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Strength Behavior of Soft Soil Treated with Municipal Solid Waste Incineration Ash and Nano Zeolite

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ABSTRACT

Nano-zeolites are crystalline, microporous aluminosilicates with nanometer-sized particles (ranging from 1 to 100 nm), recognized for their high surface area and notable pozzolanic activity. Although the stabilization of soft soils using various waste materials and chemical additives has been widely studied, the combined application of nano-zeolite and municipal solid waste incineration ash (MSWIA) has received little attention. This study introduces a novel, sustainable soil stabilization approach by utilizing MSWIA and nano-zeolite as dual stabilizers for soft soils. MSWIA is a waste material produced by municipal waste incineration plants and is now emerging as a useful material for soil stabilization. A comprehensive experimental program involving direct shear tests and unconfined compression strength (UCS) tests was conducted on soil samples treated with varying percentages of MSWIA (5–20%) and nano-zeolite (0.2–1%) by dry weight of the mix. Treated samples were cured for 1, 7, and 28 days. The results revealed a significant improvement in mechanical properties, with the UCS of soil stabilized with 20% MSWIA and 1% nano-zeolite increasing by 9.2 times at 7 days and 12.7 times at 28 days, as compared to untreated soil. The findings also highlight the positive influence of curing under natural moisture conditions on the strength development of the stabilized soil. SEM analysis showed a denser soil structure and better particle bonding, while EDX confirmed higher levels of Ca, Si, Al, and Fe, indicating pozzolanic activity. This stabilization approach is particularly well-suited for applications such as road subgrades, embankment foundations, and land reclamation.

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1. Introduction

Construction on soft soils presents significant challenges due to their inherently low shear strength and high compressibility, which substantially diminish their load-bearing capacity [1]. Stabilizing these soils is essential to improve their mechanical properties and ensure long-term structural stability. Recently, waste-based stabilizers have become increasingly popular as sustainable and cost-effective solutions [2, 3]. Municipal solid waste (MSW) management remains a critical environmental and economic issue worldwide. With large volumes of MSW generated daily from human activities, sustainable disposal methods are necessary to minimize ecological harm [4]. MSW disposal methods vary depending on factors such as local regulations, infrastructure, environmental considerations, and technological capabilities. Some common methods of MSW disposal are landfilling, incineration, composting, recycling, waste to fuel conversion, bioreactor landfills, pyrolysis, etc [5, 6]. Incineration involves the combustion of MSW at high temperatures in specialized facilities known as waste-to-energy (WTE) plants. The heat generated from incineration can be used to generate electricity or steam for heating purposes [7]. Incineration significantly reduces

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the volume of MSW while generating energy during the process. However, it also results in the production of air pollutants and a residual by-product known as Municipal Solid Waste Incineration Ash (MSWIA) [8, 9]. Apart from incineration, composting is also a process of recovering waste. It is a low-cost, sustainable solution for managing MSW, but only around 6-7% of MSW was recycled using composting [10, 11]. Kumar et al. (2021) investigated the swelling behavior of clayey soil reinforced with geocells and jute fibers. These soils are prone to excessive settling over time and have a limited bearing capacity. The study employed one-dimensional swelling tests using CBR molds to evaluate various mix proportions. Results revealed that incorporating geocells with 0.80% jute fiber content and a fiber length of 40 mm yielded the most effective reduction in swelling potential, achieving a 71.24% decrease in swelling and a 41.10% reduction in swelling pressure compared to untreated soil. However, exceeding this optimal fiber content led to an increase in swelling parameters [12]. Construction on the soft soil is challenging because of its poor shear strength and inclination for deformation. This can lead to structural damage both during construction and years later. The main cause of settlement on soft soil is the building's own weight combined with heavy loads from nearby structures, which can result in uneven settling of the building. Due to these naturally weak and soft soils, pre-construction ground treatment is necessary. Ground improvement techniques (GIT) are often employed to stabilize the soil. Soil stabilization involves enhancing the soil's strength and increasing its capacity to manage moisture by binding soil particles and imparting water resistance [13]. With advancements in nanotechnology, traditional soil improvement methods are being supplemented with the use of nanomaterials. There are many uses for nanotechnology, which works with materials smaller than 100 nm. By adding nanoparticles to the soil, it is possible to affect its atomic and molecular characteristics, including strength, permeability, and resistance. Studies have demonstrated that even small concentrations of nanoparticles can significantly enhance the mechanical properties of soft soils [14]. Due to their large specific surface area and surface charges, nanoparticles can significantly affect soil behavior even at extremely low percentages. Numerous nanomaterials, including nano-alumina, nano-zeolite, and nano-clay, have been studied by the researcher for enhancing the engineering properties of soft soils [15]. For instance, it has been discovered that using nano-alumina enhances compaction properties and lessens expansive stresses and volumetric shrinkage. Likewise, the use of montmorillonite nano-clay increases the liquid limit (LL) and plasticity index (PI) in addition to improving the soil's unconfined compressive strength (UCS) [16]. All things considered, nanomaterials have demonstrated a great deal of promise for enhancing soil strength, permeability, density, and compressibility. This study primarily investigated how different fractions of nano-zeolite influence the strength behavior of soft soil. The findings showed that even in the early stages, adding more nano-zeolite considerably enhanced the soil's UCS, indicating more sample reactivity [17]. In order to support long-term environmental sustainability, the goal of this project is to stabilize layers of soft soil for various geotechnical uses. Numerous studies indicated that nanoparticles have become a promising area of study for enhancing the mechanical properties of weak or soft soils [18]. According to Alsharef et al. [19], the addition of nano-alumina to the weak soil results in the displacement and rearrangement of soil particles. Researchers Singh et al. [20] and Khan et al. [21] have reported comparable findings. Kacha and Shah [22] reviewed the application of nanomaterials in soil stabilization, emphasizing their potential to enhance the engineering properties of in-situ soils. Traditional stabilization techniques, such as the use of lime, fly ash, rice husk ash, cement, and cement kiln dust, have been widely adopted; however, nanotechnology offers an advanced alternative due to the minimal particle size and high reactivity of nanomaterials. Soils treated with nanomaterials, commonly termed as nano-soils, exhibit notable improvements in strength, durability, and other geotechnical characteristics. This study serves as a comprehensive reference for selecting suitable nanomaterials, determining their ideal content, and understanding their impact on soil performance in geotechnical applications. Chaudhary et al. [23] critically examined the influence of nano-additives on selected geotechnical properties of soils, with emphasis on problematic clays. Soft clays, due to their high swelling and shrinkage potential, are prone to uneven settlement, posing risks to structural stability. The use of nano-additives has gained considerable attention in geotechnical research. Various nanomaterials—including nano-silica, nano-lime, and nano-carbons—have been employed to enhance soil behavior. For low-plasticity soils, nano-additive inclusion generally increases dry unit weight and reduces optimum moisture content (OMC), while fine-grained soils tend to show the reverse trend. Nano-additives can make soft soil strong and stable even when used in small amounts, unlike traditional methods that need more material. Up to an optimum level, their incorporation can

