Investigation of the Impacts of Nano-clay on the Collapse Potential and Geotechnical Properties of Gypseous Soils

Mahdi O. Karkush [1)*], Alaa D. Al-Murshedi [2)] and Hussein H. Karim [3)]

[1)] Civil Engineering Department, University of Baghdad, Baghdad, Iraq. * Corresponding Author.
E-Mail: mahdi_karkush@coeng.uobaghdad.edu.iq
[2)] Department of Geology, University of Baghdad, Baghdad, Iraq. E-Mail: Almurshedi.alaa@gmail.com
[3)] Civil Engineering Department, University of Technology, Baghdad, Iraq. E-Mail: 40062@uotechnology.edu.iq

ABSTRACT

Problematic soils, such as gypseous soils, have complex and irregular behavior, and are concentrated mainly in the dry and semi-dry regions in the world. In Iraq, gypseous soils cover from 30% to 35% of its total area in the west desert and extend to the southern parts of Iraq. Such soils experience sudden collapse upon wetting. Soil stabilization is an important technique to improve the undesired geotechnical properties of soils. In this study, laboratory tests were conducted on two gypseous soils collected from two different sites in Iraq: Al-Najaf city (42% gypsum content) and Al-Samawa city (54% gypsum content). Three percentages (1, 2 and 4%) of nano-clay (NC) were used to improve the chemical and geotechnical properties of the studied soils. Chemical and physical classification tests were performed on the treated soil samples. Also, collapsibility and shear strength tests were conducted on the soil samples in dry and soaking conditions. The test results indicated that mixing nano-clay with gypseous soils affected the consolidation behavior and hydraulic conductivity of the soils regardless of the percentage of nano-clay. The collapse potential of soil samples mixed with 4% of nano-clay decreased by 77%. In general, using 4% of nano-clay gives the best improvement of chemical and geotechnical properties of gypseous soils.

KEYWORDS: Nano-clay, Gypseous soil, Collapse, Shear strength, Soaking.

INTRODUCTION

Collapsible soil is defined as any soil that suffers from volume changes upon wetting resulting from the radical rearrangement of soil particles without change in loading (Mansour et al., 2008; Abid Awn, 2010). Gypsum is a mineral salt commonly known as hydrated calcium sulphate and has the chemical formula ($CaSO_4.2H_2O$). Gypseous soil is strong when it is dry, but it loses its strength upon wetting or soaking of soil by water, causing collapse and compressibility of the soil structure. The wetting or soaking of gypseous soils causes the dissolution of calcite silicate, cementing the particles of soil and consequently, reducing the bonds among soil particles (Al-Mufty, 1997; Al-Murshedi, 2001).

There are many additives that can be used to stabilize and improve the behavior of gypseous soil, such as lime and bitumen materials. Nowadays, nano-materials are considered among the modern methods used to improve undesired soil properties. Many civil engineering projects are built in gypseous regions, representing one of the common problems in such regions. This kind of soil can be replaced by a soil of good geotechnical properties which is adequate for construction. When the depth of soil replacement is high, this technique becomes expensive and non-economical. Many researchers have been seeking other ways to improve soil properties before building (Al-Nouri and Seleam, 1994). Soil stability is a technique to increase strength and durability by reducing compression, shrinkage, swelling limits and permeability using chemical and/or mechanical methods (Calik and Sadoglu, 2014).

Conventional stabilizers, such as lime, cement, fly ash, rice husk ash and corn leaf ash, have been widely

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used in many projects and their effects on the geotechnical properties of soils have been widely discussed in literature (Athanasopoulou, 2014; Eberemu et al., 2014; Edeh et al., 2014; Kampala et al., 2014; Sharma et al., 2017; Islam et al., 2018; Sharo et al., 2019). Nano-technology and nano-materials have attracted wide interest in recent years (Brar et al., 2010; Ibrahim et al., 2012). Some previous studies introduced using nano-materials in soil improvement. Unfortunately, not much work is available in this field in terms of the effects of using nano-materials in the improvement the undesired geotechnical soil properties.

IMPROVEMENT OF SOIL BY NANO-MATERIALS

The field of civil engineering deals with using large quantities of soil, especially in the construction of earth structures, such as roads and embankments. Therefore, it is important to estimate the suitability of a soil with considerations of strength, permeability and compressibility (Sridharan and Nagaraj, 2005). Using of nano-materials has recently increased in various applications of geotechnical engineering, especially the improvement of problematic soils, due to their availability and adequate cost. Among the common nano-materials are nano-silica (SiO_2) and nano-alumina (Al_2O_3) used in the improvement of the undesired chemical and geotechnical soil properties. The influences of nano-materials on the chemical and geotechnical properties of soils are of great interest and deserve to be investigated (Ghasabkolaei et al., 2017).

