



## Variation of Consistency Limits and Compaction Characteristics of Clay Soil with Nanomaterials

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### HIGHLIGHTS

- A significant improvement in max. density and PI depends on nanomaterials type.
- Even at a low dose, the addition of nanomaterials may improve soil characteristics.
- More than 3% of nanomaterials, particles agglomerate and the effect will be negative.

### ARTICLE INFO

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### ABSTRACT

The arrangement of the soil for every ground structure is so important and must be efficient to sustain the whole structure. The variables and properties that have influenced their behavior must be well known. The building constructed on soft soils may fail due to their low strength, and an excessive settlement of the soil under a constant load could occur, therefore, the improvement for such soils must be carried out before construction to eliminate or decrease the maintenance cost or failure in buildings. Nowadays, one of the new technologies using to improve problematic soil is nanomaterials. In this study, experimental tests were conducted to: Investigate the effect of using conventional materials and nanomaterials on the physical properties (consistency limits and compaction characteristics) of soft soil. The soft soils were gathered from one site and processed with four material types (fly-ash, silica fume, nano fly-ash, nano-silica fume). Additives were supplemented in a tiny amount ( $\leq 5\%$ ) by the dry weight of the soil. The results showed a significant improvement in maximum dry density and plasticity index and the improvement depends on the type of nanomaterials. The maximum dry density has increased as the content of nanomaterials has increased until this value of maximum dry density reduces the strength of the soil to the optimum percentage. Thus, even at a low dose, the addition of soft particles such as nano materials may improve soil characteristics.

## 1. Introduction

Soft soils can typically exist in the field with high water content, namely approaching that of the liquid limit, which results in low shear strength and high settlement potential. Therefore, a steady state should be reached to ensure that the settlement remains within the acceptance limit and higher strength is achieved to avoid the damages and deformation in construction.

The main problems associated with soft soil are the low bearing capacity and the excessive expected settlement and in a general sense, the overall stability of the structures constructed on such soils. Soft saturated fine-grained soils are distinguished by their low undrained shear strength and high compressibility. Construction of any engineering structure on soft soils usually involves problems such as excessive settlement and stability. For these reasons, many researchers studied these problems and suggested various materials and techniques to avoid or reduce these problems [1,2]. In many civil works projects, which is constructing on weak soils such as soft soils, many approaches can be employed to improve such soil, one of them is the stabilization.

Stabilization of soil is a conventional method that can be used in soil improvement to meet the requirements of different types of projects [3]. Numerous researches have been focused on the soft soils stabilizing using various materials. Conventional materials such as lime, cement, and mineral additives can be used for soil enhancement, such as silica fume, fly ash, and rice husk ash [4].

In recent years, interest in the use of nanomaterials has been greatly raised due to the wide range of applications of these materials and the pros of nanoparticles which consist of an eco-friendly approach, low cost, and rapid [5]. Priyadarshini and Arumaira [6] added various nanomaterials such as nano clay, nano magnesium oxide (MgO), and nano alumina ( $Al_2O_3$ ) at various percentages to the soft clay. They showed that Atterberg's limits decrease with the increase of Nano MgO and Nano  $Al_2O_3$ , and increase with increase nano-clay. They attributed this behavior to the characteristic of nanomaterials which have a

large specific area, so a large quantity of water will be encompassed to the outer surface. Taha et al. [7] used two phases of magnesium oxide powders, nano magnesium oxide (N-MgO) and regular magnesium oxide (R-MgO). It was found that the maximum values achieved by the plastic limit were for 1.0 percent N-MgO, which was 21.8 percent and 24.7 percent for 1 and 28 days of curing, respectively, the admixture of 0.3 percent N-MgO had the minimum liquid limit values of 27.3 percent and 26 percent for 1 and 28 days of curing, and although the N-MgO had a higher effect on decreasing the plasticity index of the treated soil, respectively. y. Priyadharshini and Arumaira [6] added nano clay, nano magnesium oxide (MgO), and nano alumina (Al<sub>2</sub>O<sub>3</sub>) at various percentages to the soft clay. Standard Proctor compaction test was done to assess the amount of compaction and water content required for the sample. They showed that the existence of nanopores leads the water to accumulate in these pores therefore, with the increasing of nano clay and nano Al<sub>2</sub>O<sub>3</sub> percentages, the optimum moisture content increases while the maximum dry density decreases. Also, with the increase in nanoMgO, optimum moisture content decreases, and the maximum dry density increases.