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decrease consolidation rates. Harsh et al. [24] explored the application of various nano-compounds in geotechnical engineering. They noted that conventional calcium-based stabilization methods raise carbon emissions, encouraging the adoption of more sustainable nanomaterials. Owing to their extremely small size and large surface area, these materials interact rapidly with soil particles, resulting in improved strength, reduced permeability, and modified plasticity. Firoozi et al. [25] conducted their study on a clayey soil in which different proportions of nano-zeolite (0.0%, 0.1%, 0.3%, 0.5%, 0.7%, 1.0%, 2.0%, and 3.0% of the soil's total dry weight) were simply added. The results of the experiments indicate that different percentages of nano-zeolite can cause different consistency limitations. Arora et al. [26] also investigated the effects of various nanomaterials (i.e., nano MgO, nano CuO, and nano clay) on the engineering properties of poor soils and discovered that as the percentage of nanomaterial increased, dry unit weight increased and consistency limits decreased. On the other hand, it was shown that augmenting the soil with nanomaterials above the optimal threshold decreased its engineering qualities. Karumanchi, M. et al. [27] investigated the impact of nanomaterials on clayey soil's strength characteristics and found that adding different amounts of nano-silica and nano-zeolite raised the soil's shear strength metrics. The study conducted by Mir and Reddy [28, 29] examined the impact of adding nano-gypsum ($CaSO_4 \cdot 2H_2O$) and nano-copper (CuO) in varying proportions (0.5%, 1.0%, 1.5%, and 2.0%) on the behavior and strength of the soil. According to the test findings, the soil's UCS increased with the amount of nanomaterial added. According to the research by A.R. Goodarzi et al. [30], the use of nano-bentonite and nano-zeolite in transportation infrastructure has increased significantly. The study investigated the use of nano-zeolite and nano-bentonite additives to improve fine-grained soil. Similar to this, Mir and Reddy [29] investigated the importance of nano-alumina's impact on stabilizing sandy soils collected from the sites.

The primary objective of this research is to evaluate the geotechnical behavior of soft soil when stabilized with MSWIA and nano-zeolite. Additionally, to determine the optimal proportion of MSWIA and nano zeolite to soil in terms of soil strengthening. In order to fill this research gap, the current research will thoroughly investigate the effects of adding different nano zeolite and MSWIA contents on the geotechnical characteristics of weak soil. In this study, index properties, Atterberg's limits, particle size distribution, specific gravity, and free swell index of collected soft soil samples were investigated in the laboratory. The stabilization of collected soil samples has been done with varying percentages of MSWIA (2.5%, 5%, 10%, 15%, 20%, and 25%) and nano zeolite (0.2%, 0.4%, 0.6%, 0.8%, and 1%) to find out the best suitable combination of soil and admixture in the aspects of soil stabilization. Investigate the effect of adding varying percentages of MSWIA and zeolite nanoparticles on the UCS, shear strength, and other key engineering properties of soft soil.

2. Materials and Methodology

2.1. Soil

Figure 1(a) depicts the location of the soil sampling site. The town of Khukhundoo in the Deoria area, which is situated at 26° 09′ 31″ N latitude and 83° 57′ 18″ E longitude, provided the soft soil samples for this investigation. The soil sample is presented in Figure 1(b). Undisturbed samples were obtained from depths of 0.5 and 0.75 meters to determine the soil in situ characteristics. Many bags of disrupted samples were also gathered, and they were brought to the lab for additional examination of their engineering and physical characteristics. Soil classification tests indicated that the collected sample belongs to the category of low-plasticity clay (CL) as per the Unified Soil Classification System.

