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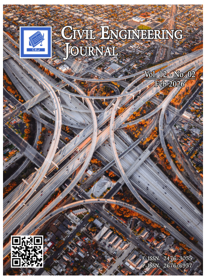

Effect of Fly Ash and Nano-Silica Fume on Soft Clay: Atterberg Limits, MDD, and OMC

Ruqaya M. Jumaa [1*], Khitam A. Saeed [2], Layth A. Al-Jaberi [1]

[1] *Department of Civil Engineering, Mustansiriyah University, Baghdad 10047, Iraq.*

[2] *Department of Water Resources Engineering, Mustansiriyah University, Baghdad 10047, Iraq.*

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Abstract

To improve the geotechnical properties of soft clay soil, this study compares and contrasts two types of micro and nano stabilizing additives: fly ash and nano-silica fume. Treatments with fly ash and nano-silica fume were applied to soft clay samples from Basra, Iraq, at varying fly ash concentrations. The samples were then subjected to the treatments. The ASTM requirements were adhered to in the laboratory tests conducted to investigate changes in plasticity characteristics, maximum dry density, and optimum moisture content (OMC). In the course of this research, Atterberg limits and standard compaction tests were undertaken. In accordance with the findings, fly ash reduces MDD (maximum dry density) by increasing the plastic limit and OMC while simultaneously decreasing the liquid limit and plasticity index. On the other hand, nano-silica fume enhances MDD, decreases OMC and the plastic limit, and increases the plasticity index and the liquid limit. The flocculation and dilution of clay particles are both promoted by fly ash, but the significant reactivity of nano-silica fume increases water adsorption and pore filling. The differences in particle size, specific surface area, and interaction mechanisms explain the observed divergent tendencies. Micro- and nanosized additives added to local soft clay at the same dosage were compared and contrasted in this study. This comparative analysis aims to help select the most effective stabilizing agents that either increase soil plasticity or improve compaction properties. The use of such an approach is a new methodological contribution.

Keywords: Soft Clay Soil; Fly Ash; Nano Silica Fume; Atterberg Limit; Compaction.

1. Introduction

Soft clay soils are problematic in geotechnical engineering due to their low strength, high compressibility, and poor bearing capacity, which often lead to excessive settlement and instability [1]. Soil stabilization is therefore essential to improve their engineering performance. Fly ash has been widely used as a traditional stabilizer because of its pozzolanic properties, with previous studies reporting reductions in soil plasticity and noticeable changes in compaction characteristics. Recently, nanomaterials such as nano-silica fume have attracted research interest due to their high specific surface area and reactivity, which significantly influence soil fabric, Atterberg limits, and dry density [2]. However, most existing studies have examined micro-scale or nano-scale additives independently, and direct comparisons under identical conditions remain limited. Consequently, the contrasting effects of fly ash and nano-silica fume on the consistency limits and compaction behavior of highly plastic soft clay soils remain poorly understood. This study addresses this gap by experimentally comparing the influence of fly ash and nano-silica fume, added at the same proportions, on the Atterberg limits, maximum dry density, and optimum moisture content of soft clay soil from Basra, Iraq.

* Corresponding author: ruqaya.m@uomustansiriyah.edu.iq

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2. Literature Review

Recent research on soil stabilization hypothesized that the nano- and micro-scale incorporation of additives could improve the characteristics of clay soils, particularly their weak or soft characteristics. Fly ash has received extensive research on its use as a traditional stabilizing agent [3]. This attention is because of its pozzolanic performance, which could affect soil's plasticity and structure. Moreover, several studies [3, 4] demonstrate that fly ash treatment of soil not only alters soil compaction properties but also decreases the plasticity index and the liquid limit.

Over the last few years, researchers have shown significant interest in using nanoparticles to modify interactions between soil particles. This is mainly because of their increased reactivity and extremely high specific surface area. The ability of nano-silica to increase the density and strength of expansive and clayey soils is also an exciting feature of this material [5]. It has been experimentally demonstrated that nanosilica can enhance soil fabric [6, 7] by increasing mechanical behavior, sealing microvoids, and enhancing particle bonding.

Experiments conducted to determine the effectiveness of nanoadsorbents compared to traditional stabilizers show that nano-scale components often provide superior performance at lower concentrations. It has been established that synergistic effects between fly ash and nano-silica can enhance unconfined compressive strength and bearing capacity, but monolithic additions produce relatively lower results [4].

More recent literature has also focused on strategies that are both sustainable and predictive. In the comprehensive study conducted by Abd & Abd [8] on soil stabilization nanoparticles, they emphasized the efficiency of these materials and the ecological benefits they provide. As shown by Waleed & Alshawmar [9], the use of silica-based additives improves the mechanical performance of low-plasticity soils. Furthermore, machine-learning models have been used to estimate the efficiency of soil stabilization with nano-additives accurately. This has resulted in the provision of revolutionary resources for the optimization of design [10]. There have been indications that nano-silica has the potential to increase shear strength and deformation resistance in applications involving slopes and infrastructure [11].

