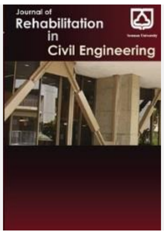

Journal of Rehabilitation in Civil Engineering

Journal homepage: https://civiljournal.semnan.ac.ir/

Effect of Nanoclay-Depended Treatment on the Mechanical Behavior of a Collapsible Soil

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ARTICLE INFO

Article history:
Received: 26 July 2024
Revised: 30 November 2024
Accepted: 15 January 2025

Keywords:
Nanoclay;
Gypseous sand;
Shear strength;
Collapse;
Direct shear.

ABSTRACT

The research investigates the effects of adding nanoclay on the shear strength properties of two gypseous sand soils. The soil samples were taken from the cities of Tikrit (55% gypsum) and Al-Najaf (29% gypsum). A direct shear test was used to examine soil specimens in dry conditions and immediately after a saturation procedure. The distributed soil specimens were remolded in the direct shear box to achieve a specific density. The shear speed was 1.0 mm/min. For both soil samples, there are different added nanoclay contents, 0, 2, 5, and 7%. Three levels of normal stress are applied, 25, 50, and 100 kPa on each soil specimen. The results state that there is a significant decrease in the angle of internal friction with saturation for both soil samples due to the gypsum solution in these soils. The resulting saturated Φ is significantly lower than the reported mean values in the literature. The Φ is recovered by adding nanoclay content up to 5% worthily. A mathematical model correlates the values of Φ and the percentage of nanoclay using a regression analysis with restricting gypsum content (29-55%) and nanoclay (≥ 0%) in saturation conditions.

E-ISSN: 2345-4423

How to cite this article:
Salih, B. Muiassar M., Raheem, H. Nadhum , Abrahim, M. Jamal, Mahmood, M. Shakir and Aldarraji, S. A. H. (2025). Effect of Nanoclay-Depended Treatment on the Mechanical Behavior of a Collapsible Soil.Journal of Rehabilitation in Civil Engineering,13(4), 229-240. https://doi.org/10.22075/jrce.2025.34865.2151

1. Introduction

Whenever collapsible soils develop, whether by nature or human activity, they pose major engineering and geotechnical issues [1,2]. Sudden collapse happens when vertical pressures (from loading or wetting procedures) exceed the bonding materials' yield strength [1,3].

The volumetric strain during sand wetting increases substantially as the gypsum concentration rises [4]. Many variables affect the collapse potential, such as the wetting procedure, permeability, void ratio, gypsum content, initial saturation degree, and soil wetting interval before loading [5,6]. The shear strength values decrease during the first two weeks of the soaking process and then increase when the grains come into contact again after four weeks of soaking [5,6,7]. Long-term water soaking duration has a more complex effect on settlement behavior than shear strength parameters [5,6]. The unsaturated condition always exists in collapsible soils where massive collapse happens with a reduction in the matric suction [3]. During the wetting process, greater mean net stress induced more severe collapse in the unsaturated condition of gypseous sand soil [8,9,10,11]. After a one-week post-remolding, the settlement decreased slightly because of the re-bonding of the gypseous sand particles within the initial decrease of the matric suction (wetting) [9,11,12,13,14]. The shear strength parameters were reduced by raising the matric suction (dry condition) [3,7,15].

A variety of additives, including bitumen and lime compounds, can improve and stabilize the behavior of gypseous soils. Using nanomaterials is one of the newest methods for improving problematic soil [16]. When 5% nanoclay was added to the gypseous (32% gypsum) sand soil, there was an optimum increase in the soil shear strength parameters [17]. For soils from Al-Najaf (42% gypsum) and Al-Samawa (54% gypsum), there was a clear rise in the apparent cohesion of the soil by nanoclay (up to 4%), but there was a slight increase in the angle of internal friction [18]. 6% of the nanoclay is the ideal percentage for decreasing gypsum dissolving [2,19]. During the pre-loading curing process, in the Oedometer collapse test, the gypsum did not make the fake re-bonding of the particles due to the nanoclay [16]. 5% of Montmorillonite nanoclay can ensure the cracks closure of the clayey soils at 100% density [20]. Optimal pollution adsorption was achieved by adding 6% zeolite to fine-grained sand, resulting in a 31.61% increase in the shear modulus index and an 18.70% increase in the friction angle index [21]. 4% NC has the highest impact on stabilizing the liquefaction of Bushehr, Iran, carbonate sand [22]. The addition of CKD to Tikrit dune soil eliminates the collapsibility of the soil [23] with a gypsum content of 59% [24].

