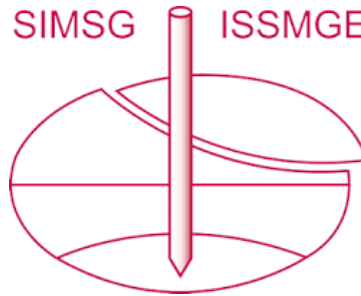


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Influence of Nanosilica on compressive strength of lacustrine soft clays

Influence de la nanosilice sur la résistance à la compression des argiles molles lacustrine

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ABSTRACT: There is not much research in the literature on the nanotechnology's application in the geotechnical field. Since lots of soil and rock minerals are nanomaterials and their chemical reactions are in the nanoscale, there is a great potential for the use of this technology in different fields of geotechnical engineering such as seepage, grouting, soil stabilization, etc. In this study the stabilization of a lacustrine soft clay was investigated using nano-SiO₂. The highly compressible soil was obtained from a site in the Texcoco ex-Lake, Mexico, and classified as high plasticity clay. Results of a set of the unconfined compression tests is study to show that the addition of nano-SiO₂ increases the strength of soil specimens, also it is demonstrated how the degree of sensitivity of the clay is reduced. Current knowledge about the behavior of soils when nano-substances are added is questioned by the unexpected response of these exceptional soils.

RÉSUMÉ : Il n'y a pas beaucoup de recherche dans la littérature sur l'application de la nanotechnologie dans le domaine géotechnique. Étant donné que beaucoup de sols et de minéraux rocheux sont des nanomatériaux et leurs réactions chimiques sont à l'échelle nanométrique, il existe un grand potentiel pour l'utilisation de cette technologie dans différents domaines du génie géotechnique tels que les infiltrations, le jointoiment, la stabilisation des sols, etc. La stabilisation d'une argile molle lacustre a été étudiée à l'aide de nano-SiO₂. Le sol hautement compressible a été obtenu à partir d'un site dans l'ex-Lac de Texcoco, au Mexique, et classé comme argile de haute plasticité. Les résultats d'un ensemble de tests de compression non confinés sont étudiés pour montrer que l'addition de nano-SiO₂ augmente la résistance de sol, il est également démontré comment le degré de sensibilité de l'argile est réduit. La connaissance actuelle du comportement des sols lorsque des nanosubstances ont été ajoutées, est défié par la réponse inattendue de ces sols exceptionnels.

KEYWORDS: Mexican clays, unconfined compression test, nanosubstance, nanoSiO₂, nano-modified clays, increased resistance.

1 INTRODUCTION.

The intention of soil stabilization is to increase the strength properties and reduce the settlement. In recent years research has focused on the exploitation of nanotechnology to modify the properties of challenging soils. *Nanotechnology* is the control, comprehension, and reformation of material based on the hierarchy of nanometers (1nm = 10⁻⁹m) to develop matter with essentially new uses and a new constitution. Considering this definition, nanotechnology is a novel approach in all sciences. Such an approach can be applied in geotechnical engineering in two ways: (1) studying the soil structure in nanometer scale to gain a better understanding of its nature; (2) conducting soil manipulation at the atomic or molecular scale, which is facilitated by the addition of nanoparticles as an external factor to soil.

Ground treatment can enhance the bearing capability of the target soil, manipulate the settlements, decrease the possibility of liquefaction and reduce the hydraulic conduciveness, water retention and discharge of the soil (Kazemian and Huat, 2009). In this investigation the enhancement of engineering properties of clays, specifically the unconfined compression resistance (as a

practical indicator to investigate the strength development), is studied. Based on past experiences in mixing fibers with highly plastic clay (polymers, plastics, word fibers, and glass fibers, to name a few), it is proposed the addition of nanosilica (nanoSiO₂) to increase the strength parameters of clayey soils. The work is conducted on lacustrine, soft and highly plastic Mexican sediments (material obtained from a site in the Texcoco ex-Lake). The purpose of this study is to show that the addition of nano-SiO₂ increases the strength of soil specimens. The UCS (unconfined compressive strength) are improved by increasing the contents of nano-SiO₂ in the soil mixture. The present-day comprehension of the behavior of soils is confronted by the unexpected response of the Mexican sediments.

