



Influence of Saline Treatments on the Geomechanical Behavior of Clayey Soils

Amira Amiour^{1*}, Souhila Rehab Bekkouche¹, Djamalddine Boumezerane², Umar Zada³

¹ Department of Civil Engineering, Faculty of Technology, University 20 Aout 1955 Skikda, Skikda 21000, Algeria

² Engineering Division, University of the West of Scotland, Paisley PA1 2BE, United Kingdom

³ Department of Civil Engineering, National Central University, Taoyuan City 32056, Taiwan

Corresponding Author Email: am.amior@univ-skikda.dz

Copyright: ©2025 The authors. This article is published by IETA and is licensed under the CC BY 4.0 license (<http://creativecommons.org/licenses/by/4.0/>).

<https://doi.org/10.18280/mmep.120910>

ABSTRACT

Received: 5 August 2025

Revised: 7 September 2025

Accepted: 12 September 2025

Available online: 30 September 2025

Keywords:

clay, compressibility, geotechnical engineering, mechanical behavior, salts, swelling

Expansive clay soils are made up of many minerals such as hydrated aluminum silicates, which have a fibrous, laminated structure and give the soil a high water absorption capacity. The volumetric change of such soils in the presence of water poses serious stability problems. Improving soil performance is an important process in the construction of geotechnical works on problem soils. There are several methods to solve these issues, among them stabilization by injection of chemical solutions into the soil. In this context, this study focuses on the injection of chemical solutions in a clay taken from the region of Didouche Mourad, in the district of Constantine in the north east of Algeria. In the first part, the physical and mechanical characterization of clay was conducted in a series of laboratory tests. The results obtained show that our clay exhibits high swelling potential (Swelling potential: 3.87%), very plastic (plasticity index: 38.55%) and moderately compressible. The second part presents the treatment of swelling clays by adding Potassium chloride (KCl) and sodium chloride (NaCl) at different concentrations of 0.5, 1 and 2 mol/l. The results show that salt addition markedly improves soil behavior, with swelling reduced by 25–72% at 0.5–1 mol/l and by up to 75% at 2 mol/l. Both salts were effective, with KCl slightly outperforming NaCl. This confirms that concentrated salt solutions are a promising method for stabilizing expansive clays in geotechnical applications.

1. INTRODUCTION

Expansive soils in the presence of water are undesirable for stability reasons. These are soils that can cause a lot of damage to light structures (torsions, cracks in the pavement, subsidence, instabilities in embankments, etc.) [1]. The annual financial losses worldwide caused by this type of soil and resulting from floods, hurricanes, tornadoes and earthquakes can be estimated between 2 and 9 billion dollars [2]. For this, expansive soils require deep studies by civil engineers before making the construction of sidewalks, residential buildings and roads etc.

Indeed, expansive soils contain many clay minerals which confer them a different behavior from that of other soils. They exhibit volumetric changes in response to changes in their moisture content. These soils swell when there is an increase in moisture content and shrink when there is a decrease in moisture content. According to previous studies [3-7], a number of factors can affect the phenomenon of soil swelling: the type and age of the rock in relation to the type and quantity of clay, the stress history (overload and stress path), the activity of the clay, existence and depth of water table, soil moisture, initial water content, initial placement conditions and air ingress characteristics.

In Algeria, it can be noted that many disorders appeared in structures built in the arid and semi-arid regions, due to the

strong swelling pressure exerted by the expansive soils. In these zones, the clay is so dry that adding a small amount of water can release tremendous energy capable of producing significant damage to the structure. This damage caused by swelling and its consequences on buildings have been well documented in the studies [7-10].