Clay soils were stabilized with a mixture of burnt-out sludge (SSA) and cement, where 15% of the soil was replaced by the mixture of SSA and cement to produce the treated soil. Thereafter, three volumetric percentages of nano-Al_2O_3 (1, 2 and 3%) were mixed with the treated soil. Replacing 15% of soil with SSA and cement and mixing it with 1% of nano-Al_2O_3 improved shear strength, swelling potential, California bearing ratio and clay permeability (Luo et al., 2012). The effect of nano-silica fume and polyester fiber on the shear strength of low-plasticity clayey soil has been investigated. Three ratios of polyester fiber ranging between 0.1% and 0.5% and three ratios of nano-silica ranging between 0.5% and 1% were used in the improvement of soil. The results showed an increase of shear strength of soil with increasing the percentages of nano-silica fume and polyester fiber. Also, the use of nano-silica fume and polyester fiber reduced failure strain (Changizi and Haddad, 2015).

Several previous studies investigated the effects of several ratios of nano-silica on the behavior of clayey soils. Also, the effects of curing time and freezing-thawing cycles on the acquired properties of fine-grained textured soils have been studied by some researchers, such as (Ghasabkolaei et al., 2017; Luo et al., 2012; Changizi and Haddad, 2015; Changizi and Abdolhosein, 2016; Iranpour, 2016; Naseri et al., 2016; Moayed and Hamidreza, 2017; Kalhor et al., 2019; Al-Murshedi et al., 2020). The main aim of this study is to investigate the effects of using three ratios (1, 2 and 4%) of nano-clay (NC) on the collapsibility and compressibility of gypseous soil. The effects of soaking and curing period on the acquired shear strength of soil have also been investigated. The shear strength parameters are measured after 7, 14, 21 and 28 days of curing. Also, the effects of nano-clay on the physical and chemical properties have been investigated in detail.

EXPERIMENTAL WORK

The experimental work includes the improvement of geotechnical properties of gypseous soil with three ratios of nano-clay (1, 2 and 4%) measured from the dry mass of soil. It also includes measuring the influences of curing period and soaking on the collapsibility and shear strength of the treated soil.

Soil Sampling and Properties

The soil samples used in this study are obtained from Al-Najaf Sea, located 10 km far from the center of Al-Najaf city and from Al-Samawa Lake, located 30 km far from the center of Al-Samawa city. The soil samples are taken from a depth of (0.5-1.5) m below the existing ground level and have a gypsum content of 42% and 54%, respectively. The soil samples were air dried for two days and then thoroughly ground to break the bulk masses into grains. The results of physical and chemical tests for natural gypseous soil samples are given in Tables 1 and 2. Sieve analysis and hydrometer test were also performed on the gypseous soil samples in order to determine the particle-size distribution curve, as shown in Figure 1.

Table 1. Physical properties of the gypseous soils

Property	Al-Najaf soil	Al-Samawa soil
Specific gravity, Gs	2.54	2.48
Maximum dry unit weight, $\gamma_{d,max}$	14 kN/m^3	13.4 kN/m^3
Optimum moisture content, ω_{opt}	18%	18%
D_{10}, D_{30}, D_{60} (mm)	0.018, 0.175, 0.5	0.075, 0.11, 0.3
Sand, S	80.0%	90.5%
Silt, M	17.0%	9.5%
Clay, C	3.0%	
Soil type (USCS)	SM	SP-SM

Table 2. Chemical properties of the gypseous soils

Property	Al-Najaf soil	Al-Samawa soil	Specification
TSS (Total Soluble Salts), %	34.1	63	Earth manual E8
SO_3, %	20	24.5	BS 1377: Part 3: 1990
pH value	6.8	6.5	
OMC (Organic Matter Content), %	2.15	0.45	
$CaCO_3$, %	4.6	6.0	
Cl^-, mg/l	0.04	0.09	
Gypsum content, %	42	54	-
EC (Electrical Conductivity), µS/cm	2.43	2.23	ASTM D1125 (2014)
ESP (Exchange Soduim Percentage), %	13	15	-
CEC(Cation Exchange Capacity) me/100g	6.54	5.33	ASTM D7503 (2010)
XRD	Quartz, Gypsum and Dolomite	Gypsum, Quartz Feldspar and Dolomite	

