World Academy of Science, Engineering and Technology
International Journal of Geotechnical and Geological Engineering
Vol:11, No:1, 2017

Effect of Nano-SiO_2 Solution on the Strength Characteristics of Kaolinite

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***Abstract*—**Today, with developments in science and technology, there is an excessive potential for the use of nanomaterials in various fields of geotechnical project such as soil stabilization. This study investigates the effect of Nano-SiO_2 solution on the unconfined compression strength and Young's elastic modulus of Kaolinite. For this purpose, nano-SiO_2 was mixed with kaolinite in five different contents: 1, 2, 3, 4 and 5% by weight of the dry soil and a series of the unconfined compression test with curing time of one-day was selected as laboratory test. Analyses of the tests results show that stabilization of kaolinite with Nano-SiO_2 solution can improve effectively the unconfined compression strength of modified soil up to 1.43 times compared to the pure soil.

***Keywords*—**Kaolinite, nano-SiO_2, stabilization, unconfined compression test, Young's modulus.

I. INTRODUCTION

THERE are many problems for construction of railways, highways and airports in clayey soils with low bearing capacity because of their high settlement potential and low shear strength. Structures constructed on soft soil can encounter engineering problems, especially settlement and swelling. Generally, chemical and mechanical stabilization are common methods for soils improvement. Investigations show that combination of these two types can help improve properties, such as durability, stiffness or strength and the capability to speed up soil treatment [1]. Chemical treatment or stabilization is one of the appropriate methods to improve the properties of very soft clay. Physical and mechanical properties of fine soil can be improved using appropriate chemical additives [2]. Borchardt ordered the chemical mechanisms such as cation exchange, anion exchange, ability to absorb, Fixation property, ability to form new minerals, property of cementation and etc. [3]. So far, lots of researches have focused on modification of soft soils using various traditional additives such as lime, cement and mineral additives such as fly ash [4]. Phanikumar et al.determined the physical and mechanical properties of the expansive clays treated with lime, fly ash, and cement [5], [6]. Brooks et al. have studied the geotechnical properties of problematic soils, stabilized with class C fly ash and limestone dust. They found that the geotechnical properties of soils are enhanced significantly by a reduction in plasticity and an increase in CBR, by stabilization with the additives [7]. Also, the strength parameters of clayey soil can be improved by reinforcement. The main concern is the in situ mix ability of fibers into clays, especially in the case of high plastic clays. Due to high plastic properties of clay, there is no possibility of mixing fibers effectively. For mechanical reinforcement, materials such as word fibers, polymers and glass fibers can be used. Also, due to high friction of coarse grain soils, an independent stabilizer can be used in these soils. For modification of clays, chemical material such as cement and lime can be useful [1].

In addition to traditional methods, rapid advancements in science and technology and the availability of new materials have promoted the development of geotechnical engineering technology including soil improvement. Several new types of nanomaterials such as laponite, colloidal silica, and bentonite suspension have been applied for soil modification purposes [8]. For the first time, the idea of using nanotechnologies was introduced by Richard Feynman's lecture in 1959 [1]. Definition for nanotechnology is different for each field of science and the National Nanotechnology Initiative (NNI) presented a comprehensive definition of nanotechnology as: “nanotechnology” is the control, comprehension, and reformation of material based on the hierarchy of nanometers to develop matter with essentially new uses and a new constitution [9].

Over the last twenty years, using of nanotechnology in soil improvement methods were of interest for many researchers [10]. Unlike traditional materials such as lime and cement, nanomaterial is permanent, nontoxic, biologically and chemically inert, and has excellent durability characteristics [11]. From an economic standpoint, the material cost of using the colloidal silica solution at 5% concentration is approximately the same as that of micro-fine cement used to stabilize an equal volume of soil [12].

In addition to mixing methods, grouting of nanomaterial such as colloidal silica was used as a new method or concept namely “passive site stabilization”. In this method, low-viscosity diluted colloidal silica is injected and transported from the site boundary to the target area through augmented or natural groundwater flow. After some time, the fluid gradually restores its viscosity as it transforms into the colloidal state, thus strengthening the bonding of the grains in the soil [13].