The current research shows that nano-silica provides better densification and strength enhancement through microstructural changes than fly ash. On the other hand, fly ash is a good mitigating agent of plasticity and increases workability compared to nano-silica. On the basis of these findings, the comparative experimental investigation that is presented in this study has a strong foundation in the scientific community.

2.1. Classification of Nanomaterials

Nanomaterials have at least one dimension of 100 nm or less, making them incredibly small. One-dimensional (like surface layers), two-dimensional (like fibers or strands), or three-dimensional (like particles) nanomaterials are all possible. They can have spherical, tubular, or irregular morphologies and be solitary, fused, aggregated, or agglomerated. Common nanomaterials include dendrimers, fullerenes, nanotubes, and quantum dots. The physical-chemical characteristics of nanomaterials—such as silica, fullerene, carbon nanotubes, silver nanoparticles, and photocatalysts—differ from those of ordinary chemicals and have applications in the field of nanotechnology. There are four types of nanostructured materials: those that are one-, two-, three-, or zero-dimensional [12].

3. Soft Clay Characteristic

The clay soil can be classified as soft clay based on the undrained shear strength (Cu) listed in Table 1.

Table 1. Soft Clay Soil Depending on Cu Value

No.	Cu and Consistency of Clay Soil
1	Soft clay soil when (Cu) is less than 10 kPa [13]
2	Very soft soils when cu is 25 kPa and soft if between 25 and 50 kPa [14]
3	Cu Varied from 20 to 40 kPa, whereas the designation "very soft" applied to soil with Cu $<$ 20 kPa [15]
4	The undrained shear strength (Cu) is $\leq$ 40 kPa, and high compressibility, Cc between (0.19 to 0.44) [16]

4. Experimental Program

4.1. Soil

The soil sample was collected from the Basra governorate; the Siba gas field is located 30 kilometers southeast of Basra, in Iraq, as shown in Figure 1. This clay soil was collected from a depth of 0.0 m (ground surface) to 2.0 m below ground surface. Soil samples are collected, bagged, and labeled by the excavator's staff, then transported to the Soil Mechanics Laboratory for further testing and analysis. Table 2 displays various characteristics of this soil. According to Atterberg, the soil is classified as having High Plasticity (CH). The flowchart shown in Figure 2 outlines the testing path to assess the impact of ash and Nanosilica fume on the characteristics of soft clay soil.

Figure 1. Location of study area

Table 2. The physical properties of clay soils

Property	Result of soil tests	Standard Specification
Sand content, %	0	ASTM D422 &ASTM D7928
Silt content, %	26	
Clay content, %	74	
USCS	CH	ASTM D (2487)
Liquid limit, %	58	ASTM D4318
Plastic limit, %	31	
Plasticity index, %	27	
Liquidity index, %	0.115	
Max dry density (gm/cm^3)	1.59	ASTM D1557
Optimum moisture content, %	24	
Specific gravity	2.79	ASTM D-854
Cu, vane shear test, kPa	20.1	ASTM D4648/D4648M-16

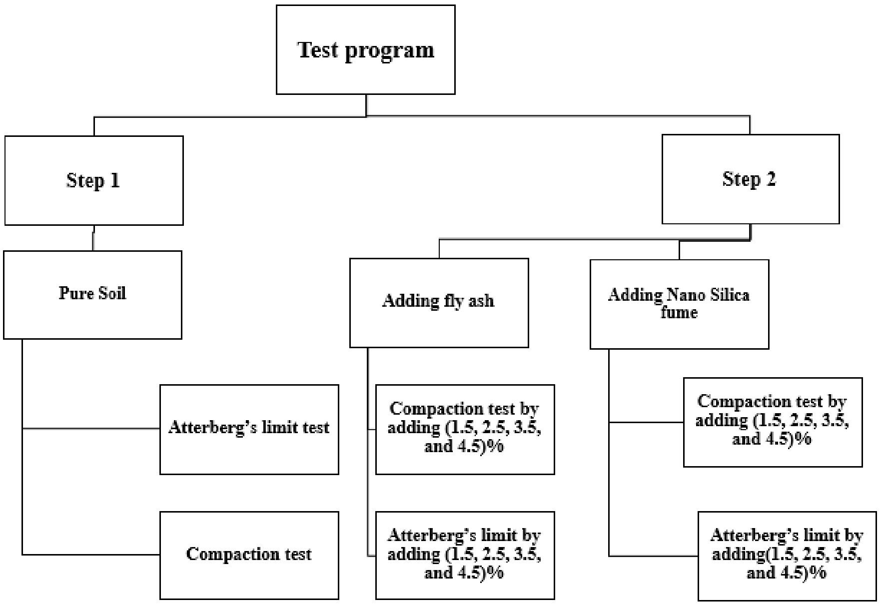

Figure 2. Flow chart for testing program

To gain more information about the soil's structure, a scanning electron microscope (SEM) was used to provide highly detailed images of the fracture surface and the size of clay particles. For more details, see Figure 3.