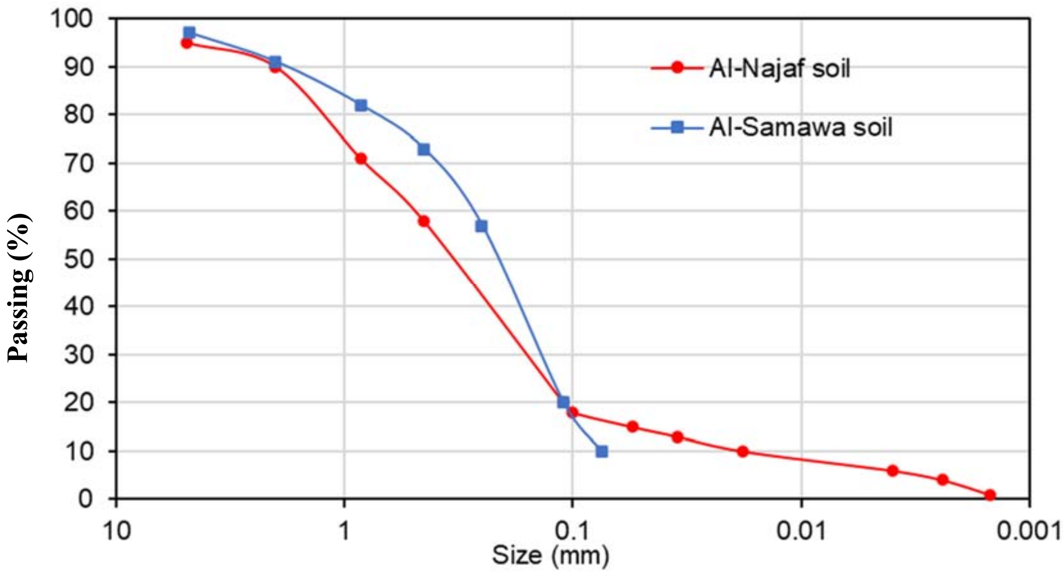

Figure (1): Particle-size distribution curves of soil samples

Nano-clay

Nano-clay (NC) is a new generation of processed clay for a wide range of high-performance cement nano-composites. Nano-clay usually has a phyllosilicate or sheet structure with a thickness of about 1 nm and surfaces of about 150–300 nm in one dimension. Depending on morphology and chemical composition of nano-clay, various classes, such as illite, halloysite, bentonite, kaolinite, montmorillonite, hectorite and chlorite, can be specified. As a pozzolanic material in nano-scale, nano-clay not only refines pore structure by reducing the porosity of the cement matrix (Yu, 2019), but also improves the hydration products of cement and alkali activation. A scanning electronic microscope (SEM) image shows nano-clay powder in Figure 2. The particle size of gamma phase nano-alumina ranged from 1 to 2 nm and the other general properties of nano-clay powder are shown in Table 3.

Table 3. Physical properties and chemical composition of NC

Property	Value	Oxide composition	Content, %
Type of mineral	Montmorillonite	Na_2O	0.98
Density, g/cm^3	0.5-0.7	MgO	3.29
Particle size, nm	1-2	Al_2O_3	19.60
Special surface area, m^2/g	220-270	SiO_2	50.95
Electrical conductivity, µS/cm	25	K_2O	0.86
Ion exchange coefficient	48	CaO	1.97
D-spacing, Å	60	TiO_2	0.62
Color	Pale yellow	Fe_2O_3	5.62
Humidity, %	1-2	LOI	15.45