2 MATERIALS AND TESTING PROGRAM

The compressive soil used was sampled from the Texcoco ex-Lake in México. Three different materials were selected for this study. According to the unified soil classification system, the samples used are classified as i) Soil No. 1 is a MH, LL 232%, LP 86%, w 185%, $\gamma_m = 1.3 \text{ Ton/m}^3$, ii) Soil No.2 is a CH, LL 205%, LP 68%, w 90%, $\gamma_m = 1.2 \text{ Ton/m}^3$ and iii) Soil No.3 is a

CH, LL 207%, LP 70%, w 245%, $\gamma_m = 1.26 \text{ Ton/m}^3$. The nano-SiO₂ selected for the mixtures is a whitish liquid with specific surface area $600\text{--}785 \text{ m}^2\text{g}^{-1}$, bulk density 0.1 gcm^{-3} , real density 2.4 gcm^{-3} , viscosity $<30 \text{ mPas}$, the solvent is water and its pH 10 ± 1 .

In order to evaluate the effect of nano-SiO₂ on strength parameters of the specimens, five groups of specimens, including one group of natural samples and four groups of specimens stabilized with nano-SiO₂, were used in the unconfined compression test. To investigate the increase in UCS due to addition of nanosilica, a series of unconfined compression tests was conducted on clay treated with different contents of nano-SiO₂ (0.5%, 0.7%, 1% and 3% of soil dry weight).

2.1 Substances preparation

Based on previous examinations (Huan-Lin et al. 2012, Mohammadi and Niazian 2013, Niroumunda et al. 2013), the contents of nano-SiO₂ selected were 0.5%, 0.7%, 1% and 3% (of soil dry weight). In the laboratory, the soil was divided into six layers and each of them was sprayed with the prescribed amount of nanosilica. The materials were fused by a cylindrical mixer during the same time periods in order to obtain homogeneous samples (To et al., 2011). The nano-composite was mixed in an impermeable metal container so that reduce water deficiency.

The unconfined compression test was performed under fixed conditions and according to standard ASTM D2166-87. The mixture was filled in a cylindrical mold (101.4 mm in diameter and 116.5 mm in height) in five equal layers and the number of blows required per layer was 30. The stainless steel tube of 38 mm in diameter and 100mm in height was pushed into the soil mixture by hydraulic jack. Then the specimen was pushed into a stainless metal tube of 38 mm in diameter and 76 mm in height. Subsequently, the specimen was pushed out from the stainless steel tube without disturbance and used for testing. For each combination of mixture, three samples were prepared and the average value of test data was obtained. The rate of strain was maintained at 1 mm/min.

3 TEST RESULTS

The results of unconfined compression test of clay stabilized with various nano-SiO₂ contents are presented in Figures 1, 2 and 3.

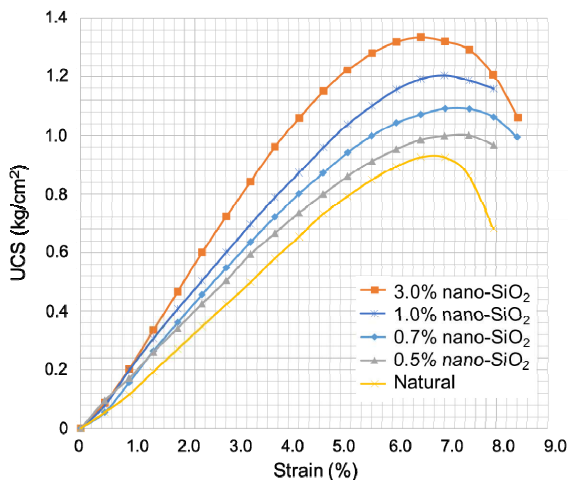


Figure 1. Stress-strain curves of clay stabilized with nano-SiO₂ obtained from unconfined compression test, Soil No.1.

The curves of resistance of this figure indicates that, with increase in nano-SiO₂ content, the peak UCS of stabilized of Soil No.1 (MH), No2 (CH) y No.3 (CH) increases and there is no evidence that the residual resistance of the materials decreases, as other researchers have pointed out (Changizi and Haddad, 2015, Sadrjamali et al 2015, Taha and Taha 2012).