2.2. Nano Zeolite

As a chemical addition in this investigation, powdered nano-zeolite ($Na_2Al_2Si_2O_8$) with an excess of 99.9% purity was supplied by Ghughali Maharajganj, India. Particles varied in size from 30 to 50 nm. Nano zeolite is composed mainly of silica (SiO_2) and alumina (Al_2O_3), along with trace elements like sodium, potassium, and calcium, enabling strong ion-exchange and adsorption properties [31]. Figure 1(c) & 1(d) show the materials that are used as a stabilizer, such as MSWIA and nano zeolite. Table 1 shows the physical and chemical composition of nano-zeolite and MSWIA.

Fig. 1(a). Soil site location, **Fig. 1(b).** Soil sample **Fig. 1(c).** MSWIA **Fig. 1(d).** Nano zeolite

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Table 1. Physical and chemical composition of Nano-Zeolite and MSWIA

Properties	Nano zeolite [31, 32]	MSWIA [7]
Molecular formula	$Na_2Al_2Si_2O_8$	-
SiO_2	69.12 (%)	10 %
$Al2O_3$	10.79 (%)	7
$Fe2O_3$	0.73 (%)	1
CaO	4.2 (%)	25
K_2O	1.09 (%)	2
Na_2O	0.84 (%)	-
MgO	0.65 (%)	19
Average grain size	30-50 nm	0.6mm to 4.75mm
Specific surface area (SSA) (m^2/g)	150-200	1-5
Density (g/cm^3)	1.18	1.0
Specific gravity	2.0-2.5	2.13
Appearance	Light brown	Gray
pH	8.1-10.5	11.5

Table 2. Index and physical characterization of MSWIA and natural soil

Sr. No.	Properties	Site Soil Sample	MSWIA
1	Natural moisture content (%)	14.17	23.98
2	Bulk unit weight (kN/m^3)	19.65	16
4	Specific gravity (G)	2.67	2.13
5	% Finer than 75 μm	98.50	3.6
6	Clay (%)	24.92	1.2
7	Silt (%)	74.03	2.4
8	Sand (%)	1.05	96.40
9	Gravel (%)	0	0
10	Liquid limit (%)	40.16	28.50
11	Plastic limit (%)	21.30	NA
12	Shrinkage limit (%)	15.19	21
13	Plasticity index (%)	18.86	NA
14	Classification (USCS)	CL	Medium to Fine Sand
15	Clay mineral	Illite	NA
16	Flow index	8.53	NA
17	Toughness index	2.21	NA
18	Activity	0.75	NA
19	Consistency index, Ic	1.37	NA
21	UCS (kN/m^2)	29.75	44
22	Cohesion c (kN/m^2)	17.58	10
23	Angle of internal friction (degree)	2.36	32
24	OMC (%)	19.56	16
25	MDD (kN/m^3)	17.15	14.43

2.3. Municipal Solid Waste Incinerated Ash (MSWIA)

The MSWIA sample was taken from a waste-to-energy plant, New Delhi. MSWIA is shown in Figure 1(c). The collected MSWIA was first oven-dried at a temperature of 110 ± 5 °C and then sieved using a 4.75-mm IS sieve to remove oversized particles. The processed ash was stored in an airtight container for subsequent testing. The physical and index properties of the MSWIA are presented in Table 2. Grain size distribution was determined using fine sieve analysis following the ASTM D6913/D6913M-17 (2017) standard [33, 34]. The results indicate that the ash predominantly consists of medium to fine-sized sand particles.

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2.4. Testing Methodology and Experimental Program

This study's experimental approach was aimed at examining how MSWIA and nano-zeolite affect the strength characteristics of soft soil. The process included preparing modified soil specimens and performing various laboratory tests to evaluate their geotechnical and mechanical behavior. MSWIA and Zeolite Nanoparticle Mixes: Various percentages of MSWIA (5%, 10%, 15%, and 20% by weight of dry soil) and zeolite nanoparticles (0.2%, 0.4%, 0.6%, 0.8%, and 1% by dry weight of soil) were added to the soil. The soil is uniformly blended with the stabilizing materials at predetermined dosages to achieve a consistent mix. The prepared specimens are then cured under natural moisture conditions for varying periods of 1, 7, and 28 days. A detailed series of laboratory tests—including grain size analysis, Atterberg limits (liquid and plastic), Standard Proctor compaction test for MDD & OMC, UCS, and direct shear tests—is conducted on both untreated and stabilized soil samples to evaluate the impact of MSWIA and nano-zeolite on their geotechnical and strength-related properties.

To examine the compaction behavior of both untreated and treated soil samples, the Standard Proctor Compaction Test is carried out as per ASTM D698 [35]. Each soil blend—containing varying amounts of MSWIA and nano-zeolite—is compacted into a cylindrical mold in three layers, with each layer receiving 25 blows from a 2.5 kg hammer dropped from a height of 30 cm. After compaction, the bulk density is recorded, and the corresponding dry density is calculated. The test is repeated across different moisture contents to generate compaction curves, which are then used to identify the OMC and maximum dry density (MDD).

