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Experimental Investigation Of Mechanical Behavior Of Improved Marl Soil Using Nano Calcium Carbonate

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Abstract

One of the problematic soil types that is found in wide areas in the world is marl soils. This soil type is more sensitive to erosion and requires modifications in pavement construction processes. In this research, mixed soil-Nano-$CaCo_3$ was considered. For this purpose, 0.3 to 2.7% Nano-$CaCo_3$, by specific dry weight, was combined with marl soils in 0.3% increments. To analyse the geotechnical properties of marl soil, optimum water content for soil compaction, maximum dry density, uniaxial compressive strength, California Bearing Ratio (CBR) and the consolidation test were investigated. The results showed dry unit weight increases with increasing Nano-$CaCo_3$ content up to 2.2%. Furthermore, the CBR of modified marl soil with 2% Nano-$CaCo_3$ is 2.7 times greater than the initial CBR; it increased from 6 to 15.5 by adding up to 2% Nano-$CaCo_3$. Moreover, adding Nano-$CaCo_3$ to marl soil increased the uniaxial compressive stress. The optimum percentage of Nano-$CaCo_3$ was 2%, which increased the compression strength about 1.4 times. Besides, with increasing Nano-$CaCo_3$ up to 2.2%, the amount of void ratio decreases from 0.46 to 0.35. Additionally, the compression index C_c and swelling Index C_s are almost constant and equal to 0.09 and 0.03, respectively.

Keywords: Soil improvement, Nanomaterials, Nano-CaCo3, Marl soils, Problematic soils

1.Introduction

In constructing a building, the underlying soils transmit the imposed load to the subsurface layers. The soil must have sufficient strength to bear the applied pressures and should control the allowable settlement. Different soil types are known as problematic soils that have unusual mechanical and geotechnical behaviours, such as erosion, swelling, collapse and dispersion. Marl soil is a type of problematic soil that has swell, erosion and creep behaviour due to its constituents. This type of soil is widespread in many countries including the USA, UK, Iran, Iraq, Turkey, Azerbaijan and Saudi Arabia.

Marl soils are a rock or soil with 35–65% carbonate and corresponding clay content. It should be mentioned that this definition cannot be generally applied to many of the rocks that are often referred to as marls in the Persian Gulf area, Britain, the USA or other countries. For example, most of the marls of the Keuper series contain less than 20% carbonate material (Bell, 1996, Bell, 2013), while Ontario and Quebec marls are reported to have more than 79% calcite (Guillet, 1969.). The properties and behaviour of this type of soil have been considered by researchers. Such soils, according to the classification of clay–lime carbonate mixtures, are marl clays (Barth, 1939). Marl soils are very sensitive to erosion and are one of the most important sources of sedimentation in catchments (Bouma and Imeson, 2000); (Jafari Ardekani et al., 2002). One of the inhibitor factors of the environmental behaviour of marl soils is its chemical properties (Sokouti and

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Razagi, 2015). Due to the great spread of marl rock in many countries, studying the characteristics of these formations is essential (Hooshmand et al., 2012). The emergence of various forms of erosion is one of the characteristics of marl areas (Ismail Nejad et al., 2007). Clay and silt are effective parameters in determining the sensitivity of marl soils derived soils to erosion (Sokouti and Razagi, 2015).

Modifying and improving bedrock and subgrades have a long history using mechanical or chemical methods. In a mechanical approach, the soils modify the texture of the soil and increase the mechanical strength of the soil by increasing the density and degree of internal friction. In chemical stabilization, the soil properties are modified by increasing the bonding between soil components. Therefore, soil improvement includes a wide range of materials such as lime, Portland cement, industrial slag, polymers, recycled materials, asphalt emulsion, etc. Among many stabilization materials, soil stabilization with lime or cement is the most widely used technique (Behnood, 2018, Sabat, 2012, Bell, 1996, Manikandan and Moganraj, 2014, Rao et al., 2011).

Nanotechnology is a relatively new approach in geotechnical engineering. Adding nanomaterial can modify the properties of soil, which implies the potential for its application in soil stabilization. The interesting features of these materials stem from the great number of atoms and molecules at their free surface and the resulting effects on their surface properties from physical, chemical and reactivity perspectives. Due to the high surface area and surface charge of nanoparticles, even small amounts of these additives can make noticeable improvements in soil behaviour. Nanotechnology has contributed to geotechnical engineering in two ways. First, it has facilitated the study of soil structure and the nature of its behaviour on a nanometre scale, and second, the analysis of soil behaviour on atomic and molecular scales have advanced the use of nanoparticles as soil additives (Choobbasti et al., 2019, Meng et al., 2017, Changizi and Haddad, 2015)

A number of studies have been performed to investigate the behaviour of stabilized soil with nanomaterials [ex. (Choobbasti and Kutanaei, 2017, Meng et al., 2017, Tabarsa et al., 2018)]. (Majeed and Taha, 2013) reviewed a wide range of nanomaterials used in soil stabilization, as well as their effects. (Khalid et al., 2015) found that the compressive strength and effective shear strength were improved and the plasticity value decreased with a different number of nano-soil particles added to soft soil. The work of (Khajehzadeh et al., 2011) had a similar conclusion. The effect of different types of nanomaterial on the expansion and shrinkage behaviour of compacted residual soil was investigated by (Taha and Taha, 2012) and both swell and shrinkage strain were found to reduce with a certain proportion of nano-material.