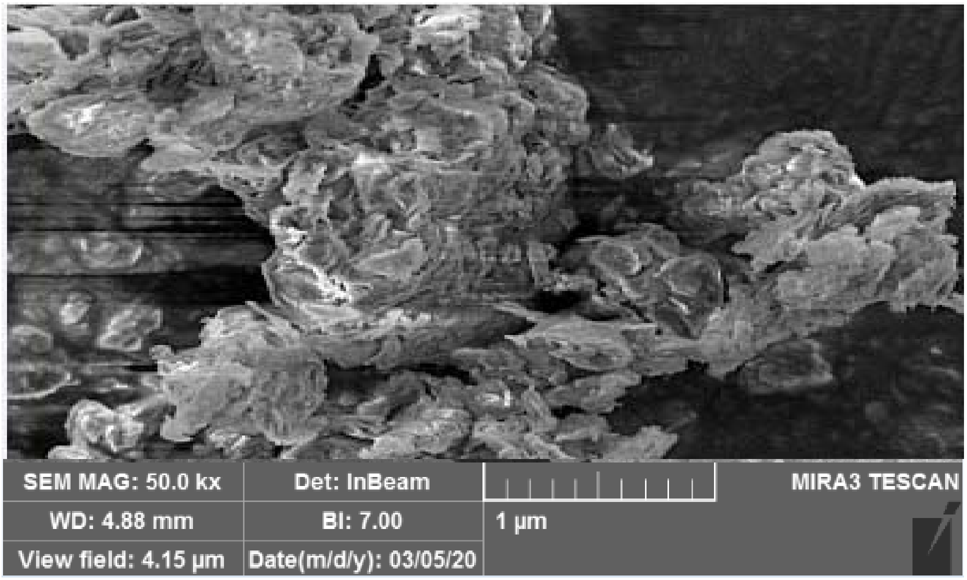

Figure (2): Scanning electronic microscope image for nano-clay

Improvement of Soil by Nano-clay

Soils used in tests has a gypsum content of 42% and 54% for Al-Najaf soil and Al-Samawa soil, respectively. It is air dried for two days and well ground by tamping. Then, the soil samples are well mixed by hand with three percentages of nano-clay (1, 2 and 4%) to get homogenous improved soil samples. The shear strength of the soil samples is tested for several periods of curing (0, 7, 14, 21 and 28 days). Also, the shear strength parameters of soil are measured before and after soaking.

RESULTS AND DISCUSSION

The main aim of this study is investigating the effects of several percentages of NC on the collapsibility and shear strength of soil before and after soaking. The geotechnical properties of soil tested in this study are: specific gravity (Gs), compaction curve, hydraulic conductivity, shear strength parameters and collapsibility. Also, the effects of several percentages of NC on the gypsum content and pH value of tested soil samples are investigated.

Physical Tests

The influence of NC content on the specific gravity of improved soil samples is presented in Table 4. It can be noticed that the specific gravity of soil samples mixed with NC increased with increasing the content of NC, which indicates that the soil- NC mixture is heavier than natural soils. The compaction curves for gypseous soil samples improved with several percentages of NC, as determined according to the standard compaction test and given in Table 4. It can be seen that the soil sample with greater NC content has higher maximum dry unit weight and corresponding moisture content. Increasing the optimum water content required to moisturize soil particles can be related to the high surface area of nano-clay fume mixed with the soil. Moreover, the water content required for the dissociation of nano-clay is increased, which causes increasing the optimum moisture content.

The hydraulic conductivity (k) values of the tested gypseous soils samples are given in Table 4. It is clear that the hydraulic conductivity (k) of gypseous soil samples decreases with increasing the content of NC. According to the results of the tests, there is an optimum content of nano-clay which can be mixed with the soil, where after 4% of nano-clay, the k value slightly decreases, as shown in Table 4. Adding nano-clay causes closing the connected paths of pores, which in turn causes tortuosity, thereby increasing time and resulting in decreasing the k value.

Table 4. Physical properties of soil samples treated with NC

Soil	NC %	Gs	$\gamma_{d,max}$ kN/m^3	ω_{opt} %	k×10^{-4} cm/s
Al-Najaf soil	0	2.54	14.00	18	0.64
	1	2.60	15.98	22	0.52
	2	2.67	18.87	24	0.33
	4	2.72	20.12	30	0.21
Al-Samawa soil	0	2.48	13.40	18	0.83
	1	2.55	15.00	22	0.71
	2	2.62	18.66	24	0.54
	4	2.68	19.76	30	0.3

Mechanical Tests

Shear Strength Tests

A series of direct shear tests were conducted to conclude shear strength parameters for natural and treated gypseous soil samples. The tests were conducted based on the procedure proposed by ASTM D3080 (2003). The sample size was (60×60×20) mm. To predict shear strength parameters (c, φ), two types of tests were performed on eight soil samples, four of which were tested in dry condition and four were tested after soaking in water for two hours. Three different confining pressures (75, 150 and 225 kPa) were applied in order to determine the stress–strain relationship for the tested soil samples. Brittle failure, defined by initiation, growth and accumulation of micro-cracks, was observed in all tested soil sample treated with NC; therefore, it can be considered the predominant failure mode.