The recent paper investigates the reliability of the shear-stress-based deformations and the alteration of the parameters of shear strength, cohesion, and angle of internal friction of the gypseous sand treated with nanoclay and subjected to a soaking process. The tests are performed using the strain control direct shear device. There are two groups of gypsum content, and for each group, three sub-groups of nanoclay are tested. The resulting data are presented in the form of the change in the shear strength parameters.

2. Research materials and methodology

2.1. Soil

Two soil samples were collected from two locations: the northern region of Al-Najaf city (south of Baghdad, Iraq) known as "SG29" and Tikrit city (north of Baghdad, Iraq) known as "SG55". The percentages of gypsum and other components of the soil were determined using a chemical analysis test that followed the specification of ASTM C25-99. Figure 1 illustrates the grain size distribution of both soil samples. The standard Proctor tests are carried out on both soil samples, and the results are shown in Figure 2. Table 1 shows the results of the experiment to classify and identify soil samples.

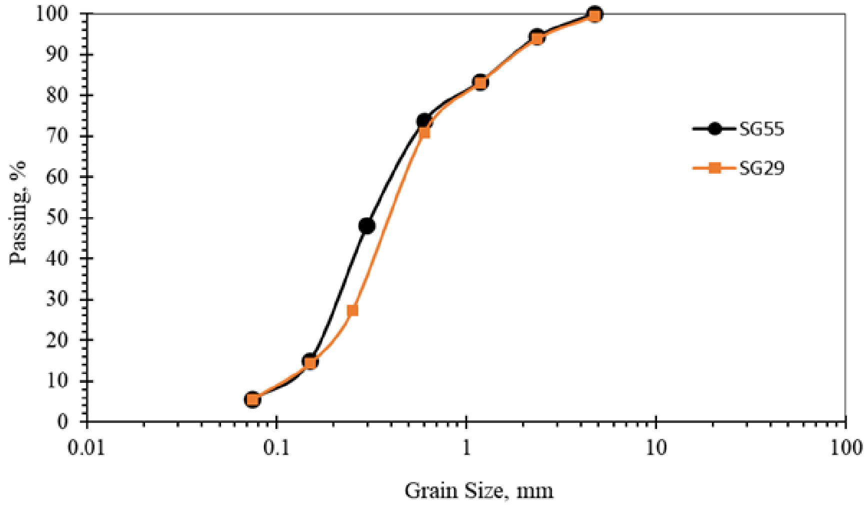


Fig. 1. The grain size distribution of the SG29 and SG55.

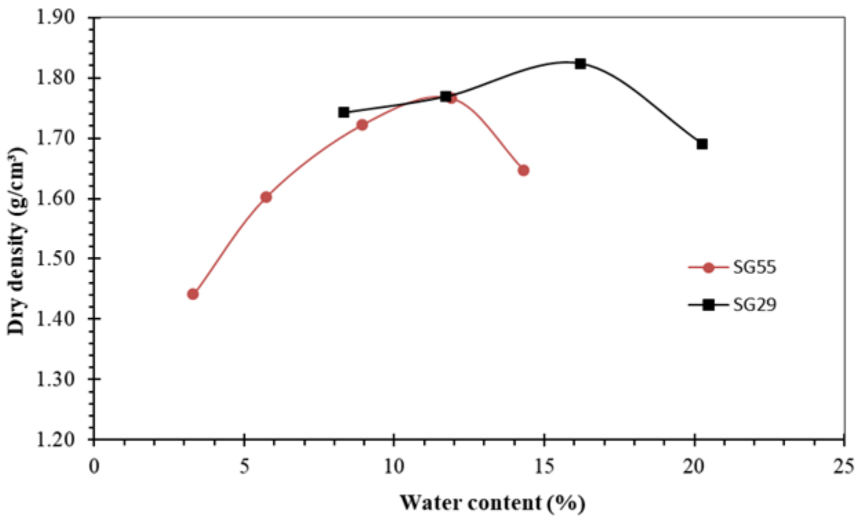


Fig. 2. The standard proctor test results.

Table 1. Summary of the soil samples tests results.

Test Designation	Values	
	SG29	SG55
Sand, %	96.7	94.4
Fine, %	2.65	5.6
Soil classification (USCS) [25]	SP	SP
Specific gravity (Gs) [26]	2.38	2.54
Gypsum content, % [27]	29	55
SO_{3}, %	13.48	26.75
Organic content, %	0.81	0.305
Ph, %	8.5	8.01
T.S.S., %	-	78.59
Maximum dry density, gm/cm^3 [28]	1.825	1.77
Optimum water content, % [28]	15	11.8

