Kochi Chapter

Indian Geotechnical Conference
IGC 2022
15th – 17th December, 2022, Kochi

Effect of Nano Silica on Dispersion and Strength Characteristics of Silty Soil

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Abstract: Dispersive soils, one of the most problematic soils due to their unstable structure when unidentified, cause numerous geotechnical problems. In this study, an attempt was made to monitor the effect of nano silica on reducing the dispersive nature as well as improvement in strength characteristics of silty soil. The soil was identified as medium dispersive soil by doing the identification tests. Crumb test, double hydrometer test and pinhole test were done to identify the dispersion percentage of the soil. Nano silica (NS) was laboratory synthesized using combustion method and was added to the soil in increments of 0.50% within the range of 0.50% - 3% of dry weight of the soil. With 1.50% of nano silica addition, the soil was brought to a lower dispersion state. By adding different nano-SiO_2 percentages, the increased values of UCS were 1.03, 1.18, 1.45, and 2.45 times than that of original soil for 0.50%, 1%. 1.50% and 3% NS respectively. Micro structure of the raw soil sample and treated specimens were analyzed using FESEM and XRD which shows that the lower dispersion rate is due to the agglomeration of the particles which occurs due to the addition of nano silica.

Keywords: Dispersive soil, nano silica, Pinhole test, Unconfined Compressive Strength

1 Introduction

Dispersive soil, which has the characteristics of low erosion resistance and high dispersivity in water, is one of the main reason for slope failures. So these type of soils are likely to cause piping on structures such as drains and embankments. The erosion of soils causes serious engineering problems such as landslides, bank failures, piping failures, and rainfall erosion resulting in sudden irreversible failures. This may pose severe damage to earthen or geotechnical structures. Study by Din et al. (2021) indicates that soil with a grain size ranging from 0.2 to 0.6 mm is most susceptible to soil erosion.

Application of nanotechnology is a new emerging area in the field of soil mechanics. Although immense studies have not taken place in this area, legislated experimental studies have given enough proof for its efficacy in the process ofstabilization of soil (Arora et al., 2019). The advantages of using nanomaterials in the field of ground improvement is not recognized completely. Using small quantities of nanosilica had a high tendency for aggregation in aqueous solutions which causes a stronger interaction between particles due to the large specific surface area of SiO_2. Pham and Nguyen (2014) demonstrated the positive effect of nanoparticles in reducing swelling potential of dispersive soil. Bahmani et al. (2014) investigated the impact of two different sizes of nano-SiO_2 on compaction, hydraulic conductivity, and compressive strength of cement-treated soil. The authors illustrated that nano-SiO_2 with smaller particle sizes (about 15 nm) was more effective in improving soil mechanical properties than an equivalent nano-SiO_2 with an average particle size of 80 nm. The studies by Masrour et al. (2021) indicated that adding an optimum amount of 1% nanosilica to dispersive clay altered the soil characteristics into non - dispersive. The present study aims to evaluate the effect of nanosilica to minimize the dispersive behaviour of silt (MH) and to monitor the strength properties of the dispersive silt treated with nano silica.

2 Materials

2.1 Soil

Soil shown in Fig. 1 was collected locally from a paddy field in Kuttanad Taluk, Alappuzha, Kerala (9.387451 N, 76.501235 E). The soil was collected from 1.5 m depth. Fig. 2 represents the particle size distribution curve of Kuttanad soil.

Fig. 1. Kuttanad soil

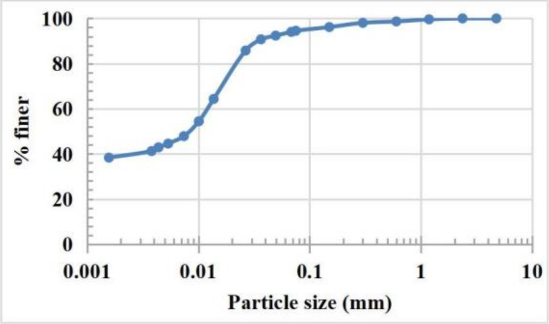


Fig. 2. Particle size distribution curve of Kuttanad soil

Table 1 shows the chemical composition (determined at X-Ray Fluorescence Lab in National Centre for Earth Science Studies (NCESS), Trivandrum) and physcal properties (determined at Geotechnical Engineering lab of College of Engineering Trivandrum) of Kuttanad soil.