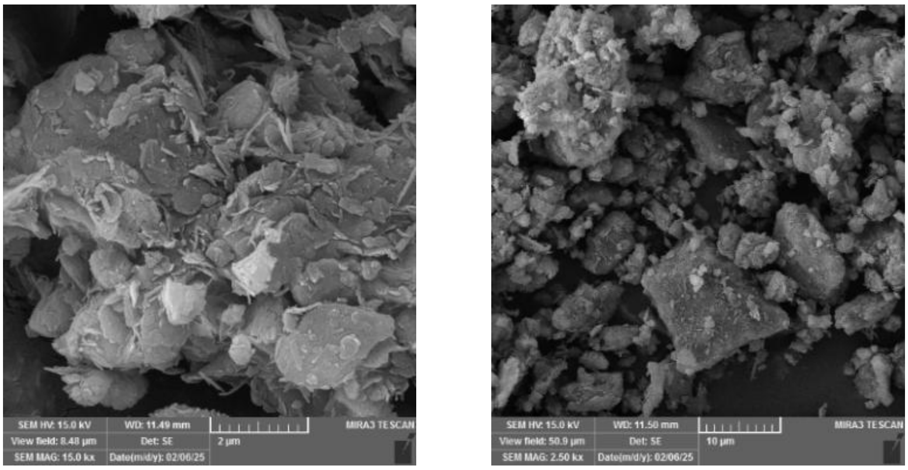

Figure 3. SEM for pure clay soil

4.2. Fly Ash

The fly ash (FA) used in this study was procured from local commercial sources. Its properties are consistent with the Class F fly ash specifications as defined by ASTM C618. The scanning electron microscope (SEM) for fly ash is shown in Figure 4.

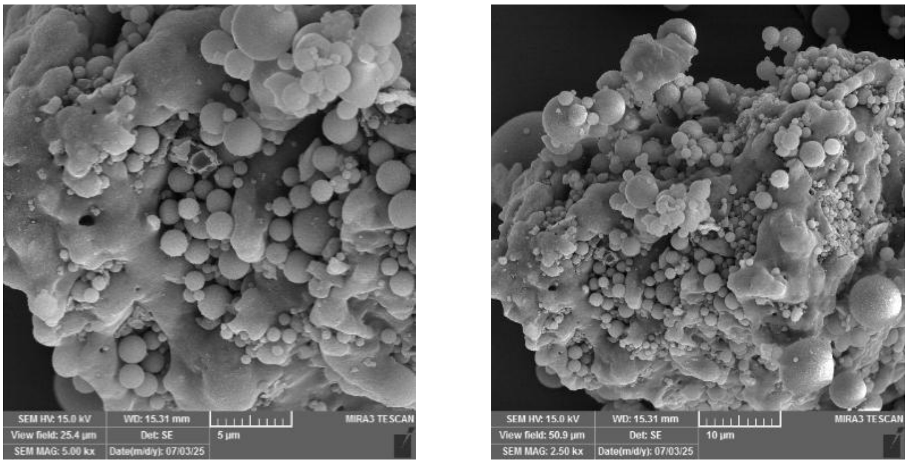

Figure 4. SEM for fly ash

4.3. Nano Silica Fume

During the production of silicon and ferrosilicon alloys, high-purity quartz is reduced with carbon in electric furnaces, yielding silica fume (SF), commonly referred to as microsilica. Additional silicon alloys such as calcium silicon ferromagnesium, ferromanganese, and ferrochromium may also offer this. The elevated silica concentration and remarkable fineness of silica fume render it a highly efficient pozzolanic material [17]. It has wide applications in concrete, incorporating nano-silica at 1–2% by cement weight, which significantly improves the compressive and flexural strength of lightweight concrete that includes recycled UPVC plastic as a partial coarse aggregate replacement [18]. To convert silica fume into a nanomaterial, it is crushed in a ball mill, a process that takes approximately 6 hours. Then, the particle size of silica fume is measured using the sonication of the particles device, and the results of the sieve evaluation are shown in Figure 5. The scanning electron microscope (SEM) for nano silica fume is shown in Figure 6.