2.2. Nanoclay

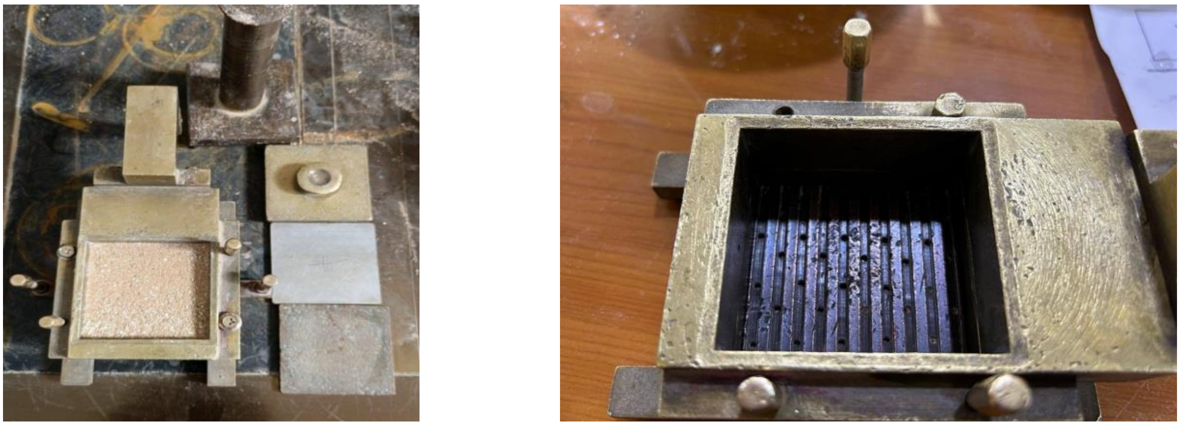
According to the material safety data sheet provided by the manufacturer, "Montmorillonite K10" nanoclay is utilized, and it is non-toxic [16]. Despite nanoclay's non-toxic properties, safety assurance tools are still required while working with it. The characteristics of nanoclay are illustrated in Table 2.

Table 2. Composition and properties of nanoclay [16].

Property	Values
Particle size, nm	100
Density, g/cm^3	2.3-2.5
Surface area, m^2/g	220-270
pH	3-4
Purity, %	99.9

2.3. Devices and tools

The tests are achieved using the direct shear device with box dimensions of 6cm in width, 6cm in length, and 2cm in height. Figure 3 presents the device with accessories. The tests were performed in the National Center for Construction Laboratories (NCCL), Baghdad, Iraq. The constant strain method is adopted in the tests with a strain of 1 mm/minute.



a- Direct shear box (sampling)

b- diect shear testing device

Fig. 3. The direct shear device.

2.4. Research methodology

The tests are performed on a strain-controlled direct shear device. The distributed soil specimens were remolded in the direct shear box of 6×6 cm cross-sectional area case-study with constant density for all specimens of 1.643 gm/cm^3 for both soil samples (SG29 and SG55). The tests are divided into two groups: dry and saturated samples. In each group of tests, there are two sub-groups of gypsum contents, 29% and 55%. For each sub-group, there are different nanoclay contents, 0, 2, 5, and 7%. A set of normal stresses are applied, 25, 50, and 100 kPa. The shear speed was 1.0 mm/min. The peak value of the shear stress is controlled with a maximum strain of 10% of the sample length (6mm). Table 3 illustrates the program of the testing. The percent changes of Φ are calculated using Eq. 1.

$$\Phi\%change = \frac{(\Phi_N - \Phi_0)}{\Phi_0} \times 100 \quad (1)$$

Where: Φ_N is the Φ with a specific percentage of nanoclay and Φ_0 is the Φ with 0% of nanoclay.

Table 3. Description of the testing program.

Soil Specimen	Initial Dry Density, gm/cm^3	Nanoclay, %	Normal Stress, kPa
SG29	1.643	0	25, 50 and 100
SG29	1.643	2	25, 50 and 100
SG29	1.643	5	25, 50 and 100
SG29	1.643	7	25, 50 and 100
SG55	1.643	0	25, 50 and 100
SG55	1.643	2	25, 50 and 100
SG55	1.643	5	25, 50 and 100
SG55	1.643	7	25, 50 and 100

3. Results of direct shear tests

Figure 4 illustrates the shear stress results under different normal stresses (25, 50, and 100 kPa) for SG29 and SG55 in dry conditions. The angles of internal friction (Φ) are 40 and 42 deg., whereas the apparent cohesions (C) are 50 and 40 kPa for SG29 and SG55, respectively.

