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Improvement of Compressibility Characteristics of Soft Clay Soil Stabilized with Fly Ash and Nano-Silica Fume

Ruqaya Mohammed Jumaa[1*] , Khitam Abdalhusin Saeed [2], Layth A. Al-Jaberi [3]

[1,3]Civil Engineering Department, Mustansiriyah University, Baghdad, 10064, Iraq.

[2]Water Resources Engineering Department, Mustansiriyah University, Baghdad, 10064, Iraq.

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ABSTRACT

Soft clay soils exhibit high compressibility and low shear strength, leading to excessive settlement and serious geotechnical challenges. This study evaluates the effectiveness of fly ash and nano-silica fume in improving the compressibility characteristics of soft clay soil obtained from the Siba gas field, Basrah Governorate, Iraq. The additives were mixed with the soil at proportions of 1.5%, 2.5%, 3.5%, and 4.5% by dry weight. One-dimensional consolidation tests were performed on untreated and treated samples to determine changes in the compression index (Cc), swelling index (Cr), coefficient of volume change (mv), and coefficient of compressibility (av). The results indicate a substantial reduction in Cc and Cr with increasing additive content, reflecting enhanced resistance to compressive deformation. Nano-silica fume showed superior performance compared to fly ash due to its finer particle size and higher pozzolanic activity. The optimum improvement was achieved at an additive content of 4.5%. The findings demonstrate that both additives, particularly nano-silica fume, provide an efficient and sustainable solution for mitigating the compressibility of soft clay soils.

1. Introduction

Problematic soils refer to a category of soil components that obstruct the planning and construction process. Consequently, investors and engineers typically choose to refrain from making construction investments in regions characterized by difficult soils. Regrettably, in densely populated regions, it is progressively the sole alternative to conduct development on challenging the soils [1]. From a geotechnical standpoint, problematic soils are defined as those capable of expansion, collapse, dispersion, excessive settlement, or failure at relatively low conditions of stress. The above described soil phenomena are linked to the soil's physical characteristics, including grain composition, saturation ratio, compaction degree, and mineralogy, along with its mechanical properties, such as preconsolidation and strength parameters [2].

Corresponding author E-mail address: ruqaya.m@uomustansiriyah.edu.iq
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2. Soft Clay Soil

The soft clay soil is has high compressibility and low shear strength. Numerous issues concerning soft clays outcomes from field investigations to their behavioural modelling. Getting undamaged specimens in soft clays is challenging due to disturbances caused by the drilling process [3]. The main problem of soft clay is lowest strength and large settlement [4-5].

3. Preparation of Nanomaterials

Nanomaterials are defined as a set of substances where at least one dimension is less than approximately 100 nanometres. A nanometre is one millionth of a millimetre - approximately 100,000 times smaller than the diameter of a human hair. Nanomaterials are of interest because at this scale unique optical, magnetic, electrical, and other properties emerge. These emergent properties have the potential for great impacts in electronics, medicine, and other fields [6-7].To convert silica fume into a nanomaterial, it is crushed using a ball mill machine, a process that takes approximately 6 hours. Then, the particle size of silica fume is checked by the Sonication of the particles device. The scanning electron microscope (SEM) for nano silica fume is shown in Figure 1.

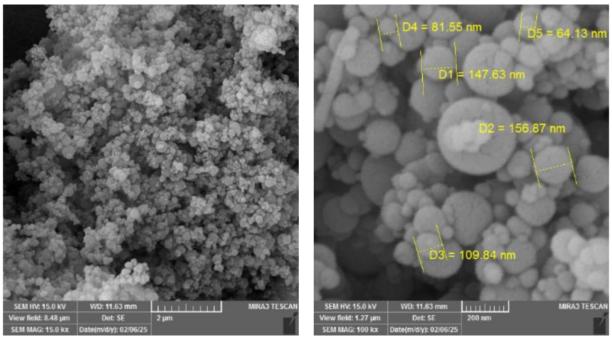

Figure 1. SEM for nano silica fume

4. Experimental Program

4.1 Soil

The soil sample was collected from the Basra governorate; the Siba gas field is located 30 kilometres southeast of the Basra governorate, in Iraq, as shown in Figure 2. 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 labelled by the excavator's staff, then transported to the Soil Mechanics Laboratory for further testing and analysis.