Figures 3 and 4 summarize the results of direct shear tests performed on gypseous soils for both dry (water content equals 5%) and soaked (water content equals 75%) conditions. It can be seen that cohesion is much higher in the dry state than in the soaked state. Also, there is a slight increase in the angle of internal friction after soaking. This behaviour may be attributed to the destruction of bonds among the soil particles, which results from the dissolution of cementation salts after soaking in water. Soaking has a significant influence on the apparent cohesion, but the angle of internal friction is only slightly affected by soaking.

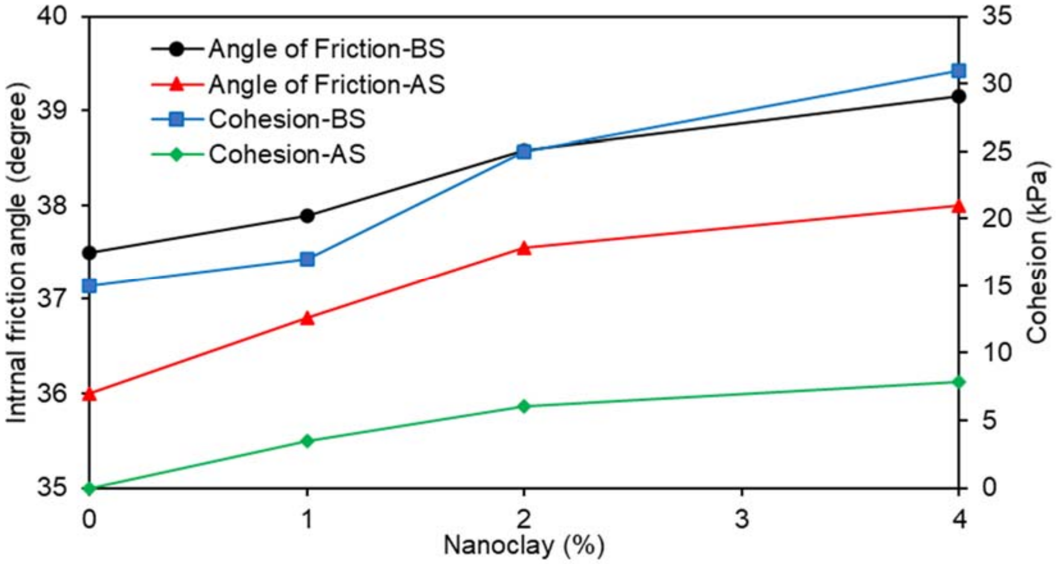

Figure (3): Effect of NC content on the shear strength parameters of Al-Najaf soil

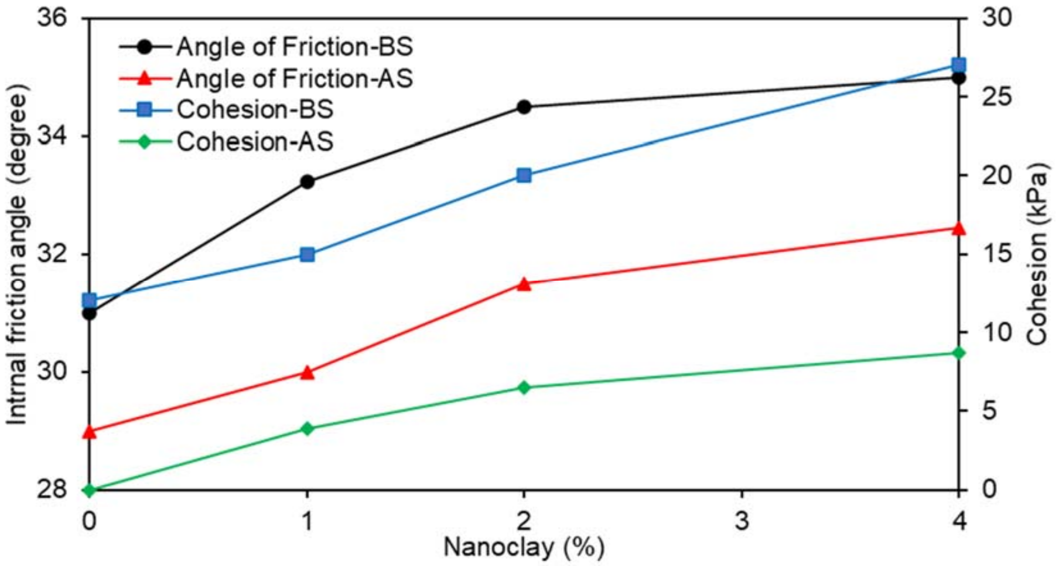

Figure (4): Effect of NC content on the shear strength parameters of Al-Samawa soil

The influence of curing time on the shear strength parameters of gypseous soil samples improved with several percentages of nano-clay content was studied and the results of direct shear tests before soaking (BS) and after soaking (AS) are presented in Table 5. The results showed a noticeable increase in cohesion and angle of internal friction of soil samples when cured for longer time. In the dry state, the cohesion of soil samples is significantly increased with increasing the period of curing due to the hardening of calcite in the pores of soil.