Figure 5 illustrates the shear stress versus normal stress for different percentages of nanoclay (0, 2, 5, and 7 %) in saturation conditions for soil specimen SG29. Figure 5a shows the results of the reference specimen (without addition), subsequently the specimen is flooded and tested directly, and the results illustrate the angle of internal friction (Φ) is 30 and the apparent cohesion is 21 kPa. A similar procedure is adopted for the other specimens with the addition of different nanoclay contents. There is a gradual and effective increase in the angle Φ with increasing of the nanoclay. From Figures 5b, c, and d, the values of Φ are 34, 36, and 36 deg., whereas the apparent cohesions are 23, 10, and 13 kPa for the nanoclay of 2, 5, and 7 %, respectively.

A similar procedure is performed for SG55. The internal friction angle (Φ) is 28 degree and the apparent cohesion is 14 kPa. As in SG29, considerable decrease in the shear strength parameters after a flooding and saturation process. The addition of nanoclay are 37, 38, and 37 deg., whereas the cohesions are 10, 8, and 8 kPa for the nanoclay of 0, 2, 5, and 7 %, respectively. Data fitting is generally with R^2 between 0.93 and 0.99.

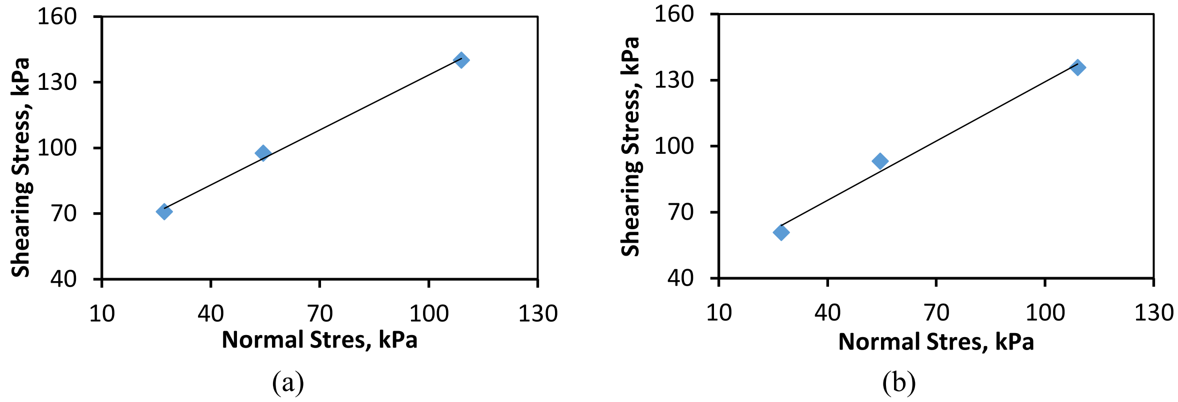


Fig. 4. Normal stress vs shear stress for dry specimens, (a) for SG29 and (b) for SG55.

