Stabilization of soft-soils with nano-aluminiumoxide

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Abstract—**This study investigates the stabilization of soft soils using nano-aluminium oxide (nano-Al₂O₃) as an innovative additive to enhance geotechnical properties. Soft soils typically exhibit low strength, high compressibility, and poor load-bearing capacity, posing challenges for construction and infrastructure development. The incorporation of nano-aluminium oxide aims to improve soil stability by promoting particle bonding, reducing permeability, and increasing shear strength. Laboratory tests were conducted to evaluate the effects of varying nano-Al2O3 concentrations on key parameters such as unconfined compressive strength, Atterberg limits, and consolidation characteristics. Results demonstrate significant improvements in soil strength and stiffness, with optimal nano-Al2O3 content yielding enhanced durability and reduced settlement potential. The findings suggest that nano-aluminium oxide is a promising stabilizing agent for soft soils, offering an effective and sustainable solution for ground improvement in geotechnical engineering applications.**

Index Terms—**Nano-aluminium oxide; soft soil stabilization; geotechnical properties; soil strength enhancement; unconfined compressive strength**

I. INTRODUCTION

Soft soils, characterized by low bearing capacity and high compressibility, present significant challenges in construction and infrastructure development (Tavakolipour, 2021). Traditional stabilization methods often involve the use of conventional additives like cement or lime, but these can be associated with environmental drawbacks and may not always provide optimal long-term performance for highly problematic soils (Aswad et al., 2023). Nanomaterials, particularly nano-aluminum oxide, have emerged as a promising alternative, offering enhanced stabilization due to their high specific surface area and reactivity (Siddiki, 2020; Wong et al., 2020). This advanced material improves soil properties by reducing the liquid limit, plastic limit, and plasticity index, while simultaneously increasing the maximum dry density, making the soil more suitable for construction applications (Siddiki, 2020). The addition of nano-alumina has been shown to decrease the crack intensity factor for high plasticity soils, with an optimal concentration around 0.1%, and concurrently reduces hydraulic conductivity, which is beneficial for applications like landfill liners and caps (Taha, 2018). Furthermore, the fine particle size of nano-alumina allows it to diffuse between larger soil particles, effectively minimizing pores and thereby decreasing the flow of water through the soil mixtures (Taha, 2018). This unique characteristic enables nano-alumina to significantly enhance geotechnical properties, thereby improving the overall stability and performance of soft soils for various engineering applications (Kulanthaivel et al., 2020). This improvement is particularly evident in the reduction of swell and creep strains in compacted residual soils, further highlighting the efficacy of nanomaterial-based stabilization techniques (Niroumand et al., 2023). Moreover, nanomaterials like nano-clay and nano-alumina effectively decrease soil shrinkage while simultaneously reducing hydraulic conductivity, making them suitable for waste containment systems (Taha, 2018). The incorporation of nanomaterials, such as nano-magnesium oxide, has also been shown to significantly improve the compressibility and unconfined compressive strength of silty clay, offering a more sustainable approach to soil

enhancement compared to conventional materials (Sadiq et al., 2023).

The application of nanomaterials in soil stabilization presents several advantages, including minimal subsurface disturbance and environmental friendliness compared to traditional grouting techniques (Sadiq et al., 2023). This approach allows for targeted improvements in soil mechanical properties through nanoscale interactions, offering a more efficient and effective stabilization method (Adnan et al., 2023). For example, nano-alumina has been shown to enhance the strength properties and decrease both the plasticity index and swelling potential of clay soils (Sharo et al., 2022).

Likewise, nanomaterials such as nano-lime and nano-magnesium oxide have demonstrated capabilities to enhance unconfined compressive strength and maximum dry density while reducing the plasticity index and linear shrinkage (Majeed et al., 2014). Additionally, nanosilica has been found to inhibit clay swelling and improve the compaction, hydraulic conductivity, and compressive strength of residual soil (Li et al., 2024). These materials also interact actively with soil particles and solutions, allowing even minute quantities to significantly influence the physical and chemical properties of the soil (Majeed et al., 2014). The addition of nanomaterials, even at low concentrations, can significantly enhance the geotechnical properties of soft soils (Majeed et al., 2014). This study aims to further elucidate the mechanisms through which nano-Al_2O_3 influences the geotechnical properties of soft soils, specifically focusing on its impact on swelling potential and shear strength.