Spencer used dynamic triaxial tests and performed a comparative analysis between the dynamic properties of different contents of colloidal silica with mixed sand and clean sand, and demonstrated that both the shear modulus and damping ratio increase with increasing colloidal silica content [14].

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Ghazi (2011) studied on the effects of Nano- material additives on the basic properties of soil and concluded that with the increasing the Modified Montmorillonite Nano clay into pure soil, the liquid limit and plasticity index increased and result to improve the unconfined compressive strength [15].

Taha (2012) determined the Influence of Nano-material on the expansive and shrinkage soil behavior and concluded that both expansive and shrinkage strains decrease with addition of nano-Al_2O_3 to the soil [16].

Conlee (2012) compared the liquefaction mitigation in different colloidal silica contents through centrifuge model testing and analyzed the factors affecting the mitigation, further verifying the effectiveness of this method [17].

The aim of this study is determination the effect of using the different percentage of Nano-SiO_2 as additive material for improvement the unconfined compressive strength of Kaolinite. This research was carried out according to the results of Unconfined Compressive Strength tests which are more common in the practice. Laboratory program consists of two parts. Firstly, index properties of soil such as soil distribution, Atterberg limits, optimum water content was determined and secondly, Strength properties of mixed soil was obtained in different content of Nano-SiO_2 by using of Unconfined Compressive Strength tests.

II. Materials

A. Soil

In this study, in order to prevent non-uniformly effect of soil on results and determine the influence of Nano materials correctly, Kaolinite was used. The index geotechnical properties of soil were obtained according to ASTM standards specification. The grain size distribution of the fine-grained soil is shown in Fig. 1.

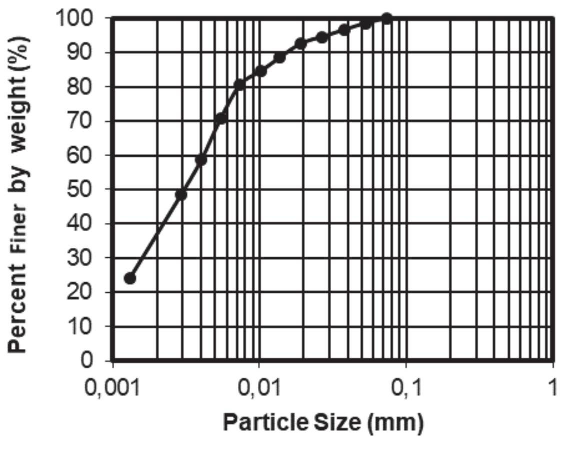

Fig. 1 Grain size distribution

The soil properties obtained from experimental tests are explained in Table I. According to the unified soil classification system, the soil used is classified as clayey soil with low liquid limit "CL".

TABLE I
PROPERTIES OF TESTED SOIL

Properties	Value
Specific gravity	2.66
Liquid limit, (LL) (%)	46
Plastic limit, (PL) (%)	24
Plasticity index, PI (%)	22
USCS classification	CL

Also, Table II illustrates the chemical components test that obtained from X-ray fluorescence (XRF).

TABLE II
CHEMICAL COMPOSITION OF KAOLINITE

Formula	Concentration (%)
SiO2	63±1
Fe2O3	0.55±0.1
Al2O3	24±1
TiO2	0.04±0.01
K2O	0.3±0.1
MgO	0.55±0.06
CaO	1.2±0.2
Na2O	0.4±0.1

The maximum dry density and the optimum moisture content of soil were determined according to ASTM D1557 standard test method [18]. Based on the results, the maximum dry density of soil is 1.75gr/cm^3 and the optimum moisture content of soil is 17%. Fig. 2 shows the modified proctor compaction curve of this soil.