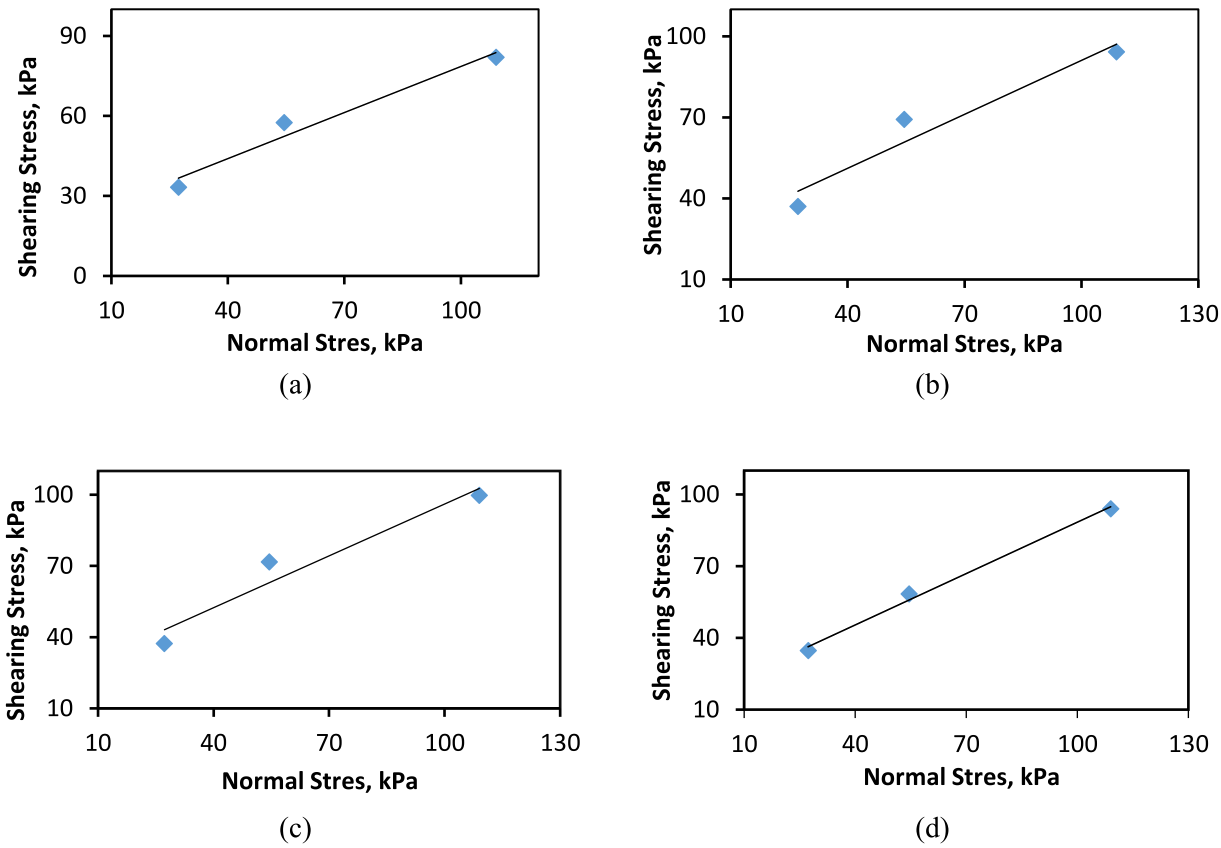


Fig. 5. Normal stress vs shear stress for saturated SG29, (a) with 0% nanoclay, (b) with 2% nanoclay, (c) with 5% nanoclay and (d) with 7% nanoclay.

4. Discussion

4.1. Effect of gypsum percentage

Figure 7 illustrates a comparison of the resulting angle of internal friction (Φ) for both soil samples (SG29 and SG55) in dry conditions and after a flooding process. The figure illustrates the results for different percentages of nanoclay. About 25% loosing is occurred in residual Φs with the flooding process for both soil samples, which may be related to the softening of the soil by the dissolution of the gypsum material.