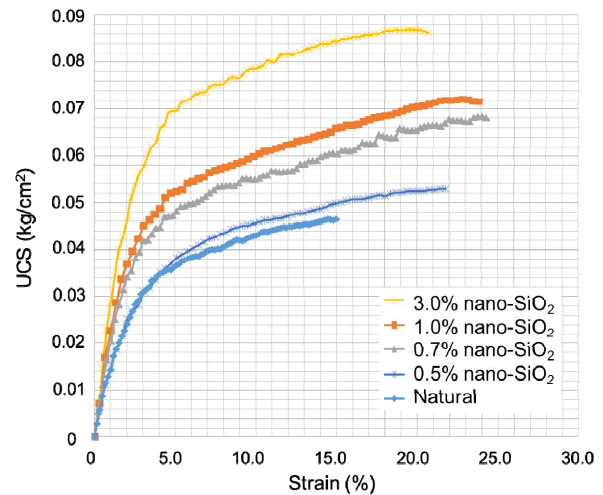


Figure 2. Stress-strain curves of clay stabilized with nano-SiO₂ obtained from unconfined compression test, Soil No.2.

The peak resistance increases with the increase in nano-SiO₂ content by $\approx 60\%$ for Soil No.1, $\approx 100\%$ for Soil No.2 and $\approx 70\%$ for Soil No.3 (comparing peak values of natural samples with those obtained for 3% nanosilica mixtures). It appears that, among the percentages of additions of nano substances tested, the optimum content of nano-SiO₂ is not found, the tendency of the curves indicates that adding more nanosilica could lead to higher levels of resistance.

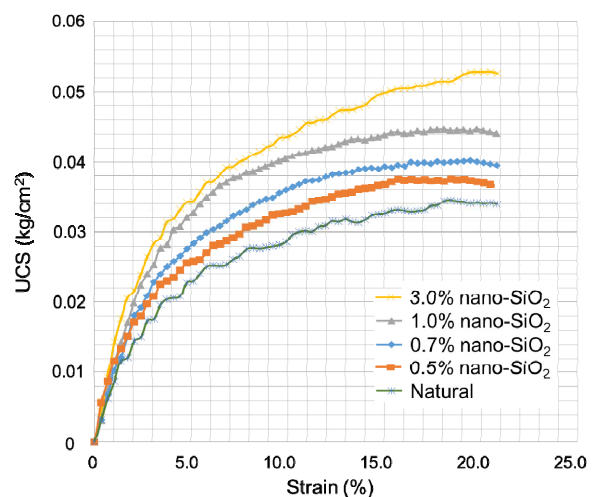


Figure 3. Stress-strain curves of clay stabilized with nano-SiO₂ obtained from unconfined compression test, Soil No.3.

By adding nanoSiO₂, the increase ratios of peak UCS are for i) Soil No.1 1.2, 1.3 1.4 and 1.6 (see Figure 1) , ii) Soil No.2 1.1, 1.5, 1.6 and 1.95 (see Figure 2), iii) Soil No.3 1.1, 1.2, 1.3 and 1.6 (see Figure 3) for nano-SiO₂ contents of 0.5%, 0.7%, 1% and 3%, respectively. Visual observations indicate that, due to the absorption of water by the nanosubstance, the clay becomes less compressible, which is exacerbated by increasing the nano-SiO₂ content.

Other researchers have found that in much less plastic clayey soils (lower LL, LP and w), there is a limit close to 1% of addition to achieve resistance increases; beyond this percentage does not seem to have an improvement in the property. There is sufficient evidence for saying that these Mexican clays have a tendency to increase strength while liquid and plastic limits suffer minimal alterations (see Figure 4).