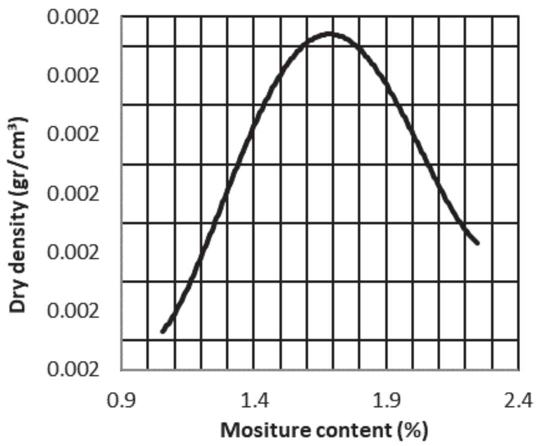

Fig. 2 Compaction curve of Kaolinite used in this study

B. Nano-SiO_2

Nano-SiO_2 solution with a concentration of 30% was used as additive material for improvement the engineering properties of Kaolinite soil. The physical properties of Nano-SiO_2 are presented in Table III.

III. Experimental Program

A. Sample Preparation

In order to compare the result at the same condition and due to practical considerations, soil samples were compacted at

95% of maximum dry density with optimum moisture content. As first step, the modified proctor compaction test was carried out to determine the moisture content-dry density relationship according to American Society for Testing and Materials specifications (ASTM D1557). To determination of Nano-SiO_2 effect on soil properties, five different contents of Nano-SiO_2 consist of 1%, 2%, 3%, 4% and 5% of soil dry weight were selected. In the second step, given that the Nano solution has a concentration of 30% and considering the water volume that is available in solution, the required water for reaching the optimum moisture content calculated and was added to the solution for each sample. Hence, the moisture contents of specimens were kept constant equally the optimum moisture content. Then diluted Nano-SiO_2 solution was sprayed to soil uniformly and mixed by hand for at least 1 hour to prepare the homogenous sample.

TABLE III
PROPERTIES OF NANO-SIO_2

Properties	Value
Color	Milky white
Purity (%)	99
Average particle size (nm)	10
Specific Gravity	1.210-1.295
Bulk density ($gr.cm^{-3}$)	1.05
PH	9.5
Stabilizing Ion	Na^+
Viscosity cps, 20^{Co} (max)	5-7

B. Experimental Test

In this study, in order to measure the strength properties of pure and treated Kaolinite, according to standard ASTM D2166 [19], the unconfined compression test was carried out to obtain the unconfined compression strength (UCS) and Young's elastic modulus under fixed conditions using strain-controlled machine and then compared the results with the original soil. After preparation of the samples, as described in Section III A, the wet soils, containing of optimum moisture content, remolded in a stainless metal tube of 38 mm in diameter and 76 mm in height. According to modified proctor compaction test results, weight of wet soil is determined so as to 95% of maximum density is reached. To perform the test, remolded specimens placed in the bottom platen device and uniform loading applied approximately with an axial strain rate of 1% per minute and recorded the load and deformation values at sufficient intervals.

IV. RESULT AND DISCUSSION

This section indicates the results achieved in present study and analysis of the results of unconfined compression tests consisting two parts: effect of Nano-SiO_2 solution on the unconfined compression strength and Young elastic Modulus of Kaolinite. Unconfined compression strength test was conducted on pure Kaolinite and Kaolinites mixed with Nano-SiO_2 solution by 1%, 2%, 3%, 4%, and 5% (by weight of dry soil) and curing time of one day in optimum moisture conditions and 95% of maximum density. Fig. 3 shows the typical prepared samples for unconfined compression test with various contents of Nano-Sio_2 solution.

Fig. 3 prepared specimens for UCS test

The stress–strain behavior of soil improvement with varying Nano-SiO_2 content obtained from unconfined compression tests is presented in Fig. 4. Patterns of this figure for all percentage of Nano-SiO_2 content indicate that the increasing the amounts of Nano-SiO_2 induced an increase in the peak strength of improved soil. Also, it shows that by increasing the Nano-Sio_2 percentage, the maximum stress occurs in lower strain and so, it follows that increasing the Nano-SiO_2 solution in Kaolinite makes the behavior of these types of soils change from ductile to brittle.