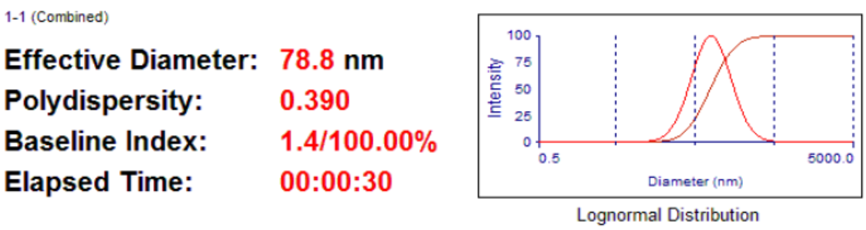

Figure 5. Results of sieve analysis for silica fume

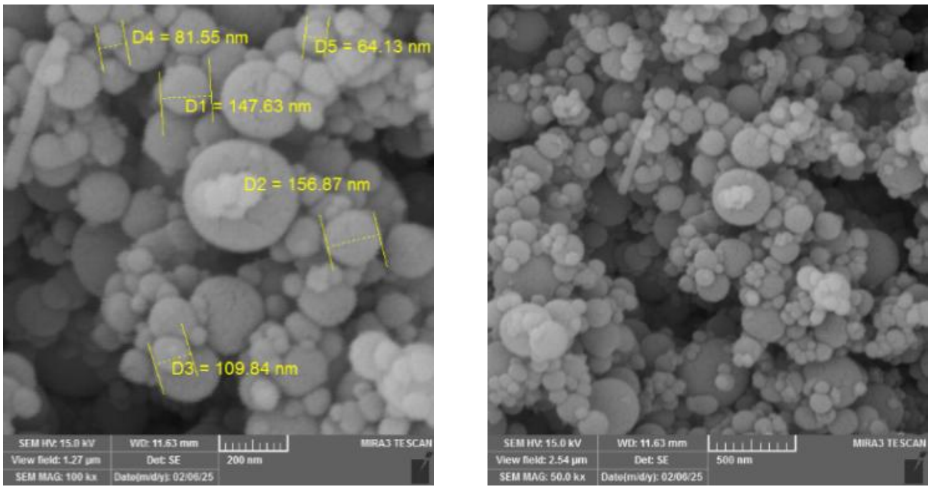

Figure 6. SEM for nano silica fume

4.4. Sample Preparation

This study incorporates fly ash and nano-silica fume into soft clay soil at varying percentages (1.5%, 2.5%, 3.5%, and 4.5%) to examine changes in the Atterberg Limits, Maximum Dry Density, and Optimum Moisture Content.

5. Results and Discussion

5.1. Atterberg Limit

The liquid and plastic limits significantly influence soil geotechnical characteristics; thus, nine samples were analyzed to determine the impact of incorporating fly ash and nano-silica fume on the consistency limits. Four percentages of the enhancement materials, namely 1.5%, 2.5%, 3.5%, and 4.5%, are employed based on the soil's dry unit weight for nano silica fume and fly ash, as shown in Figure 7.

Figure 7. Casagrande cup device and sample in the oven

The variations in Atterberg limits between native and modified soil, upon the incorporation of diverse amounts of extra elements, can be articulated as follows:

7.1.1. The Effect of Fly Ash and Nano-Silica Fume on Liquidity

Adding fly ash to the soil decreases the liquid limit from 58.0% in pure soil to 56.2%, 53.1%, 51.5%, and 49.2% at 1.5, 2.5, 3.5, and 4.5% fly ash, respectively. While the effect of adding nano-silica fume to soil leads to slightly improving the liquidity from 58.0% at pure soil to 58.8%, 59.7%, 60.2%, and 60.6% when adding 1.5, 2.5, 3.5, and 4.5% of nano-silica fume, respectively. At 4.5% addition, nano-silica increased LL to 60.6%, compared to a decrease to 49.2% with fly ash, indicating an opposite trend in soil plasticity behavior. Figure 8 shows how adding varying amounts of fly ash and nano-silica fume affects liquid limits.

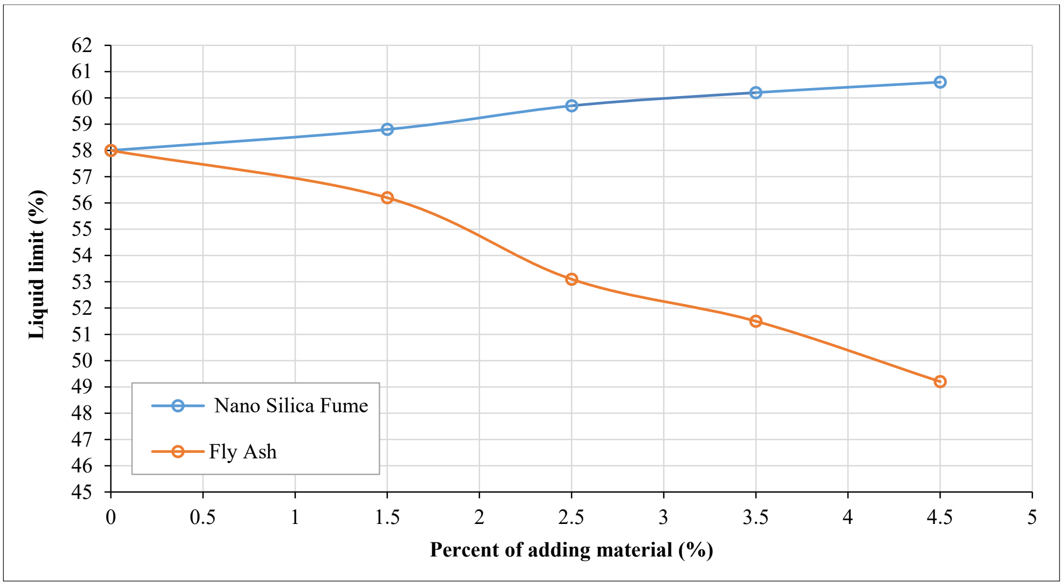

Figure 8. Effect of different materials on the liquid limit

It is possible to conclude from comparing the LL results of adding fly ash and nano-silica fume that the latter has greater liquid limits than fly ash.