Table 5. Variation of shear strength parameters with curing period for tested soil samples treated by NC

Soil	Parameter	NC %	Before soaking (BS)					After soaking (AS)				
			Curing time, days					Curing time, days				
			0	7	14	21	28	0	7	14	21	28.00
Al-Najaf soil	Cohesion, kPa	0	15	15	15	15	15	0	0	0	0	0
		1	17	19	22	25	30	3.50	4.85	5.98	7.50	8.00
		2	25	27	30	33	40	6	7.50	9	10.88	12.12
		4	31	32	35	41	48	7.88	9.65	12.50	13	15.00
	Angle of friction, degrees	0	37.5	37.5	37.5	37.5	37.5	36	36	36	36	36.00
		1	37.89	38.66	38.77	39.25	39.55	36.66	36.8	37.9	38.11	38.33
		2	38.58	39.25	39.22	39.96	40.4	37	37.55	38.15	38.55	38.78
		4	39.15	39.6	40	40.5	40.88	37.5	38	38.88	39.12	39.55
Al-Samawa soil	Cohesion, kPa	0	12	12	12	12	12	0	0	0	0	0
		1	15	17	19	23	25	2.75	3.85	4.98	6.50	7.50
		2	20	24	26	31	34	4.57	6.5	8	9.88	10.88
		4	27	30	33	42	46	6.50	8.65	11.5	12.50	14.00
	Angle of friction, degrees	0	31	31	31	31	31	29.00	29	29	29.00	29.00
		1	33.23	34	35	36.5	37.55	30.00	30.66	31.25	31.76	32.45
		2	34.50	36	37.24	38.44	40	31.50	32.08	32.65	33.00	33.58
		4	35.00	37	38.5	39.75	41	32.45	32.88	33.66	34.46	34.98

Collapsibility Test

Collapsible soil can be defined as any saturated soil suffering from a fundamental rearrangement of particles and great loss of volume due to saturation with or without loading (Abid Awn, 2010). According to ASTM-D5333 (2003), the collapse of soil is defined as "the decrease in height of confined soil sample upon wetting at a constant stress". Collapsible soil exhibits small settlement under relatively high loading when water content is low, but the same soil exhibits high settlement after wetting without additional loading. To conduct collapse test, four soil samples represent natural soil and soil samples treated with 1, 2 and 4% of nano-clay have been tested. The collapse potential of soil samples was determined by conducting single oedometer collapse test according to ASTM-D5333 (2003). Soil samples have a diameter of 75 mm and a thickness of 19 mm. The pressure was duplicated every 24 hours until reaching the target stress of 800 kPa. When the applied stress reached 200 kPa and after waiting for 24 hours, the soil samples were soaked in distilled water for 24 hours to measure the change in sample thickness (ΔH). The collapse potential (C_p) is calculated using Eq. (1).

$$C_P = \frac{\Delta e}{1+e_o} \times 100; \qquad (1)$$

where C_p is the collapse potential, Δe is the change in void ratio and e_o is the initial void ratio. According to the collapse test results presented in Figures 5 and 6, the natural gypseous soil has a collapse potential (C_p) of 11.6% and 11.76 % for Al-Najaf soil and Al-Samawa soil, respectively, which can be classified as severely collapsible soils. Mixing gypseous soil with nano-clay reduces the collapse potential, where the collapse potential of gypseous soils mixed with 4% of NC reduced to 2.66%. Therefore, the soil can be classified as moderately collapsible (ASTM-D5333, 2003). No significant change was found for using 2% or 4% of nano-clay in the improvement of the collapse potential of gypseous soils, but a slight change was noticed for using 1% of nano-clay.