Nano-$CaCo_3$ (NC) is a major nano-material currently being researched. (Liu et al., 2012) found that cement paste at an early age increased with the addition of Nano-$CaCo_3$ because the early hydration of cement was activated by Nano-$CaCo_3$ (Zhao, 2019). (Meng et al., 2017) investigated the effects of Nano-$CaCo_3$ on the properties of cemented soils in the marine environment. The addition of Nano-$CaCo_3$ improved the compressive strength, enhanced corrosion resistance and promoted hydration product generation.

(Sato and Beaudoin, 2011, Sato and Beaudoin, 2019) focused on the effect of Nano-$CaCo_3$ on the hydration of cement containing supplementary cementitious materials. Their results indicated the acceleration effect of early sample hydration was enhanced with more Nano-$CaCo_3$ added and the seeding effect of the Nano-$CaCo_3$ particles improved strength development. (Li et al., 2015, Supit and Shaikh, 2014) found that both Nano-$CaCo_3$ and Nano-SiO_2 (NS) could improve the compressive and flexural strength of concrete. NS acted as an effective filling material to reduce porous areas and accelerated the cement hydration process by a pozzolanic effect, and Nano-$CaCo_3$ acted mainly as an inert filler material to create a denser microstructure and accelerated the cement hydration process through a boundary nucleation growth effect.

Despite the problems with implementing projects on marl soils, insufficient studies have been carried out to sustain these soils with modern stabilization materials. The main objective of this study was to investigate the effect of nanocarbons on the mechanical properties of marl soils. The parameters investigated in this study included Atterberg limits, maximum dry density, specific gravity, consolidation characteristics and California Bearing Ratio (CBR).

2. Materials and Method

2.1. Mechanical and Physical Properties of Soil

The marl soil was selected from the north-west area of Shiraz City. This type of soil is found in a wide area of southern Iran. This soil is a mixture of clay, calcium carbonate and gypsum. To evaluate the effect of nanomaterials, the mechanical and physical properties of soil were measured using the same procedure proposed by ASTM standard codes. Totally, 8 group of tests performed to determine the initial specification of selected soils. Table (1) shows the mechanical properties of marl soil.

Table 1
Initial mechanical properties of studied marl soils

Optimum water content	Liquid limit (%)	Plastic limit (%)	Plasticity Index	Specific Gravity	Max dry density (kN/m^3)	Cohesive (C) (kPa)	Friction angle(φ) (Degree)
ASTM D2216	ASTM D4318	ASTM D4318	ASTM D4318	ASTM D854	ASTM D1557	ASTM D3080	ASTM D3080
13	32	23	9	2.7	18.7	100	21

2.2. Nano-Caco3

In this research, calcium carbonate nanoparticles, Nano-$CaCo_3$, with the characteristics presented in Table 3 were incorporated. The calcium carbonate type is used in many projects due to its highly reactive behaviour. The Nano-$CaCo_3$ additive was selected from US Research Nanomaterials Inc. Table (2) shows the proposed material properties.

2.3. Mineralogy And Microstructure

The mineralogy and microstructure of marlsoils was investigated using a combination of several techniques that include X-ray diffraction (XRD), X-ray fluorescence (XRF), and electron microscopy equipped with a scanning electron microscope, which can provide information on the chemical composition and microstructure of constituent particles, summarize the procedures and results obtained from these techniques, and the dominant mineralogical composition of marl soils.