Due to pozzolanic reaction, fly ash forms cementitious compounds (such as calcium silicate hydrates) when it combines with calcium in the absence of water. This reduces plasticity and binds soil particles, thereby decreasing water-holding capacity. The change in soil texture: fly ash particles are generally silt-sized, non-plastic, and spherical when mixed, diluting the clay fraction and reducing the soil's ability to retain water at higher moisture contents. Also, due to their high surface area and water adsorption, nano-silica particles are extremely fine and highly reactive; they adsorb water, increasing the amount of water required to reach the liquid state. A larger amount of water can envelop the external surfaces of nanomaterials due to their increased specific surface area. Their nanostructure also increases soil particles' ability to accumulate water. The high specific surface of nanoparticles, attributed to their minuscule size, is anticipated to enhance both the effective surface area and the volume of water that can be adsorbed [19].

7.1.2. The Effect of Fly Ash and Nano-Silica Fume on Plastic Limit

Adding fly ash to the soil increases the plastic limit, ranging from 31.0% in pure soil to 32.4%, 33.1%, 33.8%, and 34.1% at 1.5, 2.5, 3.5, and 4.5% fly ash, respectively. While adding nano-silica fume to soil leads to a decrease in the plastic limit from 31.0% at pure soil to 30.4%, 29.7%, 28.8%, and 28.1% when adding 1.5, 2.5, 3.5, and 4.5% of nano-silica fume in that order. Figure 9 presents the effect of adding varying percentages of fly ash and nano-silica fume on plastic limits.

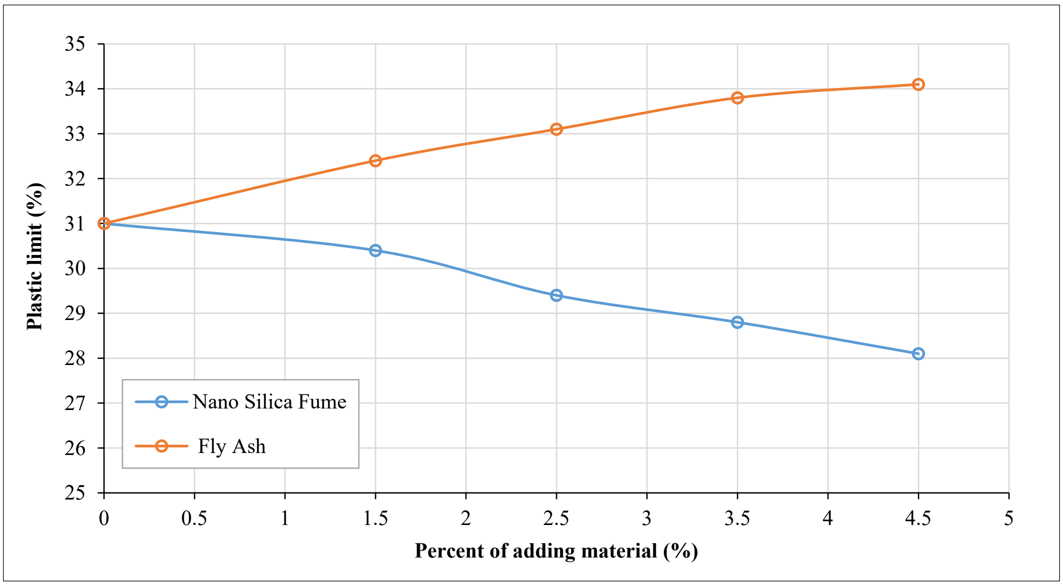

Figure 9. Effect of different materials on the plastic limit

It is known that the general increase in the plastic limit of the microcomposite mix occurs due to water absorption when fly ash is added to the soil, acting as a drying agent. Therefore, extra water was necessary to form the soil sample into a 3 mm thread until it broke, indicating that the plastic limit had been attained. Such an event is considered a sign that PL has been reached [20]. The flocculation and coagulation of soil particles result in larger aggregates or grains, altering soil structure and increasing the plastic limit due to diminished inter-particle cohesion, necessitating greater water for the soil to attain a plastic condition. A higher PL means that the soil becomes less sensitive to subtle changes in moisture and more usable in engineering applications.

7.1.3. The Impact of Fly Ash and Nano-Silica Fume on Plasticity Index

The plastic index is derived from the difference between the liquid limit and the plastic limit. Based on the test results, the plasticity index ranged from 27.0% at pure soil to 23.8%, 20.0%, 17.7%, and 15.1% at 1.5, 2.5, 3.5, and 4.5% of fly ash, respectively. While adding nano-silica fume to soil leads to an increase in the plasticity index from 27.0% at pure soil to 28.4%, 30.3%, 31.4%, and 32.5% when adding 1.5, 2.5, 3.5, and 4.5% of nano-silica fume, respectively. Figure 10 shows the effect of adding different percentages of fly ash and nano-silica fume on the plasticity index.