II. MATERIALS AND CHARACTERIZATION

2.1 Soil Samples

The soil samples utilized in this study were gathered from a location in proximity to ABR College, Kanigiri City, India. The clayey soil sample, designated as S1, was collected from a depth of 1 meter below ground level. The characteristics of these soils render them unsuitable for construction due to the excessive softness of the layers. The geotechnical properties of the collected sample are presented in Table 1. The complete soil sample was subjected to oven drying at a temperature of 100 °C and subsequently pulverized to facilitate the execution of various soil tests. The proportion of silt, clay, and organic matter present in the collected soil samples, along with their corresponding soil classification, is detailed in Table 1 in accordance with IS standards.

Table 1 The geotechnical properties of the collected silty and clayey soils

Properties	S1	Properties	S1
Specific gravity G	2.57	Plasticity index (PI)	21
Silt (%)	47	MDD (kN/m^3)	19.79
Clay (%)	45	UCS (kN/m^2)	87
Organic content (%)	8	CBR (%)	4.5
FSI	15	k (cm/s)	5.91×10^{-4}
OMC (%)	11.8	Final settlement (mm)	4.8
Liquid limit (%)	46	IS soil classification	CI

**FSI Free swell index*, OMC* optimum moisture content, *MDD* maximum dry density

The specimens S1 is categorized as Intermediate compressible clay (CI). This classification is based on the UCS values of the collected soil samples and the consistency of those samples. S1 soil is characterized as soft owing to its 8% organic content. The CBR values of the gathered soil samples indicate that the soil quality for subgrade performance is consistently inadequate, regardless of the sample analyzed. The gathered soil samples generally exhibited low permeability values, and the ultimate settling of the soil samples is shown in Table 1. The settling, compressibility, and poor compressive strength of the obtained soil samples indicate that they are weak and need stabilization.

2.2 Aluminium Oxide Nanopowder:

The Aluminium Oxide Nanopowder (Nano-Al_2O_3) used in this study was purchased from the local

market of Saveer Martixnano Pvt Ltd. Bangalore (see Fig. 1). It is creamish in color and amorphous in nature. The particle size of this Nano-Al_2O_3 is less than 100 nm (Al2O3, Purity: 99%, APS: <100 nm)

Stock No: SMN/54/110, CAS: 1309-48-4. The oxide chemical composition of the Nano-Al_2O_3 is shown in Table 2.

Table 2. Chemical Composition of Nano-Al_2O_3

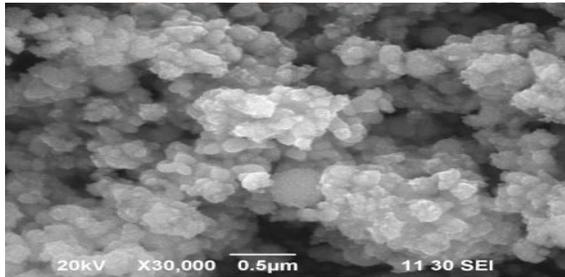| S.No.	Element	Concentration
1	Al2O3	99%
2	Ca	0.1%
3	Fe	0.15%
4	Si	0.1%
5	Al	0.0754%
6	Mn	0.324%
7	Others	<5000 ppm

Fig.1 SEM Analysis of Aluminium Oxide Nanopowder

III. METHODS

3.1 Sample Preparation:All obtained soil samples were combined with Nano-Al_2O_3 in dry powder form at varied percentages of 1%, 2%, 3%, 4%, and 5% based on the dry weight of the soil. Following comprehensive mixing under arid circumstances, the samples were introduced to distilled water and mixed once more to achieve a homogenous combination. The Nano-Al_2O_3 mixed soil samples were used for further analyses, including compaction testing, permeability testing, unconfined compressive strength testing, and consolidation testing. The lowest and maximum dose range of Nano-Al_2O_3 for each soil sample was determined by the trial and error approach in the laboratory, depending on its workability. The example photographs depicting the processing of soil samples for the UCS test.