Table 1 : Soil Properties

Chemical Composition		**Physical Properties**	
Formula	**Percentage (%)**	**Property**	**Value**
SiO_2	50.42	Specific gravity	2.3
TiO_2	1.07	Liquid limit (%)	65
Al_2O_3	23.95	Plastic limit (%)	52
MnO	0.07	Shrinkage limit (%)	42
Fe_2O_3	11.79	Plasticity index (%)	13
		Grain Size Distribution	
		% gravel fraction	0
CaO	1.32	% sand fraction	5.5
		% silt fraction	54.5
		% clay fraction	40
MgO	2.45	IS soil classification	MH
Na_2O	0.84	Max dry density (kN/m^3)	11.89
K_2O	2.49	OMC (%)	37
P_2O_5	0.52	Organic Carbon (%)	3.4
LOI	4.65	Organic Matter (%)	5.86

2.2 Nano silica (NS)

Nano silica shown in Fig. 3 was synthesized using combustion method (James et al., 2003). NS particles have high specific surface area and the size mainly ranges from 10 to 100 nm. The nano silica was synthesized at Dielectric Materials Research Laboratory, Mar Ivanios College, Trivandrum.

Fig. 3. Nano Silica

3 Methodology

Crumb test, double hydrometer test and the pinhole test were done to identify the dispersion characteristics of the collected soil. For crumb test as per ASTM - D 6572-12, the air dried specimen was made in the form of a cube of around 15 mm edge dimension and was placed at the bottom of a plastic pan after filling it with water that is required to completely immerse the specimen and was placed without any vibration for the next 6 hrs. Visual determinations of dispersion grade were made and recorded at 2 min, 1 hr, and 6 hr. Corresponding grades were given to the soil after the end of the test procedure. Crumb test is a quick test and hence the results may or may not be correct. Double hydrometer test as per ASTM - D 4221 - 99 is one of the accurate and simple method for determination of dispersive behaviour of soil. For this, two hydrometer set ups are needed. The first setup is the standard hydrometer setup carried out with mechanical agitation and addition of dispersing agent. The second will be a parallel test set up which is prepared without any dispersion agent and mechanical agitation. Percentage dispersion can be computed by taking the ratio of particle size less than 0.005 mm of that of the parallel hydrometer to that of the standard hydrometer from the particle size distribution curve. The third test used for dispersion identification was the pinhole test which replicates the actual field conditions. A pinhole test set up was fabricated as shown in Figs. 4 and 5 for the purpose of the present study as per method C of ASTM - D 4647 – 93 (2006). The testapparatus consisted of a cylindrical cast iron tube of 100 mm length and 50 mm diameter having cast iron lids at both the ends. Drainage provision is provided on the lids as circular openings of 10 mm diameter welded with 25 mm long threaded tubes having the same diameter. The drainage is provided at the center (inlet) for one lid and at the bottom (outlet) for the other. Soil sample was compacted at maximum dry density in a separate PVC tube having the same dimensions as that of the cast iron cylinder and was carefully extruded and inserted into the test apparatus. A 1 mm hole was punched into the specimen using a centering guide. The specimen was sandwiched between fine aggregates of size 2 mm to 6 mm. The cast iron cylinder with the specimen was placed on a V - shaped two legged stand such that the longitudinal axis of the cylinder is horizontal. After the assembly of the apparatus water was allowed to pass through the specimen with different heads at the level of the pinhole. The initial head given was 50 mm. After the completion of first cycle the heads were increased to 180 mm, and 320 mm as per the test observation.