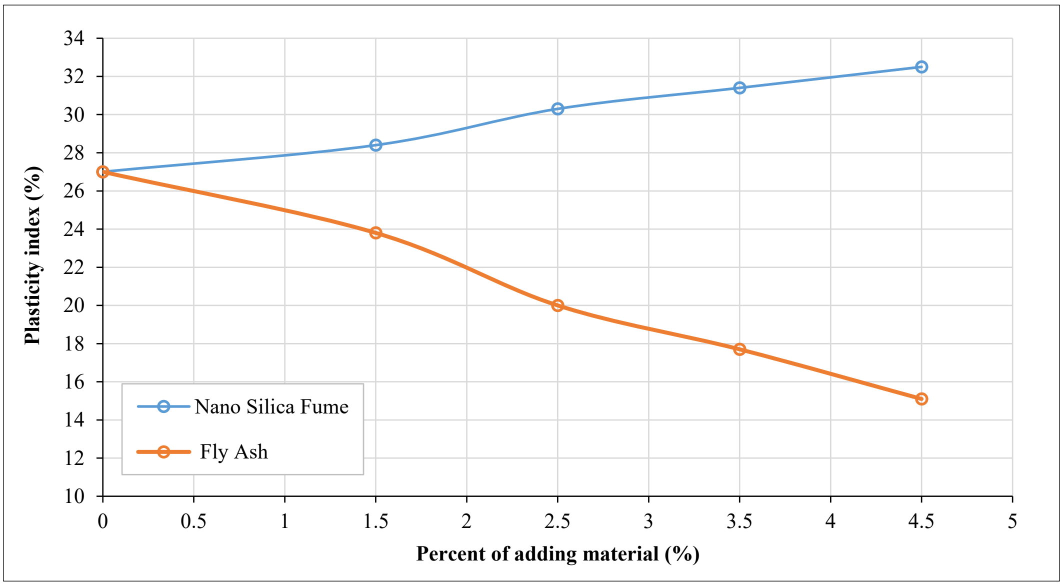

Figure 10. Effect of different materials on plastic index

The increase in plasticity index and liquid limit when using nanomaterials with a high specific surface area results in a greater volume of water surrounding the particle surfaces, while nanopores facilitate water retention within them, thereby enhancing the soil's available water capacity.

Additionally, the nanostructure of soil particles contributes to increased water-holding capacity. The reduction in plasticity index when using micro material is attributed to alterations in soil characteristics (granular composition following flocculation and agglomeration), resulting in a soil texture comparable to that of a sandy clay soil. Also, reductions in plasticity indices indicate soil improvement. In general, the specifications and standards highlighted that treated soil with a lower plasticity index is a good resource material for earthen construction as well as pavements, roads, etc. [21].

It can be inferred from the results that the addition of nanomaterials represents a stabilizing effect. Thus, the inclusion of tiny particles, namely nanomaterials, into the soil, even at low concentrations, can improve its properties through nanoparticle aggregation.

5.2. Compaction Test

Sixty-three samples of untreated soil and soils treated with various fly ash and nano-silica fume loadings were created to examine the impact of the compound admixture on the compaction test. Figures 11 and 12 display the connection between moisture content and dry weight for soil treated with various percentages of additive materials. Figures 13 and 14 present the variation in OMC "optimum water content" and the MDD "maximum dry density" of soil samples treated with admixtures.

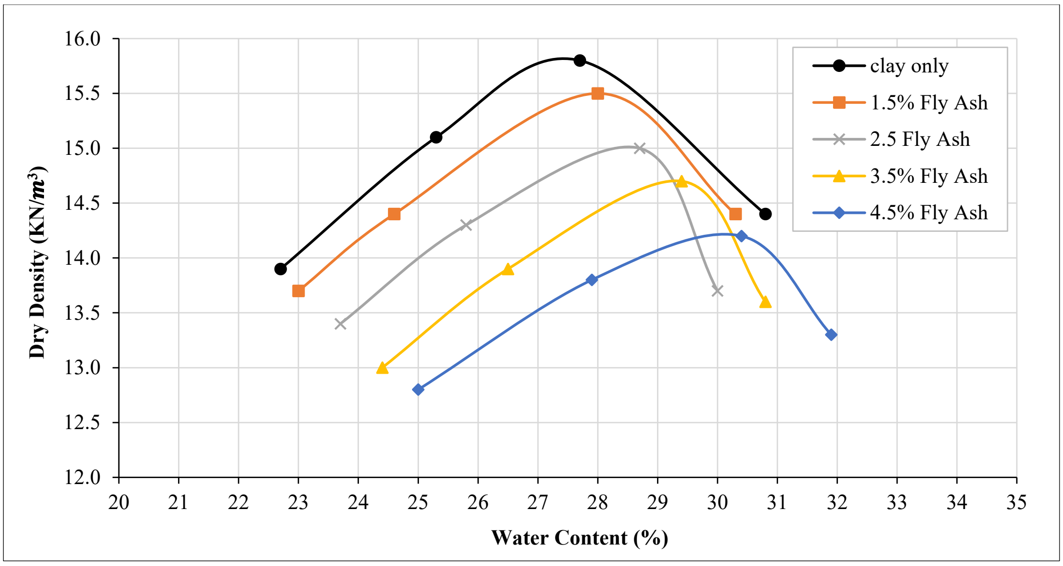

Figure 11. The relation between MDD (Maximum Dry Density) and OMC (Optimum Moisture Content) of soil with varying percentages of fly ash