3. Results and Discussion

3.1. Engineering Properties of Soil and Soil-MSWIA Composite

The results in Table 3 indicate that the incorporation of MSWIA leads to notable changes in the soil's engineering properties. Sand and silt contents increased consistently with MSWIA addition, while clay content decreased from 24.92% in the natural soil to 9.1% at 20% MSWIA, signifying a reduction in fine clay particles. The LL and PI values declined, reflecting reduced plasticity and improved workability. An increase in shrinkage limit and a sharp reduction in free swell index from 42% to 14% indicate enhanced dimensional stability and reduced swelling potential. Furthermore, the OMC increased alongside a decrease in MDD, suggesting a shift in compaction characteristics due to the lighter and more porous nature of MSWIA. These trends collectively highlight the potential of MSWIA in improving the stability and reducing the compressibility of problematic soils. Kumar and Gupta [7] have reported similar findings.

Table 3. Engineering and index properties of soil with varying percentages of MSWIA

Engineering Properties	collected a soil sample	95 S/ 5 MSWIA	90 S/ 10 MSWIA	85 S/ 15 MSWIA	80 S/ 20 MSWIA
Sand (%)	1.05	2.8	3.21	3.7	4.0
Silt (%)	74.03	80.55	83.0	85.55	86.9
Clay (%)	24.92	16.65	13.79	10.75	9.1
LL	40.16	38	36.6	35	32.2
PL	23.2	22.1	20.8	20.1	20.0
PI	16.96	15.9	15.8	14.9	12.2
SL	7.66	9.46	11.4	12.5	13.88
Free swell index (%)	42	34	25	20	14
OMC (%)	16.2	17.4	18.5	19.2	20.45
MDD (gm/cc)	1.74	1.69	1.58	1.54	1.48

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3.2. *Compaction Test for Soil with various percentages of MSWIA and Nano-Zeolite*

Table 4 shows the OMC and MDD values of soil with various percentages of MSWIA and Nano-Zeolite. The combined effect of MSWIA and nano-zeolite on the compaction characteristics of soft soil was evaluated through variations in OMC and MDD. For the 5% MSWI ash mix, OMC values ranged from 17.6% at 0.2% nano-zeolite to 18.3% at 1.0% nano-zeolite, with a corresponding MDD decrease from 1.68 g/cc to 1.61 g/cc. At 10% MSWI ash, OMC increased from 18.65% to 19.05%, while MDD declined from 1.57 g/cc to 1.55 g/cc. The 15% MSWI ash blend exhibited OMC values between 19.20% and 20.00%, with MDD decreasing from 1.54 g/cc to 1.49 g/cc. The highest MSWI ash content (20%) showed OMC increasing from 20.55% to 21.00%, while MDD dropped from 1.47 g/cc to 1.44 g/c.

A consistent trend was observed where increasing the proportion of MSWIA and nano-zeolite resulted in a gradual rise in OMC, accompanied by a reduction in MDD. The increase in OMC is attributed to the high-water absorption and hydration demand of nano-zeolite and MSWIA, while the reduction in MDD results from their lower densities compared to the untreated soil minerals. The results of this test guided the moisture conditioning and compaction of all samples prior to strength testing, ensuring uniformity and accuracy across experimental conditions.

Table 4. OMC & MDD values of Soil with various percentages of MSWIA and nano-Zeolite

Soil Samples		OMC (%)	MDD (gm/cc)
Soil + 5 % MSWIA	0.2% Nano zeolite	17.6	1.68
	0.4% Nano zeolite	17.75	1.66
	0.6% Nano zeolite	17.95	1.66
	0.8% Nano zeolite	18.2	1.62
	1.0% Nano zeolite	18.3	1.61
Soil + 10 % MSWIA	0.2% Nano zeolite	18.65	1.57
	0.4% Nano zeolite	18.7	1.57
	0.6% Nano zeolite	18.9	1.56
	0.8% Nano zeolite	18.95	1.55
	1.0% Nano zeolite	19.05	1.55
Soil + 15 % MSWIA	0.2% Nano zeolite	19.20	1.54
	0.4% Nano zeolite	19.35	1.53
	0.6% Nano zeolite	19.55	1.50
	0.8% Nano zeolite	19.75	1.50
	1.0% Nano zeolite	20	1.49
Soil + 20 % MSWIA	0.2% Nano zeolite	20.55	1.47
	0.4% Nano zeolite	20.55	1.46
	0.6% Nano zeolite	20.65	1.46
	0.8% Nano zeolite	20.70	1.45
	1.0% Nano zeolite	21	1.44

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3.3. Impact the Strength of Soil with MSWIA and Nano-Zeolite

In geotechnical engineering, strength parameters are essential for evaluating soil performance. Thus, this study examines the influence of MSWIA and nano-zeolite on soft soil stabilization through UCS and direct shear tests.