3.2 Experimental Investigation
The soil samples were prepared in accordance with IS 2720 (Part I)—1983. The soil categorization of

samples was determined according to IS 1498 (1970). The liquid limit and plastic limit were determined in accordance with IS: 2720 (Part V)—1985. The light compaction test, unconfined compression strength test, and California Bearing Ratio test were conducted in accordance with IS: 2720 (Part VII)—1980, IS: 2720 (Part II)—1973, and IS: 2720 (Part XVI)—1987. IS 2720 (Part XVII)—1986 was used to ascertain the coefficient of permeability for both untreated and Nano-Al_2O_3-treated soil samples. The wetting and drying test of the soil, both with and without nanomaterial, was conducted according to the guidelines specified in IS: 4332 (Part IV)—1968.

IV. RESULTS AND DISCUSSIONS

4.1 Determination of Optimum Dosage of Nano-Al_2O_3 for the Stabilization of Collected Soil Sample:
The ideal quantity of Nano-Al_2O_3 in soil is contingent upon compaction characteristics (maximum dry density and optimum moisture content), unconfined compressive strength, and California bearing ratio values. The aforementioned geotechnical tests were conducted on the prepared untreated and Nano-Al_2O_3-treated soil samples in the laboratory, with results shown in Table 3. The Nano-Al_2O_3-treated soil combination exhibiting the greatest UCS value was selected as the optimal dose for each soil sample. The test findings indicate the optimal dose of Nano-Al_2O_3 for the soil samples (S1). The amount of Nano-Al_2O_3 necessary for stabilizing clayey soil is determined by a lower void ratio in the soil samples.
The typical Proctor compaction test was conducted on all six soil samples with the incorporation of

Nano-Al_2O_3 in varying percentages from 1% to 5%. Table 3 indicates that the maximum dry density increases with the percentage of Nano-Al_2O_3 up to the optimal concentration, regardless of the untreated silt and clay soil samples.

Table 3 Optimum dosages of Nano-Al_2O_3 from compaction, UCS and CBR test results

soil	Nano Al2O3 (%)	OMC (%)	MDD (kN/m^3)	UCS (kN/m^2)	CBR (%)
S1	0	11.8	19.79	87	4.5
	1	12.7	18.20	169	5.5
	2	13.9	19.94	245	7.5
	3	14.5	21.09	355	9.5
	4	14.9	20.35	325	8.9
	5	15.1	20.13	319	8.5

The maximum dry density (MDD) rose to about 21.09 kN/m³ with the addition of 3% Nano-Al_2O_3 to the clayey sample. The percentage increase in MDD for clay samples is smaller compared to the rise seen with the addition of Nano-Al_2O_3. Clay soil, owing to its compact and dense characteristics, may have a less subdued reaction to the addition of Nano-Al_2O_3, leading to a less significant enhancement in maximum dry density compared to the more porous and loose structure. An additional 3% of Nano-Al_2O_3 seems to enhance the optimum moisture content and maximum dry density.

4.2 Unconfined Compression Strength Test and CBR Test

The Nano-Al_2O_3-treated soil specimens were prepared for the Unconfined Compressive Strength (UCS) test and the California Bearing Ratio (CBR) test at their respective Maximum Dry Density (MDD) and Optimum Moisture Content (O.M.C), along with the test results. The UCS test findings indicate that the highest UCS for S1 reached 355 kN/m², compared to 87 kN/m² for the untreated sample, after the incorporation of 3% Nano-Al_2O_3. The test findings indicate that the incorporation of Nano-Al_2O_3 into the collected soil sample at optimal levels enhanced the UCS strength by creating robust connections and generating a CSH gel, which effectively tightens the connection between soil particles and reduces the amount of nanovoids. Nano-Al_2O_3 enhances pozzolanic activity and increases the binding strength of soil particles. It imparts optimal strength to the soils after stabilization with Nano-Al_2O_3.