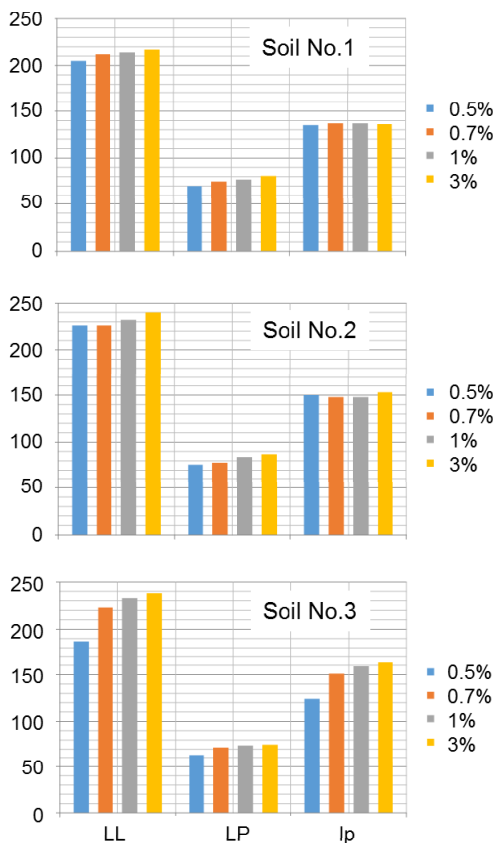


Figure 4. Liquid and Plastic Limits for Soils No.1, No.2 and No. 3

The increase in UCS of nanomodified clay occurs at slightly lower strain levels compared to the natural clay. The change in consistency of the remoulded clays when the nanosubstance is added it is clearly evident as degree of sensitivity diminishes. Figure 5 shows that specimens treated by nano-SiO₂ illustrate very brittle behavior and the tensile cracks do not lead to creation of the failure mechanism. It can be noted that increasing nanosubstance contents does not contribute to the creation of tensile cracks in the treated specimens as in other materials happen, for example concretes and low plasticity clays (Changizi and Haddad 2015).

The scanning electron microscopy (SEM) images of soil samples are shown in Figures 6,7 and 8. In the SEM photos the natural samples show a dispersed structure that is likely to develop because the quantity of pore water is enough to develop a complete double layer of ions that are attracted to the clay particles.

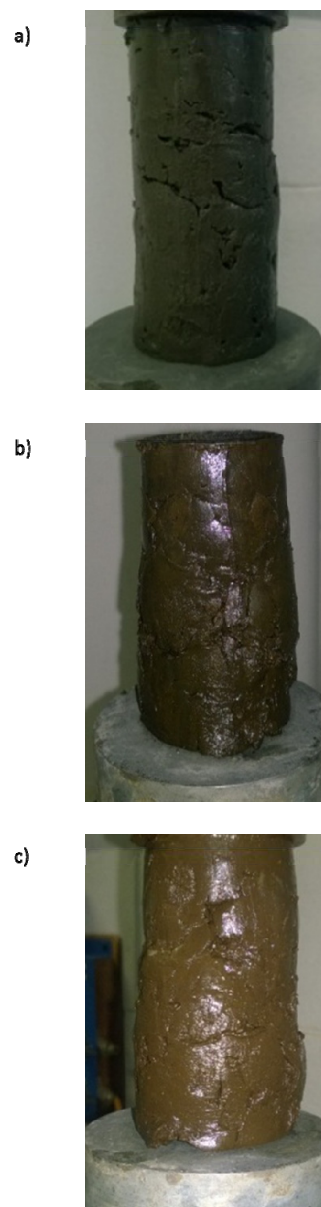


Figure 5. Effect of nano-SiO₂ on failure characteristics of soil: (a) Natural clay, b) Clay stabilized with 0.7% nano-SiO₂, and c) Clay stabilized with 3% nano-SiO₂.

As such, the clay particles and clay clusters easily slide over each other when sheared, which causes low strength and stiffness.

On the nanomodified side the nanoSiO₂ works as a viscous gel, so there is not sufficient water to develop a complete double-layer, consequently, the distance between two clay platelets is small enough for van der Waals type attraction to dominate. Such an attraction leads to flocculation with more surface to edge bonds; thus, more aggregates of platelets lead to compressible flocs, which make up the overall structure. Under this condition, the nanomodified samples exhibits the higher strength and stiffness (Horpibulsuk 2012, Landman et al. 2014). Another aspect that contributes to the increase of resistance is the composition of soils. The sediments of Texcoco ex-Lake subsoil include biochemically precipitated calcite (ostracod valves and occasional gastropod shells) and biogenic silica (diatom frustules). The water in diatoms is, to some extent, responsible for the unusual physical properties of these soils such as high plasticity and at the same time high angles of

internal friction. It is possible also that the calcite and biogenic silica permit the nano-SiO₂ to develop a stronger connection via the viscous gel, leading to an increase in frictional strength and making the distance between clay particles smaller (causing stronger clay particles contacts).

