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Mechanical Behaviour of Nano-material (Al_2O_3) Stabilized Soft Soil

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ABSTRACT

Rapid urbanization and requirement of infrastructure, stable construction sites are not available. Therefore, there is a dire need for improvement of marginal soils to be used as a construction material. However, weak soils comprise of saturated clays, fine silts, and loose sand, which are susceptible to failure and pose problems of stability. Therefore, this research aims to study the strength and microstructural behavior of soft soils treated with nano-alumina (Al_2O_3) additive. In this study, Al_2O_3 of different percentages (0.5, 1.0, 1.5, and 2.0%) by dry weight of soil was added to a clayey soil and subjected to compaction and unconfined compression strength tests. The compaction tests showed that nano-Al_2O_3 (< 2.0%) stabilized soils exhibit higher unit weight and lower water content compared to untreated soils. This may be attributed due to the fact that nano-materials possess higher unit weight compared to untreated soils and these materials occupy the pore spaces in-between the soil grains, which reduce soil porosity and increase the shear strength. The unconfined compressive strength test on cured treated soil specimens showed a significant increase in shear strength on the addition of nano-alumina. The scanning electron microscopic analysis on untreated and treated soil specimens showed that untreated soil samples exhibit a compact array of clay grains and nano-material treated soil display closely packed and condensed fine structure, which authenticates an increase in shear strength. Thus, with the addition of Al_2O_3, there has been a significant improvement in the engineering properties of soft soils.

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1. INTRODUCTION

Soil is being used as an engineered construction material and as a foundation medium to support virtually all structures, becomes an indispensable component of the construction industry and, therefore, plays a most prominent role in geotechnical engineering design. However, rapid urbanization and the requirement of infrastructure, stable construction sites are not available. Therefore, there is a dire need for improvement of marginal soils to be used as a construction material. Previous researchers have done their research by using nanomaterials with the combination of additives like Fly ash, Lime, cement, etc on the weak soils. In this present research, different percentages (0.5, 1.0, 1.5, and 2.0%) of nanomaterials were used to enhance the improvement of soft soils. But the weak soils comprise of saturated clays, marine clays, fine silts, and loose sand, which possess low bearing capacity and are susceptible to failure and pose problems of stability [1-2]. These soils are not suitable in its in situ state to be used either as building stuff or as foundation support and pose high- risk engineers in terms of both strength and serviceability requirements [3-4]. However, their mineralogy and geotechnical properties allow using of these soils if properly characterized and improved [5]. Thus, there is a dire need for establishing suitable strategies for the improvement of weak soil deposits to avoid stability problems. Among various ground improvement techniques available, the nanotechnology is eco-friendly and sustainable improvement techniques for stabilization of soft soils in which nano-material as an additive in nanoscale can be used in soil stabilization to enhance mechanical characteristics of weak/soft soil deposits [6].