Alsharaf et. al. [8] used two types of nano-carbons, carbon nanofiber, and multiwall carbon nanotube to clarify their effect on compaction characteristics. They concluded that there is a relationship between using the optimum ratio of nanomaterials and increasing the optimum water content because nanocarbons were tended to fill the pores in the soil skeleton and as a result, the OMC decreased. Also, nanomaterials have particle density more than natural soil and therefore, the maximum dry unit weight (MDD) of treated soil will be increased. Yazarloo et. al. [9] studied the effect of nano kaolinite percentages (0.5, 1, 1.5, 2, 3, and 4%) on silty clay (CL-ML type). The findings of the Atterberg limit tests showed that the increment in the nano kaolinite amount in the silty loess soil of the Golestan province increased the liquid limit and plastic limit. But the plasticity index was constant in the lower percent then, it showed more decrease after adding 5% nano kaolinite.

This study presents the results of a systematic investigation on the effects of using conventional materials and nanomaterials on the physical properties (consistency limits and compaction characteristics) of soft soil

This search introduces the results of systematic testing to clarify the impact of using conventional materials and nanomaterials on the physical properties (consistency limits and compaction characteristics) of soft soil.

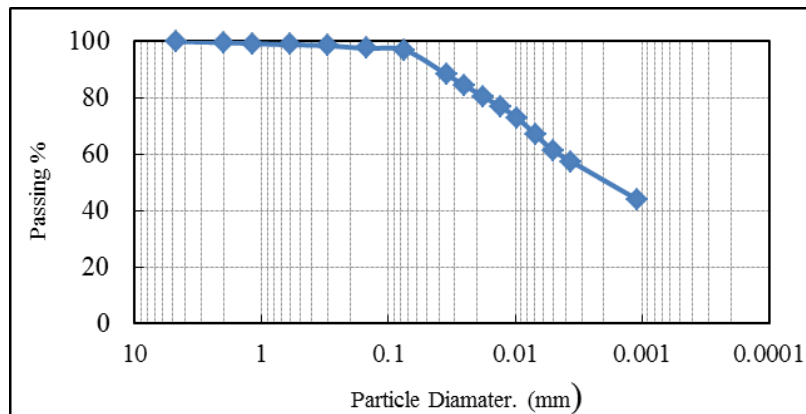
## 2. Materials and methodology

### 2.1 Soil used

Soil samples were collected from one site in Rustmia Region in the South of Baghdad City. All samples were disturbed soils taken from the excavated pit at depth of 0.5 to 1.5 m underneath the natural ground level, then placed in nylon bags, and brought to the Lab for testing. Before testing, the samples were pulverized and air-dried to investigate and specify the influence of additives (conventional and nono materials) on soil properties. Unified Soil Classification System (USCS). Table 1 depicts the values of the tests which consist of the classification test and compaction characteristics of the untreated soil. The particle size distribution of soil is shown in Figure (1).

**Table 1:** Properties of Used Soil

Index Property	Index Value	Standard Specification
Specific gravity, G <sub>s</sub>	2.70	ASTM D 854-2002
Sand% (0.075 to 4.75 mm)	3.00	ASTM D 422
Silt% (0.005 to 0.075 mm)	36.0	ASTM D 422
Clay% (< 0.005mm) %	61.0	ASTM D 422
Liquid limit, LL (%)	42	ASTM D 4318
Plastic limit, PL (%)	20	ASTM D 4318
Plasticity index, PI (%)	22	ASTM D 4318
Optimum moisture content, OMC (modified) (%)	16	ASTM D 1557-2000
Modified dry unit weight, MDD (kN/m <sup>3</sup> )	18.8	ASTM D 1557-2000
Undrained shear strength (C <sub>u</sub> ) (kN/m <sup>2</sup> )	7.16	ASTM D 2166
Cohesion of the soil, c(kps)	4.7	ASTM D3080-72
friction angle of the soil, φ	CL	ASTM D2487-11



**Figure 1:** Particle Size Distribution of Soils Used.

## 2.2 Materials used

In order to clarify the influence of conventional materials and nanomaterials on the physical properties of soft soil and make a comparison between them, four materials were used (fly-ash, silica fume, nanofly-ash, nan-silica fume).