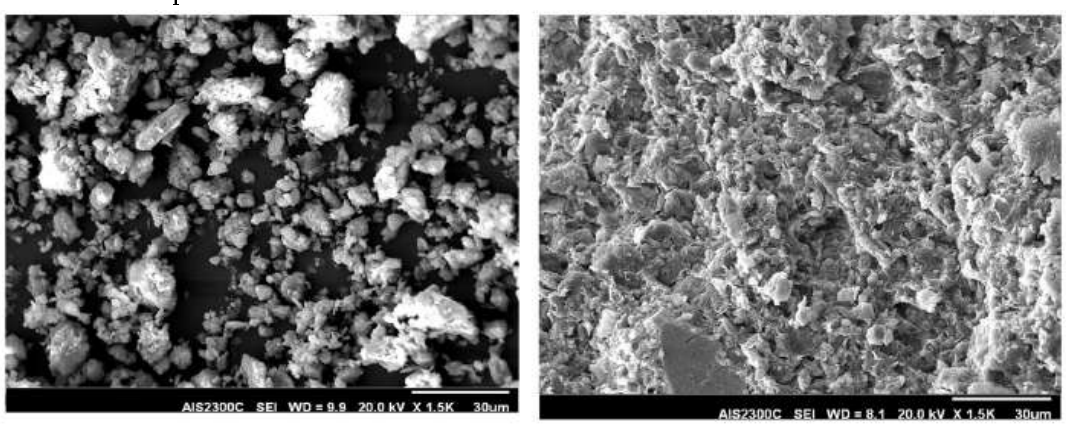
Table 2

Chemical and mechanical characterization of Nano-$CaCo_3$ (US RN Inc.)

Colour	Brightness	Moisture	Specific Gravity g/cm3	DOP Oil Absorption ml/100g ≤	PH	MgO	SiO2	Al2O3	Fe2O3	Particle Shape	Activation Grade % ≥
White	96	<0.4	2-3	32	8-10	<0.35	<0.1	<0.1	<0.1	Cubic	>98

2.3.1. Microscopic Illustration of Soils Structure

With the purpose of evaluating the materials used, the marl soils were photographed using a scanning electron microscope. Figures 1 shows the microscopy picture of a marl soils sample on the 30-micrometre scale. According to the picture, the examined soils were composed of sand and silica and can be considered as the boundary of sedimentation cycles.



(a) (b)

Fig1.Microscopy picture of sample in 30 micrometre scale:

a) photography working distance: 9.9 mm; b) photography working distance 8.1 mm

2.3.2. X-Ray Fluorescence (XRF)

The X-ray fluorescence (XRF) test is used for chemical analyses of rocks, minerals, sediments and fluids. This test has been used to determine the elemental composition of materials including metal composites, minerals, soils and rock. In this spectrometry method, the individual atoms, are excited by external energy and, therefore, obtain X-ray photons. XRF has the capability to analyse various elements, such as sodium, calcium, potassium and other minerals, in different concentrations from parts per million to high percentages. The results of the XRF analysis of the studied marl soil were carried out according to 92zr-4502 Standard. Table 3 shows the XRF analysis result of the studied marl soil.

Table 3

Elemental analysis of Nano-$CaCo_3$ used in research from XRF decomposition

Compound	marl
SiO_2	26
CaO	27
Al_2O_3	8
MgO	6
Fe_2O_3	5
K_2O	2
TiO_2	0.5
Na_2O	0.4
SO_3	0.2
LOI*	24.9

Loss on Ignition (1000°C, 2 h)

2.4.Tests Procedures

To evaluate the effect of Nano-$CaCo_3$ on the geotechnical parameters of marl soils, different dry weight percentages of Nano-$CaCo_3$ were separately added to the soils. The main purpose of this research was to determine the percentage of Nano-$CaCo_3$ and soil mixture that exhibits the highest strength and the least deformation of underlying soils. Since a disproportionate distribution of nano in the soil reduces the efficiency of nano-stabilized soils, it is necessary to mix the soil and Nano-$CaCo_3$ in a suitable manner to achieve a homogeneous composition. Various methods, such as ball milling, have been developed to evenly distribute these particles in the soil. In this regard, the dry soil samples, mixed with different percentages of Nano-$CaCo_3$ were poured into a ball mill for one to two hours. Each mixture was stirred slowly while adding an accurate amount of water, to achieve a homogenous stabilized soil mixture with a water content. To ensure a more uniform moisture distribution throughout the mixed soil-nano-$CaCo_3$-water were stored in a sealed container for 16 h. Modified marl soils were tested for the maximum dry density, optimum water content, unconfined compressive strength, consolidation and California Bearing Ratio (CBR) using the appropriate ASTM standards. Totally, 56 different tests carried out to evaluate the effect of Nano-$CaCo_3$ on mechanical properties of marl. the tests results are summarized in table (4). The data were thoroughly analysed and the results are shown in the respective graphs.