After identifying the soil to be in medium dispersive, different percentages of nano silica were added to the soil to find the optimum percentage of NS to make the soil to a lower dispersion state. Unconfined compressive strength tests were done to monitor the strength behaviour of the soil treated with nano silica. To understand the mechanism behind lowering the dispersion and improving the strength, analysis was done at micro structural level with the help of FESEM and XRD of natural soil sample and treated sample.

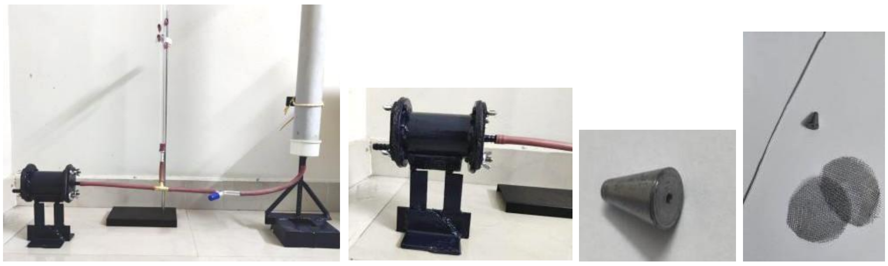

(a) (b) (c) (d)

Fig. 4. Fabricated pinhole test equipment (a) test setup (b) pinhole equipment (c) centering guide (d) wire punch, needle

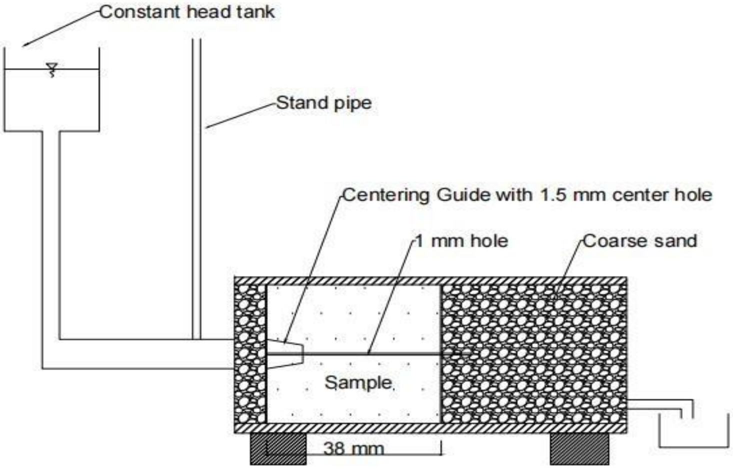


Fig. 5. Schematic diagram of the pinhole test equipment

3.1 Identification Test Results

From all the tests, Kuttanad soil showed a moderate dispersion behaviour. From crumb test results shown in Fig. 6, it can be inferred that the soil shows a Grade 3 dispersion. From pinhole test results shown in Fig. 7, the end hole diameter after test completion was found to be 1.8 mm. This was observed when the head was raised to 180 mm. The water collected had a cloudy appearance. So it can be inferred that the Kuttanad soil showed some dispersive behaviour and can be classified as moderate dispersive soil (ND3) from pinhole test. From the double hydrometer test results shown in Fig. 8, Kuttanad soil was found to be medium dispersive with percentage dispersion equals 39.32%. The summary of the test results are presented in Table 2.