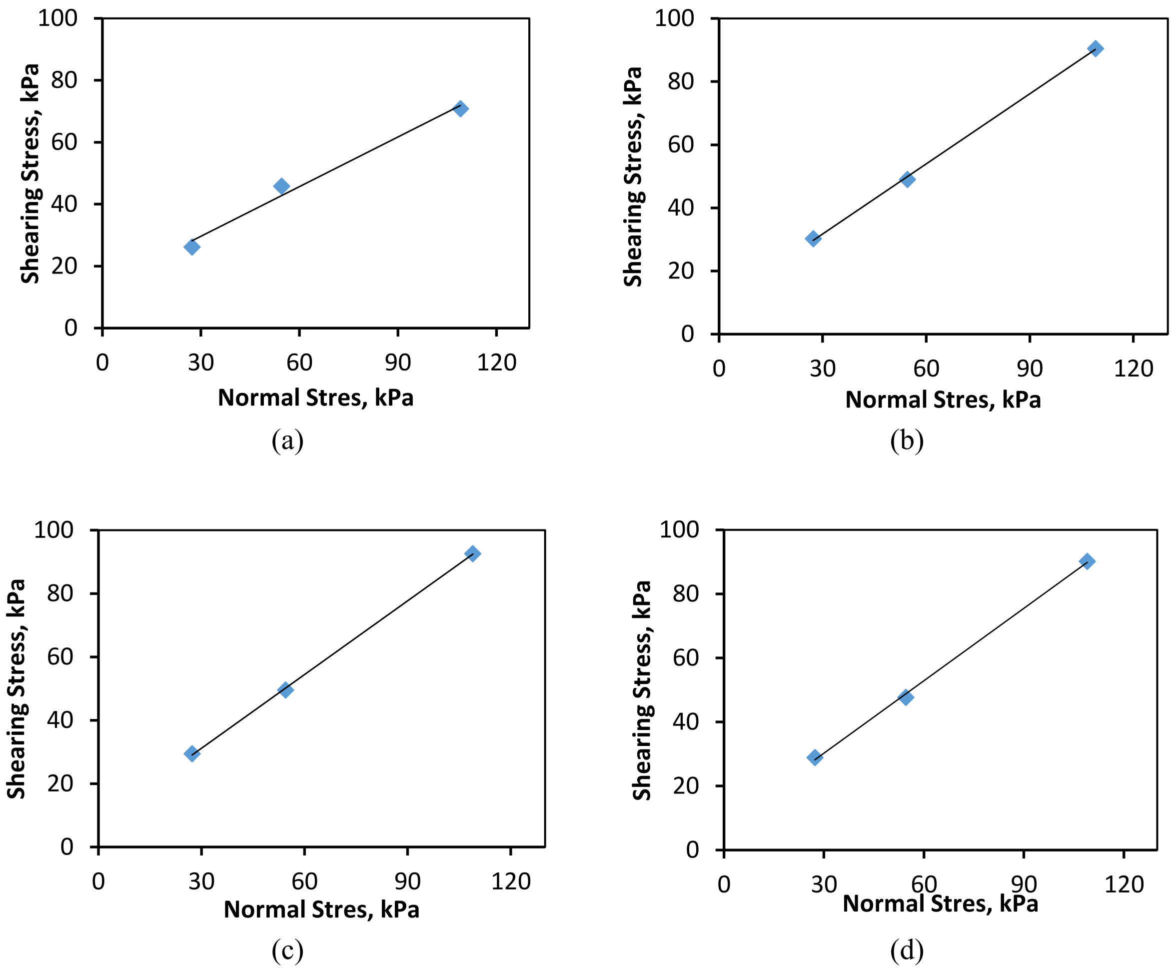


Fig. 6. Normal stress vs shear stress for saturated SG55, (a) with 0% nanoclay, (b) with 2% nanoclay, (c) with 5% nanoclay, and (d) with 7% nanoclay.

With adding nanoclay, a significant recovery of Φ is achieved, but still, the values remain lower than those in dry conditions. The nanomaterial may work as a cover for the gypsum material and prevent it from the softening process. The optimal improvement is within the 5% of nanoclay whereas the addition of more than 5% is not worth it.

Figure 8 shows that flooding reduces apparent cohesion (C) when compared to dry conditions. Even residual cohesion can be ignored due to the effect of the soaking process on gypsum demolition.

Al-Mamoori et al., 2020 stated that the mean values of Φ are from about 34° to 36° in the city center of An-Najaf and Kufa city and be an appropriate resistance to shearing failure [29]. Whereas the recent flooded result of Φ without addition ranges from 28° to 30°, i.e., there is a significant decrease in Φ compared to the recorded data with the flooding process. That must be considered in the analysis of the soil-bearing capacity. With adding a nanoclay material up to 5%, the values of Φ are improved and were close to the recorded mean values, as shown in Figure 7.

4.2. Effect of nanoclay

Figure 9 shows a comparison of the results Φ for the different gypsum content (29% and 55%) with different nanoclay content. For both soils, there are an increase in Φ with increasing the nanclay content. This increase is not worth after a 5% nanoclay. The values of Φ for both soils are founded to be an average ratio (Φ55/Φ29) equal to 1.03 for dry, saturated, and different nanoclay content.

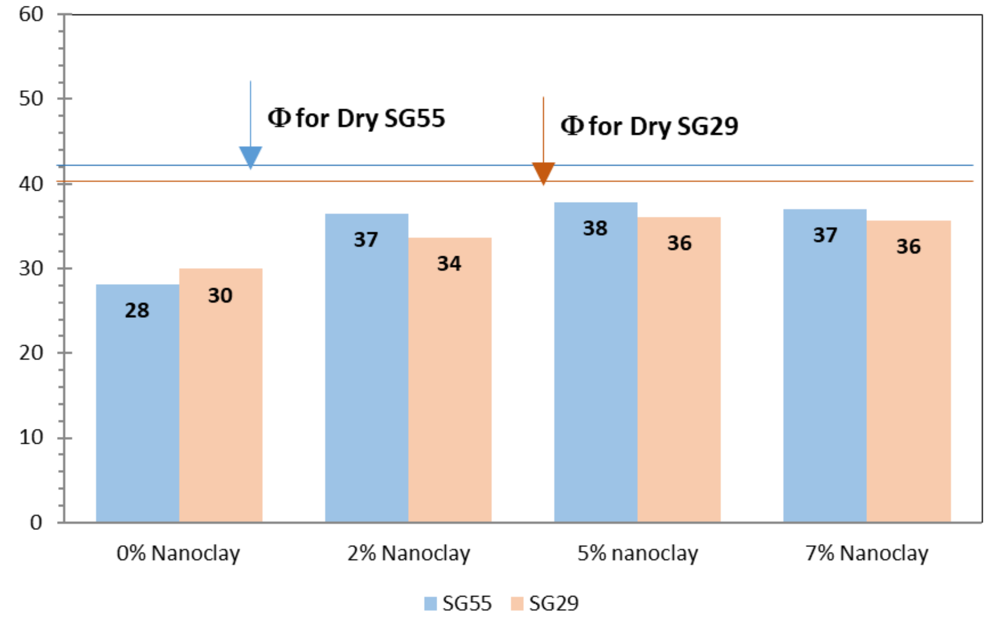


Fig. 7. The internal friction angle (Φ) for saturated SG29 and SG55 with different nanoclay percentages compared to the dry Condition.