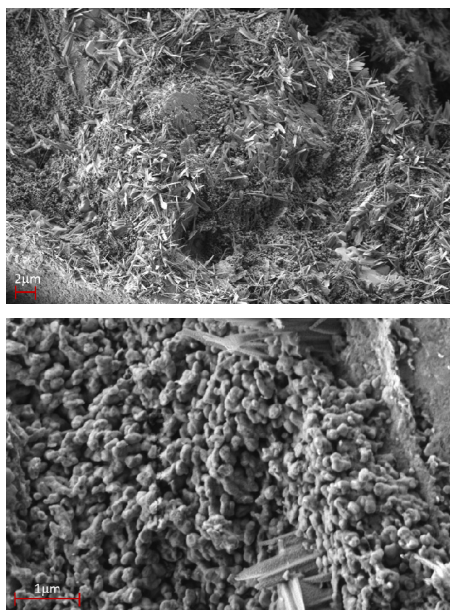


Figure 6. SEM images of Soil No.1: (top) natural specimen, (bottom) clay+3% nano-SiO₂.

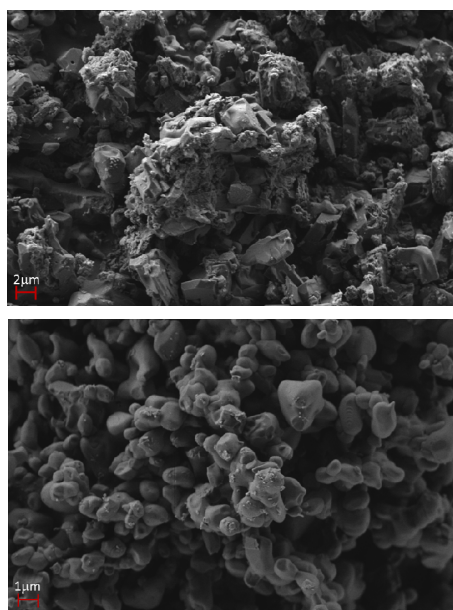


Figure 7. SEM images of Soil No.2: (top) clay+0.7% nano-SiO₂, (bottom) clay+1% nano-SiO₂.

4 CONCLUSIONS

This study investigates the effects of nano-SiO₂ on the mechanical properties of highly plastic clay, based on the results obtained from a series of unconfined compression tests. The following conclusions are drawn: (1) The UCS of the samples containing nano-SiO₂ increases with the increase in the contents of the nanosubstance. With 3% nano-SiO₂, an increase of 100% in strength is observed for the mixtures with a higher

water content (w~200%). (2) All the additions tested have positive influence on the increase in peak and residual UCSs of clays. In all samples, the maximum increase in both, peak and residual, UCSs is found at the contents of 3% and (3) The nano-SiO₂ increases the interlock force between soil particles and bond characteristics. The use of nanosilica has not a negative effect on the ductility of clay, cracks on the surface of the failed samples are not observed.

Based on this results, it can be settled that the stabilization of clay with nano-SiO₂ can be a good alternate method of ground improvement. It is clearer the possibility that, in a near future, strata of soils can be designed as materials “à la carte”.

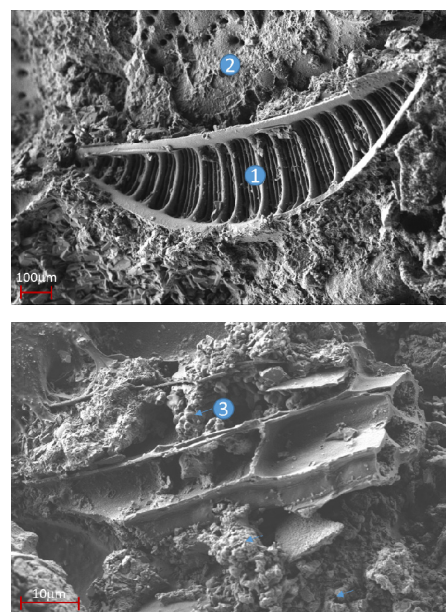


Figure 8. SEM images of diatoms frustules (1 and 2), viscous gel of nanoSiO₂ (3)

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