Figure 2. Location of study area

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 chemical formulation of the fly ash used in this study, as summarized in Table 1, the data was acquired by X-ray fluorescence (XRF) analysis.

Table 1: Chemical composition of fly ash Class F used in the tests

Constituents	Content (%)
SiO2	45.98
Al2O3	21.05
CaO	2.62
Fe2O3	8.18
MgO	1.95
K2O	2.03
Na2O	0.75
MnO	0.07
TiO2	1.29

4.3 Nano Silica Fume

During the manufacturing of silicon and ferrosilicon alloys, extremely pure quartz is reduced using carbon in electric heating systems, yielding silica fume, also referred to as micro-silica. The high silica content and exceptional fineness of silica fume make it an extremely effective pozzolanic material [8]. Also X-ray fluorescence (XRF) study to determine the chemical structure of chemicals of the nano silica fumes which be used in this study is illustrated in Table 2.

Table 2: The chemical formulation of the nano silica fume employed in the experimental tests

Constituents	Percentage (%)
SiO2	98.08
Al2O3	1.25
CaO	1.24
Fe2O3	1.85
MgO	0.85
K2O	2.30
Na2O	0.31
TiO2	1.00
SO3	0.63
ZnO	0.61

5. 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 the alterations in compressibility of the soft clay soil. The consolidation test is conducted on a natural soil sample and on samples with that percentages of fly ash and nano-silica fume to assess the impact about these compounds on the coefficients of consolidation, represented by the compression index (Cc), rebound index (Cr), coefficient of volume change (mv), and coefficient of compression (av). Figure 3 shown the Consolidation test apparatus.

Figure 3. Consolidation test apparatus

6. Results and discussion

Loading pressures of 25, 50, 100, 200, 400, and 800 kPa were applied to the loading arm, while unloading pressures of 400 and 200 kPa were utilized. The loading and unloading pressures were assessed at intervals of 0, 0.25, 0.5, 1, 2, 4, 8, 15, 30, 60, 120, 240, 480, and 960 minutes. The test findings are presented in Figures 4 and 5, and Table 3, while the implications of fly ash and nano-silica fume on C_c and C_r are illustrated in Figures 6 and 7.

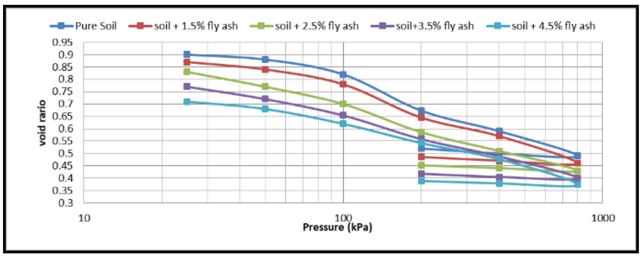

Figure 4. The effect of fly ash on the e-p graph

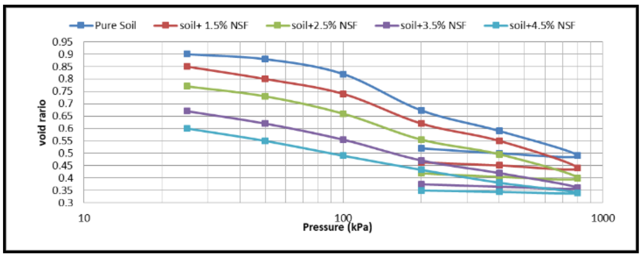

Figure 5. The effect of nano-silica fume on the e-p graph

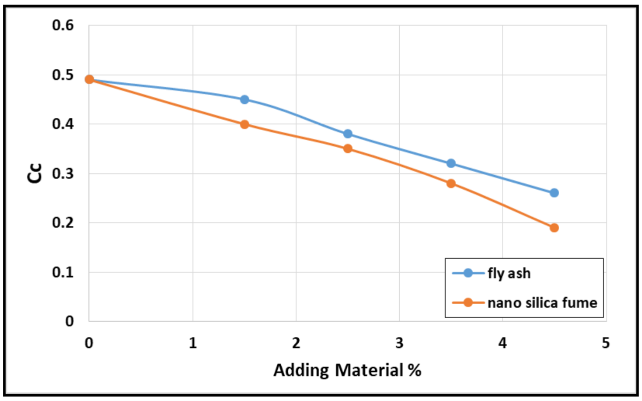

Figure 6. The contribution of fly ash and nano-silica fume on C_c.