Fig. 5 shows the maximum unconfined compression strength value (q_u) of the mixture with 1, 2, 3, 4, and 5% of Nano-SiO_2, when the samples were cured in laboratory temperature at 25^0c for 1 day. According to the Fig. 5, the peak values of UCS ranged from 6.8 to 9.72 Kg/cm^2 for pure soil and soil mixed with 5% Nano-SiO_2 respectively.

To better comparison the influence of Nano-SiO2 solution content in improvement of unconfined compression strength parameter, the normalized q_u values (ratio of q_u values of modified soil to the natural soil) are shown in Fig. 6.

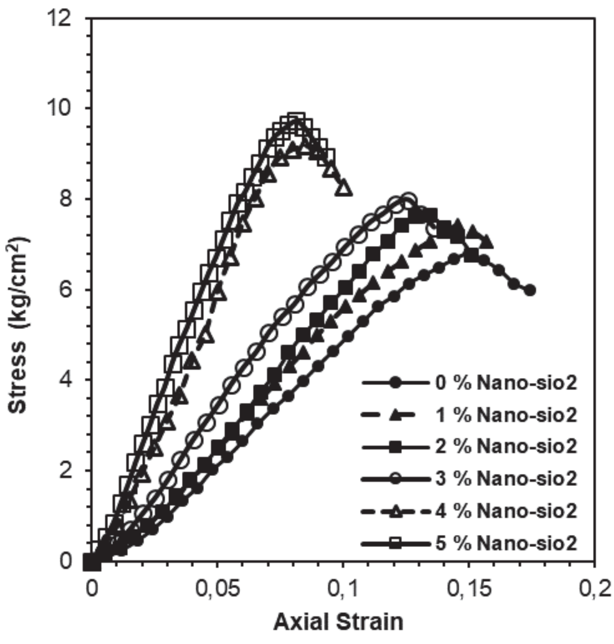

Fig. 4 Stress-strain curves of modified Kaolinite with Nano-SiO_2

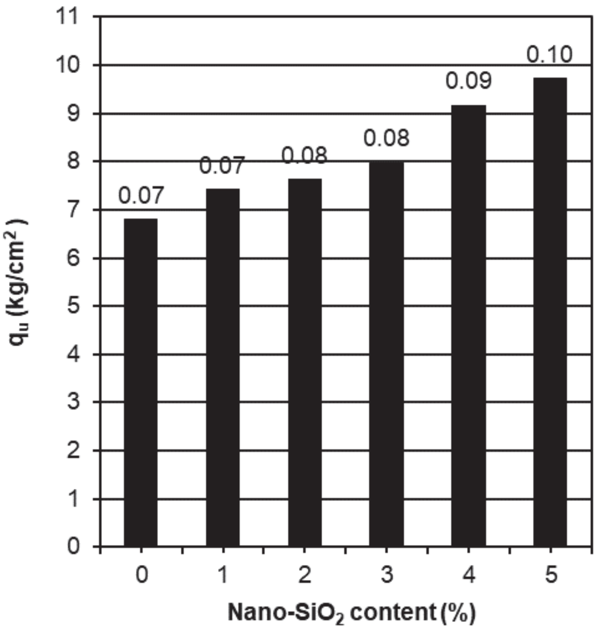

Fig. 5 The effects of Nano-SiO_2 on the UCS of modified Kaolinite

As is clear from Fig. 6, the variation of normalized q_u against the used percent of Nano-SiO_2 is nonlinear. The normalized strength of Kaolinite stabilized with 1%, 2% and 3% Nano-SiO_2 are approximately close to each other. By increasing the amount of Nano-SiO_2 up to 3 %, the normalized q_u increases to 1.17 times of natural soil and beyond which, the normalized q_u value suddenly reaches 1.35 % in specimen mixed by 4% of Nano-SiO_2. But the difference of this parameter between the samples with 4 and 5 % of Nano-SiO_2 is not significant and hence, due to economic considerations, the optimum Nano-SiO_2 content in this study is found to be 4% Based on one-day UCS results.

