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Effect of nano-SiO_2 and lime on characteristics and mechanical properties of coastal clay

***Wentao Shang*[1,2], *Zhong Liu*[3], *Yuqin Gao*[3]**

[1]Research Center of Geotechnical and Structural Engineering, Shandong University, Jinan, China
[2]College of Architectural Engineering, Binzhou University, Binzhou, China
[3]Yellow River Institute of Hydraulic Research, YRCC, Shunhe Road, Zhengzhou, China

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In this study, the effect of nano-SiO_2 and lime on the characteristics and mechanical properties of coastal clay were investigated. The California bearing ratio (CBR) test and hydraulic conductivity tests were performed to investigate the improved coastal clay strength and hydraulic parameters. The clay specimens were prepared in 5 groups: unmixed, mixed with 3 % lime, 5 % lime, 3 % lime + 1.5 % nano-SiO_2 and 5 % lime + 3 % nano-SiO_2. The results show that the cementation of nano-SiO_2 and lime leads to larger CBR values and lower permeability of the coastal clay. Scanning electron microscopy reveals that nano-SiO_2 particles fill in the interspace between lime particles or gel pores, with the diameters of capillary pores and micro-pores reduced.
Keywords: coastal clay, nano-SiO_2, lime, mechanical properties, improvement.

Исследовано влияние нано-SiO_2 и извести на гидро характеристики и механические свойства прибрежной глины. Для определения прочности глины и гидравлических параметров в прибрежной зоне использовался эмпирический тест CBR. Образцы подготовлены для 5 групп: смешанные, смешанные с 3 % извести, 5 % извести, 3 % извести + 1.5 % нано-SiO_2 и 5 % извести + 3 % нано-SiO_2 соответственно. Результаты показывают, что цементация нано-SiO_2 и извести упрочняет прибрежную глину и обеспечивает более низкую гидро проницаемость. С помощью сканирующей электронной микроскопии показано, что частицы нано-SiO_2 заполняют пространство между частицами извести или гелевыми порами с уменьшением диаметров капиллярных пор и микропор.

Вплив нано-SiO_2 і вапна на характеристики і механічні властивості прибережної глини. *Wentao Shang, Zhong Liu, Yuqin Gao.*

Досліджено вплив нано-SiO_2 і вапна на гідро характеристики і механічні властивості прибережної глини. Для визначення міцності глини і гідравлічних параметрів у прибережній зоні використовувався емпіричний тест CBR. Зразки підготовлено для 5 груп: змішані, змішані з 3 % вапна, 5 % вапна, 3 % вапна + 1,5 % нано-SiO_2 і 5 % вапна + 3 % нано-SiO_2 відповідно. Результати показують, що цементація нано-SiO_2 і вапна зміцнює прибережну глину і забезпечує більш низьку гідро проникність. За допомогою скануючої електронної мікроскопії показано, що частинки нано-SiO_2 заповнюють простір між частинками вапна або гелевими порами зі зменшенням діаметрів капілярних пір і мікропор.

Table 1. Physical characteristics of the coastal clay

Specific gravity, Gs	Liquid limit	Plastic limit	Plastic index	Optimal moisture content	Cohesion	Internal friction angle	CBR
2.71	49.3	31.4	17.9	17.8	89.6	23.45	6.12 %

1. Introduction

The suitable lands for construction buildings or roads are decreasing as a result of population growth in recent years. The soil existing in some specific sites is not desirable for construction, especially for the region of coastal clay. Low shear strength, high liquid limit, poor water permeability are the properties of coastal clay. The soil improvement is assumed to be one of the appropriate solutions for dealing with this kind of soils. Soil improvement refers to a set of operations that results in the removal of some improper soil behaviors. Regarding the mentioned concept, the method of addition of lime and other additive chemicals can be used [1].

Lime is the most commonly used material for soil improvement as it hardens in air and water. The properties of lime depends is the content of active CaO and MgO, the higher of the content, the stronger is the cementation ability. The process of lime improving the soil material has both physical and chemical effects, and the combination of the two promotes essential changes in soil properties [2–6].

Nowadays, the use of nanomaterials in soil improvement has received a lot of research interest. In [7] studied the effects of different nanomaterials on the unconfined compressive strength of the soil, and suggested that there should be an optimal range of the mixing amount of nano-SiO_2 for the improvement of soil strength. Only when the content of nano-SiO_2 was within the optimal range, the soil strength would improve with the increase of the mixed content; and it would be opposite once the content of nano-SiO_2 went beyond the optimal range. In [8] added the mixture of cement into weak soil and conducted unrefined compressive strength test, permeability test, limit moisture content test, etc. The results showed that nano-Al_2O_3 could raise the unrefined compressive strength and CBR of the soil and effectively reduce the expansion rate of the soil. The addition of 1 % nano-Al_2O_3 could bring the best improvement effect.