Thus, soil stabilization is a geotechnical process that includes mechanical and chemical treatment techniques where the chemicals are intended to maintain the stability and improve the compressibility of the soil by limiting the water absorption capacity [11]. In order to limit problems and damage in buildings and different structures, many solutions based on stabilization techniques have been developed with more or less satisfactory results; the most common improvement method for expansive soils is chemical modification. This technique aims to improve the stability of expansive soils by increasing the particle size of soils, decreasing the plasticity index, aiming to reduce the swelling potential, and / or revise the resistance of the soil by improvement of mechanical properties. However, the literature shows that the efficiency of chemical stabilization strongly depends on the type and concentration of the additive used. Despite this, few studies have specifically investigated the controlled injection of KCl and NaCl into Algerian expansive clays, particularly under semi-arid climatic conditions. Moreover, the effects of these two salts at different

concentrations on both the physical and mechanical behavior of local soils remain insufficiently documented.

After improving the physical and mechanical performance of these soils through chemical treatment; potentially expansive soils can be used or reused as backfill or foundation or sub-foundation soil for road works.

Some researchers [7, 12-14] studied the use of KCl to modify heavy clay in the laboratory. Their results showed that the addition of KCl significantly reduces the swelling potential, resulting in a decrease in the activity of the clay and a significant improvement in its mechanical properties. Gueddouda et al. [15] obtained similar conclusions after injection of NaCl into clay soil.

The aim of this study is to look into the use of chemical injections as a stabilization technique of swelling soils. A series of tests were carried out to stabilize an expansive soil collected in the region of Didouche Mourad in the district of Constantine (Algeria) by using a chemical stabilization technique consisting in addition of salts (KCl and NaCl) at different concentrations. The originality of this work lies in assessing the effect of these two salts at various concentrations to evaluate their efficiency and provide practical recommendations for the stabilization of expansive soils under Algerian conditions. This technique of injecting chemicals into the soil was first introduced by Blacklock and Pengelly. Many studies followed their work by injecting a variety of chemical agents into the soil [16, 17, 1].

Initially, the soil was selected for the experimental program to determine; physical, chemical, geotechnical and mechanical properties of untreated soil from laboratory experiments. Secondly, the study examined the effects of different salts (KCl and NaCl) on the physical and mechanical properties and the swelling parameters of the soil.

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Location of the study area

The soil was extracted from an area located below a watershed limited by a road overlooking the city of Al-Amal in Didouche Mourad, in the district of Constantine Figure 1, located 431 km to the east of the capital Algiers. The area is composed of several geological formations, the first of which is covered by a reddish silty clay with carbonate concretions followed by a layer of reddish to yellowish marly clay, gypsum and plastic with wet passages. From the hydrogeological point of view, this area is framed by several temporary watercourses which constitute a natural drainage of the existing slope in the rainy seasons towards river Oued El Hamma.

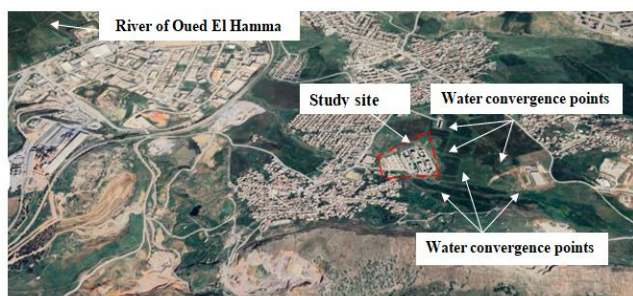


Figure 1. Location of the study area



Figure 2. Soil sampling operation in the study area

2.1.2 Identification of clay soils

The soil was extracted at a depth of 3.5 m to 5 m as shown in Figure 2, and characterized by conducting different geotechnical tests at the Public Works Laboratory of the East Constantine (PWLE).

This study area has several layers of soil, each thickness having a certain lithology as follows:

- m to 0.50 m: Backfill composed of concrete blocks, gravel and clay.
- 0.50 m to 1.50 m: Reddish marly clay, gypsum, finely gravelly in places.
- 1.50 m to 3.00 m: Reddish marly clay.
- 3.00 m to 5 m: Reddish marly clay, Reddish to yellowish marly clay, gypsum and plastic with wet passages.

