Article

Performance Evaluation of Nano-Stabilized Expansive Soils Using Laboratory Testing

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Abstract

Expansive soils are one of the most widely considered problematic soils, characterized by a high montmorillonite content, significant swell-shrink behavior, and severe volumetric changes with moisture variation. These soils cause significant structural damage globally, especially in dry and semi-arid areas. Nanomaterials have been shown to be one of the best and most advanced ways to stabilize soil. This study uses a comprehensive laboratory testing program to examine the effectiveness of nanosilica as a stabilizer for expansive soil. The natural soil had a liquid limit of 56.2% and a plasticity index of 29.9% and was categorized as CH by the USCS and A-7-6 by the AASHTO classification systems. Nanosilica was incorporated at 0.5%, 1.0%, and 1.5% (dry weight) to assess its influence on the physio-mechanical properties of the soil. According to test results, considerable improvement in volumetric stability was observed by adding up to 1.5% nanosilica. The expansion index decreased from 92.5 to 48.5. The engineering properties gradually improved with the addition of nanosilica. According to direct shear testing, cohesion and friction angle increased from 32.3 kPa to 62.8 kPa and from 1.10° to 3.14°, respectively. Similarly, unconfined compressive strength increased from 98 kPa to 141 kPa.

Keywords: Expansive soil, Nanosilica, Soil stabilization.

1. Introduction

The indigenous expansive soils present in the Nandipur region of Gujranwala pose significant geotechnical challenges due to their high swell-shrink potential and low shear strength and volume changes in response to seasonal moisture variations. These undesirable soil behaviors have contributed to frequent structural failures in pavements, shallow foundations, and other civil engineering infrastructure, adversely affecting the safety, functionality, and maintenance costs of local development projects. Expansive soils cause over 15 billion dollars in damage to buildings and infrastructure in the US each year [1].

Traditional soil stabilizing methods employing lime, cement, and fly ash have been employed to mitigate these problems, yet they suffer from some major drawbacks, including excessive carbon emission, high cost, low reactivity, and unreliable performance, particularly in the enhancement of the microstructure of native soils. These limitations necessitate an alternative, more sustainable stabilization system, specifically tailored to the characteristics of expansive soils at Nandipur [2].

Recent advances in nanotechnology have introduced nanosilica, nanoclay, and other nanomaterials as promising soil stabilizers. Nanoparticles for soil stabilization have a size range of 14-36 nanometers, penetrate soil microstructure effectively, fill voids, and enhance particle bonding. Research indicates that nanostabilizers can achieve equal or superior performance at significantly lower dosages (0.5-3% by weight) than traditional additives [3]. Many researchers have demonstrated that nanoparticles serve as effective stabilizing agents of expansive soils, leveraging the high surface area, pozzolanic reactivity, and physicochemical characteristics to achieve substantial soil improvement. For instance, the addition of nanosilica (1.2%) combined with plantain leaf ash (15%) yielded optimal results, increasing compressive strength up to 4.6 times and cohesion, and angle of internal friction up to 3.3 times and 1.6 times, respectively, after 28 days [4]. Similarly, white cement mixed with 2 percent nanosilica significantly improved the soil consistency, shrinkage and expansion indices, and bearing performance [5]. Furthermore, the addition of 3% nanosilica to geopolymer-treated expansive soils led to a 15 percent increase in the unconfined compressive strength due to enhanced bonding and filling properties [6].

Despite these promising findings, the application of nanomaterials in stabilizing expansive soils remains largely unexplored. Therefore, the objectives of this research are to characterize the expansive potential of natural soil and evaluate the effectiveness of nanosilica in stabilizing expansive soil.

2. Materials and Methods

2.1. Material

2.1.1. Soil

The indigenous expansive soil used in this investigation was obtained from the Nandipur region of Gujranwala, Punjab. Soil samples were collected from a depth of 1 m below the natural ground surface to ensure representative specimens. Preliminary characterization classified the soil as CH (high plasticity clay) per USCS and A-7-6 per AASHTO, with liquid limit (LL) of 56.2%, plastic limit (PL) of 26.3%, and plasticity index (PI) of 29.9%, confirming high expansiveness [7]. Expansive soil possesses adequate shear strength in dry form but experiences significant loss in shear strength and marked swelling when it comes into contact with water. Untreated soil properties are listed in Table 1.