The purpose of this study was to investigate the influences of different content of nano-SiO_2 and lime on mechanical properties of coastal clay. In order to accomplish this aim, a series of laboratory tests was carried out. The microstructural properties of treated and untreated coastal clay were inspected using the California bearing ratio (CBR) test and hydraulic conductivity test.

Table 2. Relative contents of coastal clay minerals

Semectite	Illite	Kaolinite	Chlorite
16 %	61 %	10 %	13 %

2. Experimental

2.1 Materials

The materials used in this study were coastal clay, lime and nano-SiO_2.

The coastal clay was collected from Shandong province China, and its Physical characteristics indexes and contents of coastal clay mineral are listed in Table 1 and Table 2.

The lime was collected from Weifang, China. The mass fraction of CaO is over 70 % and the mass fraction of MgO is over 2 %.

The nano-SiO_2 was from Suzhou, and the physical properties are presented in Table 3. Nano-SiO_2 is a kind of amorphous white powder (soft aggregates), with many different saturated bonds and hydroxy groups of different bonding states distributed on the surface of its particles, the molecules of which are of 3D silica structure. When nano-SiO_2 with large specific surface is added to coastal clay and the two of them blend together with the help of water, metasilicic acid (H_2SiO_3) is easily produced, from which SiO_3^{2-} and H^+ dissociate. That is, fine-grained nano-SiO_2 or their aggregates interact with water to form micellar structure. The H^+ attached to the micellar structure get attracted by the negative charge of the clay particles, wrap around them and cement with them, hence improving the connection between clay particles and further enhancing their cohesion.

Table 4 shows the experimental scheme of lime and nano-SiO_2 to coastal clay.

2.2 Laboratory tests

CBR is the ratio of the specific pressure with a material's penetration of 2.5 mm to the standard bearing capacity with the

Table 3. Physical properties of nano-SiO_2

Name	Particle size	Purity	Shape	Specific suface area	Bulk density
Nano-SiO_2	15 nm	99 %	spherical	200 m^2/g	0.05 g/cm^3

Table 4. Experimental scheme of lime and nano-SiO_2 to coastal clay

Group 1	coastal clay
Group 2	coastal clay + 3 % lime
Group 3	coastal clay + 5 % lime
Group 4	coastal clay + 3 % lime + 1.5 % nano-SiO_2
Group 5	coastal clay + 5 % lime + 2.5 % nano-SiO_2

equal penetration of a standard crushed stone. It can reflect certain bearing capacity of soil under partial lateral confinements:

$$CBR = \frac{\rho}{7000} \cdot 100, \quad (1)$$

where p – specific pressure (KPa).

CBR test is introduced to investigate the effect of nano-SiO_2 addition on the strength of the lime-improved coastal clay. The specimens were cured in two plastic bags to prevent moisture change. After 7 days of curing, the specimens were tested. They were placed on the lifting platform of the tester, with adjusting the base of the lower hemisphere to make the specimens remain horizontal in direction of the penetration rod, so that the penetration rod is fully connected to the upper surfaces of the specimens. Setting the pre-load to 45KN, and, when the preloading was completed, the readings of dynamometer and dial indicator were taken. Then, the penetration rod is pressed into the surface of the specimens at a speed of 1–1.25 mm/min, and the readings of the two dial indicators [10] are noted.

The laboratory measurement of the hydraulic conductivity of coastal clay was carried out. The falling head permeability test involves the flow of water through a relatively short soil sample connected to a standpipe which provides the water head and also allows measuring the volume of water passing through the sample. The diameter of the standpipe depends on the permeability of the tested soil. The test can be carried out in a falling head permeability cell [11]:

$$k = 2.3\frac{aL}{A(t_2 - t_1)}\lg\frac{H_1}{H_2},$$

k — permeability coefficient; a — sectional area of the variable head permeameter; L — height of the specimens; t_1, t_2 — starting time and finishing time to read the head; H_1, H_2 — starting head and finishing head.

3. Results and discussion

The results of measurements of the SDR of various samples (see Table 4) are presented in Fig. 1.

The strength of coastal clay with lime is improved due to the replacement of Ca^{2+} and Mg^{2+}, which reduces the thickness of water films absorbed on the soil particles, thus making soil particles gather together to form soil aggregates. Subsequently, the strength of coastal clay with lime is improved due to net structures formed by hard crystals (produced through carbonation), hydraulic gel materials (produced through coacervation) and soil aggregate cementation. The expansion and heating effects during lime hydration also make the soil more compact and strength improved. Therefore, in group 2, the addition of 3 % lime makes CBR increase from 6.12 % to 8.01 %. However, the addition of 5 % lime makes CBR drop to 5.83 %. The reason is that: the content of water grows with the increase of lime's content, but the corresponding hydration time has not increased.