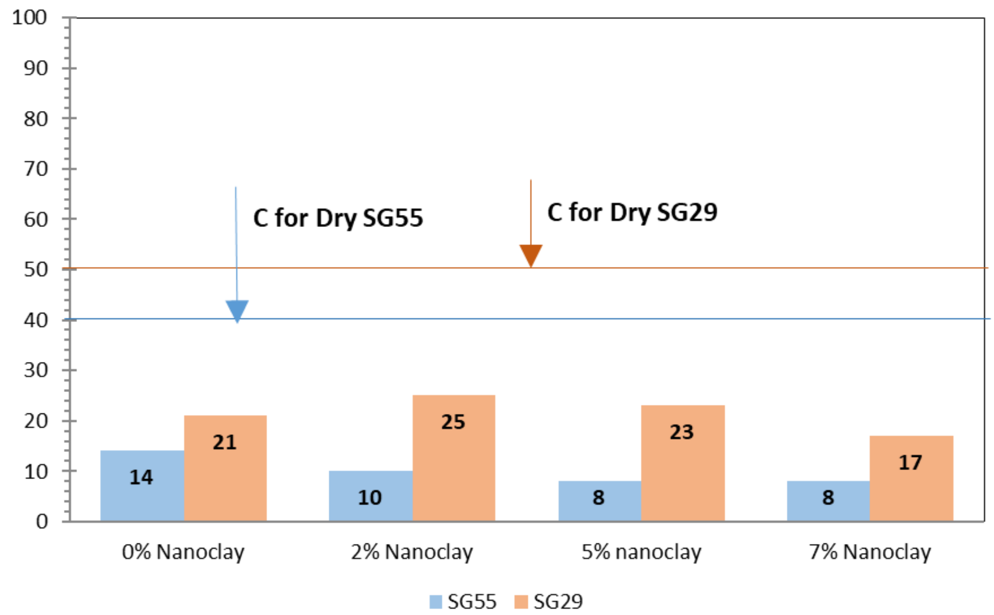


Fig. 8. The cohesion values for saturated SG29 and SG55 with different nanoclay percentages compared to the dry Condition.

Table 4 certifies that the mean values of Φ are 37 and 35 for saturated SG55 and SG29, respectively, and different nanoclay (> 0%). The standard deviation of the mean values is unity. Using Eq. 2, the percentage change of the Φ is about 32% for saturated SG55, whereas this percentage is about 17% for saturated SG29.

Adding the nanoclay improves the shear strength of the problematic soil, gypseous sand, with the soaking process of such soil up to 32% with gypsum content ≤55%. This improvement can increase the safety of the construction above or within such soil. Nanoclay works as a cover for the gypsum, and this cover prevents the soluble salt (gypsum) from dissolving in water. This result matches those in the literature.

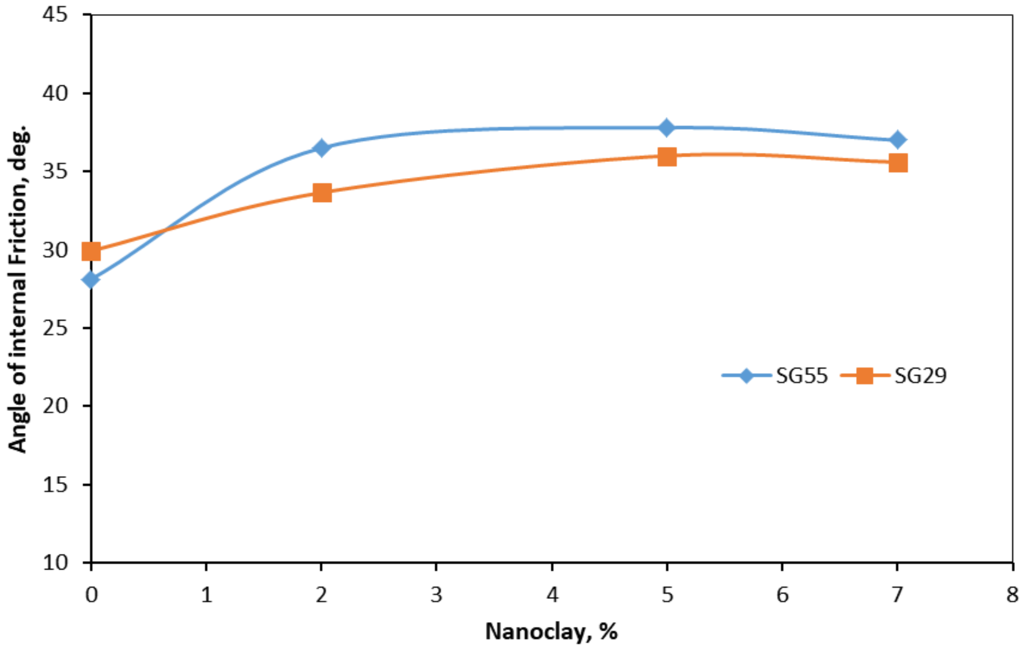


Fig. 9. The comparison of the Φ for the different gypsum content.