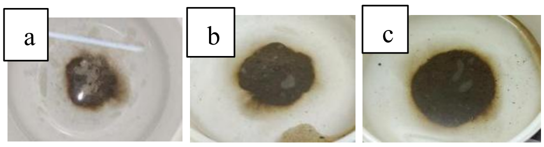


Fig. 6. Different stages of crumb (a) 2mins (b) 1 hr (c) 6 hrs

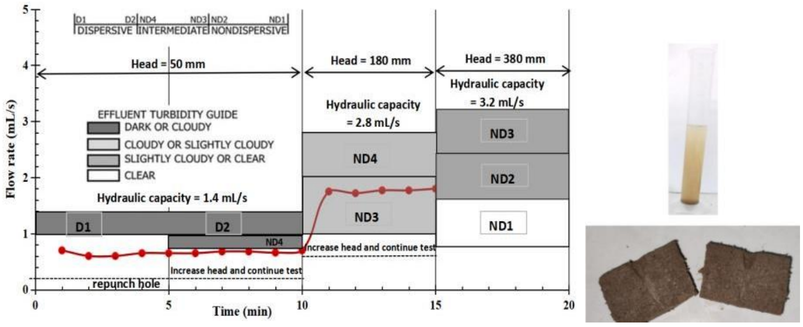
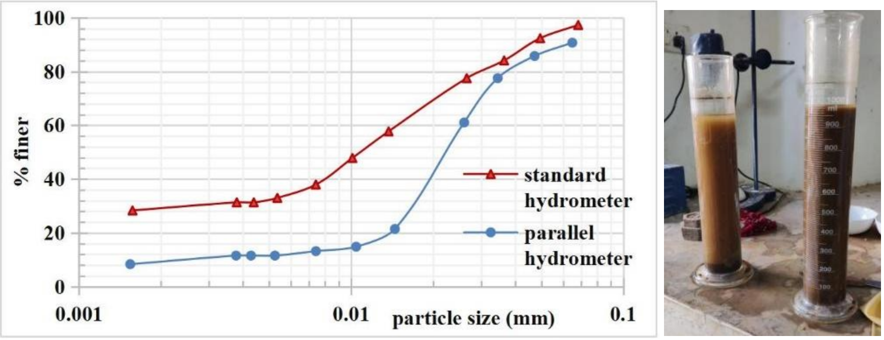


Fig. 7. Results of pinhole test (a) Flow rate and dispersive grade of Soil (b) End pinhole (c) collected effluent



(a) (b)

Fig. 8. Double hydrometer test(a)Particle size distribution (b) Test setup

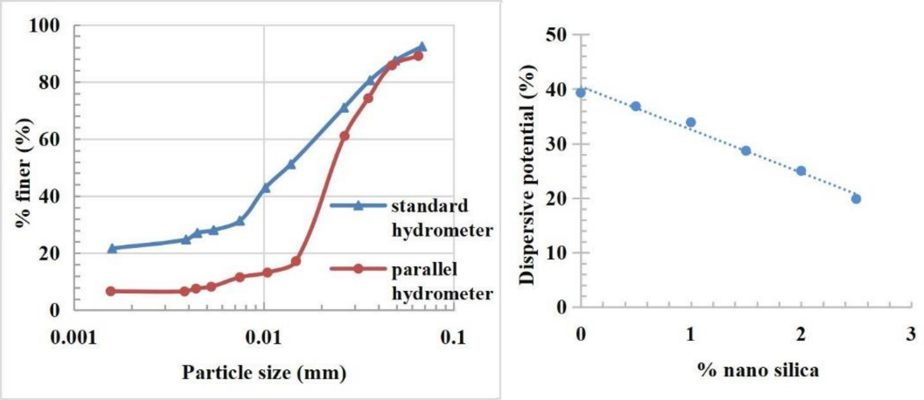
Table 2. Dispersive soil test results

Crumb test	Double Hydrometer test (% dispersion)	Pinhole test	Inference
Grade 3 at test completion	39.32 Medium dispersive	ND3 slightly to moderately dispersive	Moderate dispersion

4 Results and Discussion

4.1 Effect of Nano Silica on Dispersion behaviour of Soil

From the double hydrometer test results shown in Fig. 9 (a), it was observed that on adding 1.5% nano silica, the dispersion potential of soil was brought below 30% which means that the soil had a low dispersive nature. At 1.5% NS addition dispersion percentage was 28%. Therefore 1.5% was found to be the optimum percentage of nano silica in treating the medium dispersive Kuttanad soil. Fig. 9 (b) shows the variation in dispersion percentage with nano silica addition and it clearly gives the values of dispersion percentages of the soil when treated with different NS percentages.The cation exchange and agglomeration at an early age are the main reasons which attributed to the reduction in dispersion potential of the NS treated specimens which is evident from the micro structural studies reported at the end of this paper.