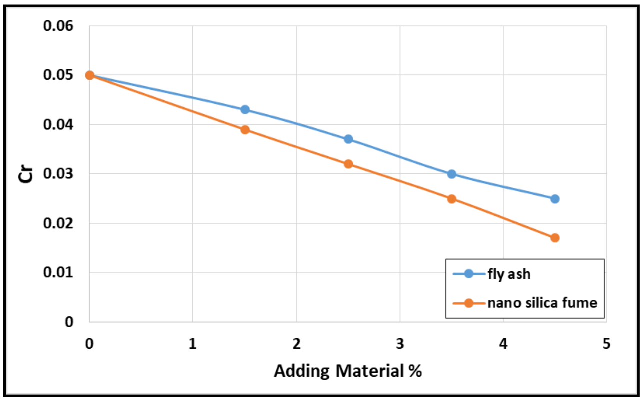

Figure 7. The contribution of fly ash and nano-silica fume on C_r

Table 3: Results of consolidation tests.

Addictive material	Rate of additives %	Consolidation coefficients					I% for C_c	I% for C_r
		e_o	C_c	C_r	a_v *10^4 (m^2/kN)	m_v *10^4 (m^2/kN)		
Fly Ash	0	0.93	0.49	0.050	14.70	7.61	0.0	0.0
	1.5	0.90	0.45	0.043	13.50	7.11	-8.16	-14.0
	2.5	0.86	0.38	0.037	11.40	6.13	-22.45	-26.0
	3.5	0.80	0.32	0.030	9.60	5.33	-34.69	-40.0
	4.5	0.75	0.26	0.025	7.80	4.46	-46.94	-50.0
Nano-Silica Fume	0	0.93	0.49	0.050	14.70	7.61	0.0	0.0
	1.5	0.88	0.40	0.039	12.00	6.38	-18.37	-22.0
	2.5	0.80	0.35	0.032	10.50	5.83	-28.57	-36.0
	3.5	0.71	0.28	0.025	8.40	4.91	-42.86	-50.0
	4.5	0.66	0.19	0.017	5.70	3.43	-61.22	-66.0

* (-) sign represents the reduction and I is the improved factor.

The outcomes indicate that the compression index (C_c) diminished with the addition of additives. This suggests that incorporating addictive substances into the soil enhances its compressive resistance, with an optimal concentration identified at 4.5% of fly ash and nano-silica fume.

The soil-additive mixture exhibits superior resistance to compressive loading, resulting in reduced compressibility. Compressibility is shown to rise with rising effective consolidation pressure and decrease with an increase in additive content. It is evident that as cure time increases, compressibility decreases. This arises from the cementation bonds formed during the curing phase between free lime and reactive silica, hence improving the compressibility characteristics of the clayey soil. The cation exchange reaction promotes increased flocculation and aggregation, causing a chemically induced pre-consolidation effect that raises the vertical effective yield stress and reduces compressibility characteristics [9].

By calculating the compression index for all consolidation samples, it is evident that its value is reduced by adding treated materials compared to untreated soil, which indicates an improvement in soil compressibility and increased the bearing capacity. This results from the establishment of cementation connections among soil particles. Furthermore, when pressure increases, the soil's void ratio progressively diminishes, and at elevated consolidation pressures, the rate of decline in the void ratio slows [10].

Additives in soil modify cohesiveness, decrease void ratio and size among soil particles, alter microstructure, and enhance clay's resistance to compressive deformation. The enhancement of soil utilizing nanomaterials (nano silica fume) surpasses that of traditional micro materials (fly ash) due to the diminutive size of nanomaterial particles and their distinct surface lattice structure. When integrated with soil, these particles facilitate the aggregation of soil particulates and the infill of voids, thereby altering the cohesion among soil particles and establishing a novel cementation between them [11-12].

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