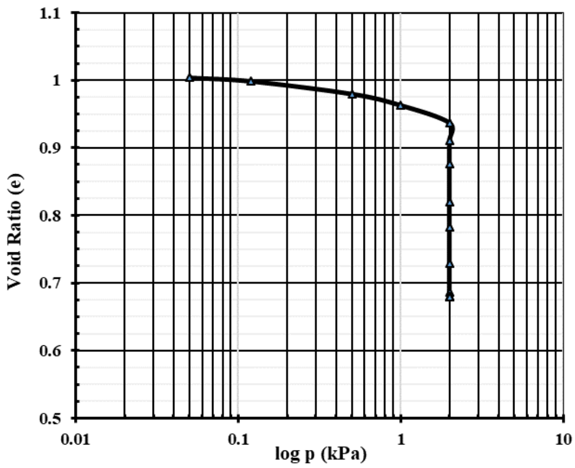


Figure 2. The result of collapse potential test of undisturbed soil

3. 3. Direct Shear Test

The direct shear test, one of the most common shear strength tests, was conducted according to ASTM-D3080 on remolded samples at natural moisture content and corresponding unit weight, with a 1 mm/min shear rate. Considering that the soil sample depth was 1.5-2 meters, the direct shear test was performed on three samples under different normal stresses of 0.5, 1, and 1.5 kg/cm².

3. 4. Microstructural analysis

After calculating the results of the collapse potential and direct shear tests, the best-performing sample from each nanomaterial was selected for further analysis. To better understand the nanomaterials' mechanisms at the microstructural level, these selected samples were examined using Scanning Electron Microscopy (SEM).

4. RESULTS AND DISCUSSION

4. 1. Effect of Nano Materials on Collapse Potential

Four types of nanomaterials were utilized to improve the soil's collapse potential: Nano Silica, Nano Clay, Nano Aluminum Oxide, and Nano Calcium Carbonate. These nanomaterials were added in different percentages of 0.5%, 1%, 1.5%, and 2%. Figure 3 illustrates the collapsibility potential of different samples enhanced with these additives. The graphs indicate that the addition of nano additives significantly reduces the collapsibility index. As the proportion of these materials increased, the collapsibility index decreased. The results show that incorporating Nano Silica has a more substantial impact on improving the soil's collapsibility compared to the other additives.

Adding nano clay up to 1% by the weight of the soil resulted in a greater reduction in collapsibility potential than adding nano calcium carbonate up to 1%. However, at 1.5% and 2% percentages, nano calcium carbonate reduced collapsibility potential more than nano clay.The addition of nano-aluminum oxide impacted the collapsibility potential of the soil, but it showed less effect than other additives. When comparing the graphs, it is evident that increasing the percentage of nano silica and nano calcium carbonate in the soil (from 0.5% to 2% by weight of the soil) led to a greater reduction in collapsibility potential.

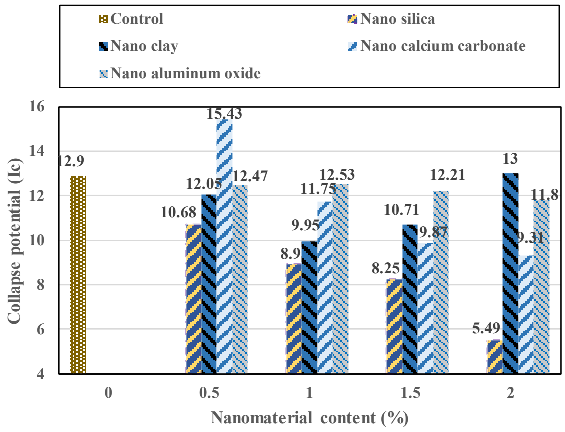


Figure 3. The collapse potential of control and nano-improved specimens

When the percentage of nano aluminum oxide increased from 0.5% to 2%, there was a significant increase in the reduction of collapsibility potential. This means that increasing the percentage of nano aluminum oxide had a significant effect on reducing the collapsibility potential of the soil. The most significant reduction in collapsibility potential was observed when nano-silica was added at a concentration of 2%. This addition shifted the studied soil's collapsibility potential from severe to moderate. This outcome demonstrated a highly favorable effect of nano-silica compared to the other additives.