## 2.3 Fly ash additive

Fly ash is an undesirable product which is mainly formed from the burning the coal in thermal power stations which hurts the environment due to cause extra pollution. The properties and chemical composition of fly ash are affected by the nature of the coal burning. In the current study, fly ash with type C is used which was brought up from Al-Doura thermal power station. This type of fly ash has both cementitious and pozzolanic properties and it comprises more than 20% of lime.

## 2.4 Silica fume additive

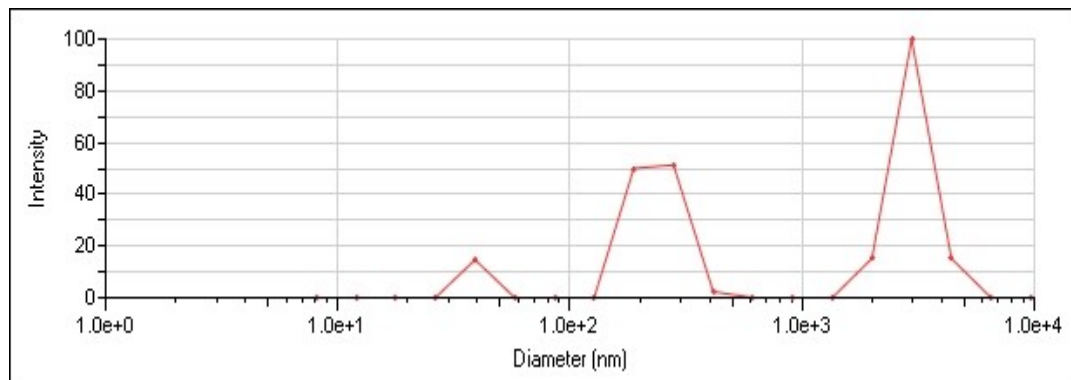
Silica fume (SF), which is also recognized as a microsilica, is a secondary product resulting from the reduction of high-purity quartz with the carbon in the electric furnaces during the manufacturing of ferrosilicon alloys and silicon. Silica fume has the specific surface area of 20,000 m<sup>2</sup>/kg approximately when measured by nitrogen absorption techniques. It is composed of very fine glassy particles of about 100 times less than the particles average of the cement. The chemical composition of the silica used in the present study is tabulated in Table 2.

## 2.5 Preparation of Nanomaterials

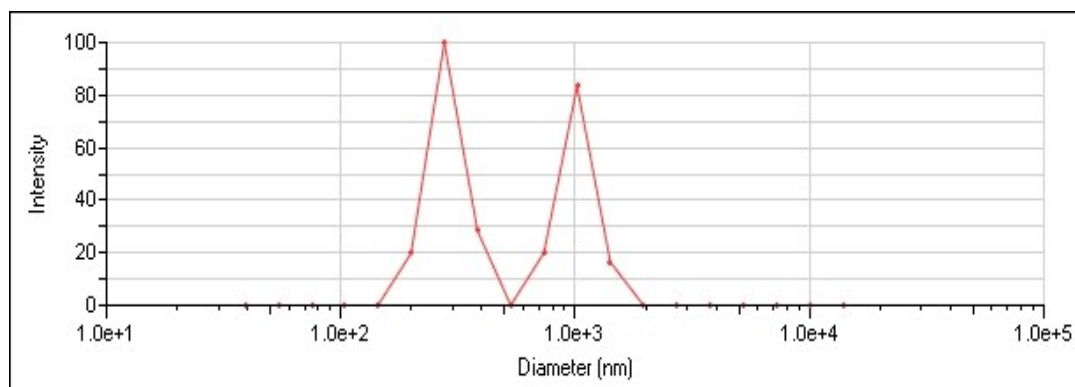
In order to transform the ordinary materials (fly-ash, and silica fume) to the nanomaterials and use them as additives to the weak soil examined in this study, the following procedure was employed:

The stabilizing materials such as fly-ash, and silica fume should be oven-dried first. The sample is ground in a ball mill for 10,000 revolutions or it should be ground for 10-14 days. Grinding of the material sample continuously is a difficult process as the material particles stick to the wall of the cylinder. Thus, the cylinder should be cleaned every four hours for uniform grinding. The fine ground sample is analyzed in Particle Size Analyzer to determine the size of the particle (Figure 2) which works on the principle of Dynamic Light Scattering (DLS). Particle size measurements can be made from 0.3nm-8µm. The sample should be dispersed in dispersing agents such as ethanol, sodium hexametaphosphate or sodium carbonate, or KNO<sub>3</sub>. Thus, 1mg of the sample is dispersed in KNO<sub>3</sub> and taken in a test tube for half an hour such that the material particle disperses well. Then, the test tube is kept inside the instrument for analysis. The particle sizes obtained for nano fly-ash are between (10-10000) nm, the effective diameter is 808.22 nm, nano-silica fume is between (100-1000) nm, the affect diameter is 408.35nm.