(a) (b)

Fig 9. (a) Double hydrometer result on soil+1.50% NS **(b)**Variation in dispersion potential with nano silica addition from double hydrometer test

From the crumb test results shown in Fig. 10, it was observed that when 1.5% of nano silica was added to the soil, the crumb test sample did not show any reaction and no cloudiness was observed and was transformed to Grade 1 category which is non dispersive. Results of crumb test are represented in Table 3.

Table 3 : Results of crumb test as per ASTM - D 6572-12

Percentage nano silica (%)	**Time** **2 mins** **Grade**	**1 hr** **Grade**	**6 hrs** **Grade**
0	2	2	3
1	1	1	2
1.5	1	1	1

(a) **(b)**

Fig. 10. Results of crumb test after 6 hrs (a) soil (b) soil + 1.5% NS

Pinhole test was done for natural soil and soil with varying the nano silica content (0.50%, 1% and 1.50%). The main aim was to confirm the test results obtained from double hydrometer and crumb test. When 1.5% nano silica was added the effluent from the outlet was clear under all the heads and the end pinhole dimension did not change much compared to the initial diameter which confirms to non dispersive soil which is shown in Fig. 11. Fig. 12 represents the graph of flow rate with time for soil treated with 1.5% NS. 1% nano silica also resulted in non dispersive type of soil. Considering the results of all the three tests, the optimum amount of nano silica was fixed as 1.5%.

Fig. 11. (a and b) Size of hole and (c) clear effluent after 1.5% NS addition

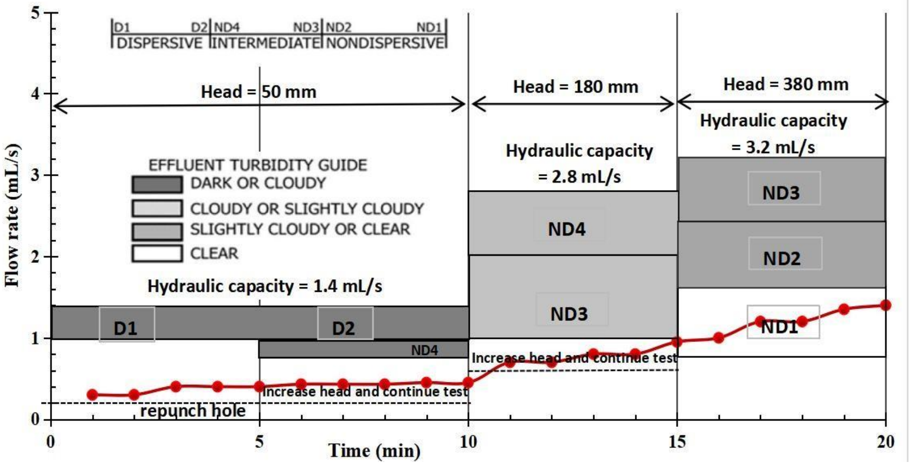


Fig. 12. Flow rate and dispersive grade of 1.5% NS treated Soil

This mechanism of lowering the dispersion behaviour of soil is mainly attributed to the agglomeration of the particles when treated with nano silica. The dispersion is mainly caused by the clay fraction present in the soil and the presence of organic matter. With application of nano silica the concentration of multivalent cations such as Si^{3+} in the pore fluid can be increased due to solubility or partial solubility of NS. Cations having higher valance can easily substitute the cations having lower valance. Therefore, a base exchange may occur with the multivalent cations of NS. This phenomenon, which is a part of short-term reactions between soil and stabilizer, can result in the formation of agglomerated structure and reduce the dispersion potential.

This is also substantiated by the micro structural studies reported at the end of this paper.

