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Comparative Study between Silica Fume and Nano Silica Fume in Improving the Shear Strength and Collapsibility of Highly Gypseous Soil

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ABSTRACT

Soils with highly gypsum content signify known as soils that exhibit collapsibility and sudden failure when being submerged to wetting. Many of the constructions built on this soil showed cracked and/or collapsed at some parts as these soils immersed or leached with water. The utilization of extremely fine materials, for example, Microscale or Nanoscale, is generally utilized these days. This research compared the use of Silica fume (SF) (micro material) and Nano Silica fume (NSF) (Nanomaterial) to explore the capability of these very fine materials to mend the shear strength and collapsibility properties of highly gypseous soils. The soil as Poorly Graded Sand (SP) was used, with a gypsum amount equal to 62%. A succession of direct shear tests and double odometer tests were carried on dry and submarined specimens of soil at various percentages of SF and NSF. The obtained results indicate that mixing the highly gypseous soils with SF or NSF improved the engineering properties of these soils, especially for the wet condition. The average increment in apparent cohesion when adding SF (5-20) percentage varies between (140-310) % in dry soil and (20-40) % in soaked soil. Same results obtained when mixing the gypseous soils with (1-5) % of NSF. Also, the Nanomaterial provided an improvement of the friction angle in dry and submerged cases respectively. Considering that, the SF gives adverse results upon the friction angle of the soil. The SF and the NSF both condensed the dangers of gypseous soil collapsibility. Consequently, the use of NSF can be assertively suggested to improve the engineering characteristics of highly gypseous soils when compared with SF, where only mixing of 3% of NSF gives the best results.

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دراسة مقارنة بين غبار السيليكا ونانو غبار السيليكا في تحسين مقاومة القص والانهيارية للتربة العالية الجبس

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الخلاصة

التربة الجبسية هي نوع من انواع الترب التي لها قابلية للانهيار والفشل المفاجئ عند تعرضها للترطيب. لوحظ في العديد من المنشآت المشيدة على هذه التربة وجود تشققات في اجزائها أو انهيار في البعض منها عندما غمرت هذه التربة بالمياه. بدأ استخدام وتطبيق المواد الدقيقة للغاية مثل Microscale أو Nanoscale على نطاق واسع في الوقت الحاضر في معالجة العديد من الحالات. في هذه الدراسة، تمت مقارنة استخدام غبار السيليكا (كمادة دقيقة) و نانو غبار السيليكا (كمادة نانوية) لبيان قدرة هذه المواد الدقيقة جدًا على تحسين خاصية قوة القص وخصائص الانهيارية للتربة العالية الجبس. التربة المستخدمة هي تربة رملية رديئة التدرج (SP) وذات محتوى جبس يساوي 62 ٪. أجريت سلسلة من فحوصات القص المباشر وفحوصات الاوديوميتر المزدوج على التربة العالية الجبس الجافة والمغمورة بالماء بحالتها الطبيعية ومع اضافة نسب مئوية مختلفة من غبار السيليكا فيوم ونانو غبار سيليكا فيوم. بينت النتائج إلى أن خلط التربة عالية الجبس مع غبار السيليكا أو نانو غبار السيليكا قد حسن الخصائص الهندسية لهذه التربة ، وخاصة في الحالة الرطبة. بلغ متوسط الزيادة في التماسك الظاهري(140-310)٪ نتيجة إضافة غبار السيليكا بنسب (5-20)٪ في التربة الجافة و (20-40)٪ في التربة الرطبة. كما تم الحصول على نفس النتائج عند خلط التربة الجبسية مع (1-5)٪ من نانو غبار السليكا أيضا ، اعطت اضافة المواد النانوية زيادة في زاوية الاحتكاك الداخلي للتربة في الحالات الجافة والمغمورة على التوالي. اما اضافة غبار السيليكا فقد اعطى نتائج سلبية على زاوية الاحتكاك الداخلي. كما ان اضافة غبار السيليكا ونانو غبار السيليكا كلاهما قللا من قابلية انهيار التربة الجبسية. نتيجة لذلك ، يمكن اقتراح استخدام نانو غبار السليكا لتحسين الخصائص الهندسية للتربة العالية الجبس عند مقارنته باضافة مادة غبار السليكا حيث يعطي خلط 3٪ فقط من مادة نانو غبار السليكا افضل النتائج.