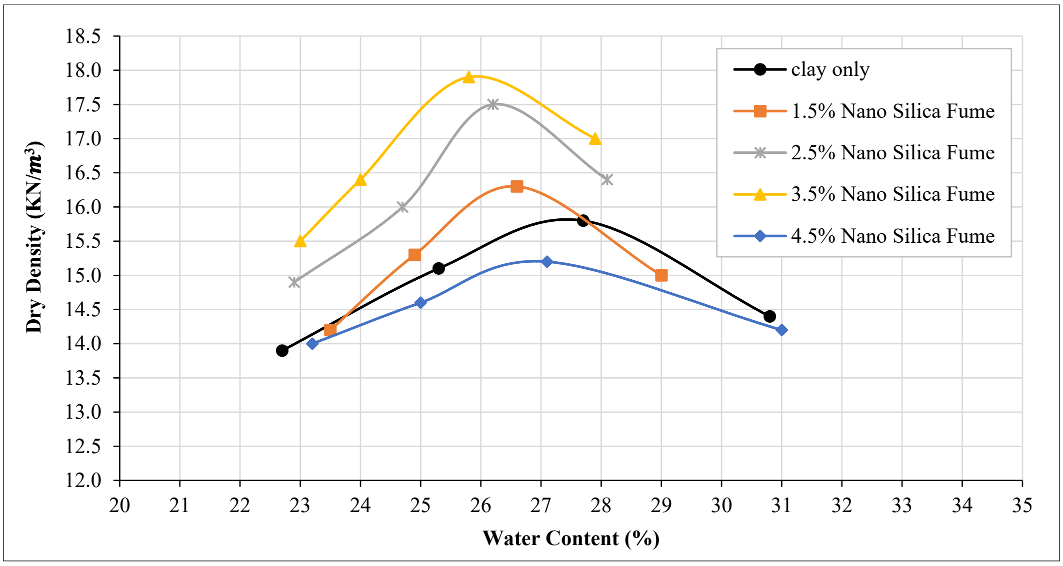

Figure 12. The relation between MDD and OMC soil with nano silica fume percentage