3.Results and Discussion

3.1.Standard Proctor Compaction Tests

The purpose of the compaction test is to determine the maximum dry density of the soil at optimum water content. The standard proctor test was performed for both the natural soils and the soil-Nano-$CaCo_3$ mixtures to determine the compaction parameters. The specimens were prepared following the ASTM D697-07 standard as a base for these tests. The soils were sealed in plastic bags and allowed to hydrate for at least 24 h before compaction. The standard proctor compaction curves were found to be significantly affected by the addition of small amounts of Nano-$CaCo_3$ (i.e., between 0.3% and 2.7%), as shown in Figure 2 and Figure 3. There was a consistent and fairly significant increase in the dry unit weight with increasing Nano-Caco3 content, with the maximum dry unit weight decreasing from 19.1 to 19.8 kN/m3 as the Nano-Caco3 content was increased from 0% to 2.2%. The optimum water contents increase by about 3.7% with the addition of 2.5% Nano-$CaCo_3$, after which it decreased in a consistent manner by about 1.3% as the Nano-$CaCo_3$ content was increased from 2.2 to 3%. The effect of Nano-$CaCo_3$ on the shape of the compaction curve is slightly more pronounced on the dry side of optimum.

3.2.Compressive Strength Unconfined Test

The uniaxial shear strength (UCS) of adhesive soil is measuring by the unconfined uniaxial test. This test used to determine in-place soil strength. The test is determined as a triaxial shear test with zero lateral compressive stress. In fact, the shear strength of soil depends on friction angle and coefficient of adhesion. The friction shear strength is the internal force commonly seen in granular soils, whereas the adhesive shear strength is a function of surface forces. Due to its facility and simplicity, the unconfined compressive strain control test was preferred over the stress control test. The soil strain ranged from 0.5 to 2% per minute. Samples for this test were prepared from modified marl soils.

To achieve maximum strength, the samples were prepared with the calculated optimal moisture in the compaction test. Calculations were based on axial stress amount and strain ratio, and the ultimate stress value was obtained from stress-strain curves. If there was no definite maximum strength, the strength at 11 to 15% strain was considered the maximum and the slope at the origin of the stress-strain curve was calculated as the initial elasticity modulus.

As Figure 4 shows, adding Nano-$CaCo_3$ to marl soil increased the uniaxial compressive stress. The optimum percentage of Nano-$CaCo_3$ is 2% which increased the compression strength about 1.4 times. The compression strength is decreased by adding more Nano-$CaCo_3$ than 2%.

2.2.4. California Bearing Ratio (CBR) Test

The CBR test has been used to determine the bearing capacity of the subgrade, sub-base and base of pavement, and roadbed. This is the generally used method for determining the thickness of flexible pavement. This test was performed according to ASTM D1883-87. The CBR test was carried out on compacted samples at an optimum water content. To perform the CBR test, the samples were prepared according to the modified compaction test (ASTM

D1557). Marl soils and various percentages of Nano-Caco3 were mixed. The compaction test was performed at certain intervals to achieve an optimum moisture percentage. The soil-Nano-$CaCo_3$ mixture with the optimum water content, as determined in the compaction test, was subjected to the CBR test.

Table 4
Geotechnical properties of Nano-$CaCo_3$ improved marl soils

Test		Percent of mixed Nano-$CaCo_3$ (%)									
Compaction	Optimum water content (%)	13.5	14.2	14.9	15.3	15.8	16.6	17.1	17.7	17	16.4
	$(\gamma_d)_{max}$ (kg/cm^2)	1.92	1.93	1.935	1.93	1.94	1.94	1.96	1.98	1.96	1.93
UCS (kN/m^2)		197	202	213	234	242	252	260	274	253	212
Consolidation	Cc	0.13	-	-	0.15	-	-	0.1	-	-	0.098
	Cs	0.05	-	-	0.033	-	-	0.044	-	-	0.054
	e_0	0.46	-	-	0.39	-	-	0.35	-	-	0.4
CBR		6	8	9	9.5	10.7	12	14	15.5	12.3	7.7