الكلمات الدالة: الترب الجبسية ، مقاومة القص للتربة ، انهيارية التربة ، غبار السليكا، نانو غبار السليكا.

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1. INTRODUCTION

Some soils are often relatively hard and suffer small deformation under normal foundation loads. However, these soils show sudden volume change related to the rise in moisture content under constant stress. The strain prompted by change in substance dampness is the normal conduct of a marvel called collapse [1]. Collapse behavior has been found in numerous parts of the world, especially in tropical regions. Soils with high gypsum content can be considered as collapsible soil. These soils distribution covers about 18% of the United States, 16% of Europe, 15% of Russia and Siberia, and twenty percent of the total area of Iraq. These soils also exist in Argentina and Uruguay and southern Africa [2].

Instances of collapsibility of gypseous soils and loosening of shear strength had been documented extensively in many parts of the world. These cases are typically associated with saturation of soil by water, broken pipe water, another kind of artificial flooding from the land, or upward water saturation from perched water, [3] [4].

The improvement of gypseous soils had attracted many authors; several types of researches were conducted using different types of material, procedures, and methods. The improvement of gypseous soils means remolding these soils from sudden losses in strength and extreme compressibility as the water seeps through the soil. The method of improvement depends on the type of structures and the type of encountered defect. In this manner, two types of improvement can be achieved: the physical and the chemical improvement. The physical implies that the soil properties are improved by utilizing mechanical methods, for example, compaction, stone columns, pre-wetting, dynamic compaction, and so on, [5], while the chemical improvement methods means that the soil characteristics are improved with some chemical additives, such as chloride, dehydrate calcium, lime, cement, bentonite, cutback asphalt, etc. [6], [7], Whereas the synthetic improvement implies that the soil properties are improved with some added substances, for example, dried out calcium chloride, concrete, lime, bentonite, reduced black-top, and so on.

2. MICRO AND NANO MATERIALS

Over the last 15 years, especially in the recent decade, micro materials and Nanomaterials, as an interdisciplinary area, has witnessed much growth. While nanotechnology is a recent trend, it is a mixture of chemistry, physics, biology, and engineering [8].

Silica fume is a by-product of the manufacturing process in the silicon and ferrosilicon industry. The decrement of high-purity quartz to silicon at temperatures up to 2,000 °C produces SiO_2 fume, which oxidizes and shrinks in the low-temperature zone to modest particles comprising of non-crystalline Silica. SF is also called micro Silica, condensed SF, volatilized Silica, or Silica dust [9].

Al-Azzawi et al. [10] investigated the behavior of silty-clay soils by mixing SF in three percentages (5, 10, and 15) with soils. The test results revealed a substantial improvement in swelling pressure and compressive strength. The stabilization of cohesive soil by SF was also investigated by Bharathan et al. [11]. The result of this stabilization technique indicated a reduction in permeability and settlement with an increase in SF percentage. The Silica content was used in four trails (5, 10, 15, and 20) %; the results show the increment of unconfined compression strength (UCS) as an increase of SF percentage until 15% after that UCS is decreased.

Developments in nanotechnology, particularly over the past 15 years, have been fully tapped for its advantage in all fields of knowledge. This cannot be much said for geotechnical engineering. However, geotechnical engineers are amongst the earliest “nanotechnologists” who, in the past, have dealt with materials at Nano sizes and phenomenon which operate at the Nanoscale, [12].