The reduction in the collapsibility index is attributed to structural changes and the rearrangement of soil particles due to the addition of nanomaterials. SEM images revealed that collapsible soil contains both microscopic and macroscopic pores. Adding an additive could disrupt larger pores, creating stronger correlations between soil particles. This resulted in a reduction in collapsibility, as evidenced by the presented results.

Nano clay, with its dominant oxide composition of alumina (Al_2O_3) and silica (SiO_2), is a key player in soil stabilization. Despite not inherently possessing adhesive properties, its fine particles react with calcium hydroxide in the presence of moisture at normal temperatures to form compounds with adhesive and cementitious properties. Furthermore, adding nano clay to the soil would facilitate positive ion exchange reactions involving calcium, aluminum, and iron ions in the nano clay with soil elements, thereby significantly improving collapsible soil. Nano silica, as a highly active pozzolan, significantly enhances the strength of samples through cementation reactions. Reducing silica particles to the nanoscale enhances gradation consistency, decreases voids, and increases strength, durability, and lightweight granulation. Silica plays a crucial role in adhesion and filling processes. The high surface charge of nano-silica particles led to rapid agglomeration, which was evident in SEM images. These particles would accumulate around clay particles due to their high specific surface area, resulting in more compact soil with reduced permeability.

Analyzing the collapsibility potential diagrams for calcium carbonate and aluminum oxide revealed that nano calcium carbonate, due to its higher specific surface area, forms more bonds with soil particles. Consequently, it reduces the collapsibility index more effectively in CL soil from the Allahabad region of Kerman. Conversely, aluminum oxide, despite its higher cation exchange capacity (+3 compared to calcium carbonate), exhibits lower efficacy due to its smaller specific surface area.

4. 2. Effect of Nanomaterials on Shear Parameters

Figures 4 and 5 indicate the internal friction angle (*Φ*) and cohesion (*c*) of control and nano-improved specimens, respectively. After analyzing the results, it is clear that increasing the percentage of nano calcium carbonate in the soil led to a rise in cohesion up to 2%. The results also indicated that the angle of internal friction increased by adding nano calcium carbonate. Specifically, adding 0.5% nano calcium carbonate to the soil resulted in an angle of internal friction of 40 degrees. However, the angle of internal friction decreased by adding nano calcium carbonate up to 2%. The addition of nano aluminum oxide caused a decrease in the internal friction angle of the soil at all percentages compared to unimproved soil. Increasing the amount of nano aluminum oxide led to a further decrease in the angle of internal friction. The results also showed that the cohesion coefficient of the soil increased slightly with the addition of nano aluminum oxide. Furthermore, there was no significant change in the soil's cohesion with an increase in the amount of nano aluminum oxide. Adding 1% nano clay to the soil resulted in a significant increase in cohesion, while adding 1.5% of this nanomaterial decreased cohesion. Overall, there was no clear trend in adhesion changes with the increase in nano clay added to the soil. This lack of trend was also observed in the internal friction angle changes due to the addition of nano clay. For instance, at 1% nano clay content, the internal friction angle reached its lowest level, indicating a lack of clear trend with changes in the percentage of nano clay.