4.2 Effect of Nano Silica on UCS of Soil

Fig. 13 represents the stress-strain graph from UCS test which plots strain response for increased loading. UCS of the soil was obtained to be 61 kPa. From the graph, it is evident that UCS value of stabilized soil specimens increased with the addition of increasing NS content. However the residual strength of the samples were much low with NS addition. On adding nano-SiO_2 by varying percentages of 0.50%, 1%. 1.50% and 3%, the values of UCS increased by 1.03, 1.18, 1.45, and 2.45 times respectively than that of original soil. Failure strain kept decreasing with nano silica addition. But with 0.5% nano silica, no reduction in strain was observed. The decreased values of failure strain for soil stabilized by nano-SiO_2 were 0.92, 0.88, and 0.65 times than that of original soil for 1%, 1.5%, and 3% NS content respectively. The nano silica occupies the pore spaces in the soil structure and makes a denser matrix which is the main reason for the initial strength gain as the soil gets more denser and stiffer. Fig.15 presents the failure pattern of nano-SiO_2 stabilized Kuttanad Soil. The failure mechanism of treated specimens is the formation of tensile cracks due to the very brittle behaviour of the soil due to NS addition. NS is hydrophilic in nature which can transform the soil into a stiffer state which makes the soil brittle.

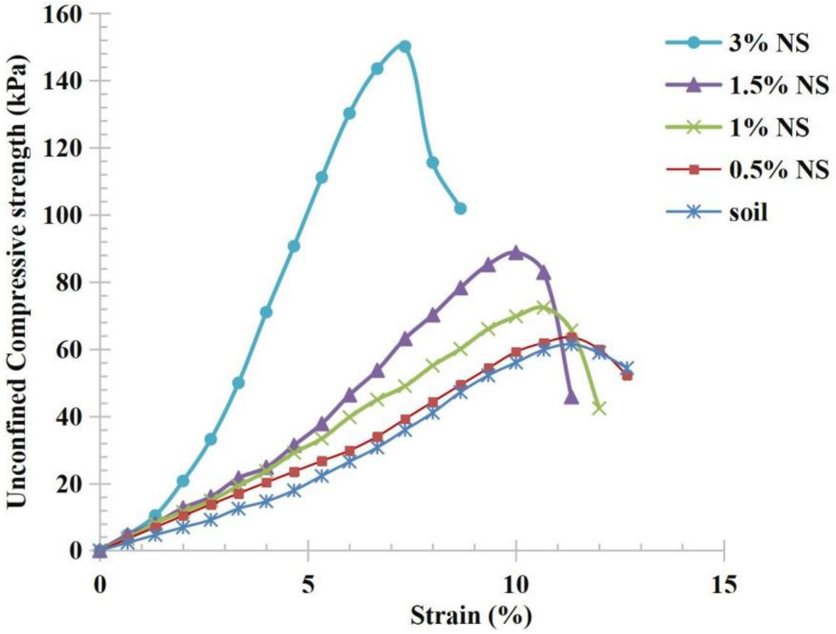


Fig. 13. Stress-Strain curves for varying nano silica content

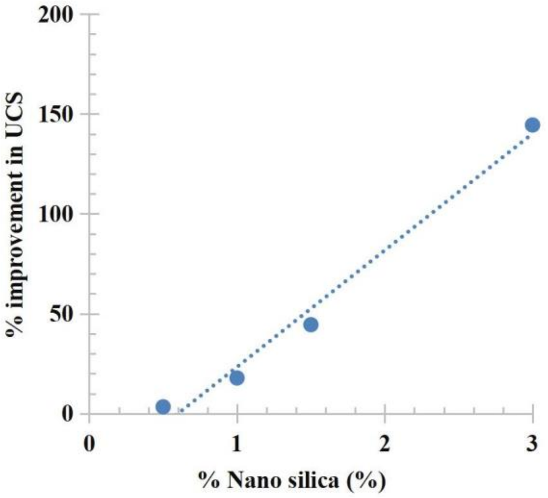


Fig. 14. % Improvement in UCS with NS

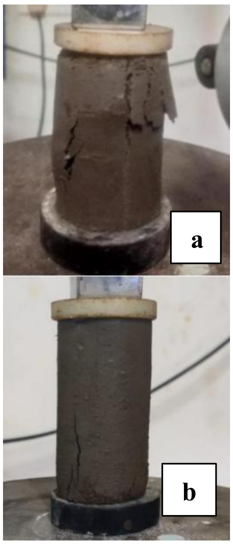


Fig.15. (a) Soil (b) Soil+NS