Different Nanomaterials had been used to improve the properties of cohesive soils. Majeed, and Taha, [13], made experiments on the effect of the mixing of more than one nanomaterial, including Nano CuO, Nano MgO, and Nano clay, on the properties of soft soil samples. In the same manner, Taha and Taha [14] present the results of a laboratory study carried out on four types of clayey soils mixed with three types of Nano-material (Nano-clay, Nano-alumina, and Nano-copper) with several percentages. While the study of Verma and Maheshwari [15], focused on the addition of Nano Titanium dioxide in five different proportions (0 to 1% by weight) in a selected clayey soil. On the other side, Gallagher et al., [16], and Choobbasti and Kutanaei [17] used Nano-materials practically in sandy soils.

Iranpour and Haddad [18] studied the impacts of Nano-materials on collapsible soil behavior by applying four types of Nano-materials, i.e., Nano-clay, Nano-alumina, Nano-copper, and Nano- Silica. The results showed that using the optimum percentage of various Nano-materials reduced the collapse potential. Also, Albusoda and Khdeir, [19] investigated the effect of fly ash and SF as very fine materials on the collapsibility of disturbed gypseous soil. The results marked that (2) % of fly ash and (4) % of SF decreases the collapsibility with more than 83 % as been achieved at this optimum percent of the used Nano-material.

This study focuses on using Micro and Nanomaterials, because there are few studies on the improvement of gypseous soil by these materials. Thus, it aims at examining the effect of SF and NSF to improve the engineering properties of gypseous soils. Also, a comparison between these materials was presented and discussed.

3. SAMPLING AND PREPARATION OF MICRO AND NANOMATERIALS

3.1 The soil

The samples were collected at depth ranging (1.0-2.0) m from Tikrit City at the campus of Tikrit University. The physical and classification tests of the selected soil were tested following the ASTM vol. 4.08 and 4.09 [20], as shown in Table 1. While the amount of gypsum in the soil was found according to Al-Mufty and Nashat [21] method, as shown in Table 2.

According to the results, the relative density specifications and the classification of gypseous soils by

Table 1
Physical and chemical properties of the soil

Properties		Value	Properties		Value
Water content (ω)%		3.18	Coefficient of uniformity (CU)		5.36
Minimum Unit weight (kN/m^3)		11.21	Coefficient of curvature (CC)		0.68
Maximum Unit weight (kN/m^3)		16.12	M.I.T classification	Sand %	96.5
Field Unit weight (kN/m^3)		13.65		fines %	3.5
Relative density, (Dr) %		58.7	Standard compaction Test	Optimum dry density (gm/cm^3)	1.68
Specific gravity, (Gs)		2.41		Optimum moisture content %	11.68
Atterberg limits	Liquid limit (L.L)%	26.0	Gypsum content (%)		62.0
	Plastic limit (P.L)%	NP	Organic Matter Content (%)		1.34
	Plasticity index (P.I)%	NP	TSS (%)		64.07

Al-Barzanji, [22], the soil can be classified as moderately dense light gray to white poorly graded sand with no fines (SP), and it can be considered as very highly gypseous soil.

Table 2
Classification of gypseous soils, (after Al-Barzanji, [21])

Gypsum content %	Classification
0 – 0.3	Non-gypseous
0.3 – 3	Very slightly gypseous
3 – 10	Slightly gypseous
10 – 25	Moderately gypseous
25 – 50	Highly gypseous
>50	V. Highly gypseous

3.2 Additive Materials

The SF, also known as micro Silica, is an amorphous (non-crystalline) polymorph of silicon dioxide, Silica. It is an ultrafine powder and comprises of spherical particles with an average particle diameter of 150 µm. Fig. 1, shows the SF used with the SEM image. Table 3 shows the properties of SF.