Figure 1. Natural Soil

Table 1. Natural soil properties.

Test	**Standard**	**Value**
Liquid Limit	ASTM D4318	56.2%
Plastic Limit	ASTM D4318	26.3%
Plasticity Index	ASTM D4318	29.9%
Grain Size Distribution	ASTM D6913	CH (Sandy Fat Clay) USCS A-7-6 (Clayey Soil) AASHTO
Maximum Dry Density	ASTM D698	1.63 g/cm^3
Optimum Moisture Content	ASTM D698	14.8%
Specific Gravity	ASTM D854	2.713

2.1.2. Nanosilica

The nanosilica utilized in this investigation was sourced from commercial suppliers. Nanosilica is manufactured from rice husk waste through thermal and mechanical processing. This nanosilica serves as the primary stabilizing agent for the treatment of expansive soils. The product specifications are listed in Table 2.

Figure 2. Nanosilica

Table 2. Nanosilica properties.

Description	**Formula**	**Results**
Chemical formula		Sio$_2$ nH$_2$O
Original particle size	nm	14-36
Grain size distribution	nm	≤120-180
Bulk density	g/cm^3	0.1-0.15

2.2. Methods

A comprehensive experimental program comprising standard geotechnical characterization and mechanical testing on untreated and nanosilica-treated soil specimens was conducted to evaluate the efficiency of stabilization. Index property tests, including grain size distribution analysis (ASTM D6913), Atterberg limits determination (ASTM D4318), and standard proctor test (ASTM D698), were performed to establish the optimum moisture content and maximum dry density. These tests were conducted on untreated soil and on specimens stabilized with nanosilica at 0.5%, 1.0%, and 1.5% by dry weight of soil. The index property testing provided fundamental soil characterization and quantified the influence of nanosilica on classification parameters.

The expansion potential of the soil was evaluated through the expansion index test (ASTM D4829), conducted on both untreated and nanosilica-treated specimens under specified surcharge loads. The nanosilica treated soil specimens were subjected to a 24-hour curing period under controlled laboratory conditions prior to testing to allow for initial pozzolanic reactions and soil-stabilizer interaction. Shear strength parameters, including cohesion (c) and angle of internal friction (φ), were determined through a direct shear test (ASTM D3080) performed on untreated and stabilized specimens. Furthermore, unconfined compressive strength testing (ASTM D2166) was performed to determine the axial compressive strength and analyze the extent of strength improvement made by the use of nanosilica. Collectively, these mechanical tests provided a systematic evaluation of the improvements in engineering properties attributable to nanosilica treatment.

3. Results

This section demonstrates the geotechnical properties of the natural soil tested with 0%, 0.5%, 1.0%, 1.5% nanosilica.

3.1. Atterberg Limit Test

The Atterberg limits tests conducted on natural soil and nanosilica-treated specimens (0.5%, 1.0%, and 1.5% by dry weight) revealed significant changes in the soil's consistency parameters. The natural soil exhibited a liquid limit of 56.2%, plastic limit of 26.3%, and plasticity index of 29.9%, confirming its highly expansive nature [7]. With the incorporation of nanosilica contents of 0.5%, 1.0%, and 1.5% by dry weight, the measured LL values are 52.8%, 49.6%, and 47.4%, respectively, while the corresponding PL values are 28.7%, 30.6%, and 32.8%.

The resulting PI values decrease progressively from 29.9% for untreated soil to 24.1%, 19.0%, and 14.6% at 0.5%, 1.0%, and 1.5%, respectively, indicating a transition from highly expansive behavior towards low expansive behavior at 1.5% nanosilica content [7].

This decreasing trend in liquid limit is due to the small particle size of nanosilica filling intergranular spaces and reducing the water required to reach the liquid state.