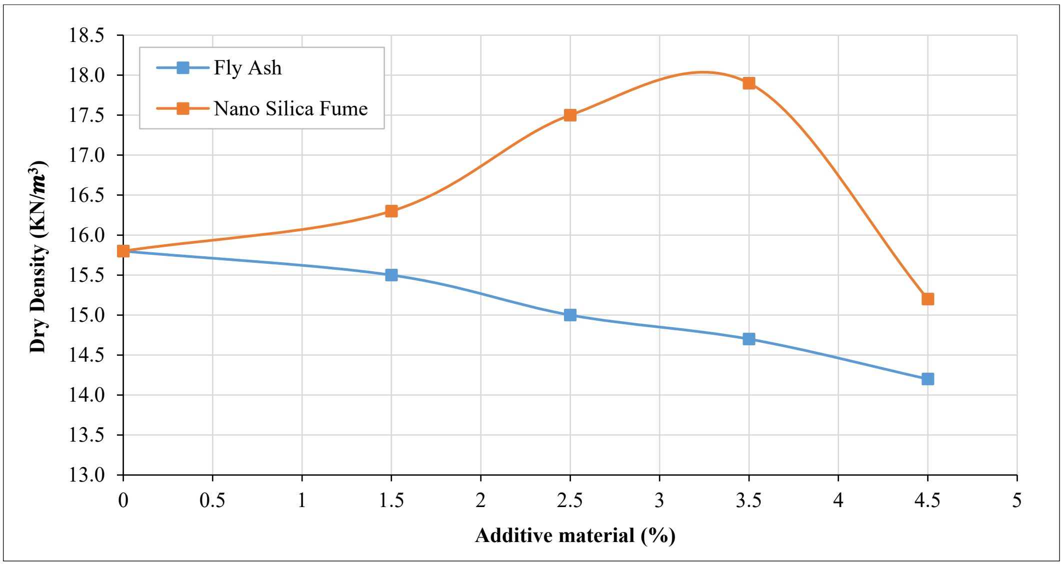

Figure 13. Impact of material addition on the maximum dry

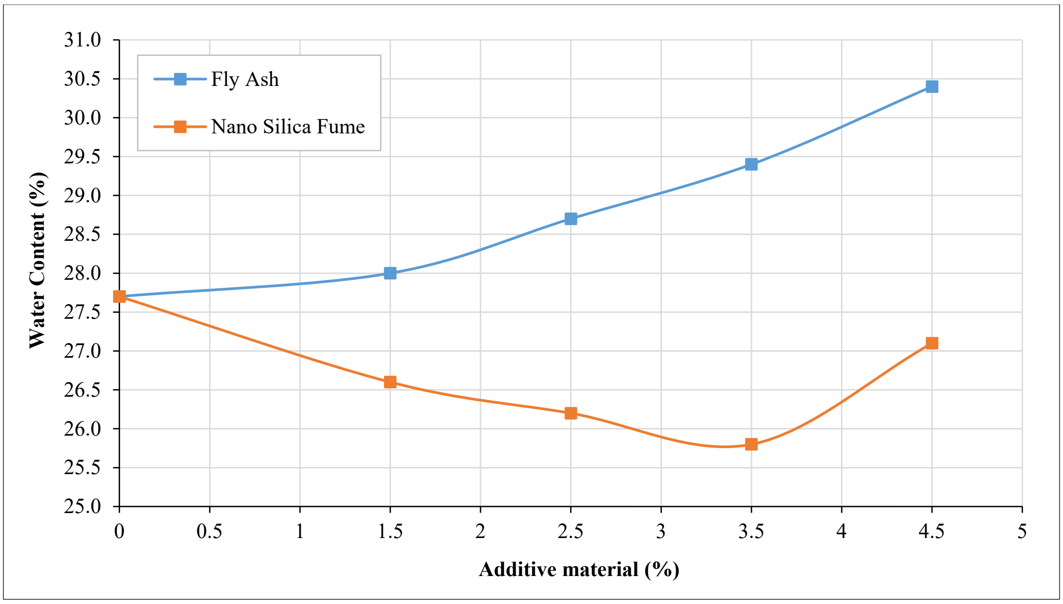

Figure 14. Effect of additives on the optimum water content for soil

Figure 14 shows that, at optimal moisture content, the incorporation of micro-materials may be defined in terms of the compound's water absorption resulting from pozzolanic processes; fly ash functions as a drying agent, necessitating additional water for the compaction of soil-compound mixes. In addition, traditional materials are considered coarse compared to nanomaterials. So, these activities require more water and limit the amount of free clay fractions, since the treated soil tends to be coarser and have a larger surface area when such additives interact with it. The propensity of nanomaterials to absorb water from wet soil may explain the reduction in the optimal soil moisture content observed in soil treated with nanomaterials. This behavior is because nanomaterial particles have a large surface area, which allows them to absorb water from the soil [22].

From Figure 13, it can be seen that MDD decreased when micro materials were added and increased when nanomaterials were added. The reduction in the case of adding fly ash may be attributed to the soil being coated by the compound mixture, which results in large particles with large voids (increasing particle size increases the void ratio) and hence lower density.

The increase in maximum dry density of soil treated with nanomaterials is likely attributable to the higher particle densities of the nanomaterials compared to those of natural soil. Furthermore, the particles are aggregated, thereby decreasing porosity by occupying the interstitial spaces between soil particles. Excessive increases in nanomaterials beyond the optimal threshold may result from nanoparticle agglomeration, leading to an elevated void ratio, increased water content, and a subsequent drop in density.

6. Conclusion

This study provides a systematic experimental evaluation of the influence of micro- and nano-stabilizing additives on the engineering behavior of highly plastic soft clay soil from Basra, Iraq. Fly ash and nano-silica fume were incorporated at identical dosages (1.5%, 2.5%, 3.5%, and 4.5% by dry weight of soil), and the resulting changes in Atterberg limits, MDD, and OMC were assessed in accordance with ASTM standards. The outcomes clearly demonstrate that the scale of the stabilizing material plays a decisive role in governing soil response, even when similar replacement levels are applied.

The results indicate that fly ash significantly reduces the plasticity index and liquid limit while increasing the plastic limit and OMC, thereby reducing MDD. These trends are primarily attributed to the flocculation and agglomeration of clay particles, the dilution of the active clay fraction by non-plastic fly ash particles, and the formation of cementitious bonds through pozzolanic reactions. Conversely, the incorporation of nano-silica fume results in an increased liquid limit and plasticity index, a reduced plastic limit and OMC, and a noticeable increase in MDD. This behavior is governed by the ultra-fine particle size, high specific surface area, and strong physicochemical interactions of nano-silica, which promote enhanced particle packing, micro- and nano-scale void filling, and modification of the soil fabric.

7. Declarations

7.1. Author Contributions

Conceptualization, R.M.J.; methodology, R.M.J.; software, R.M.J.; validation, R.M.J., K.A.S., and L.A.A.; formal analysis, R.M.J.; investigation, R.M.J.; resources, K.A.S. and L.A.A.; data curation, R.M.J.; writing—original draft preparation, R.M.J.; writing—review and editing, K.A.S. and L.A.A.; visualization, R.M.J.; supervision, K.A.S. and L.A.A.; project administration, R.M.J.; funding acquisition, R.M.J. All authors have read and agreed to the published version of the manuscript..

7.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

7.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

7.4. Conflicts of Interest

The authors declare no conflict of interest.

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