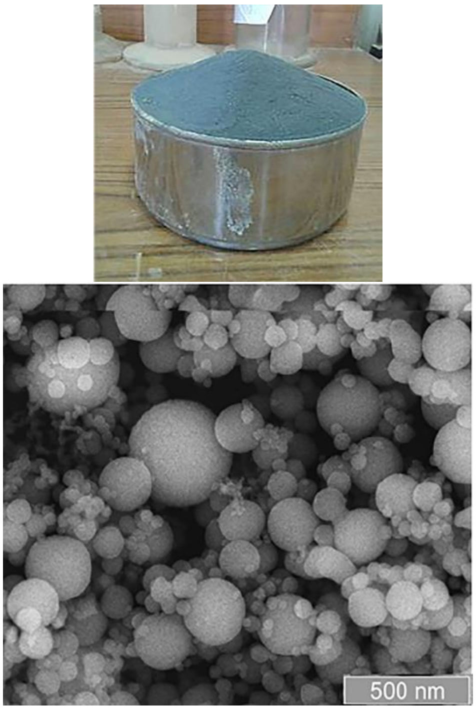

Fig. 1. The SF used with the SEM image.

Table 3
The properties of the Silica fume used.

Properties	Value
Specific Gravity	2.2
Bulk Density (kg/cm^3)	576
Size, (Micron)	0.1
Surface Area, (m^2/kg)	20,000
SiO_2 %	90-96
Al_2O_3 %	1.2-0.8

The NSF was prepared by using the Millipore filter technique, which is an effective technique for preparing Nanomaterials. It includes fewer preparation steps than many traditional methods. The Millipore filter (as shown in Fig. 2) involves a funnel, filter support grid, anodized aluminum assembly clamp, base and cap with Pyrex lateral tubing, vacuum vial with the ground neck. Membrane filter has a known uniform porosity size (0.45) µm sufficiently small to trap Nanoparticles. The sample passes through the membrane filter using a vacuum system and filter funnel. Fineness test was conducted on the Millipore filter passing materials to ensure it is NSF depending on its specific surface area (SSA). A number of physical and chemical properties of Nano-Silica fume are listed in Table (4)

Fig. 2: The Millipore filter device

Table 4
Physical properties of the Nano-Silica fume

Property	Value
Particle size(µm)	< 0.45
Specific gravity	2.23
Specific surface area (m2/gm)	189000
Color	light gray

4. SAMPLES PREPARATION

The gypseous soil samples were prepared, depending on the results of the standard compaction test. The soil was compacted using special tools in the direct shear mold, i.e., 60*60*25 mm. The samples were cured for 24 hours in tied plastic baggage, and then allowed to air dry until the water content reaches the field value; the same procedure was used to prepare the samples for double Oedometer test, as shown in Fig. 3.

For soils mixed with SF, firstly, the soil is oven-dried (at 45C°) for 24 hours and then pulverized. The SF powder was added as a percentage of dry soil weight to the prepared samples (5, 10, and 20) %, and well handy mixed and the amount of distilled water equal to the O.M.C was added to the dry mixtures, and then mixed carefully until a uniform color was obtained. The samples compacted in the direct shear or the oedometer molds to the optimum density, then put in plastic bags and cured for seven days. In the same manner, the soils mixed with NSF were prepared, except that the percentage add of NSF was (1, 3, and 5) %. Also, the oven-dried samples were mixed thoroughly in sealed plastic bags with an iron ball placed inside the bags for the mixing process to achieve homogeneity before the test was carried out and to ensure no Nanomaterials was lost. (Fig. 4) illustrated the sample preparation process and the samples were prepared in layers to reach the desired density. The specimens were cured after preparing them in sealed plastic bags to complete the maturation process for seven days. The bags were then opened to deliver the samples to the water content of the soil equal to the field water content. Special masks and gloves must be used in the preparation of mixed soil with nanomaterials.

Fig. 3: Prepared gypseous soils for (a) the direct shear test, (b) double oedometer test.