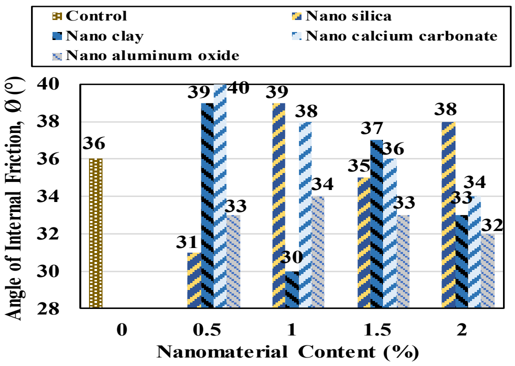


Figure 4. The internal friction angle (Φ) of control and nano-improved specimens

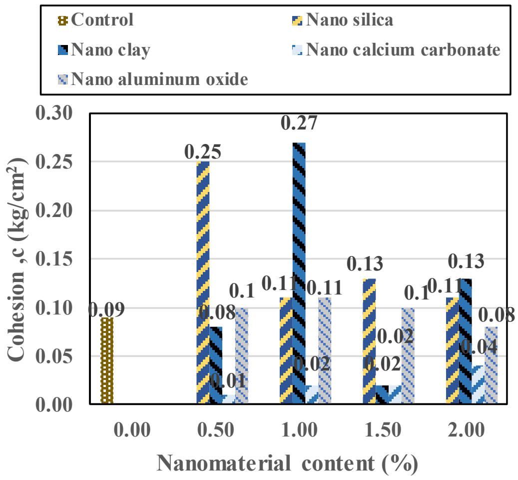


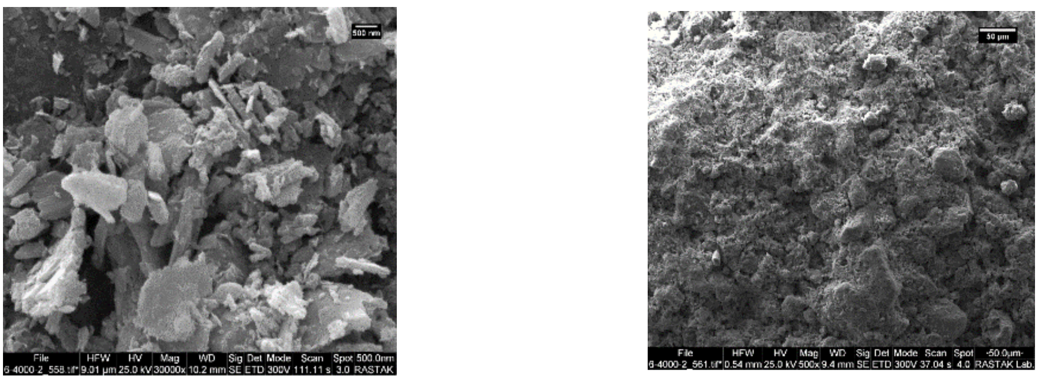
Figure 5. The cohesion (c) of control and nano-improved specimens

The test results showed that adding nano silica to the soil did not significantly affect adhesion or the angle of internal friction. When 0.5 percent of nano silica was added to the soil, there was a noticeable decrease in the angle of internal friction and a corresponding increase in cohesion. When the amount of nano silica was increased to 1% of the soil's weight, the angle of internal friction visibly increased, but adhesion decreased from 0.25 to 0.1 kg/cm^2. Increasing the percentage of nano silica up to 2% of the soil's weight resulted in an increase in cohesion compared to unimproved soil, although the changes observed were relatively small.

4. 4. Microstructural Analysis Using Scanning Electron Microscope (SEM) images

SEM images of control soil and nano-improved specimens are displayed in Figures 6-10 at two scales: 500 nanometers and 50 micrometers.

According to the scanning electron microscope (SEM) analysis shown in Figure 7, the addition of nano clay to the soil led to the disruption of false bonds between soil particles due to its high specific surface area and the supply of essential ions required for the formation of clay minerals. This disruption reduced the soil's pore spaces by breaking down its skeletal structure. As a result, the soil developed a more compact, flaky structure, thereby reducing its collapsibility potential.



a ***b***

Figure 6. SEM images of the studied soil: a) 500 nm scale, b) 50 micrometer scale