3.3.1. Unconfined Compressive Strength (UCS) Test

The UCS test serves as a standard method to evaluate the load-bearing capacity of untreated and stabilized soils. In this study, the UCS test is performed to examine the effect of incorporating MSWIA and nano-zeolite on the strength behavior of soft soil. As per ASTM D2166 [36], the UCS test is employed to assess the compressive strength of cohesive soils without applying lateral confinement. The UCS (qu) was determined using the following equation:

$$UCS\ (q_u) = P/A$$

P = Maximum axial load at failure (N)

A = Cross-sectional area of the specimen (mm^2).

UCS increases with curing time due to continued hydration and pozzolanic reactions. At 28 days, the treated soil achieves maximum strength improvement. Compare the curves for untreated soil and soil treated with varying dosages of MSWIA and nano-zeolite. Figure 2(a) to 2(e) illustrates a consistent improvement in UCS for soft soil treated with various combinations of MSWIA and nano-zeolite. For instance, after 28 days of curing, UCS increases up to 17–20 times compared to untreated soil. According to the test results, 1-day UCS values of 56 kPa, 67.5 kPa, 81 kPa, and 101 kPa were obtained for additions of 5%, 10%, 15%, and 20% MSWIA by dry weight of soil, respectively. The UCS value of stabilized samples with 20% MSWIA was 3.5 and 3.9 times that of untreated soil after 7 and 28 days of curing, respectively. MSWIA improves soil strength due to pozzolanic reactions, which bind soil particles and form cementitious compounds (e.g., calcium silicate hydrate). Increasing the proportion of MSWIA enhances strength, but excessive addition of MSWIA can lead to environmental concerns, particularly regarding leaching behavior. High proportions of MSWIA can increase the soil's pH (up to 11–12), creating a highly alkaline environment that may accelerate the mobilization of certain heavy metals like arsenic.

These findings suggest that adding MSWIA to soft soil improves its strength. But if the increased strength is not sufficient, then the strength has been found to increase by adding a sufficient amount of nano zeolite in soft soil. Nano-zeolite accelerates pozzolanic reactions due to its high specific surface area, improving UCS significantly. Strength improvement is particularly notable at lower dosages (0.2% to 1% nano-zeolite). Combining MSWIA with nano-zeolite results in higher UCS values compared to using either material alone, especially after 7 and 28 days of curing. After curing the samples of soil with 20% MSWIA and 1% nano zeolite, the soil strength obtained increased from 300 to 402 KPa after curing the sample from 1 day to 28 days. It indicates that curing enhanced the composite soil strength by approximately 34%. Soil treated with 20% MSWIA and 1% nano-zeolite may show a 12.7 times increase in UCS compared to untreated soil. While Shahriar Kian et al. [37] demonstrated the effectiveness of zeolite in improving the strength and behavior of cement-stabilized soils, the present study similarly explores the role of zeolite in enhancing the performance of soil mixed with MSWIA, showing comparable improvements in strength and stabilization behavior.

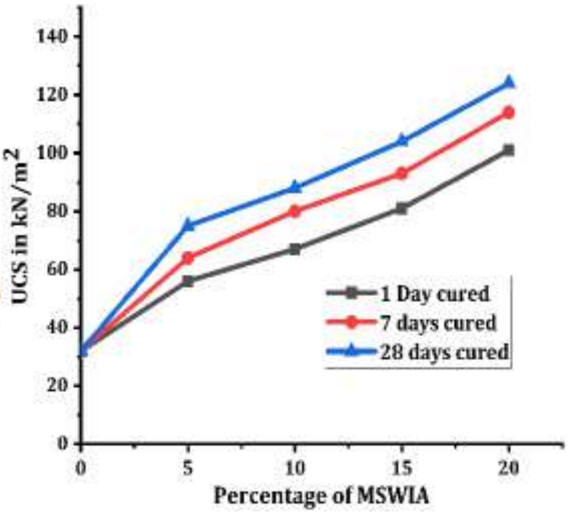

Fig. 2(a). UCS value of soil with different % of MSWIA

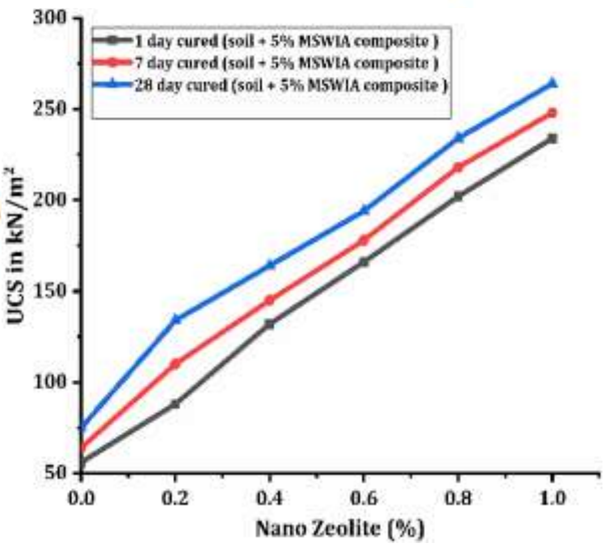

Fig. 2(b). UCS value of soil+ 5% MSWIA composite with different proportions of nano zeolite