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Nanotechnology, as a ground improvement technique could be utilized to improve the physical and engineering properties of weak soils and to avoid the stability problems. It has been reported that the use of nanomaterials as an additive is one of the most effective and eco-friendly stabilization techniques for improving engineering behaviour of marginal soils in various geotechnical applications [7-8]. It is a well-established fact that clayey soil exhibits the smallest particle size (< 2um) and there are also some commonly occurring soil nanoparticles classified as "nanoscale particles" formed in an uncontrolled natural environment, which possess large specific surface area and would impact the engineering behaviour of soil [9]. These soil nanoparticles or "nanoscale particles" are entirely different from the conventional type of micro-sized soil minerals in terms of engineering behaviour of soils [10]. Zohair et al. [11] in their research analyzed the slope at different angles in silty soil. The proposed methods to stabilize the existing slope are replacing soil-cement (7% by weight) by vertical layering and layering along the slope. After replacing soil-cement with both methods, the FOS improved significantly. Ekeleme et al. [12] conducted an experimental dispersion coefficient in soil by using three different soil samples which include sand, clay and silt soil. Each sample was gradually introduced into a fabricated iron column with a dimension of 30cm*60.96cm. Silver nitrate solution was allowed to pass through the vertical column. Samples of soil were collected at a constant distance of 10cm and a time interval of 5mins for up to 60mins. The absorption of nitrate was taken at a constant distance of 10cm. Thereafter, the dispersion coefficient was calculated. In this research work, Kassou et al. [13], estimated the undrained shear strength of clay by using SHANSEP method as well as the slope stability analysis of embankments on soft soils during staged construction. In additin, the variations of undrained shear strength and the safety factor have been presented. However, at the nano-scale, a nano-material is a particle with one dimension at the nanometer scale (1nm-100nm) and has a very high specific surface area (SSA), contain intraparticle nanoscale voids compared to classical clay particles at micro-scale and exhibits different forms such as nanoplatelets, nanowires, nanotubes and nanodots [14]. Due to high SSA, surface charges and different formations, there is a tremendous potential of nanomaterials in various geotechnical applications, which can significantly improve the physical and engineering characteristics of soft soils [15-16]. Norazlan et al. [17] in their study reported that due to a higher ratio of surface to volume, a small proportion of nanoparticle of kaolin significantly altered the geotechnical properties of kaolin clay. Nano kaolin has been successfully used for many high-quality constructions works in geotechnical applications for civil engineering design [18].

Many researchers have reported that adding nano-material as an additive to clayey soils reduce the swelling index of clay [19], increase index properties of soil [20], decrease permeability [21] and increase the compressive strength of the treated soft soils [22]. Lee et al. [23] conducted extensive research on the use of nanomaterials in the construction industry and found that the application of nanotechnology helps in developing unique products, which can improve conventional construction materials in terms of strength and serviceability. Arabania et al. [24] also reported that use of nano clay improved the microstructure and mechanical properties of soil stabilized by cement. Çelik [25] injected different percentages of nanoparticles of nano-silica oxide (SiO_2) and nano alumina oxide (Al_2O_3) into poorly graded sand and found that the compressive strength increased significantly at an optimum content of 0.9% of nano-silica and 0.6% of nano alumina oxide and there was a marginal effect of nanoparticles beyond optimum content. Nazari et al. [26] investigated some tests on nano alumina stabilized concrete and concluded that not only the tensile and flexural strength of concrete improved but the cement could also be replaced by adding high purity Al_2O_3 as an additive. Similar results have also been by various researchers [27-28]. Jahromi and Zahedi H [29] and Khalid et al. [30] found that Al_2O_3 as an additive in combination with cement content rapidly improved strength and CBR value at an early stage of soil stabilization, which is advantageous in completion of projects with time-bound constraints. There are extensive studies available on soft soil treated with SiO_2 nanoparticles [31-34], however, only a few results are available on soft soil treated with Al_2O_3 nanoparticles and hence more investigations are desirable. Therefore, the main objective of the aforementioned research was to study the effect of nano-alumina as a stabilizing agent on the physical and engineering characteristics of soft soils. The nano-material (Al_2O_3) was chosen as an additive for determination of the compaction parameters (e. g. maximum dry unit weight and optimum moisture content) and the unconfined compression strength (UCS) of stabilized samples at different curing periods of 0, 7, 14 and 28 days. Further, the test results were supported by conducting SEM analysis tests on untreated and treated soil samples.

2. MATERIALS AND METHODS

2. 1. Soil In this study, disturbed and undisturbed soil samples were obtained at a depth of 0.5-1.0m below the ground surface from two sites at

Nagbal (Site: S-1) and Pampore (Site: S-2) in J&K respectively. All the basic tests, which physical properties [35-37], index properties [38], compaction characteristics [39] and strength parameters [40-41] were determined as codal procedure as given in Table-1. Scanning electron microscopy tests were conducted on untreated soil samples, which clearly depicted that soil samples collected from site-1 exhibit large size clay lumps while as soil samples from site 2 show clay particles of different arrangements. The pore void spaces are clearly observed between the soil particles and exhibits dispersed structure with no aggregations.