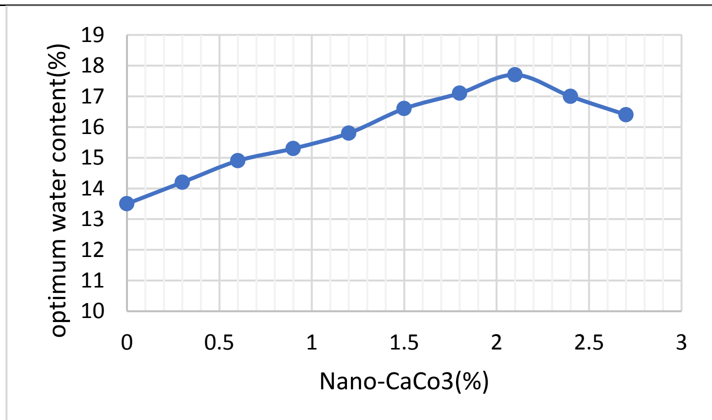


Fig.2.Variation of optimum water content marl soil modified with Nano-$CaCo_3$

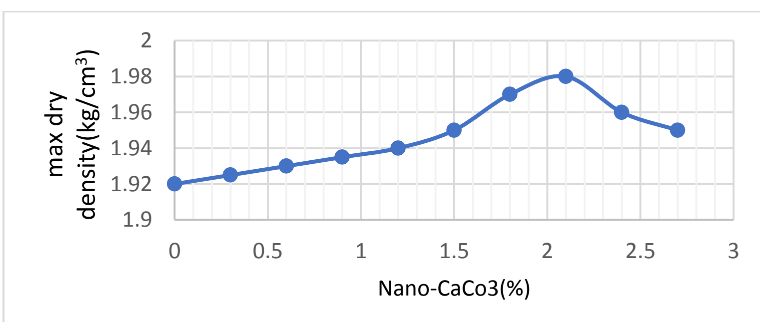


Fig.3. Variation of maximum dry density of marl soil modified with Nano-$CaCo_3$

According to the results, the CBR values of soil samples modified with Nano-Caco3 increased relative to the initial soil sample as well as during the curing time. The initial CBR was 6. Based on Figure 5, the CBR is increased up to 2%. The CBR of modified soil with 2% Nano-$CaCo_3$ was 2.7 times the initial CBR and the soil had a tendency toward coarse granulation in terms of soil classification. As a result of hydration in the Nano-$CaCo_3$-soil mixture, soil particles get together and stabilize, and soil strength parameters increase.

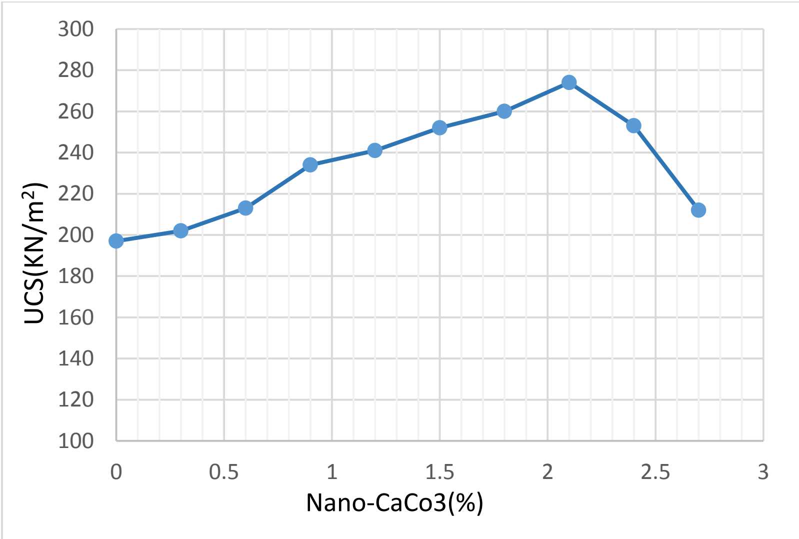


Fig.4. Variation of unconfined compression strength of marl soil modified with Nano-$CaCo_3$