A nanometer is defined in various prospects based on their application. Generally, 1nm-100nm sized particles are named as ultrafine particles, 100nm-250nm particles as finer particles, and 250nm-1000nm as coarser particles in the nano range. Thus, from the particle size analysis result, the materials are in the finer particle range of nanometer.



(a) fly-ash



(b) silica fume

**Figure 2:** The particle size analyzer works on the principle of Dynamic Light Scattering (DLS).

**Table 2:** Chemical composition of silica fume used in the tests conducted by the Ministry of Science and Technology

Composition	Silica fume
SiO <sub>2</sub>	98.87%
Al <sub>2</sub> O <sub>3</sub>	0.01%
Fe <sub>2</sub> O <sub>3</sub>	0.01%
CaO	0.23%
MgO	0.01%
K <sub>2</sub> O	0.08%
Na <sub>2</sub> O	0.00%

## 2.6 Soil samples preparation and testing procedure

Soil samples are prepared by using the mixing method and compacted at the (OMC) optimum water content and (MDD) maximum dry unit weight using modified Proctor test before and after adding the materials additives. The modified Proctor compaction test was executed to concern the OMC-MDD curve.

Liquid and Plastic Limits were conducted to study the variation of consistency limits with addition of nanomaterials.

The weight of material is added to the soil according to the equation below [12]:

$$pf = \frac{wf}{w} * 100 \quad (1)$$

Where:

$\rho_f$  = material content ratio,

$W_f$  = material weight, and

$W$  = air-dried soil weight

Each additive used in this study was added to the soil with four percentages (0.5, 1, 3, and 5) %. The mixtures of soil – additives are prepared by mixing the dry quantity of the soil with a specific weight of (fly ash, silica fume, nano fly ash, nano-silica fume) in a mixing pan to get a uniform color for 5 minutes at a minimum. Then, the required water amount is adding to the mixture, mixing carefully till to obtain a homogeneous color, and finally covering and leaving for two days (48 hrs.) as a curing period.

## 3. Results and discussion

### 3.1 Compaction characteristics

The compaction characteristics of the soil sample with four percentages of additives materials are to be determined. A relation between the optimum water content and maximum dry density with various materials (i.e., fly-ash, silica fume, nano fly-ash, nano-silica fume) is shown in Figures 3 to 6 respectively. For ordinary additives (i.e., fly-ash, and silica fume), the optimum water content increased while in the case of nanomaterials, the OMC is reduced with the increase of the materials percent as shown in Figure 7. Using ordinary materials and due to pozzolanic reactions which causes absorption in the water, the optimum moisture content will increase. So that fly-ash and silica fume work as a drying factor and thus additional water is required in order to compact the soil-additives mixtures. In nanomaterials, the reduction in water content is associated with the capability of nanomaterials in absorbing the water from the wet soil. In addition, due to the high surface area of the nanomaterial powders, the optimum moisture content decreases when the nanomaterials add to the soil. These results are conjugated with the findings of Taha, and Taha [13]. Also, Bowles [14] stated that the decrease in the moisture content resulted due to a reduction in the volume of the voids in the soil matrix. For ordinary additives (i.e., fly-ash, and silica fume), the maximum dry density decreased while in the case of nanomaterials, the maximum dry density increased with the increase of the materials percent as shown in Figure 7. When using ordinary materials, the reduction in the maximum dry density is occurred due to the covering of the soil particles by the compound mixing which producing large particles with large voids and thus less density [15]. In nanomaterials, the increase in maximum dry unit weight is achieved because the nanoparticles have density more than particles in the natural. Moreover, the particles of nanomaterials tend to fill the spaces between soil particles and therefore, the soil porosity will be decreased which means the soil strength increased and this is referring to soil improvement. These results conjugated with findings of [16] stated that the components that affect compaction included the particle size and specific gravity of the soil and the stabilizer.