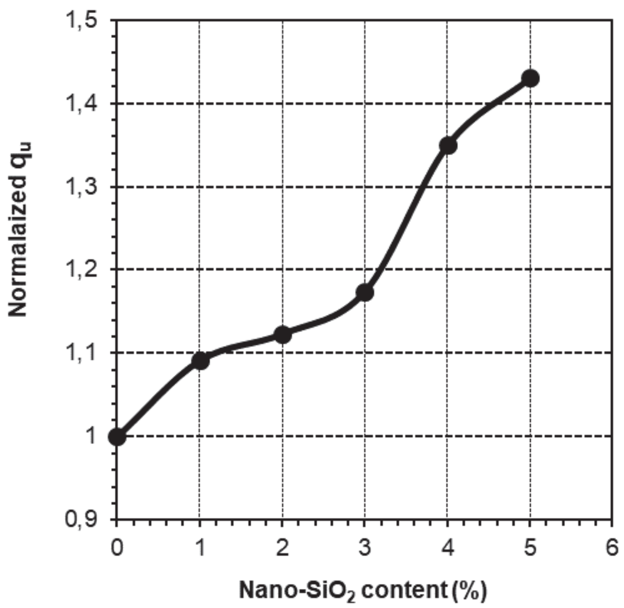

Fig. 6 Variation of Normalized q_u versus the Nano-SiO_2 content

The Young's modulus of Kaolinite samples mixed with varying Nano-SiO_2 contents achieved from unconfined compression tests are shown in Fig. 7. It can be concluded from Fig. 7, by increasing the Nano-SiO_2 content, the elastic modulus of improvement soils increase. The values of Young's modulus for original soil and Kaolinite mixed with 5% of Nano-SiO_2 solution ranged between 54.9 and 143.4 kg/cm^2 respectively.

Similar to determination the effect of Nano-SiO_2 content on the unconfined compression strength, the normalized Young's modulus (ratio of Young's modulus values of modified soil to the natural soil) variation with used percentage of Nano-SiO_2 illustrate in Fig. 8 for better evaluation of Nano-SiO_2 effect on Young's modulus parameter in Kaolinite. The observation of this figure indicates that the increase ratios of Young's modulus (normalized Young's modulus) are 1.15, 1.28, 1.43, 2.47 and 2.61 respectively, for different Nano-SiO_2 content of 1%, 2%, 3%, 4% and 5%. Similar to the previous result, up to the 3% of Nano-SiO_2 content, the severity of Young's modulus changes is low and then by increasing the Nano-SiO_2 percentage up to 4%, a considerable increasing occurs. Then by increasing the use of Nano-SiO_2 up to 5%, the intensity of variation is low. Hence, for improvement the Young's modulus of Kaolinite, the usages of 4% Nano-SiO2 by dry weight of soil can be as optimum content for practical projects.