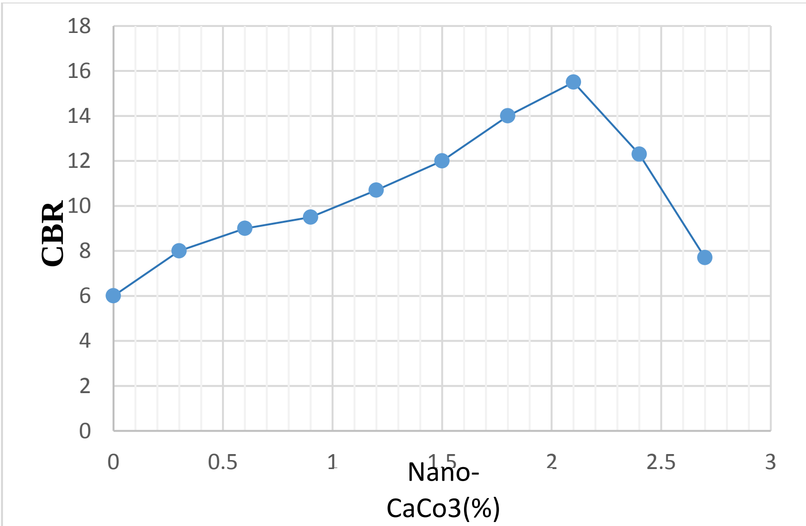


Fig.5.Variation of CBR of marl soil modified with Nano-$CaCo_3$

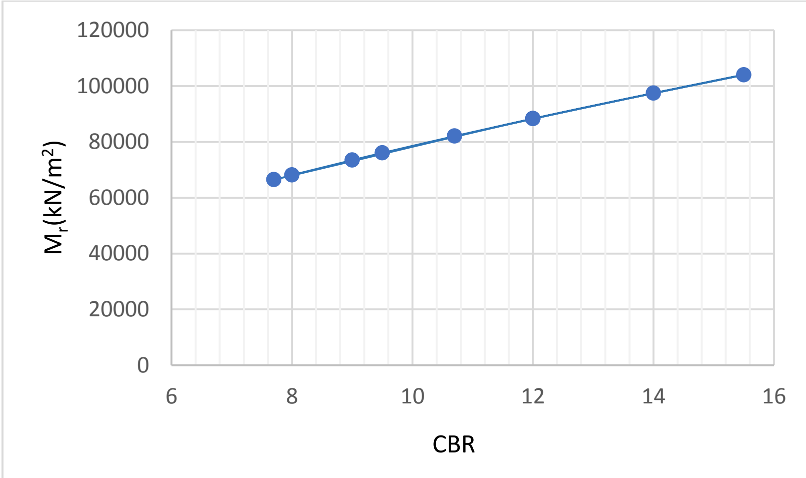


Fig. 6.Variation of resilient modulus of a subgrade with the CBR of marl soils

According to Equation (1), for resilient modulus (M_r) in soils based on the AASHTO Soil Classification System:

$$M_r(\frac{kN}{m^2}) = 18000 \times (CBR)^{0.64} \quad (1)$$

In an applied perspective, the increase in the resilient modulus is associated with an increase in the layer coefficient; as a result, the thickness of the designed pavement layers decreased. This coefficient was 1.6 times the initial value in the soil sample modified with 2% Nano-$CaCo_3$ by weight. Figure 6 illustrates the relationship between the resilient coefficient of marl soils and the amount of CBR.

2.2.5. Consolidation Test

To investigate the consolidation characteristics of marl soil mixed with nano-$CaCo_3$, three Nano-$CaCo_3$ contents (0.9, 1.8 and 2.7%,) were selected and compared with the results of pure marl soil. The specimens were prepared using the same procedure described in the previous sections.

The one-dimension consolidation test was performed following the ASTM D2435 procedure recommended for an oedometer test. First, the initial void ratio of soil samples was measured, as presented in Table 4. After that, the soil samples were consolidated with different percentages of nano-materials. This process continued until a stress of 8 kg/cm^2 was reached. Last, an unloading step was performed by decreasing the load to 2 kg/cm^2.

As can be seen, with increasing amounts of Nano-$CaCo_3$, the void ratio decreases due to the fine pores filling with nano-material. This procedure continues until the Nano-$CaCo_3$ ratio reaches the optimum amount; after that, the void ratio is increasing with increasing Nano-$CaCo_3$ amount. Figure 7 shows the void ratio changes with the addition of Nano-$CaCo_3$ in marl soils.

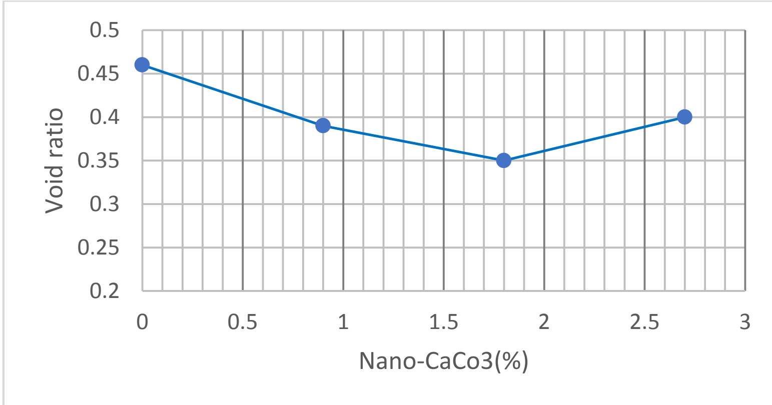


Fig.7.Variation of the initial void ratio by variation in Nano-Caco3 per cent

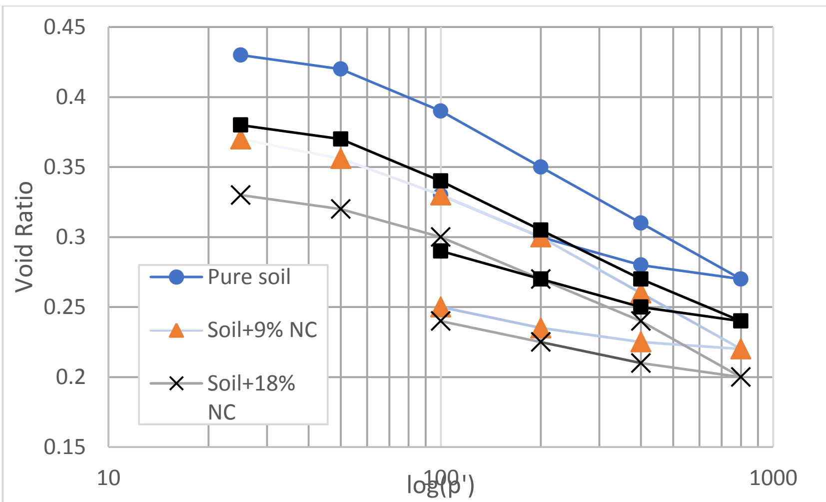


Fig.8. e-log curve of the consolidation test for Nano-$CaCo_3$ modified marl soils