It worth noting that the increase in adding of the nanomaterials that exceeded the optimum limit may cause a conglomerate in nanomaterials particles in the soil matrix and this is caused an increase in the void ratio so, the soil density decreased and the water content will be increased.

### 3.2 Consistency limits

The results of Liquid Limit, Plastic Limit, and Plasticity Index with varying percentages of four additives are shown in Figures 9, 10, and 11 respectively.

It was found that the liquid limit and plasticity index decreased, while the plastic limit increased whenever the material content (i.e., fly-ash, silica fume) increased.

Many studies have been stated that the reduction in liquid limit for the treated soil may depend on the type of soil [17]. The decrease in the LL of the improved soil may relate to the aversion of the water at the clay surface; this modification is caused by the compound's hydration. In general, the plastic limit increases for treated soil due to water absorption that occurs when the additive material (i.e. fly-ash and silica fume) is mixed with the soil. However, also the result indicates a drop in the plasticity index in all of them. Also, the soil strength sensitivity to water is decreased and the soil will be more workable. The plasticity index which is the measure of the sensitivity of the soil to changes in its moisture content. These limits were developed over a century ago [18]

When increasing the nanomaterial content, the consistency limits are decreased. Soil enhancement is motivated by a decrease in the plasticity index. Thus, the reduction in plasticity index (PI) is indicated that the soil is enhanced when the nanomaterials add to the natural soil even at a small amount [19]. It can be attributed to the agglomeration of nanoparticles when the dosage of nano (silica fume, fly ash) exceeded 3%. Nanoparticles have high specific surfaces due to their very small size. A high specific surface material would increase the wet able surface area and the amount of water adsorbed. These properties can lead to an increase in the liquid limit and as a result of increases in LL and PI increases.