Conversely, the plastic limit exhibited an increasing trend with nanosilica addition. This behavior can be attributed to the pozzolanic reactions between nanosilica and clay minerals, which alter the electrical double-layer structure and modify water holding capacity at the plastic state. The combined effect of decreasing liquid limit and increasing plastic limit resulted in a substantial reduction in plasticity index, transforming the soil from highly expansive to low expansive [7]. The effect of nanosilica on Atterberg limits is shown in Figure 3.

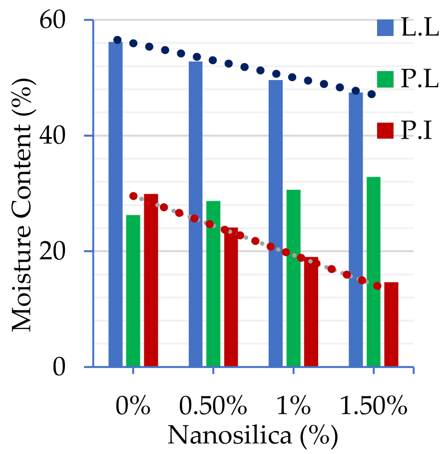

Figure 3. Effect of nanosilica on Atterberg Limit

3.2. Expansion Index Test

The expansion index test (ASTM D4829) revealed the natural soil's expansion index of 92.5, classifying it as having very high expansion potential. The value of the expansion index decreased progressively to 71.5, 60.5, and 48.5 at 0.5%, 1.0%, and 1.5% nanosilica content, respectively. The incorporation of nanosilica demonstrated remarkable effectiveness in mitigating the expansive nature of soil. The optimal percentage of 1.5% nanosilica successfully reduced the expansion potential from "very high" to "low" category.

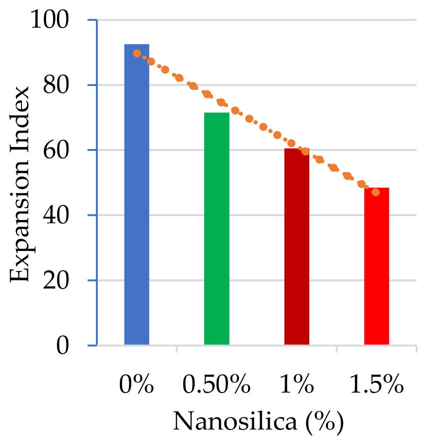

Figure 4. Effect of nanosilica on Expansion Index

3.3. Direct Shear Test

The direct shear test results revealed substantial improvements in both cohesion and internal friction angle with increasing nanosilica content, directly translating to enhanced shear strength characteristics. For the natural soil, cohesion is 32.30 kPa with a friction angle of 1.10°. With the addition of 0.5% nanosilica, cohesion increased to 43.21 kPa and the friction angle to 2.20°, followed by further enhancement at 1.0% nanosilica, where cohesion and friction angle reached 50.93 kPa and 2.12°, respectively. At the optimum percentage of 1.5% nanosilica, cohesion attained a maximum value of 62.76 kPa, while the friction angle increased to 3.14°. The progressive increase in cohesion can be attributed to the pozzolanic reaction products (CSH and CAH gels) that create strong bonds between soil particles, effectively cementing the soil matrix. Results are shown in Figure 5.