Fig. 4. Prepared soil samples mixed with nanomaterials for direct shear test and double oedometer test.

The purpose of these tests is to determine the shear strength and the collapsibility of the soil in the natural state and after adding the SF and nanoparticles with different percentages. These tests were carried out in the dry state and after submerging it in water for 24 hours.

5. RESULTS AND DISCUSSIONS

The results of the direct shear test on untreated highly gypseous soils and treated gypseous soils with SF at different percentages added (5%, 10%, and 20%) are shown in Figs 5 and 6. In these Figures, it can be noticed that there is an increment in the apparent cohesion as the percentage of SF increased, in both dry and soaked cases. However, this is due to the fact that SF can be considered as an adhesive material. On the other hand, the treated highly gypseous soil with SF, reduced the angle of internal friction, especially if the additive percentage is less than 5%. After this percent, the angle of internal friction improved but is still low for untreated soil. This behavior may be due to the fact that the particles of SF are less coarse than gypsum particles.

The effect of NSF on the shear strength parameter of highly gypseous soil at dry and soaked cases are shown in Figs. 7 and 8. The trend of the curves in these Figures indicates that the NSF improved the shear strength of the highly gypseous soils in dry and soaked cases. Also, it can be observed that the optimum value of the NSF percentage is 3% to obtain peak apparent cohesion and angle of internal friction. Additional values of NSF is useless.

However, Figs 9 and 10can give a more precise explanation and a reliable comparison between the effect of Silica fume (SF) and Nano Silica Fume (NSF) on the shear strength parameters of highly gypseous soils at dry and soaked states. The SF added to the soil improved the apparent cohesion by (43-47) % for a soaked case, and up to 350% for a dry case, the same improvement had been observed but with the addition of NSF of only 3%. This behavior reflects the effect of Nanomaterial that provides a large surface area than micro material. Mixing gypseous soil with NSF enhanced the angle of internal friction in both dry and soaked cases while adding SF does not affect, and give negative results on, the angle of internal friction; this phenomenon is attributed to the fact that the SF particles are so smooth that cannot provide sufficient friction than gypsum particles.

The results of double oedometer tests are scoffed in order to calculate the collapse potential (C_p %) and the collapsibility index (I_e %). These parameters give a good indication about the danger of soil collapse according to the suggestion of Jennings and Knight, [23] and ASTM D5333, [20], as shown in Table (5).

The variation of the collapse potential (C_p %) and collapsibility index (I_e %) with the percentage of SF and NSF added are shown in Fig. 11.

The curves in this Fig. indicate that mixing the gypseous soil with SF or NSF reduced the collapse potential (Cp %) and the collapsibility index (Ie %). The amount of reduction varies between (50-80) % for both micro and Nanomaterial. However, adding 3% of NSF make the gypseous soils moderately problematic soil or slightly collapsible soil, while to reach this situation, it needs 10% of SF. Again, the large surface area of the Nanomaterial is the essential factor that controls the dissolution of gypsum in the soil through its adhesion and enclosing the gypsum particles and thus prevents the arrival of water to it