Figure 8 shows the e-log(p) curves to illustrate the consolidation behaviour of improved marl soils. The slope of the loading and unloading graphs, which are equivalent to the compression index (Cc) and the swelling index (Cs), were calculated. According to the figures, Cc and Cs are almost constant and equal to 0.09 and 0.03, respectively, unless their void ratios are varied by Nano-$CaCo_3$ content variation, as discussed above.

Due to the wide distribution of marl soil in the world, it is recommended that improving of marl soil evaluated with other types of nanomaterials.

3.Conclusions

In this research, the effects of Nano-$CaCo_3$ on the geotechnical properties of marl soils were investigated. The samples were examined for Atterberg limits, compaction, unconfined compressive strength, CBR and consolidation. The following conclusions were drawn from analysing the test results:

1. There was a consistent and fairly significant decrease in the dry unit weight with increasing Nano-$CaCo_3$ content as the Nano-$CaCo_3$ content increased from 0 to 3%.
2. The optimum water content decreased by about 0.6% with the addition of 0.5% Nano-$CaCo_3$, after which it increased in a consistent fashion by about 1.3% as the Nano-$CaCo_3$ content was increased from 0.5% to 3%.
3. According to the results of unconfined compressive tests, the best improvement in sample strength, which was about 100%, was achieved by adding 2% Nano-$CaCo_3$. This is due to the surface area of Nano-$CaCo_3$, which increases surface area by decreasing the particles size and, therefore, caused an increased surface area reaction between the Nano-$CaCo_3$ and soil particles. An increase of 40% in unconfined compressive strength is observed with 2% Nano-$CaCo_3$.
4. According to the results, by adding small amounts of Nano-$CaCo_3$, the CBR values increased in the soil samples. The CBR of modified soil with 2% Nano-$Caco_3$ was 2.7 times the initial CBR. Moreover, adding up to 2% Nano-$CaCo_3$ to marl soils increases the resilient modulus by 1.5 times compared to the initial CBR.
5. Mixing 0.3% to 2.7% Nano-$CaCo_3$ into the marl soil has little effect on the original consolidation characteristics. However, by increasing the pressure, the final settlement is gradually increasing. It seems that Nano-$CaCo_3$ have less effect on the compression index and swelling Index, and these parameters are almost constant unless the void ratios are varied by Nano-$CaCo_3$ content variation.
6. After adding a small amount of Nano-$CaCo_3$, the marl soil exhibits different consolidation characteristics. When the Nano-$CaCo_3$ mixing content is 1.8%, the final settlement reaches a maximum and the final void ratio is the smallest. Under high-pressure conditions, the consolidation increases with the increase in Nano-$CaCo_3$ mixing content, which indicates that Nano-$CaCo_3$ modifies the consolidation of marl soils.

References

[1] BARTH, T. F. W., CORRENS, C.W., ESKOLA, P., 1939. Die enstehung early hydration of the system. Springer, Berlin.

[2] BEHNOOD, A. 2018. Soil and clay stabilization with calcium-and non-calcium-based additives: A state-of-the-art review of challenges, approaches and techniques. Transportation Geotechnics, 17**,** 14-32.

[3] BELL, F. 1996. Lime stabilization of clay minerals and soils. Engineering geology, 42**,** 223-237.

[4] BELL, F. G. 2013. Foundation engineering in difficult ground, Elsevier.

[5] BOUMA, N. & IMESON, A. 2000. Investigation of relationships between measured field indicators and erosion processes on badland surfaces at Petrer, Spain. Catena, 40**,** 147-171.

[6] CHANGIZI, F. & HADDAD, A. 2015. Strength properties of soft clay treated with mixture of nano-SiO2 and recycled polyester fiber. Journal of rock mechanics and Geotechnical Engineering, 7**,** 367-378.

[7] CHOOBBASTI, A. J. & KUTANAEI, S. S. 2017. Microstructure characteristics of cement-stabilized sandy soil using nanosilica. Journal of Rock Mechanics and Geotechnical Engineering, 9**,** 981-988.