Table 1. Results of chemical, physical and mechanical identification tests

Parameter	Value	Standard
Water content (%)	15.44	ASTM-D2216-10 [20]
Liquid limit (%)	76.62	
Plastic limit (%)	38.07	
Plasticity index (%)	38.55	
Consistency index	1.58	ASTM-D4318-17e1 [21]
Methylene Blue Value	7.5	
Grain size distribution		ASTM-C837-09 [22]
Fine sand (%)	02	
Silt (%)	23	
Clay (%)	75	
Insoluble rate (%)	70.80	ASTM-D7928-16e1 [23]
Carbonate rate (%)	14.96	
Sulfate levels (%)	5.88	
Apparent Friction Angle (°)	3.90	ASTM D4373-96 [24]
Apparent cohesion (bars)	0.222	
Effective Friction angle (°)	13	ASTM-D2850-15 [25]
Effective Cohesion (bars)	0.193	
Compressibility pressure(bars)	1.47	ASTM-D3080 [26]
Compressibility coefficient	0.182	
Swelling coefficient	0.069	ASTM-D2435-04 [27]
Swelling pressure(bars)	3.75	
Force applied F (kg)	315.17	ASTM-D2166-06 [28]
Compressive strength (MPa)	0.401	
Maximum dry density (t/m ³)	1.532	ASTM-D1557-12 [29]
Optimal water content (%)	23.78	
Swelling potential (%)	3.87	ASTM-D1883-16 [30]

The results of the identification tests are presented in Table 1. According to the classification system AASHTO, and the Casagrande chart, the soil of Didouche Mourad has been

classified as very plastic (class A3) and very consistent. It showed high values of plasticity index and liquid limit at 38.55% and 76.62% respectively, with a consistency index of 1.58. The analysis concluded to very fine clay with more than 75% of particles having a diameter less than 2 μm . According to the methylene blue test and the formula of Tran (21*MBV). S.S.T (m^2/g), the total specific surface is 157.5 m^2/g [18].

The initial water content was measured to reach 15.44% with a saturation up to 99.96%. Which indicate a moist and saturated soil.

The rate of carbonates measured is 14.96%, which confirms that the nature of this soil is a marly clay. In addition, the presence of sulphates reaches a percentage of 5.88%, which indicates a very strongly aggressive soil.

The oedometer compressibility test revealed the presence of moderately compressible soil. Generally, the higher the plasticity index of a soil, the greater the swelling potential. According to the classification of Bigot and Zerhoni [19], the chart of Williams and Donaldson, and Chen. It can be said that the studied soil belongs to the category of very expansive soils.

2.1.3 Salts

The saline solutions (distilled water + salts) used in this research are: potassium chloride (KCl) and sodium chloride (NaCl), at different concentrations of 0.5 M, 1 M and 2 M (M is the molarity of saline solution ($\text{M} = \text{mol/liter}$)).

2.2 Methods

In this phase the chosen methodology consisted mainly in conducting experiments and collecting data. Samples were taken from the selected site of Didouche Mourad and laboratory equipment was used to determine the soil properties by performing acceptable standard tests. The tests were, first, carried out on the natural soil and secondly on the mixture of soil and saline solutions (KCl and NaCl). The obtained results were compared with the results of past research and conclusions with discussion were drawn.

The extracted samples were transported to the laboratory in two ways:

- To maintain moisture content, remolded samples were obtained using a backhoe loader at a depth of 3.5 m to 5 m and transported in plastic bags as shown in Figure 3(a), in order to carry out the various identification tests (water content, grain size, Atterberg limits).

- Intact samples were obtained using a core drill, as shown in Figure 3(b).

The latter is installed at the chosen location, where the engine is then started to begin drilling, which is done vertically. The drill is removed with the soil sample. The samples are collected in special tubes to be preserved, so they are ready for mechanical tests (triaxial, oedometer, unconfined compression) to determine the nature of the soil and establish geological profiles.

To perform different laboratory tests, about 100 kg of samples were dried in an oven at 105°C for 24 h, followed by manual grinding as shown in Figure 4(a). Sieving was done with 3 sieves: the first is a 5 mm sieve as shown in Figure 4(b) to perform the Proctor test, Simple Compression and Methylene Blue Value (MBV); the second is a 20 mm sieve Figure 4(c) for carrying out the California Bearing Ratio (CBR) test and the third is a 400 μm sieve for conducting the Atterberg Limits in order to obtain a dry and homogeneous soil. In this step, the material is wet sieved.