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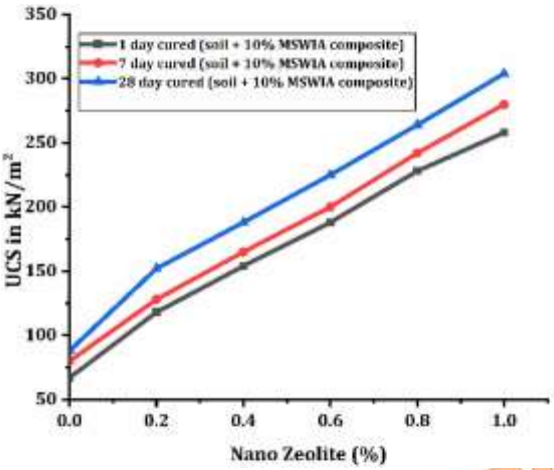

Fig. 2(c). UCS value of soil + 10% MSWIA composite with different proportions of nano zeolite

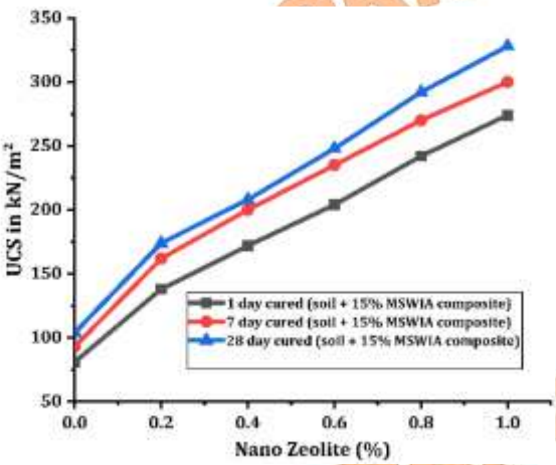

Fig. 2(d). UCS value of soil + 15% MSWIA composite with different proportions of nano zeolite

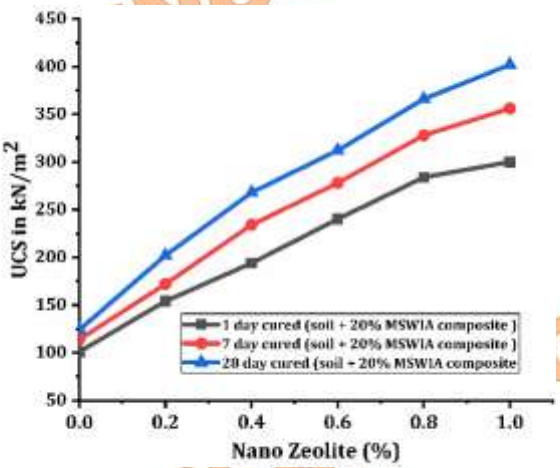

Fig. 2(e). UCS value of soil + 20% MSWIA composite with different proportions of nano zeolite

3.3.2. Direct Shear Test

The direct shear test has been done according to ASTM D3080:1981 [38]. Figure 3 presents the direct shear test results for soils stabilized with varying MSWIA contents and a fixed 1% nano-zeolite by dry weight. The graph illustrates the relationship between normal stress and shear stress for mixtures containing 0%, 5%, 10%, 15%, 20%, and 25% MSWIA.

In the figure, it is evident that both shear strength and normal stress increase consistently with higher MSWIA content. The untreated soil (0% MSWIA with 1% nano-zeolite) exhibits the lowest shear strength, while the sample with 25% MSWIA and 1% nano-zeolite shows the highest shear strength. This enhancement in shear strength can be attributed to the pozzolanic reactions between the calcium- and silica-rich MSWIA and the reactive components of the soil and nano-zeolite. The results clearly indicate that as the percentage of MSWIA increases, the cohesion and internal friction angle of the treated soil also improve, contributing to a steeper and more robust shear strength envelope. However, incorporating 25% MSWIA into the soil resulted in a reduction in shear strength, indicating that the optimal shear strength is attained with a combination of 20% MSWIA and 1% nano-zeolite.

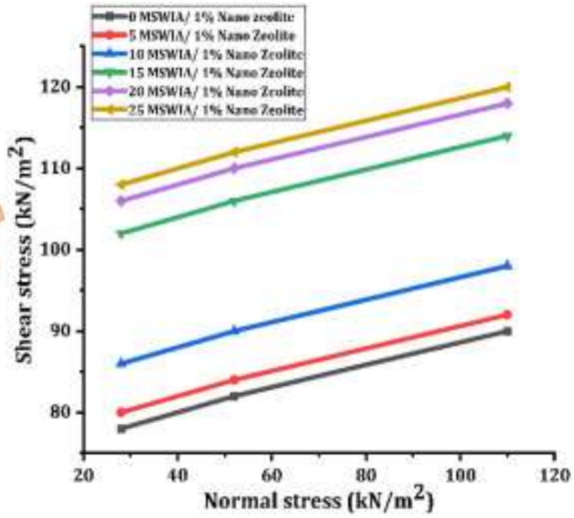

Fig. 3. Direct shear failure envelope of the soil and soil-ash-Zeolite composite

3.4. Microstructural characteristics

3.4.1. Scanning Electron Microscopy (SEM)

The SEM images of clay soil stabilized with 20% MSWIA and 1% nano-zeolite reveal significant microstructural changes contributing to improved soil properties. Figure 4(a) shows tubular formations indicative of C–S–H gel and other hydration products, suggesting active pozzolanic reactions between the MSWIA, nano-zeolite, and the clay matrix. These structures fill the pores and initiate bonding within the soil.