2. 2. Nano-material Nanomaterial (Nano-Al_2O_3) *in* powder form having purity higher than 99.5% was procured from M/S Nano Research Lab. Jharkhand. The average particle size (APS) of nanomaterial particle was about 30nm. The chemical properties of nanomaterial powder are given in Table 2.

Scanning electron microscopy and XRD tests were also conducted nano-alumina powder samples. The SEM images of the nanoparticles showed (Figure. 1a) that the nano Al_2O_3 are agglomerated particles with large pore voids. Also, the X-ray diffraction (XRD) analysis is used for mineral phase's identification and quantification present in a sample. In this study, XRD technique was also conducted to access the crystallite size of nano-material particles, to measure the average spacings between layers of rows of atoms in a substance and to determine the orientation of an individual grain or crystal. XRD tests were performed by irradiating a crystalline sample with a beam of X-rays, which interact with the sample in such a way that these rays are diffracted from the atomic planes. The interaction of the incident rays with a certain set of atomic planes produces constructive interference when the interference angle 2**θ** satisfies the Bragg's Law:

$$n\lambda = 2dSin\theta \quad (1)$$

where: **n** is an integer number (known as diffraction order), λ is the wavelength of the used radiation and **d** is the lattice spacing between the atomic planes **θ** ***is*** the diffraction angle.

Figure 1b shows the XRD image of the Nano-Al_2O_3, which illustrates that the diffraction angle and the intensity of each of the diffraction peaks can be measured, processed and counted. Nine reflections were observed at 2θ angles around 19, 20, 28, 38, 41, 49, 53^0, 64 and 71^0 respectively. Average particle size was calculated from all peaks and was found to be 30 nm.

2. 3. Testing Materials and Research Plan The testing programme includes soil classification and preparation of test specimen [35], specific gravity [36],

TABLE 2. Chemical Properties of Nano-Alumina Oxide (Al_2O_3)

Property	Value
Purity (%)	99.9 %
Molecular formula	Al_2O_3
Color and form	White powder
Al_2O_3	>99.5 %
CaO	<0.017 %
Fe_2O_3	<0.035 %
MgO	<0.001 %
SiO_2	<0.05 %
Average particle size	30-50 nm
Specific surface area (SSA)	120-140 m^2/g
Bulk density	1.5 g/cm^3
True density	3.97 g/cm^3
pH	7-9
Morphology	Spherical
Crystallographic structure	Rhombohedral
Atomic weight	101.96 g mol^{-1}
Melting point	2072 ºC
Boiling point	2977°C
Loss on ignition (850°C/2h)	< 0.5 %

TABLE 1. Properties of soil test data

Property	Site-1	Site-2
In situ or natural water content, w_n (%)	30.3	35.7
In situ or natural water content, w_n (%)	15.4	14.6
Specific Gravity, G_s	2.67	2.65
Sand (%)	01	04
Silt (%)	89	91
Clay (%)	10	5
Liquid limit, LL (%)	37	42.8
Plasticity index, PI (%)	14.4	26.3
Plasticity index of A-line, PI_A (%)	12.4	16.6
Plasticity index of A-line, PI_U (%)	26.1	31.3
Clay mineral type	Illite	Illite
Soil classification (as per USCS)	ML	ML
Consistency index, I_C	0.47	0.43
In situ cohesion by UCS test, c_u (kN/m^2)	28.6	24.3
In situ cohesion by DST test, c_u (kN/m^2)	16.7	14.9
Angle of internal friction by DST, ϕ_u (Deg)	31	25
Optimum moisture content, OMC (%)	23.1	24.9
Maximum dry unit weight, MDU (kN/m^3)	15.4	14.9