Table 4. Statistical analysis of the Φ values after adding the nanoclay.

Nanoclay, %	SG55	% change (Eq. 2)	SG29	% change (Eq. 2)
2	37	30	34	12
5	38	34	36	20
7	37	32	36	19
Mean	37	32	35	17
Standard deviation	1	2	1	3

4.3. Correlation equation

With restricted to a gypsum content range from 29% to 55%, a fitting equation is adopted using non-linear regression, as in Eq. 3 with R^2 of 0.82. It means that the predictors (Φ) explain 82% of the variance of $\sqrt{Nanoclay\%}$, i.e., a very strong correlation between the predicted data and the measured data of Φ. The p-value of 0.0026 means a higher chance that the regression model is significant (< 0.05). Linear regression assumes normality for residual errors with a p-value of 0.53. This equation is restricted to the specific range of the gypsum material and nanoclay ≥ 0% in addition to being immediately tested after a flooding (saturation) process. Figure 10 illustrates a comparison of the predicted (Eq. 3) and measured values of Φ with a good relationship ($R^2 = 0.82$).

$$\Phi = 29.77 + 3.0\sqrt{Nanoclay\%} \tag{3}$$

We can use this equation in the prediction of the Φ for adding different percentages of nanoclay for gypseous sand with gypsum ≤55%.

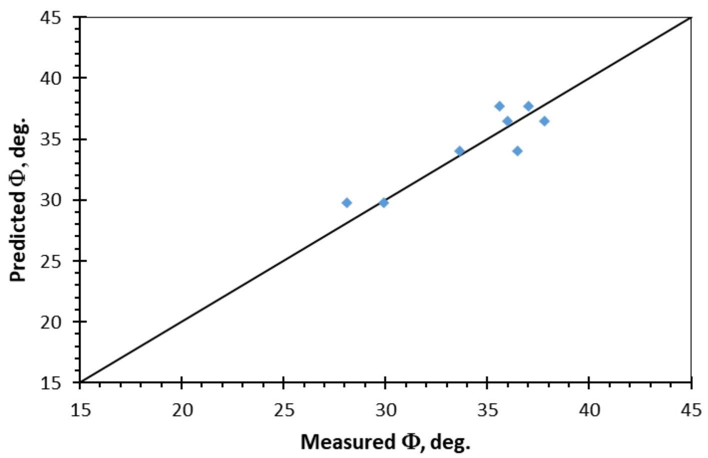


Fig. 10. relationship of the predicted Φ and measured Φ.

5. Conclusions

The paper investigates the effect of adding nanoclay on the shear strength parameters of two gypseous sand soils. The soil samples are from Al-Najaf city (29% gypsum) and Tikrit city (55% gypsum). The soil specimens are tested dry and immediately after a saturation process using a direct shear box. The resulting values of the shear strength parameters are compared with those available for the city. The apparent cohesion is neglected due to its effect on the saturation process. The recent conclusions are:

1. After a saturation process, there is about a 25% decrease in the values of the internal friction angle (Φ) for both soils.
2. With the addition of a nanoclay, there is an increase in internal friction angle Φ. The percentage increase depends on the gypsum content. The improvement in angle of internal friction Φ is 17 to 32% for 29% and 55% of gypsum, respectively.
3. The significant increase in angle of internal friction Φ is within 5% nanoclay.
4. The resulting saturated Φ is significantly lower than the reported mean values in the literature, but with the addition of nanoclay, the measured values are close to those reported.
5. With no significant effect of the gypsum within the range of 29% to 55%, an equation (3) relating the Φ with nanoclay is adopted using a regression with a good correlation (R^2=0.82).

Funding

This research received no external funding.

Conflicts of interests

The authors declare no conflict of interest.

Authors contribution statement

Bilal Muiassar M. Salih and Mustafa J. Abrahim: Proposed The Research Problem, Prpject Administration.

Hind N Al salami, Mohammed Sh. Mahmood and, Suha A. H. Aldarraji: Supervision, Methodology, Developed the Theory and Performed the Computations.

Mohammed Sh. Mahmood and Mustafa J. Abrahim: Verified the Analytical Methods, Investigated the Findings of This Work, Resources, Writing - Review & Editing.

Mohammed Sh. Mahmood: Conceptualization, Supervised the Findings of This Work.

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