Microstructural characteristics observed in this study are comparable to those reported by Ali et al. [39], who investigated soft soil stabilization using zeolite nanoparticles. However, while their study focused primarily on the role of zeolite alone, the present work

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integrates both MSWIA and nano zeolite, resulting in a more heterogeneous but denser matrix. The addition of MSWIA not only introduces supplementary silicates and aluminates but also enhances the overall matrix cohesion observed under SEM.

Fig. 4 (a). SEM images of the soil sample treated with MSWIA and nano zeolite

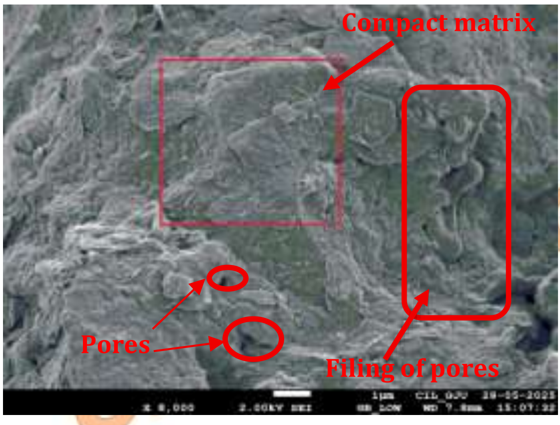

Fig. 4 (b). SEM images of the soil sample treated with MSWIA and nano zeolite

Figure 4(b) displays a denser and more compact matrix with fewer visible pores, indicating the formation of stable reaction products and enhanced particle packing. The combined effect of MSWIA and nano-zeolite results in reduced porosity, improved binding, and a more cohesive microstructure, which are critical for enhancing the strength and durability of stabilized clay soils.

3.4.2. Energy Dispersive X-ray Spectroscopy (EDX)

Figures 5(a) and 5(b) illustrate the EDX spectra for untreated soil and soil treated with 20% MSWIA and 1% nano-zeolite. The EDX spectrum illustrates the elemental composition of the soil sample treated with MSWIA and nano-zeolite. Prominent peaks corresponding to silicon (Si), aluminum (Al), calcium (Ca), and iron (Fe) are observed, indicating their significant presence within the matrix. These elements play a key role in the formation of cementitious products such as C–S–H (calcium silicate hydrate) and C–A–H (calcium aluminate hydrate), which contribute to improved strength and stability. Minor elements, including magnesium (Mg), sodium (Na), potassium (K), zinc (Zn), cadmium (Cd), and palladium (Pd), are also detected, suggesting the complex chemical interactions during the stabilization process. The spectrum confirms the successful incorporation of active minerals and supports the enhancement of geotechnical properties in the treated soil [40]. These elements, contributed by both MSWIA and nano-zeolite, interact within the soil system to initiate pozzolanic activity.

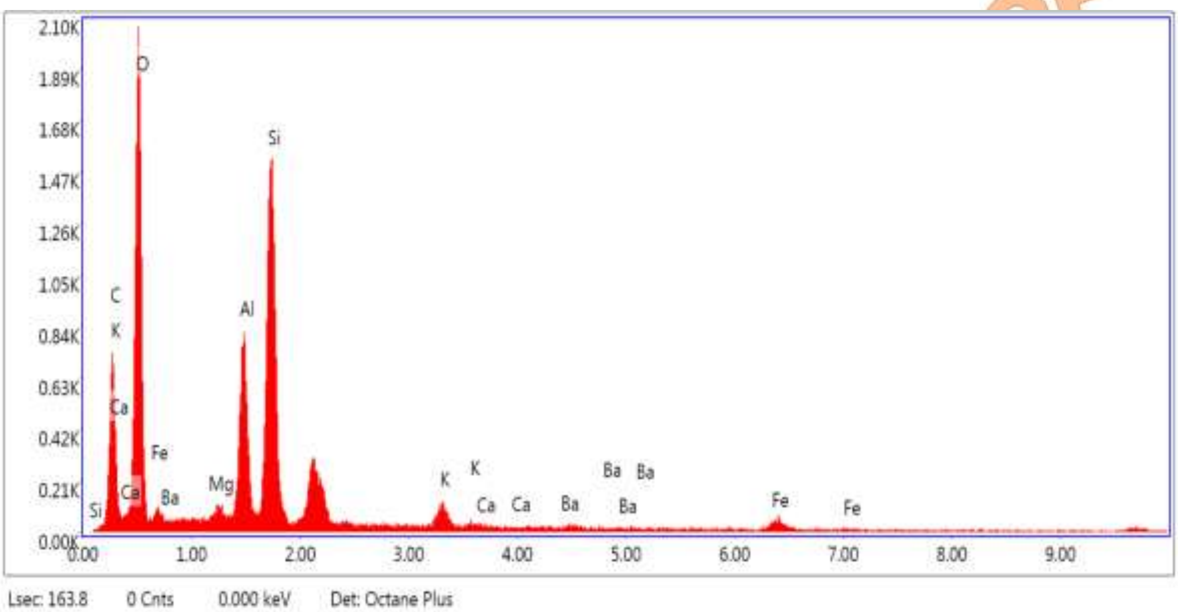

Fig. 5 (a). EDX spectrum of the original soil sample.