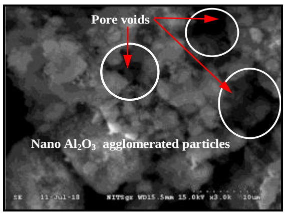


Figure 1a. SEM image of the Nano-Al_2O_3

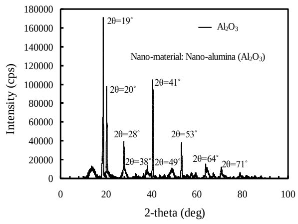


Figure 1b. XRD image of the Nano- Al_2O_3

gradation [37], the Atterberg limits [38], compaction test [39] and shear strength tests [40-41]. Table 1 shows the physical properties of the two soil samples. In this study, the experimental program includes Standard Proctor compaction tests and unconfined compression strength (UCS) tests on nano-material stabilized soil samples with varying nano-Al2O3 percentages (0.5, 1.0, 1.5, and 2.0%) by dry weight of soil. The soil samples admixed with different proportions of nanomaterial were prepared in a custom-designed UCS set-up of a cylindrical mold of a diameter of 38 mm and 76mm long. All soil samples for UCS tests were mixed on the basis of optimum moisture content at 0.95γdmax (Standard Proctor test) maximum dry unit weight of soft soil samples and then extruded from the cylindrical tube using a soil sample extractor carefully. The unconfined compression tests were carried out immediately on remolded soil samples and other soil samples were stored for 7, 14 and 18 days curing period in the desiccator respectively. After completion of the UCS test on uncured and cured soil samples, sample pellets were collected for the SEM analysis on/along the failure plane.

3. RESULTS AND DISCUSSIONS

3. 1. Physical and Engineering Properties of Virgin Soil Samples Based on basic soil investigations, the soil is poorly graded clayey silt with low compressibility (ML). The specific gravity values of soil samples are in the narrow range of 2.65 to 2.67. The standard Proctor light compaction tests were carried out on untreated soil and the optimum moisture content varies between 23-25% and the maximum dry unit weight varies in the range of 14-16 kN/m^3 respectively. The unconfined compression strength and direct shear tests were carried out to determine the shear strength parameters of the in-situ soil samples as per codal procedures. Based on test results, it is seen that soil can be classified as soft consistency and as such cannot be used either as building material or as foundation support and hence needs improvement.

3. 2. Effect of Nano-material on Compaction Characteristics of Soil The soil samples were prepared by adding different proportions of nano-alumina (0.5, 1.0, 1.5 and 2.0%) by dry weight of soil and thoroughly mixed before compaction tests. The Standard Proctor compaction test [39] was performed to determine the maximum dry unit weight (MDU) and optimum moisture content (OMC) of nano-alumina admixed soil samples. The effect of nanomaterial additive on the compaction characteristic of stabilized soils is illustrated in Figure. 2. It is seen that OMC gradually decreases and the dry unit weight increases for both sites. The soil samples are admixed with 1.5% nano-alumina turns-out to be optimum content to yield MDU and OMC for both sites. The MDU varies in the range of 15.4 kN/m^3 to 16.4 kN/m^3 for site-1 and 14.9 kN/m^3 to 15.5 kN/m^3 for site-2. Similarly, the OMC decreased from 23 to 20% for site-1 and from 25 to 22% for site-2 respectively. This may be attributed due to the fact that nano-materials possess higher unit weight compared to untreated soils and these materials occupy the pore spaces in-between the soil grains, which reduce soil porosity and increase shear strength. However, it is also observed that the moisture content gradually increased beyond the optimum content of nano-material. This is understandable since the nano-materials exhibit a very large surface area, which absorbed more water resulting in a gradual increase in water content. Furthermore, there would be the formation of agglomeration of nano-material particles beyond the optimum limit, which would result in an increase in pore void spaces, which results in absorbing higher water content. Similar results have also been reported by various researchers [42].