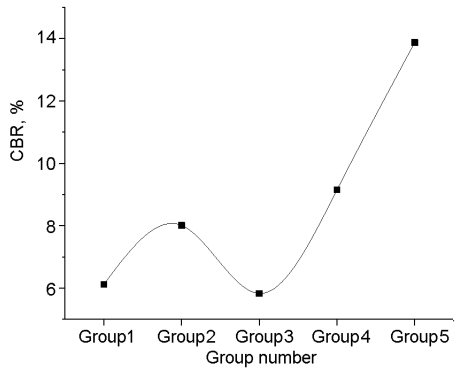

Fig. 1. Variation of CBR with the contents of lime and nano-SiO_2.

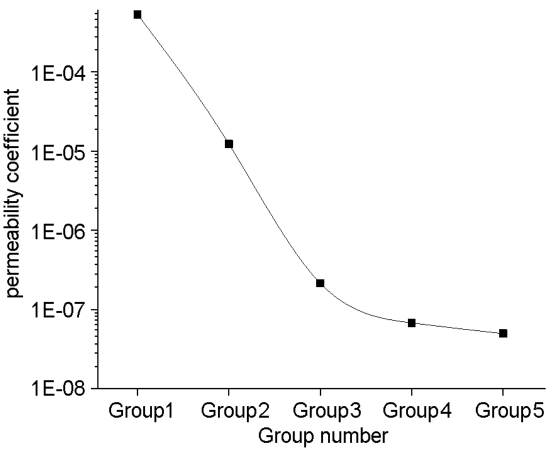

Fig. 2. Variation of permeability coefficient with the contents of lime and nano-SiO_2.

During the process of CBR test, water is squeezed out from the side of specimens, and the value of CBR will be brought down.

The cementation of nano-SiO_2 makes the coastal clay mixed with lime more compact, and the filling effect makes the pores in the clay more saturated. Denser clay has greater strength and CBR value. Compared with Group 2, except for the equally added 3 % lime in the clay of the two groups, an extra 1.5 % nano-SiO_2 is added in the clay of Group 4, making its CBR increase by 14.23 %. Compared with Group 3, except for the equally added 5 % lime in the clay of the two groups, an extra 2.5 % nano-SiO_2 is added in the clay of Group 5, making its CBR increase by 73.16 %. The greater increase of CBR of Group 5 is due to the greater amount of nano-SiO_2 which can absorb redundant water with a larger specific surface. The interaction of nano-SiO_2 and lime produces good effect.

Measurement results of changes in the permeability coefficient with different content of lime and nano-SiO_2 presented in Fig. 2.

The permeability coefficient of lime-improved coastal clay is much smaller than of the not improved. The reason is that the adding of lime changes the structure of coastal clay particles, the number of coarse particles increases, resulting in better grading and better permeability performance (Fig. 3). In addition, ion replacement leads to thinner water films in the aggregate structure thinner and lower hydrophilicity of the coastal clay. Gel reaction produces hardened cementation of calcium silicate hydrate and calcium aluminate hydrate and soil aggregates, which prevent water from entering the clay and reduces the permeability coefficient.

The filling of nano-SiO_2 makes the coastal clay more compact and low permeability. However, the reduction degree of permeability coefficient is much smaller than the reduction of permeability coefficient of coastal clay with single lime addition. Indeed, the content increase of nano-SiO_2 makes the cementation reaction of it with lime more complete, the filling effect more obvious and the permeability coefficient much lower. However, with an excessive content, some nano-SiO_2 will not be wrapped by the coastal clay and will dissolve in the water. Some seepage paths may be formed under water pressure, thus reducing the seepage-control performance.

The active SiO_2 and Al_2O_3 in the coastal clay react with lime to produce calcium silicate hydrate and calcium aluminate hydrate. The pozzolanic reaction of nano-SiO_2 can consume a great deal of $Ca(OH)_2$, which not only accelerates the consumption of lime, but also facilitates the reaction of active SiO_2 and Al_2O_3 with lime [9]. Similarly, lime will further improve the activity of nano-SiO_2 and promote various reactions of nano-SiO_2. Therefore, the properties of coastal clay can be improved by nano-SiO_2 and lime at the same time.

The pozzolanic reaction can consume and refine $Ca(OH)_2$ crystals. While generating high-Si/Ca calcium silicate hydrate, it also generate low-Si/Ca calcium silicate hydrate. Characterized by a high condensation degree of Si–O chain, small grain size, large specific surface and more contact points in the crystal intergrowth, low-Si/Ca calcium silicate hydrate has a higher strength than that of high-Si/Ca calcium silicate hydrate. There are different saturated residual bonds on the surface of hydrophilic nano-SiO_2, the molecules of which are of 3D silica structure. The bonding effect in the gel of calcium silicate hydrate is very weak, so nano-SiO_2 can become the core of calcium silicate hydrate gel and make the generated calcium silicate hydrate gel closely knitted together.