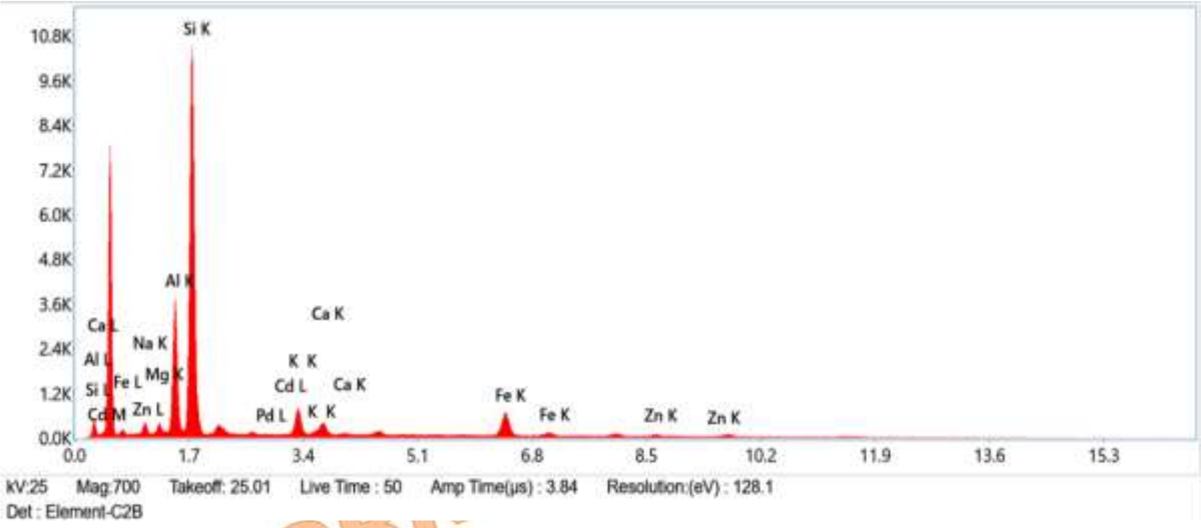

Fig. 5 (b). EDX spectrum of soil treated with 20% MSWIA and 1% nano-zeolite.

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4. Conclusions

This study demonstrates that incorporating MSWIA and nano-zeolite significantly improves the strength of soft soils. The pozzolanic activity of MSWIA, combined with the high surface reactivity of zeolite nanoparticles, enhances particle interaction and soil densification, leading to increased durability. Additionally, this approach supports sustainable construction practices by utilizing waste materials and minimizing dependence on conventional stabilizers. The effectiveness of stabilization depends on selecting suitable mix proportions tailored to specific soil properties. The main conclusions of the study are as follows:

1. The test findings showed that 1-day UCS values of 101 kPa, 154 kPa, 194.5 kPa, 240 kPa, 284.4 kPa, and 300 kPa were obtained by adding 20% MSWIA with 0.2%, 0.4%, 0.6%, 0.8%, and 1% nano-zeolite by dry weight of soil, respectively. After mixing the 20% MSWIA and 1% nano-zeolite, the UCS value of stabilized samples increases to 9.2 and 12.7 times that of untreated soil. According to these results, adding nano-zeolite and MSWIA strengthens weak soil.
2. The test findings showed that a 1-day UCS value of 300 kPa was obtained by adding 20% MSWIA with 1% nano-zeolite by dry weight of soil. After 7 and 28 days of curing, the UCS value of the composite soil sample increases by 18.67% and 34% respectively. The strength result showed a time-dependent pattern, showing a gradual growth with curing age. This further suggested that an increase in specific surface area and cation exchange capacity is causing cementitious reactions to occur in the mixtures.
3. The addition of nano-zeolite and MSWIA to soil results in a notable improvement in its shear strength properties, as reflected by increased cohesion and friction angle. Nano-zeolite, with its high surface area and reactive properties, enhances particle bonding and soil structure, while MSWIA contributes to pozzolanic reactions that create cementitious compounds, further binding the soil particles.
4. SEM analysis revealed a denser and more compact soil matrix in samples treated with 20% MSWIA and 1% nano-zeolite compared to untreated soil, with visible cementitious gels bridging soil particles. EDX results confirmed the presence of key elements such as Si, Al, Ca, and Fe, indicating the formation of pozzolanic reaction products (e.g., C–S–H and C–A–H), which contribute to the enhanced mechanical strength of the stabilized soil.

This study shows that using MSWIA and nano-zeolite can improve soft soil. Future studies should look at how well the treated soil holds up in harsh conditions like freezing and chemical exposure. Study the Life Cycle Assessment (LCA) and cost-benefit analysis to evaluate the environmental and economic sustainability of large-scale implementation. Testing it on different types of soil will show if it works well everywhere. These steps will help us use this technique in real projects like roads, embankments, and land development.

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript.

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