3. 3. Effect of Nano-material on Strength Characteristics of Soil The unconfined compression strength (UCS) test is the quickest test to determine the undrained shear strength of clayey soils for short-term stability analysis. The test was carried out as per BIS [40]. In this study, soil specimens were prepared and compacted under standard compaction at

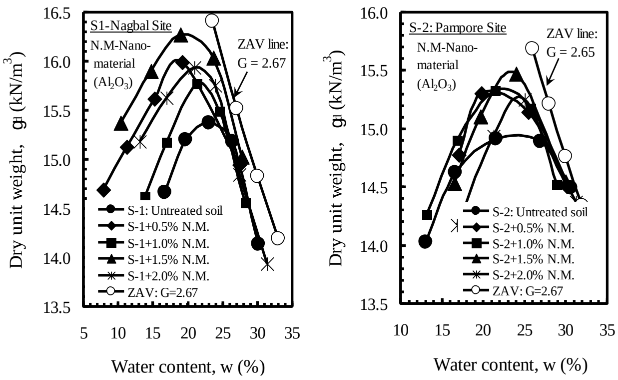
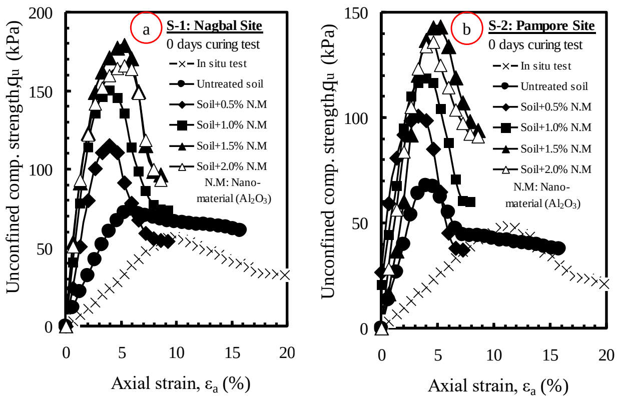


Figure 2. Compaction curves for Nano-Al_2O_3 stabilized soils for: (a). site-1 and (b). site-2

0.95 γ_{dmax} and optimum moisture content in a custom-designed UCS set-up. The UCS tests were conducted in two stages. In stage first, UCS tests were conducted immediately after preparing nano-material admixed soil specimens at varying percentages of nano-material (0.5, 1.0, 1.5, and 2.0%) by dry weight of soil material. In stage two, the UCS specimens were cured for 7days, 14days and 28days curing period before testing. The UCS tests were also carried out on cured soil specimens and specimens were collected for SEM analysis. The effect of the addition of nano-material on strength behaviour of soils for the two sites for immediate and 14 days curing period is illustrated in Figure. 3. Figure 3 demonstrates that the virgin soils possess very low shear strength and exhibit non-linear behaviour. However, the undrained strength increases and the failure strain decreases by adding nano-material with varying proportions at different curing periods. The maximum unconfined compressive strength is achieved at an optimum nano-material content of 1.5% as shown in Figure. 3. It is seen that beyond the optimum content of nano-material, the strength decreases. The undrained strength increases gradually for the initial curing period of 7 days (179 to 187 kPa), after which a rapid enhancement by curing for 14 days (187 to 236 kPa) and a rapid decrease in strength after 14 days of the curing period (236 to 128 kPa) at 28days for site-1 treated for an optimum content of nano-material of 1.5% as shown in Figure. 3. This may be attributed due to the fact that there is a very slow pozzolanic reaction between nano-materials and soil particles for initial curing period 7days and a rapid pozzolanic reaction for site-2, which indicates that soil from site-2 has higher reactive minerals compared to site-1.

The nano-material particles interact very actively with other reactive particles present in the soils, which can alter the soil behaviour. The decrease in strength beyond the optimum limit of nano-material at higher curing period may be attributed due formation of a stiffer soil matrix and flocculated structure, which resulted in lower strength. The variation of strength with