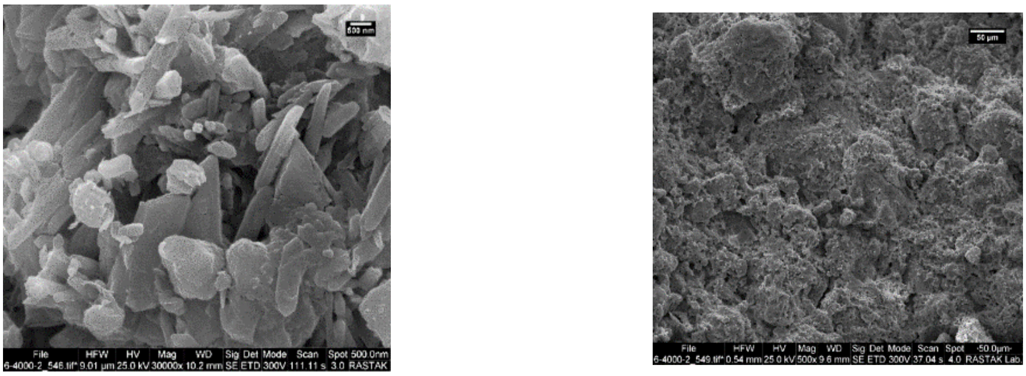


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Figure 7. SEM images of the improved specimen by nano clay: a) 500 nm scale, b) 50 micrometer scale

Similarly, in Figure 8, the interaction between nano silica and soil appeared to create a more integrated structure than the untreated soil sample. These reactions led to the formation of cementitious gels, such as calcium silicate hydrate and calcium aluminate hydrate, along with calcium carbonate. Developing these gels reduced the size of soil pores and, consequently, the overall soil porosity. This process could also increase the clay-additive mixture's strength while blocking or occupying portions of the pore volume. For this reason, nano clay showed a greater reduction in the collapsibility index compared to nano aluminum oxide and nano calcium carbonate.

By comparing the SEM images of calcium carbonate and aluminum oxide additives in Figures 9 and 10, it is evident that at a 1% additive concentration, calcium carbonate, with its larger specific surface area, formed bonds with a greater number of soil particles. This would result in a more significant reduction in the collapsibility index of the soil. On the other hand, while aluminum oxide has a higher cation exchange capacity (+3), making it effective at attracting negative soil ions, its smaller specific surface area results in fewer bonds compared to other additives studied in these experiments.

Comparing the results in Figures 7 to 10 also reveals that nano clay and nano aluminum oxide exhibit a greater ability to induce crystallization and form flaky structures than nano silica and nano calcium carbonate.

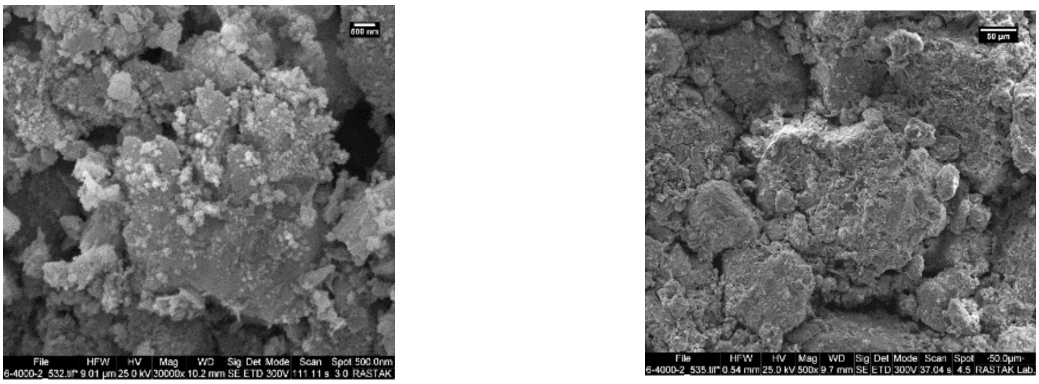

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Figure 8. SEM images of the improved specimen by nano silica: a) 500 nm scale, b) 50 micrometer scale