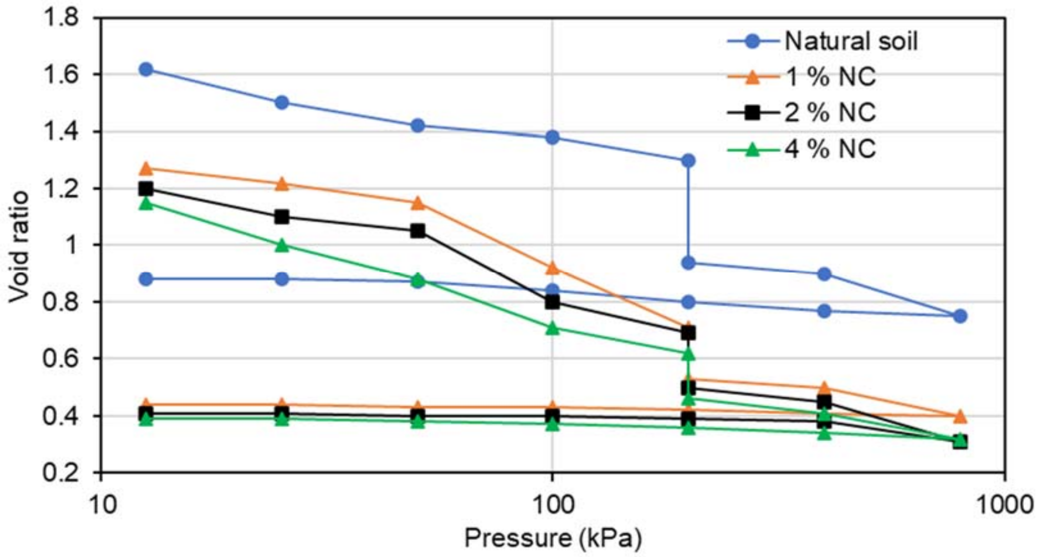

Figure (5): Collapse tests of Al-Najaf soil treated by nano-clay

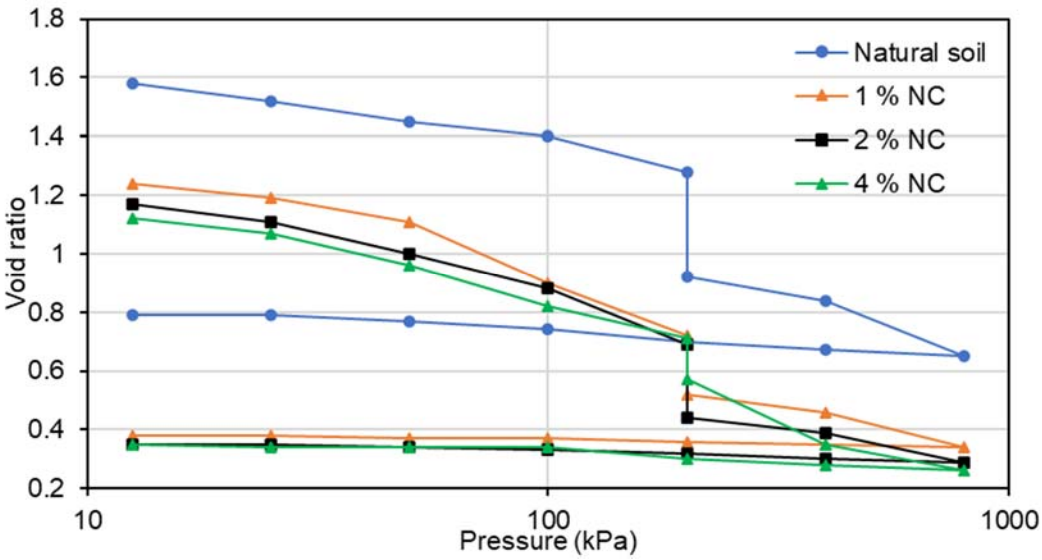

Figure (6): Collapse tests of Al-Samawa soil treated by nano-clay

Chemical Tests

Gypsum content and pH value of natural gypseous soil and soil samples treated with 1, 2 and 4% of nano-clay are measured in this study.

Gypsum Content

The method suggested by Al-Mufty and Nashat (2000) was used based on drying of soil in a drying oven at a temperature of (45°C) until the weight of the soil sample becomes constant and does not change with further drying. The sample weight was recorded at (45°C). The same sample was then dried at 110°C until the weight is constant and the weight is again recorded. Gypsum content can be calculated according to Eq. (2) (Al-Mufty and Nashat, 2000).

$$\lambda\,(\%) = \frac{W_{45^\circ C} - W_{110^\circ C}}{W_{45^\circ C}} \times 4.778 \times 100; \qquad (2)$$

Or the gypsum content is determined from the sulphate content using Eq. (3).

$$\lambda\,(\%) = SO_3(\%) \times 2.15; \qquad (3)$$

where

λ = Gypsum content (%).
$W_{45°C}$ = Weight of the sample at (45°C).
$W_{110°C}$ = Weight of the sample at (110°C).
SO_3 = Sulphate content (%).