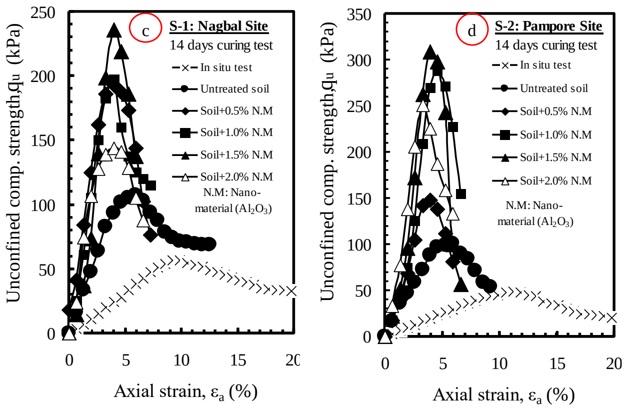


Figure 3. Effect of *nano-*Al_2O_3 content on stress-strain behaviour of soil collected from site-1 (a &c) & site-2 (b & d) for different curing periods (0 and 14 days)

increasing percentages of nanomaterials for both sites is shown in Figure. 4, and it is observed that 1.5% nano-material is the optimum limit for maximum strength for nano-material stabilized soils for different curing periods. Beyond the optimum limit, nano-material is not beneficial and cost-effective. Similar investigations have also been reported by various other researchers [19, 43].

3. 4. Microstructural Behaviour of Nano-material Treated Soils

In this study, SEM specimens extracted near the shear failure plane of tested untreated and treated soils were prepared as per the required pallet size of 10mmx10mm in the laboratory as shown in Figure 5.

The SEM tests were conducted in the CRF laboratory, NIT Srinagar to assess the microstructural arrangement and particle shape of untreated and treated soil specimens. The SEM images of nano-material stabilized soil specimens (1.5%) for different curing periods are shown in Figure 6. From SEM analysis, it is

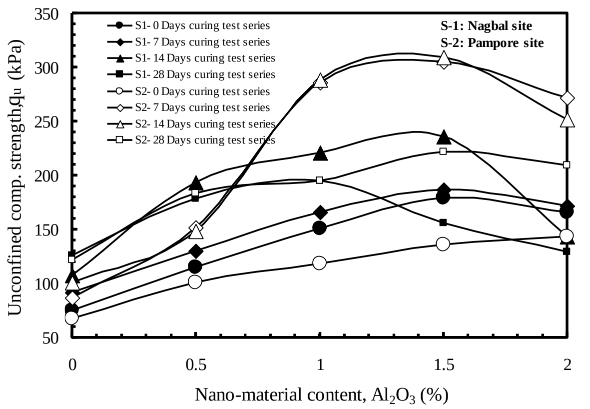
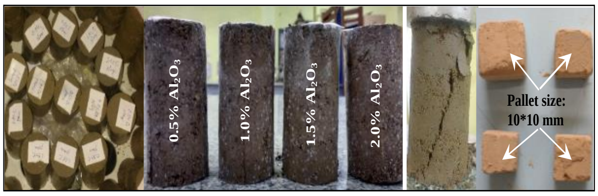


Figure 4. Variation in UCS for nano-material (Al_2O_3) stabilized soil samples



(a). Curing soil samples (b). Nano-Al_2O_3 stabilized cured samples (c). Soil samples for SEM test

Figure 5. Cured soil samples for 28days for UCS tests

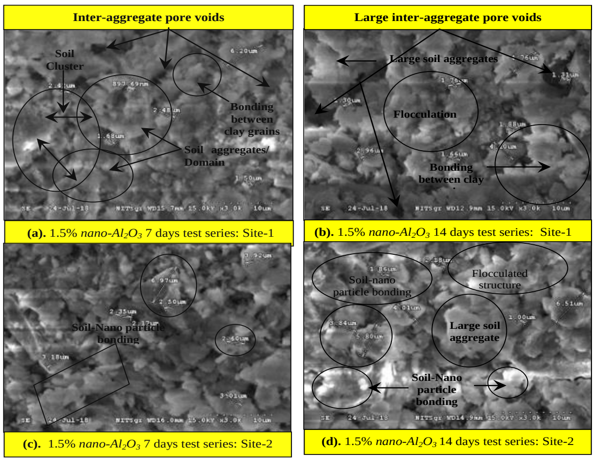


Figure 6. SEM images of nano-Al_2O_3 stabilized soil at optimum content (1.5%) during different curing periods

seen that soil samples collected from site-1 exhibit large size clay lumps while soil samples from site 2 show clay particles of different arrangements. However, the particles of treated soil specimens are closely packed with a dense microstructure with complete destructuration along the shear plane. The inter-aggregate pore void spaces are clearly seen between the soil particles and the nanomaterial particles agglomerated more than that of soil particles due to van der Waal forces between the nanoparticles. Similar investigations have also been reported by various other researchers [44, 45].