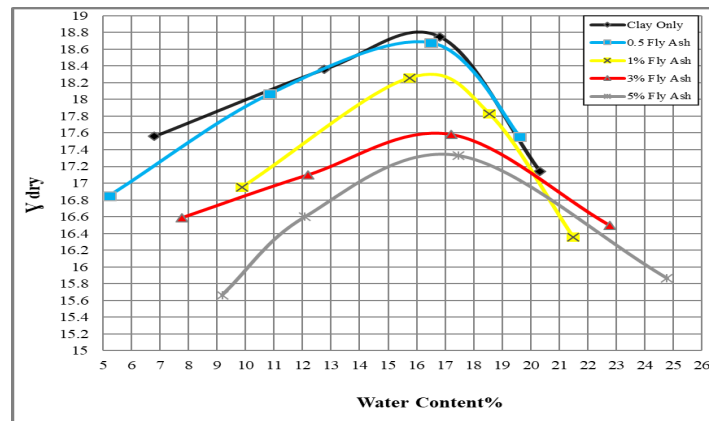


Figure 3: OMC and MDD curves with various ratios of FLY-ASH

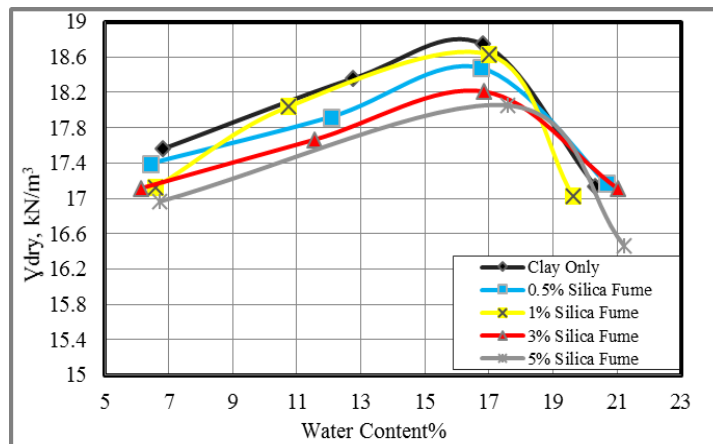


Figure 4: OMC and MDD curves with various ratios of silica fume

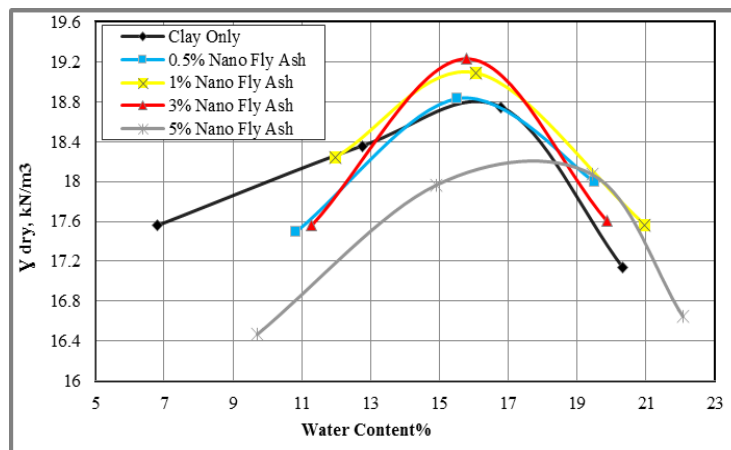


Figure 5: OMC and MDD curves with various ratios of Nano fly-ash

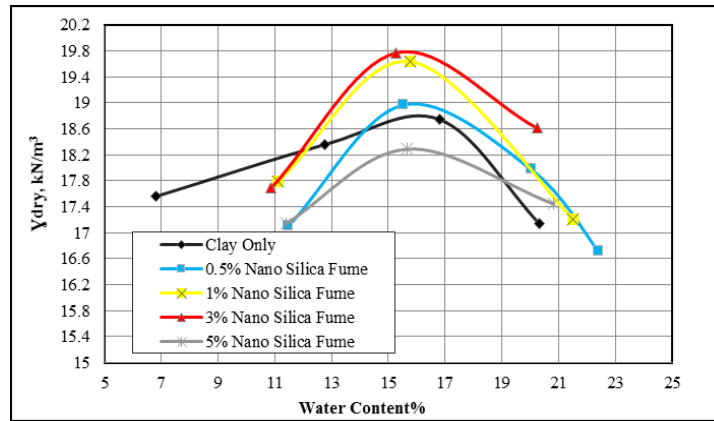


Figure 6: Figure 6: OMC and MDD curves with various ratios of Nano silica fume

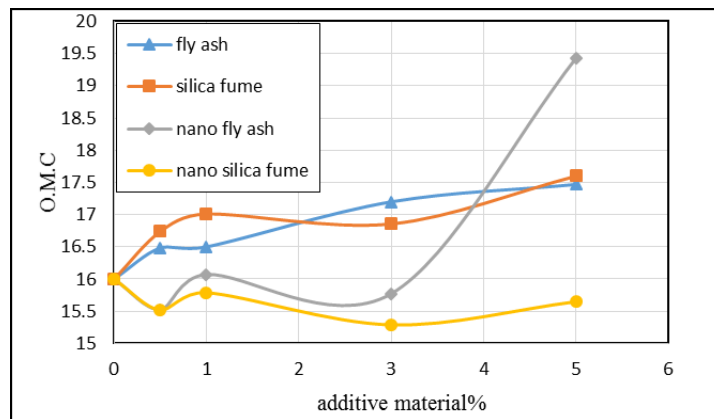


Figure 7: Effect of adding material on the optimum water contents for soil

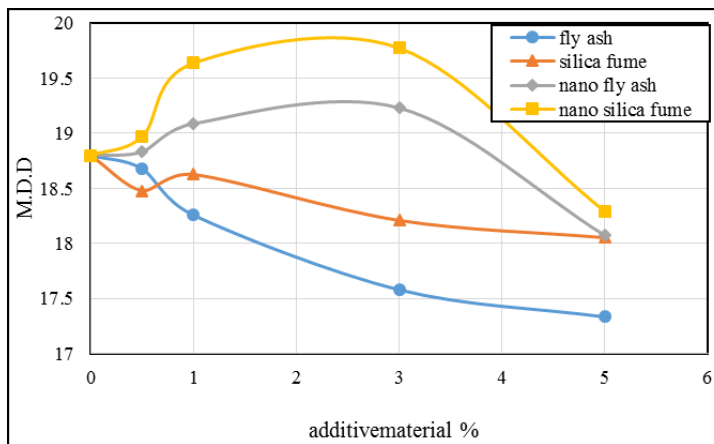


Figure 8: Effect of adding material on the maximum dry density

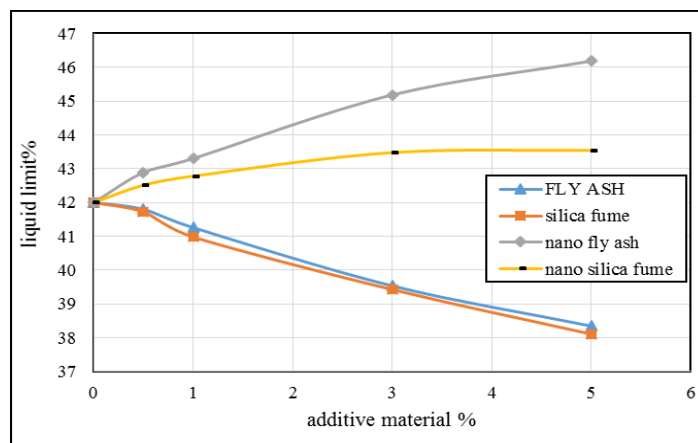


Figure 9: Effect of different materials on liquid limit

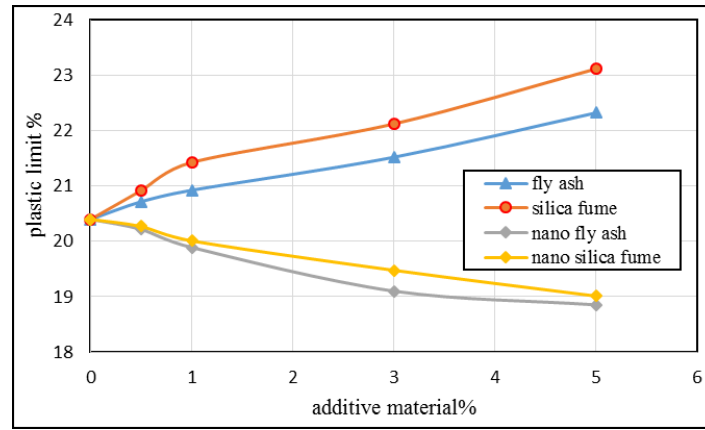


Figure 10: Effect of different materials on plastic limit

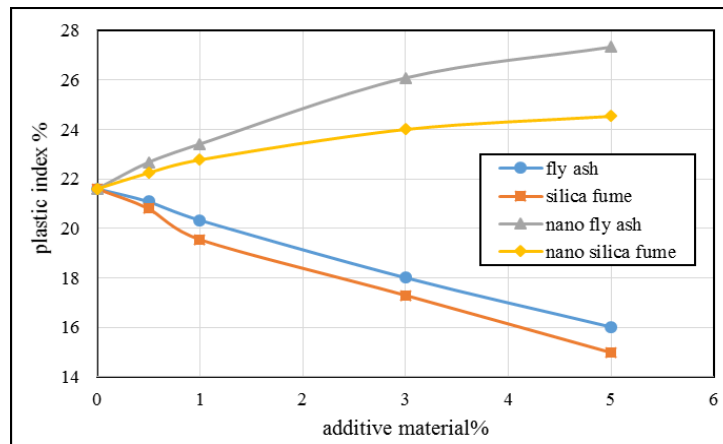


Figure 11: Effect of different materials on plastic index

#### 4. Conclusions

This research was conducted to study the effect of the addition of four materials on the physical properties of the soft soil (i.e., fly-ash, silica fume, nano fly-ash, and nano-silica fume). The compaction parameters and consistency limits (LL and PL) of the soil were determined. Evaluation of testing results approved the following:

1. The increase in the dry density is occurs with the increase of the nanomaterial content (nano fly-ash, and nano-silica fume) until reaching the optimum contents (3%), while dry density decrease in the case of continuing increase in the ordinary additives.
2. With the increase in nanomaterial percent in treated soil, the optimum moisture contents decreased until reaching the optimum contents (3%), and they increased in ordinary materials.
3. Adding nanomaterials decreases the liquid limit, plastic limit, and plasticity index of the soil. fly-ash and silica fume caused a decrease in the liquid limit, an increase in plastic limit, and a decrease in plasticity index of the soil. Furthermore, when nanomaterials content becomes more than the optimal content (3%), the particles will agglomerate, and the effect of these additives will be negative on properties of soft soil and the soil enhancement is not achieved.

#### Author Contribution

All authors contributed equally to this work.

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#### Data Availability Statement

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

#### Conflicts of Interest

The authors declare that there is no conflict of interest.

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