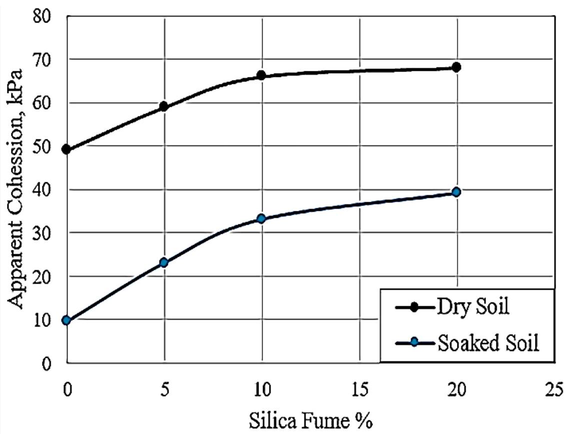

Fig. 5: Effect of silica fume on the apparent cohesion in dry and soaked tests

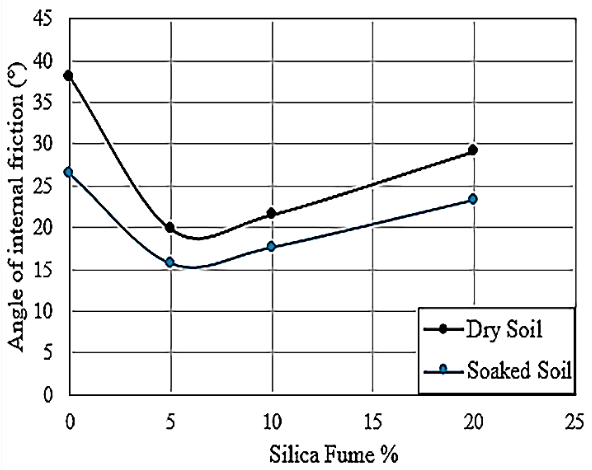

Fig. 6: Effect of silica fume on the angle of internal friction in dry and soaked tests

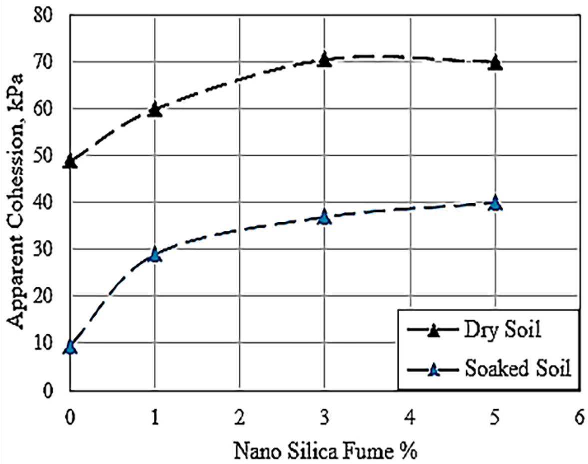

Fig. 7: Effect of Nano silica fume on the apparent cohesion in dry and soaked tests

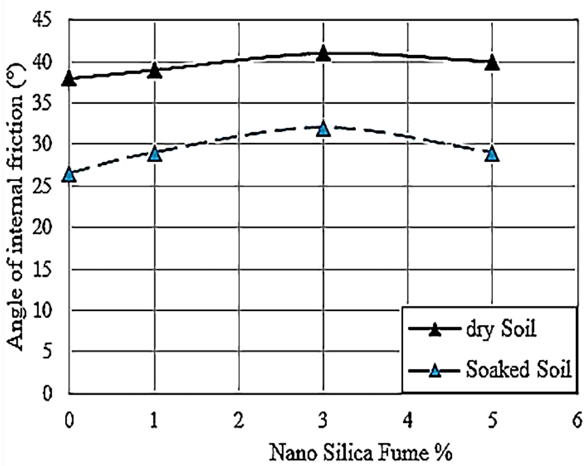

Fig. 8: Effect of Nano silica fume on the angle of internal friction in dry and soaked tests

6. CONCLUSIONS

The results the carried test indicate that mixing the highly gypseous soils with Silica fume or Nano Silica fume improves the engineering properties of such soil, especially at the soaked condition. As SF is an adhesive, increasing its amount in the gypseous soil leads to improve engineering properties, but this situation needs more water added for the hydration process, which may give negative results.

The average increment in apparent cohesion due to adding SF (5-20) % varies between (140-310) % in dry soil and (20-40) % in soaked condition. Same results obtained when mixing the gypseous soils with (1-5) % of NSF. Also, the Nanomaterial provided an increment of (10-20) % and (3-7) % in the angle of internal friction in dry and soaked cases, respectively. Considering that, the above ratio of SF (5-20) %, gives negative results upon the angle of internal friction when the SF added to the gypseous soils in both dry and soaked cases.