4. SUMMARY AND CONCLUSIONS

This present research provides an overview of the applications of nanometric (*Nano-alumina*) additive for the stabilization of marginal soils in Geotechnical engineering applications. The main findings are summarized as:

1. The maximum dry unit weight increased in the ratio of 1.1 for an optimum content of nano-Al_2O_3 of 1.5% for site-1 and 1.05 for site-2 respectively.
2. The unconfined compression strength of the soil improved with addition of varying proportions of nano-material (0.5, 1.0, 1.5 and 2.0%) and curing periods (0, 7days, 14 days and 28 days) for both sites.
3. The maximum strength was achieved for an optimum content of 1.5% nano-material. The increase ratios of the maximum strength for nano-material stabilized soil specimens cured for different curing periods (0, 7, 14 and 28 days) are 2.5, 2.1, 2.1 and 1.5 for site-1 and 2.5, 3.8, 3.1 and 1.9 for site-2 respectively for nano-material content of 0, 0.5, 1.0, 1.5 and 2.0%.
4. The SEM images demonstrated that the addition of various percentages of nano-material to the soil changes the structural arrangement of the clay particles with curing time.

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Persian Abstract

چکیده

شهرسازی سریع و نیاز به زیرساخت ها ، سایت های ساختمانی پایدار در دسترس نیست. بنابراین ، نیاز مبرم به بهبود خاکهای حاشیه ای وجود دارد تا به عنوان ماده ساختمانی استفاده شود. با این حال ، خاکهای ضعیف شامل رسهای اشباع ، ذرات ریز و ماسه های سست هستند که مستعد شکست هستند و مشکلات پایداری را ایجاد می کنند. بنابراین ، این تحقیق با هدف بررسی مقاومت و رفتار ریزساختاری خاکهای نرم تیمار شده با افزودنی نانو آلومینا (Al_2O_3) انجام می شود. در این مطالعه ، Al_2O_3 با درصد های مختلف (0.5٪ ، 1.0٪ ، 1.5٪ و 2.0٪) از نظر وزن خشک خاک به خاک رسی اضافه شده و تحت آزمایشات فشردگی و مقاومت فشاری غیر محدود قرار گرفت. آزمونهای تراکم نشان داد که نانو- Al_2O_3 (2/0٪)خاکهای تثبیت شده نسبت به خاکهای تیمار نشده دارای واحد وزن بالاتر و مقدار آب کمتری هستند. این ممکن است به دلیل این واقعیت باشد که مواد نانو در مقایسه با خاکهای تیمار نشده دارای وزن واحد بیشتری هستند و این مواد فضاهای منافذی بین دانه های خاک را اشغال می کنند ، که باعث کاهش تخلخل خاک و افزایش مقاومت برشی می شوند. آزمون مقاومت فشاری بدون محدودیت در نمونه های خاک تیمار شده ، افزایش قابل توجهی در مقاومت برشی بر افزودن نانو آلومینا را نشان داد. تجزیه و تحلیل میکروسکوپی الکترونی روبشی روی نمونه های خاک تیمار شده و تیمار نشده نشان داد که نمونه های خاک تصفیه نشده آرایه ای فشرده از دانه های رس و صفحه نمایش خاک با تیمار با مواد نانو را نشان می دهند که ساختار ظریف بسته بندی شده و متراکم شده است ، که افزایش مقاومت برشی را تأیید می کند. بنابراین ، با افزودن Al_2O_3 ، بهبود قابل توجهی در خصوصیات مهندسی خاک نرم وجود دارد.