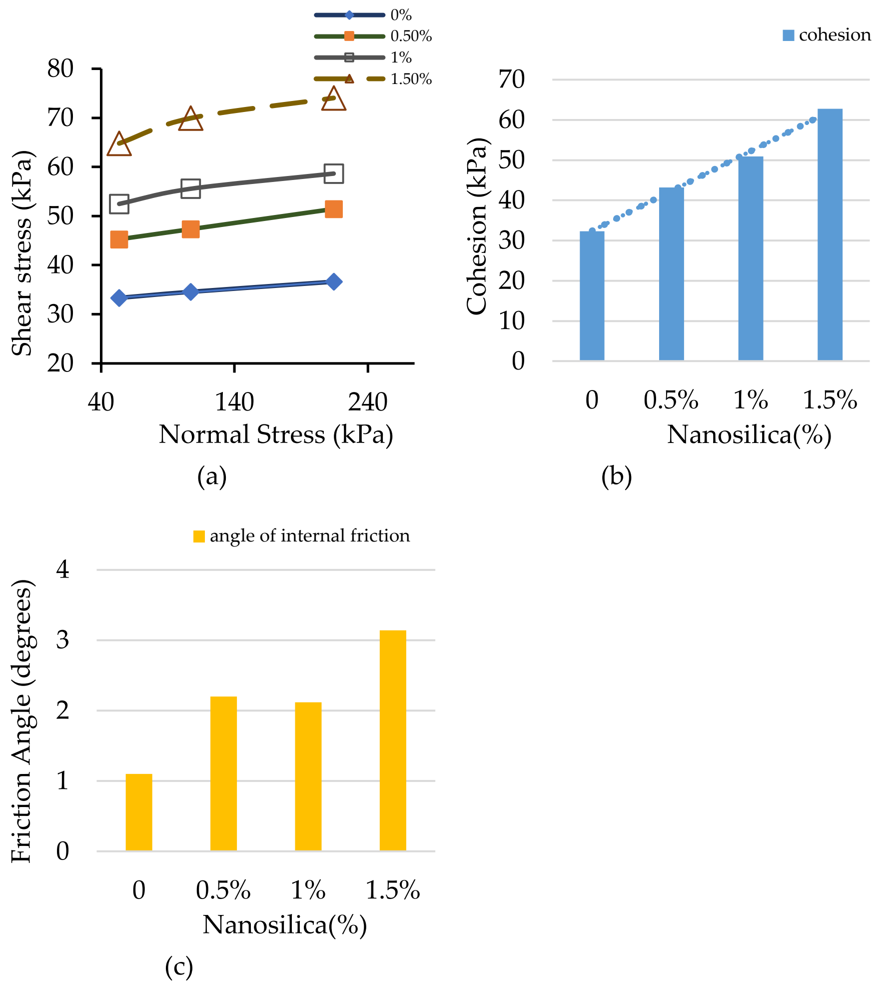

Figure 5. Effect of nanosilica on Shear Strength Parameters

3.4. Unconfined Compressive Strength (UCS) Test

The unconfined compressive strength testing revealed significant improvements in the mechanical behavior of the natural soil upon treatment with nanosilica. For the untreated soil, the UCS value is 98 kPa, which rose to 116 kPa at 0.5% nanosilica. At 1.0% nanosilica, the UCS value further increased to 129 kPa. The maximum UCS of 141 kPa was obtained at 1.5% nanosilica. Results are shown in Figure 6.

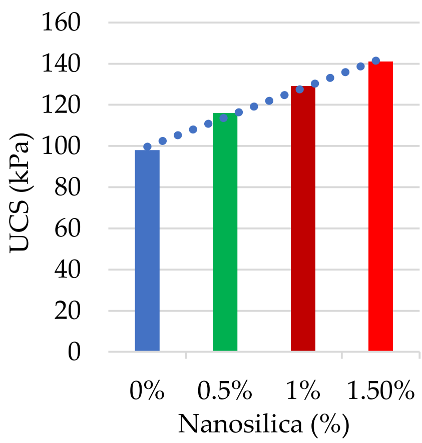

Figure 6. Effect of nanosilica on Unconfined Compressive Strength

4. Discussion

This experimental investigation on the stabilization of Nandipur Sandy Fat Clay using nanosilica has yielded significant findings that contribute to sustainable geotechnical engineering practices:

1. Plasticity Reduction: Nanosilica effectively reduced the plasticity index by 51% at 1.5% nanosilica, transforming the soil from highly expansive to low expansive, consistent with observations by previous studies [4-5, 7].
2. Swelling Mitigation: The expansion index decreased dramatically by 47.6% at 1.5% nanosilica. This represents a transition in expansion potential from a very high to a low category. This outcome corroborates similar patterns documented in prior investigations [5].
3. Strength Enhancement: Shear strength parameters showed remarkable improvements, with cohesion increasing by 94% and internal friction angle rising by 185% at 1.5% nanosilica content. These improvements align with the trends observed in previous research [3].
4. Improved load-bearing capacity: The unconfined compressive strength increased by 43.9% for 1.5% nanosilica, showing material effectiveness. These strength gains support findings from earlier studies [6].

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