Based on the UCS value, the consistency of the soil can be determined. It can be categorized to different categories such as very soft, soft, medium, stiff, very stiff and hard. If the UCS value is less than 25 kPa it is considered to be very soft, 25 - 50 kPa is soft, 50- 100 kPa is medium, 100 - 200 kPa is stiff, 200 - 400 kPa is very stiff, and greater than 400 kPa is hard. The initial UCS of the soil was 62 kPa which is initially in a medium stiff category (Arora, 2003). It can be observed that on treating with lower percentages of nano silica, the soil was still in a medium stiff state. At 3% addition of nano silica, the soil was transferred to a stiff consistency. Fig. 16 shows the variation of secant modulus values on changing nano silica content with soil.

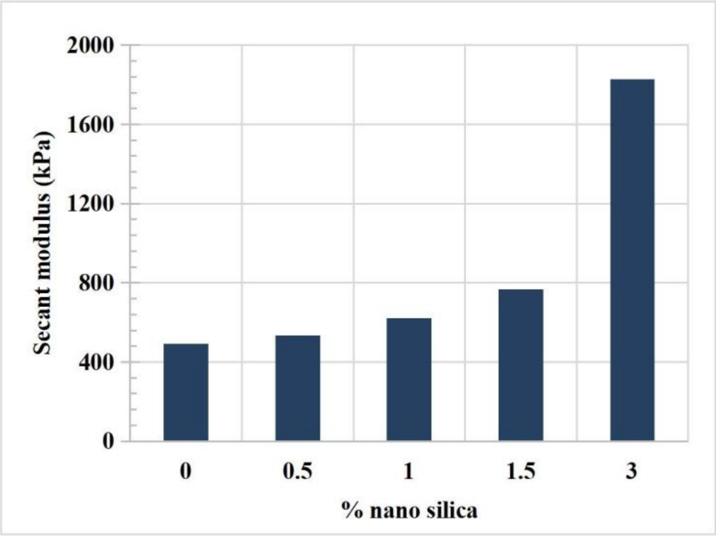


Fig. 16. Secant modulus for soil treated with varying nano silica

4.3 Micro Structural Analysis

The comparison of the Figs. 17 (a) and (b) reveals that the untreated soil specimen has a dispersed like structure. It can also be seen that the number of pores present in untreated specimen is more than treated specimen. With 1.5% addition of NS to the soil sample, the particles showed agglomeration, and number of pores decreased as the NS was found to enter into the pore spaces. As per the study of Goodarzi and Salimi (2015), these transformations were followed by short-term reactions such as cation exchange. Addition of NS to the soil leads to chemical reactions and a denser soil matrix which ultimately increase the strength of the soil. It can be inferred from Fig. 17 (b) that pores between the particles were filled with nanosilica which resulted in smaller pores, and denser particle packing contributing to a denser soil matrix. Fig.18 shows the X- ray diffraction pattern of treated and untreated soil.