[8] CHOOBBASTI, A. J., SAMAKOOSH, M. A. & KUTANAEI, S. S. 2019. Mechanical properties soil stabilized with nano calcium carbonate and reinforced with carpet waste fibers. Construction and Building Materials, 211**,** 1094-1104.

[9] GUILLET, G. R. 1969. . Marl in Ontario. . Department of mines, Reardon,.

[10] HOOSHMAND, B., SOLOMON, A., KåREHOLT, I., RUSANEN, M., HäNNINEN, T., LEIVISKä, J., WINBLAD, B., LAATIKAINEN, T., SOININEN, H. & KIVIPELTO, M. 2012. Associations between serum homocysteine, holotranscobalamin, folate and cognition in the elderly: a longitudinal study. Journal of internal medicine, 271**,** 204-212.

[11] ISMAIL NEJAD, L., RAMAZANPOUR, H., SHABANPOUR, M. & BAKHSHIPOUR, R. Physical and chemical factors affecting the development of the gully and badlands of southern part of Gilan province. Proceedings of the Tenth Congress of Soil Science, Tehran University, Iran, 2007. 1213-1215.

[12] JAFARI ARDEKANI, A., PARTOVI, A., PAYRAVAN, H. R. & GHODDOUSI, J. 2002. Effect of gypsum on runoff and erosion in various slopes of unstable soils (1994-19998).

[13] KHAJEHZADEH, M., TAHA, M. R., EL-SHAFIE, A. & ESLAMI, M. 2011. Modified particle swarm optimization for optimum design of spread footing and retaining wall. Journal of zhejiang university-science A, 12**,** 415-427.

[14] KHALID, N., MUKRI, M., KAMARUDIN, F., GHANI, A. H. A., ARSHAD, M. F., SIDEK, N., JALANI, A. Z. A. & BILONG, B. 2015. Effect of nanoclay in soft soil stabilization. InCIEC 2014. Springer.

[15] LI, W., HUANG, Z., CAO, F., SUN, Z. & SHAH, S. P. 2015. Effects of nano-silica and nano-limestone on flowability and mechanical properties of ultra-high-performance concrete matrix. Construction and Building Materials, 95**,** 366-374.

[16] LIU, X., CHEN, L., LIU, A. & WANG, X. 2012. Effect of nano-CaCO3 on properties of cement paste. Energy procedia, 16**,** 991-996.

[17] MAJEED, Z. H. & TAHA, M. R. 2013. A review of stabilization of soils by using nanomaterials. Australian Journal of Basic and Applied Sciences, 7**,** 576-581.

[18] MANIKANDAN, A. & MOGANRAJ, M. 2014. Consolidation and rebound characteristics of expansive soil by using lime and bagasse ash. International Journal of Research in Engineering and Technology, 3**,** 403-411.

[19] MENG, T., QIANG, Y., HU, A., XU, C. & LIN, L. 2017. Effect of compound nano-CaCO3 addition on strength development and microstructure of cement-stabilized soil in the marine environment. Construction and Building Materials, 151**,** 775-781.

[20] RAO, D. K., PRANAV, P. & ANUSHA, M. 2011. Stabilization of expansive soil with rice husk ash, lime and gypsum–an experimental study. International Journal of Engineering Science and Technology, 3**,** 8076-8085.

[21] SABAT, A. K. 2012. Utilization of bagasse ash and lime sludge for construction of flexible pavements in expansive soil areas. Electronic Journal of Geotechnical Engineering, 17**,** 1037-1046.

[22] SATO, T. & BEAUDOIN, J. 2011. Effect of nano-CaCO3 on hydration of cement containing supplementary cementitious materials. Advances in Cement Research, 23**,** 33-43.

[23] SATO, T. & BEAUDOIN, J. J. 2019. Effect of nano-CaCO3 on hydration of cement containing supplementary cementitious materials. ICE Themes Low Carbon Concrete. ICE Publishing.

[24] SOKOUTI, R. & RAZAGI, S. 2015. Erodibility and loss of marl drived soils. Eurasian Journal of Soil Science, 4**,** 279-286.

[25] SUPIT, S. W. & SHAIKH, F. U. 2014. Effect of nano-CaCO3 on compressive strength development of high volume fly ash mortars and concretes. Journal of Advanced Concrete Technology, 12**,** 178-186.

[26] TABARSA, A., LATIFI, N., MEEHAN, C. L. & MANAHILOH, K. N. 2018. Laboratory investigation and field evaluation of loess improvement using nanoclay–A sustainable material for construction. Construction and Building Materials, 158**,** 454-463.

[27] TAHA, M. R. & TAHA, O. M. E. 2012. Influence of nano-material on the expansive and shrinkage soil behavior. Journal of Nanoparticle Research, 14**,** 1190.