The variation of gypsum content with nano-clay content is shown in Figure 7. The results indicated a decrease in the gypsum content with increasing the nano-clay content. The decrease ranged from 7% to 16% for Al-Najaf soil and from 6.5% to 13% for Al-Samawa soil samples treated with 1 to 4% of nano-clay.

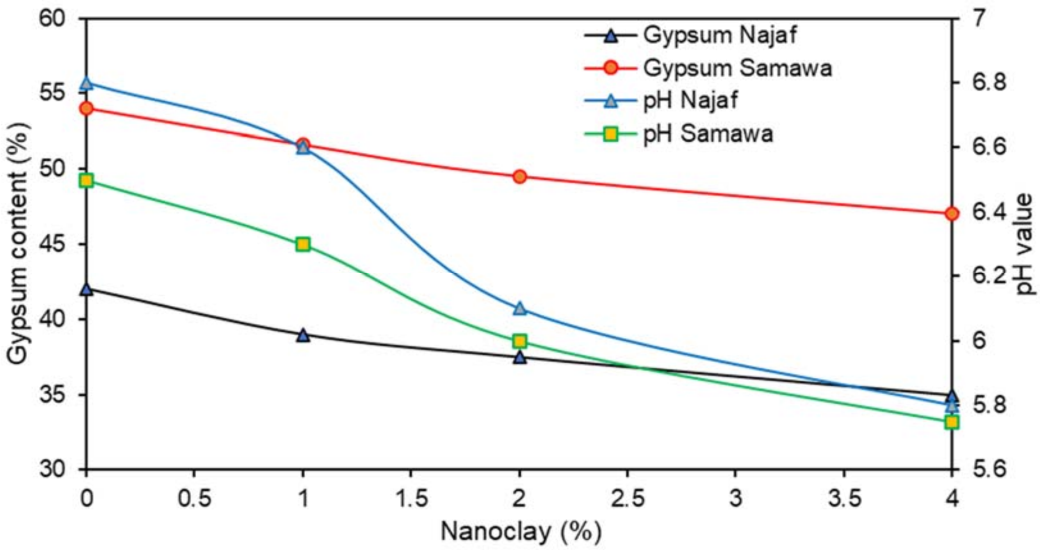

Figure (7): Effect of nano-clay content on gypsum content and pH value

pH Test

The pH of the soil is an important parameter that has an essential effect on the behavior of treated gypseous soil. The pH value is the main indicator of hydrogen activity in the soil. When the soil has a pH value of more than 7 (classified as alkaline), the soil geotechnical properties become better. Lower pH value of soil indicates an acidic material. When acids come into the soil, they destroy/dissolve the chemical bonds or cementation between the soil particles (Sunil et al., 2006).

In this study, the electromechanical method (BS 1377: Part 3: 1990: Section 9) was used to determine the pH value of suspended soil in water (BS 1377-3, 1990). This method requires solving the soils in water with a ratio of 1: 2.5, which can be obtained by passing an amount of 30 g of soil through a 2 mm sieve and diluting it with 75 ml of distilled water for at least 8 hours. The effect of nano-clay on pH value was studied to estimate chemical reactions after mixing nano-clay with the tested soil. The effect of nano-clay on the pH value of gypseous soil samples is shown in Figure 7. The results showed a decrease in the pH of the soil samples treated with 2% and 4% of nano-clay. The soil sample mixed with 1% of nano-clay showed a slight increase in the pH value, which can be neglected. Nano-clay has an acidic action, thereby reducing the pH value of treated soil samples.

CONCLUSIONS

The present research investigated the outcome of three percentages of nano-clay on the collapse potential and shear strength of gypseous soil in dry and soaked conditions. The following conclusions can be drawn from the test results.

- Addition of nano-clay causes an increase in optimum moisture content and maximum dry unit weight.
- Mixing nano-clay with gypseous soil causes a significant reduction in the compressibility of gypseous soil, but it is not worth mixing more than 2% of nano-clay with soil.
- There was a significant increase in the apparent cohesion of soil resulting from cementation of soil

particles by nano-clay, but a slight increase was noticed in the value of angle of internal friction.

- The collapse potential of soil is reduced with increasing the content of nano-clay, where the collapse potential of soil is transferred from severe to moderate when the soil is mixed with 4% of NC.
- Mixing of nano-clay causes a slight change in the hydraulic conductivity of soil due to pore clogging and interparticle interaction by nano-clay.

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