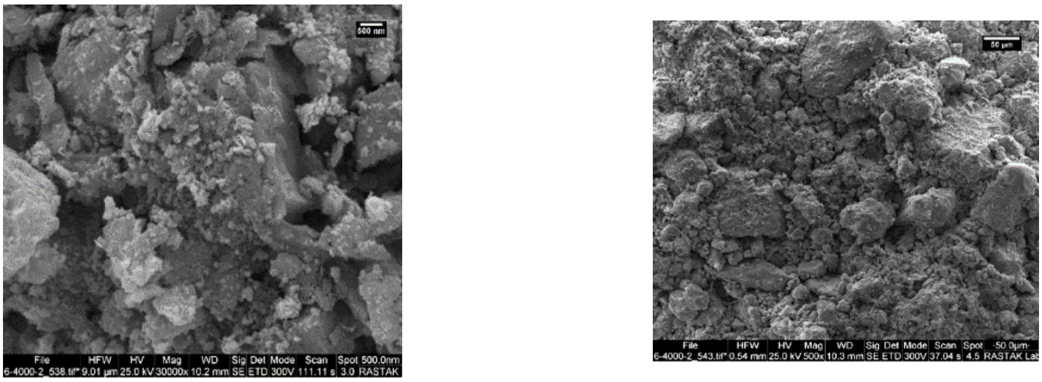

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Figure 9. SEM images of the improved specimen by nano calcium carbonate: a) 500 nm scale, b) 50 micrometer scale

4. 5. Relationship between Soil Collapsibility Potential and Nanomaterials

Figure 11 illustrates the changes in the soil's collapsibility potential after treatment with nanomaterials.

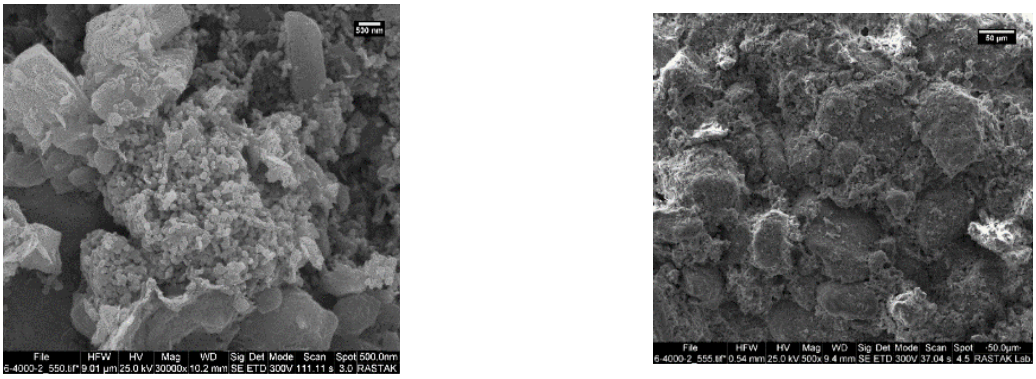

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Figure 10. SEM images of the improved specimen by nano aluminum oxide: a) 500 nm scale, b) 50 micrometer scale

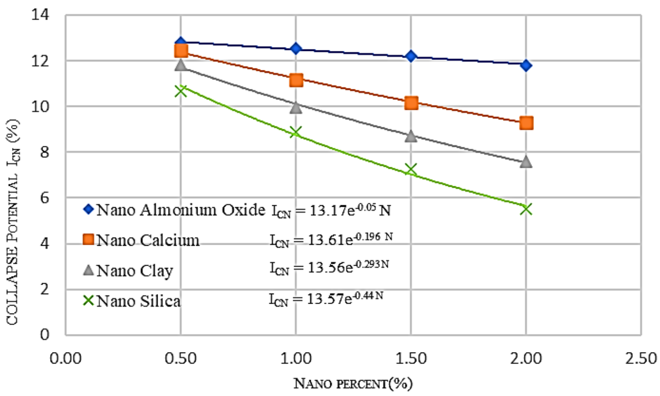

Figure 11. Changes in collapsibility potential based on nanomaterial type

To assess the normalized collapsibility potential, the collapsibility potential of the treated soil, I_{CN} with that of the control sample, I_{CS} were compared. The relationship between the normalized collapsibility and other factors is represented by a set of equations in Figure 12.