Researchers observed that incorporating 3% Nano-Al_2O_3 into sandy clay of moderate plasticity enhanced the unconfined compressive strength by a factor of 4.08 relative to its original value. The substantial surface area of Nano-Al_2O_3 facilitated its reaction with the soil sample, hence enhancing the soil's strength.

4.3 Permeability and Consolidation Test

The falling head permeability test was used to assess the permeability of untreated and Nano-Al_2O_3-treated soil samples. It was noted that there was an absence of water movement in the standpipe of the permeability apparatus during the execution of the falling head permeability test. The production of Nano-Al_2O_3 gels in vacuum spaces is responsible for impeding water transport, hence reducing soil permeability. The influence of Nano-Al_2O_3 on the hydraulic characteristics of kaolinite was examined, revealing a reduction in the coefficient of permeability from around 10–4 to negligible cm/s, indicating a virtually impermeable condition consistent with the findings of the current investigation.

A consolidation test was conducted on soil samples before to and after treatment with Nano-Al_2O_3. The test findings indicate that, like to previous experiments, the ultimate settling value of the soil sample decreased in comparison to the untreated soil samples at their optimal dose.

V. CONCLUSIONS

The study investigated the effect of Nano-Al_2O_3 on various silt and clay samples and came to the following conclusion based on geotechnical factors and Nano-Al_2O_3 stabilization. Intermediate compressible clay (CI) specimen S1. Nano-Al_2O_3

(99% purity, APS <100 nm) is listed as less than 100 nm. All soil samples were mixed with dry powder Nano-Al_2O_3 at 1%, 2%, 3%, 4%, and 5% by dry weight.

The addition of 3% Nano-Al_2O_3 to the clayey sample increased the maximum dry density (MDD) to 21.09 kN/m³. With Nano-Al_2O_3, MDD increases more than with clay samples. Clay soil, which is compact and solid, may react less strongly to Nano-Al_2O_3, resulting in a lower maximum dry density than porous and loose soil. A 3% increase in Nano-Al_2O_3 improves moisture content and dry density.The Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR) tests were performed on Nano-Al_2O_3-treated soil specimens at their Maximum Dry Density (MDD) and Optimum Moisture Content (O.M.C), along with the test results. After adding 3% Nano-Al_2O_3, the greatest UCS for S1 was 355 kN/m², compared to 87 kN/m² for the untreated sample. The test results showed that optimum Nano-Al_2O_3 absorption into the soil sample increased UCS strength by building strong connections and a CSH gel, which tightens soil particle connections and minimizes nanovoids. Nano-Al_2O_3 boosts soil binding and pozzolanic activity. It gives soils excellent strength following Nano-Al_2O_3 stabilization.

Researchers found that adding 3% Nano-Al_2O_3 to sandy clay with moderate plasticity increased unconfined compressive strength by 4.08. Increased surface area of Nano-Al_2O_3 enhanced soil strength by reacting with the sample. The falling head permeability test assessed untreated and Nano-Al_2O_3-treated soil samples. The falling head permeability test showed no water movement in the permeability equipment standpipe. Nano-Al_2O_3 gels made in vacuums block water movement, limiting soil permeability. Using Nano-Al_2O_3 on kaolinite's hydraulic properties reduced the coefficient of permeability from 10–4 to insignificant cm/s, suggesting a practically impenetrable state compatible with the present study. Pre- and post-Nano-Al_2O_3 soil consolidation tests were performed. As in earlier trials, the soil sample's final settling value reduced compared to untreated soil samples at their maximum dosage.

VI. ACKNOWLEDGEMENTS

VII. DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

VIII. CONFLICT OF INTEREST

The authors have made a declaration that they have no competing interests in having this research published.

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