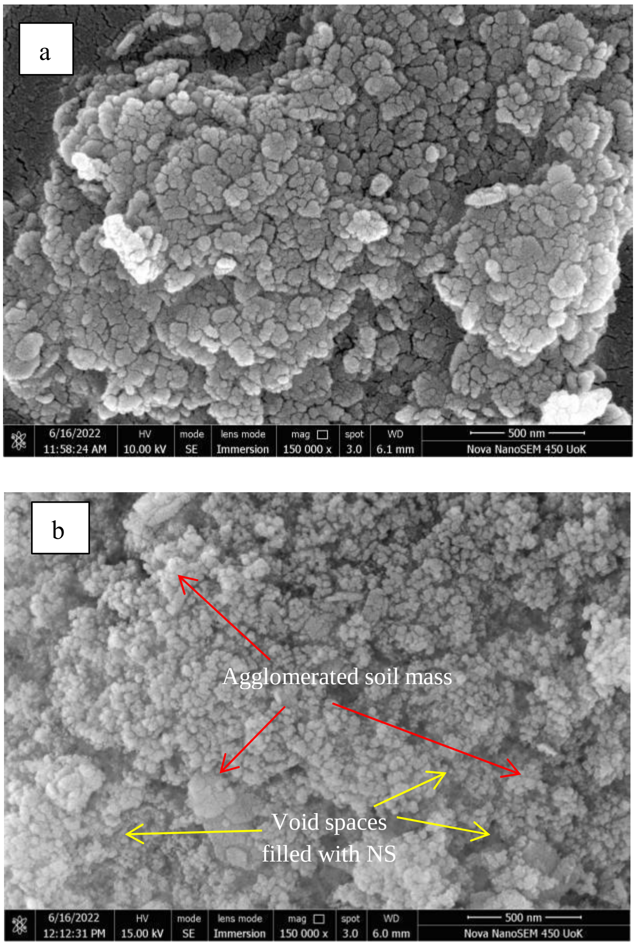


Fig. 17. FESEM Images (a) untreated specimen (b) 1.5% NS treated specimen (Magnification : 1,50,000)

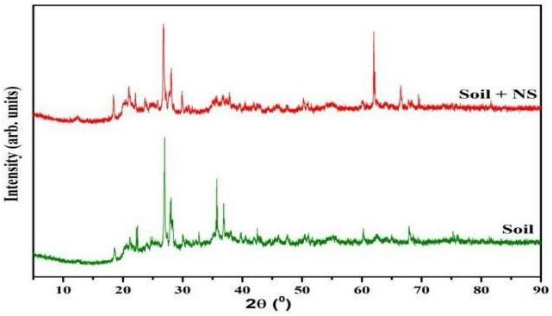


Fig. 18. XRD Patterns of soil and soil + 1.5% NS

The peaks shown in Fig. 18 represents Kaolinite (12.96, 21.11, 26, 35.75, 39.72,46.04, 49.55, 51, and 65.68), Calcite (23.2, 29.89, 30.99, 44.09, 48.29, 60.3, 62.01, and 64.99) and Quartz (26.93, and 36.84) minerals. It is evident from the pattern that the presence of nano silica reduced the intensities of certain peaks corresponding to Kaolinite and Quartz and increased the intensities of the characteristic peaks ofCalcite. New peaks developed in the nano silica treated specimen is due to theformation of C-S-H gel which is shown by the peak at 29.2 ° . This result can be endorsed by the observations reported by Consoli et al. (2019), and Masrour et al. (2021).

5 Conclusions

With increasing nano silica content, the dispersion was found to decrease and at 1.50% NS, the medium dispersive soil was reduced to a low dispersion state. The unconfined compressive strength also increased with nano silica addition but with decreasing strain values.

- Nano silica was added in varying proportions to the soil and the optimum percentage of nano silica obtained was 1.5% in lowering the dispersion potential of the soil.
- The UCS increased with the increase in nano-SiO_2 content. By adding different nano-SiO_2 percentages, the increased values of UCS were 1.03, 1.18, 1.45, and 2.45 times than that of original soil for 0.50%, 1%. 1.50% and 3% NS respectively.
- With 1.5% optimum content of nano silica obtained for reducing the dispersion potential, UCS value was increased by 45% at 10% strain value.
- The increase in strength is due to the fact that nano silica have a very large surface area and these nano sized particles occupy the pore spaces between the soil particles and makes the soil matrix to a more denser state. However the soil becomes more brittle than the initial soil with low residual strength which may be due to the water absorption capacity of these nano silica to make the soil to a more stiffer state.
- From FESEM analysis, it was observed that the micro and macro pores of the soil matrix were filled with nano silica particles hence a denser matrix was observed which is one of the main reasons for strength improvement. Moreover the soil can be seen to have transformed to a more agglomerated state which in turn reduced the dispersive behaviour. From XRD analysis, it was observed that calcite peaks increased which is one of the reasons for strength improvement. These are the reasons for the reduction of dispersion behaviour of the soil.

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