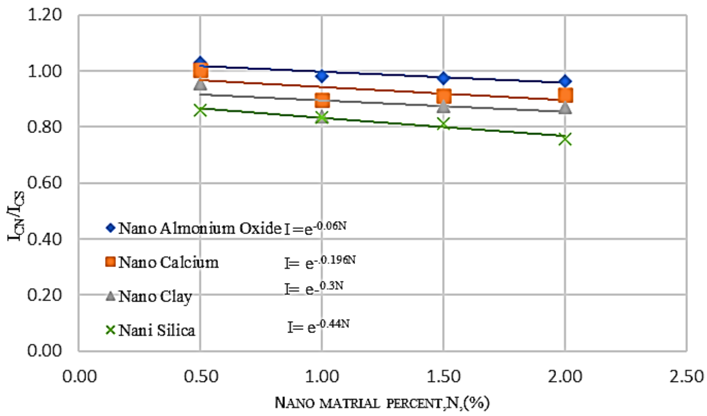

Figure 12. Normalized correlation equations of collapsibility potential changes according to nanomaterial type

In Figure 12, the correlation relationships follow then Equation 2:

$$\boldsymbol{I = e^{-mp'}} \qquad (2)$$

Where I is a normalized collapsible potential and m represents the values related to the type of nanomaterial, as detailed in Table 7.

TABLE 7. The coefficient *m* values related to the type of nanomaterials used in Equation 2

Nanomaterial	m
Nano silica	0.44
Nano clay	0.3
Nano calcium carbonate	0.2
Nano aluminum oxide	0.06

5. CONCLUSIONS

Recent advancements in soil improvement have incorporated nanomaterials alongside traditional methods. This study investigated the effects of four nanomaterials nano silica, nano clay, nano aluminum oxide, and nano calcium carbonate at varying concentrations (0.5% to 2% of soil's weight) on the collapsibility potential, shear strength, and cohesion of a collapsible soil from the Allahabad region in Kerman, Iran. The key findings are summarized as follows:

1. The addition of nanomaterials significantly reduced the soil's collapsibility index. Among these, nano silica exhibited the most pronounced effect due to its low mass density and effective role as a filler, enhancing soil structure and reducing collapsibility potential more efficiently than other additives.
2. Up to 1% by weight, nano clay reduced collapsibility potential more effectively than nano calcium carbonate. However, at higher concentrations (1.5% and 2%), nano calcium carbonate outperformed nano clay in reducing collapsibility.

3. Nano aluminum oxide, while impactful, demonstrated a lower effect on collapsibility reduction compared to the other additives.
4. Higher percentages of nano silica and nano calcium carbonate resulted in greater reductions in collapsibility potential, with the steepest decline observed for these materials. nano silica, at a 2% weight ratio, shifted the soil's collapsibility classification from severe to moderate, highlighting its superior performance.
5. The high Al_2O_3 and SiO_2 content in nano clay enables pozzolanic reactions when combined with calcium hydroxide, forming cementitious compounds that improve soil strength and durability.
6. Nano calcium carbonate's higher specific surface area allowed it to form more bonds with soil particles, reducing the collapsibility index more effectively than nano aluminum oxide, which had a lower surface area despite a higher cation exchange capacity.
7. The interaction of nano silica with soil resulted in the formation of cement-like gels (calcium silicate hydrate, calcium aluminate hydrate, and calcium carbonate), reducing pore sizes and overall porosity while enhancing soil strength.
8. SEM analysis revealed that nano clay and nano aluminum oxide promote greater crystallization and flaky structure formation compared to nano silica and nano calcium carbonate. Nano calcium carbonate formed more bonds with soil particles, further reducing collapsibility.

The findings underscore the potential of nanomaterials to improve collapsible soils significantly, particularly nano silica and nano calcium carbonate. However, these results are specific to soils from the Kerman region in Iran, and additional studies are required to validate their applicability to other types of collapsible soils.

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