4. Conclusions

In this paper, coastal clay was taken as the object of study. The characteristics and mechanical properties of coastal clay with lime and nano-SiO_2 added simultaneously are studied. With a small particle size and large specific surface, nano-SiO_2 will react $Ca(OH)_2$ with to generate $C{-}S{-}H_{34}$ once it is evenly mixed in the lime slurry, accelerate the hydration of lime and facilitate the formation of gel phase. Meanwhile, unreacted

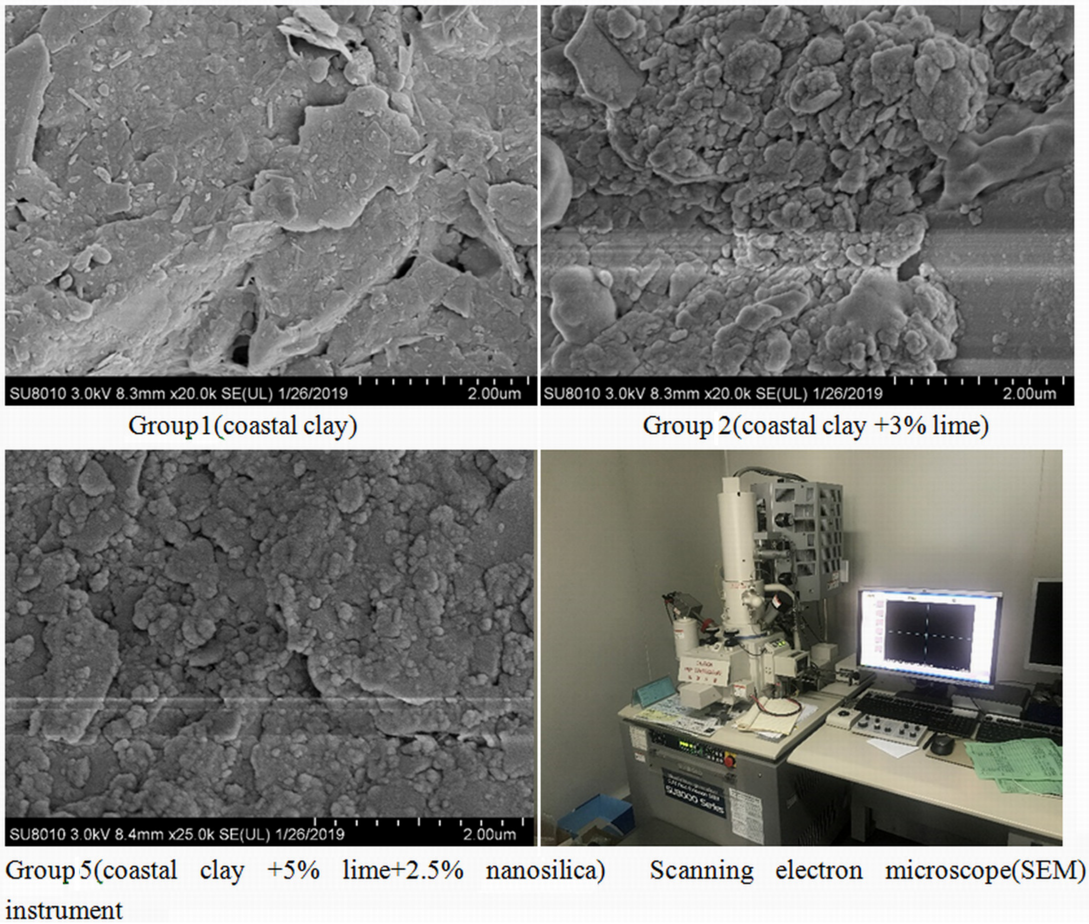

Fig. 3. Scanning electron microscope of improved coastal clay.

nano-SiO_2 particles fill in the interspace between lime particles or gel pores formed by reaction, and the diameters of capillary pores and microspores will be reduced. Hence the overall porosity of the slurry will be lowered, and the strength and compactness of the clay will be improved.

The test results show that compared with the addition of single material (lime) in the clay, the addition of two materials (lime and nano-SiO_2) can result in greater increase of CBR value of the coastal clay, and the permeability coefficient of the coastal clay will be substantially reduced. The CBR strength grows dramatically with the increase of the content of nano-SiO_2. However, some nano-SiO_2 particles non-wrapped by the coastal clay will dissolve in the water and some seepage paths may be formed under water pressure, thus reducing the seepage-control performance of coastal clay.

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