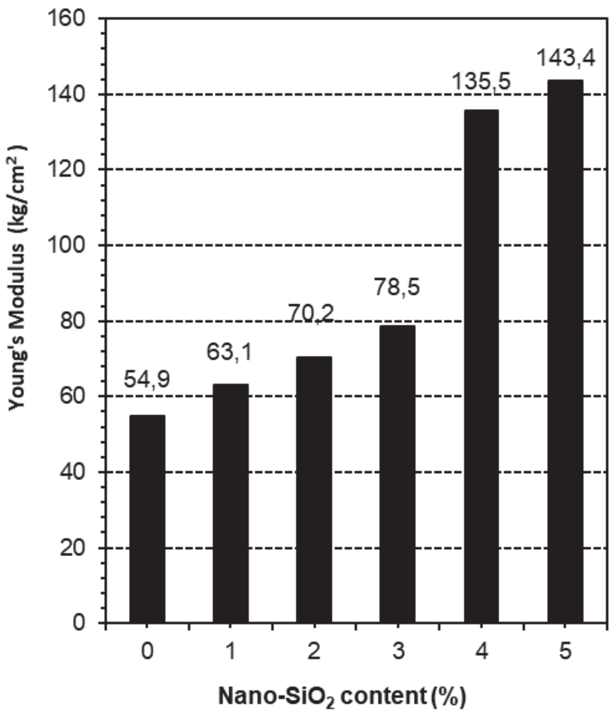

Fig. 7 The effects of Nano-SiO_2 on the Young's modulus of modified Kaolinite

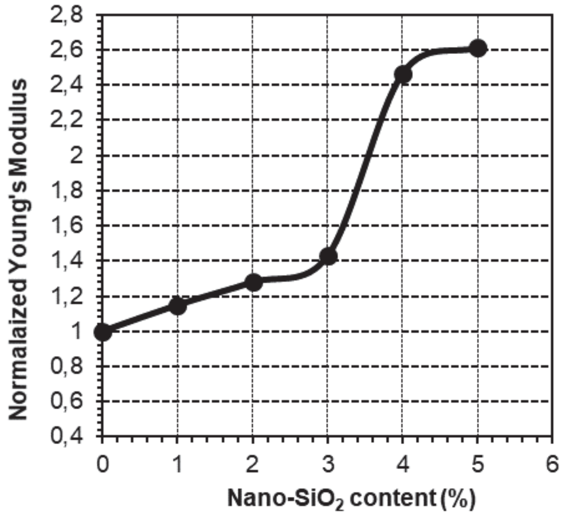

Fig. 8 Variation of Normalized Young's modulus with the Nano-SiO_2 content

V. Conclusions

Chemical stabilization is one of the appropriate methods to improve the properties of very soft clay such as Kaolinite. Physical and mechanical properties of fine soil can be improved by using of appropriate chemical additives. In this study, the application of Nano-SiO_2 solution as an additive material for improvement the strength parameters of mixed Kaolinite was investigated. For this purpose, a series of unconfined compression test were considered. Usually mixing and grouting of nanomaterial such as colloidal silica are common method for using of nanomaterial, but based on practical considerations, the mixing method was selected to prepare the test specimens. According to the laboratory tests results the following conclusions are drawn:

Considering of the stress–strain curve of Kaolinite mixed by Nano-SiO_2 solution with various content and natural Kaolinites indicates that modified soils showed higher deviator stress compared to the untreated specimens. In other word, by increasing the Nano-SiO_2 content in Kaolinite, the unconfined compression strength of mixed soil increases.

The values of UCS for all of the improved specimens are: 7.42, 7.63, 7.98, 9.17 and 9.72 kg/cm^2 and increase ratios of UCS values comparing with original sample are: 1.09, 1.12, 1.17, 1.35 and 1.43 corresponding to 1, 2, 3, 4 and 5 % of Nano-SiO_2 respectively. This means that, the strength of Kaolinite stabilized with 1%, 2% and 3% Nano-SiO_2 are approximately close to each other and then increases considerably in 4% of Nano-SiO_2, but there is no significant increasing in 5% of Nano-SiO_2. Hence, in this study the optimum Nano-SiO_2 content for stabilization the Kaolinite is found to be 4%.

The strain corresponding to the maximum deviator stress is increased by increasing of Nano-SiO_2 content. Pattern of the stress–strain response, it can be seen that increasing the Nano-Sio_2 solution in Kaolinite makes the behavior of these types of soils change from ductile to brittle.

According to the test results, the Young's modulus parameter values for modified specimens are 59.4 kg/cm^2 for pure soil and 63.1, 70.2, 78.5, 135.5 and 143.4 kg/cm^2 corresponding to 1, 2, 3, 4 and 5 % of Nano-SiO_2 respectively. Normalized Young's modulus rather than natural soil are 1.15, 1.28, 1.43, 2.47 and 2.61 in the same way mentioned. Like the result of UCS, it can deduce that the optimum value of Nano-SiO_2 content for improvement the Young's modulus of Kaolinite is 4%.

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