The Silica fume and the NSF both reduced the dangers of gypseous soil collapsibility with ratio varied between (50-80) %.

Consequently, the use of NSF can be assertively suggested to improve the engineering properties of highly gypseous soils compared with SF where only mixing of 3% of NSF gives these results.

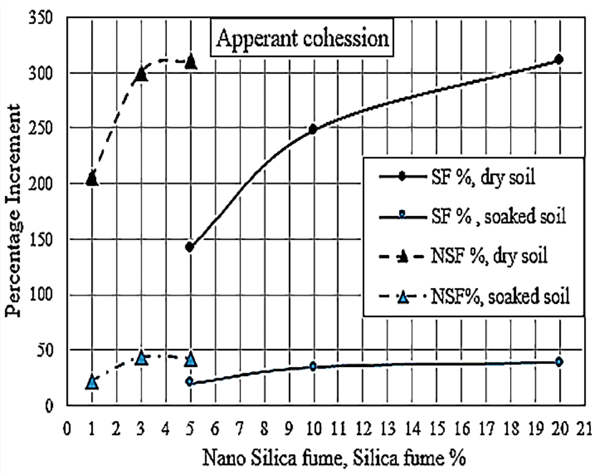

Fig. 9: The percentage increment in the apparent cohesion with Nano silica fume % and Silica fume %

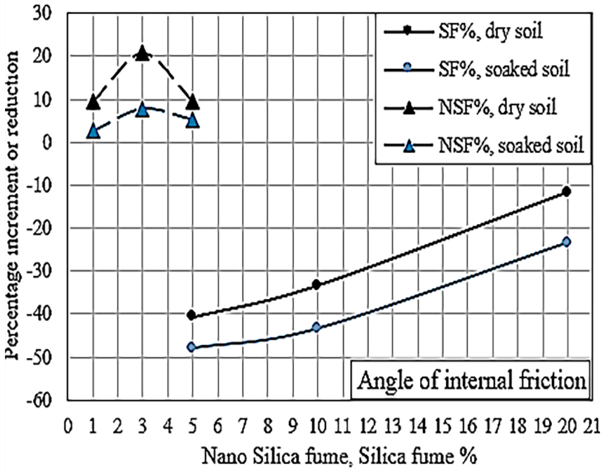

Fig. 10: The percentage increment and reduction in the internal angle of friction with Nano silica fume % and Silica fume

Table 5

Classification of Collapsibility index I_c %, [19].

I_e %	Degree of specimen collapse
0	None
0.1-2	Slight
2-6	Moderate
6.1-10	Moderately severe
>10	Severe

Table 6

Collapse potential values [22]

C_p %	The severity of the problem
0-1	No problem
1-5	Moderate problem
3-10	Trouble
10-20	Severe trouble
>20	Very trouble

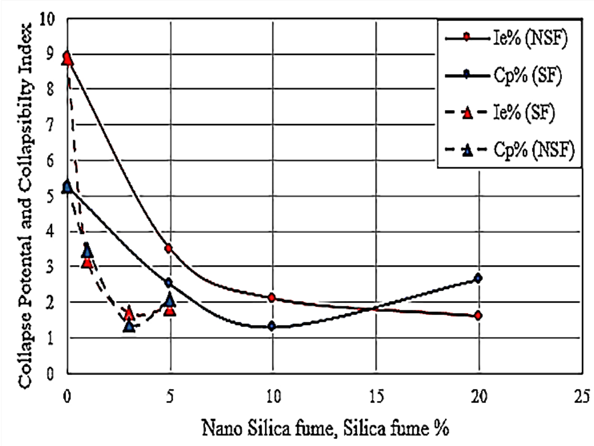

Fig. 11: The Cp % and Ie% for gypseous soil mixed with SF or NSF.

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