(a) Remolded samples in plastic bags



(b) Intact samples (carrots)

Figure 3. Sample transport and storage method



(a) Grinding



(b) Sieving with a 5 mm sieve



(c) Sieving with a 20 mm sieve

Figure 4. Sample preparation methods

The sample was mixed with salts potassium chloride (KCl) and sodium chloride (NaCl) at different concentrations (0.5, 1 and 2 mole/liter) in a homogeneous way. This is done by adding a specified amount of saline solution to the crushed and dried soil sample; this mixing was carried out using a spatula for a few minutes to ensure that the solutions are well distributed in all parts of the sample where there is a change in color and texture. These homogeneous samples are kept in hermetically sealed plastic bags for 24 hours, followed by compaction in a CBR and Proctor mold.

The optimum water content obtained from Proctor test was

23.78% and the maximum dry density 1.532 t/m³.

After demolding, the samples were subjected to a series of physical and mechanical tests, as shown in Table 2.

- Atterberg limits are the water levels at which soil changes from one state to another, they are used to determine how fine-grained soils are formed [31].

- Oedometer Compressibility: This is a consolidation and compressibility test that allows the vertical deformation of the soil to be assessed. The sample is placed in a rigid cylindrical cell (oedometer) between two porous stones, subjected to a constant vertical axial force in stages, drained at the top and bottom (the state of the sample is saturated during the test).

- Unconsolidated Undrained (UU) triaxial test: is carried out using a triaxial device of revolution which was initially designed by Bishop and Henkel in 1962, the UU test is used on saturated or unsaturated soils which have low permeability.

- Free swelling with the Oedometer consists of measuring the swelling pressure (the pressure that must be applied to the soil sample to prevent it from swelling on contact with water) [32].

- Standard Proctor consists of determining the maximum dry density and optimum water content, it is carried out by humidifying a material at several water contents and compacting it in a standardized mold using a standardized tamper, according to a very precise process, the soil sample is well studied by measuring its properties.

- The CBR immersion index is measured after 4 days of immersion in water (the test period from 1 hour to 4 days). For this, the test piece is covered with overloads which allow the surface of the sample to be fretted, therefore the measurement of the desired CBR index is known as the greatest value between a penetration of 2.5 mm in percentage of 13.2 kN and a penetration of 5 mm in percentage of 19.8 kN.

- Unconfined compressive strength (UCS) test is performed on a cylindrical sample placed between two parallel plates of a press. After putting the two plates in contact with the sample, the axial load is applied with a constant displacement rate. From the maximum (axial) breaking force (Fmax) displayed by the machine, the compressive strength was calculated resulting from the ratio between the breaking force Fmax and the cross-section of the specimen.

Table 2. The physical and mechanical tests carried out

Test	Standard	Objective
Atterberg Limits	ASTM-D4318-17e1 [21]	Determine the Atterberg limits: liquid limit, plastic limit, plasticity index and consistency index.
Oedometer Compressibility	ASTM-D2435-04 [27]	Determine the compressibility parameters: consolidation pressure, the compressibility coefficient and the swelling coefficient.
Free Swelling on the Oedometer	ASTM-D2435-04 [27]	Determine the swelling pressure.
UU	ASTM-D2850-15 [25]	Determine the parameters of the resistance: the apparent cohesion and the angle of internal friction.
Compaction (Standard Proctor)	ASTM-D1557-12 [29]	Determine maximum dry density and optimum water content.
CBR	ASTM-D1883-16 [30]	Determine the strength and load-bearing capacity of soil.
UCS	ASTM-D2166-16 [28]	Determine the compressive strength.

3. RESULTS AND DISCUSSION

3.1 Effect of KCl and NaCl salts on the Atterberg limits

As observed, the plasticity index decreased with an increase in salt concentration. This could be due to the ionic reactions of salts with clay minerals, which tend to cause soil flocculation [33].

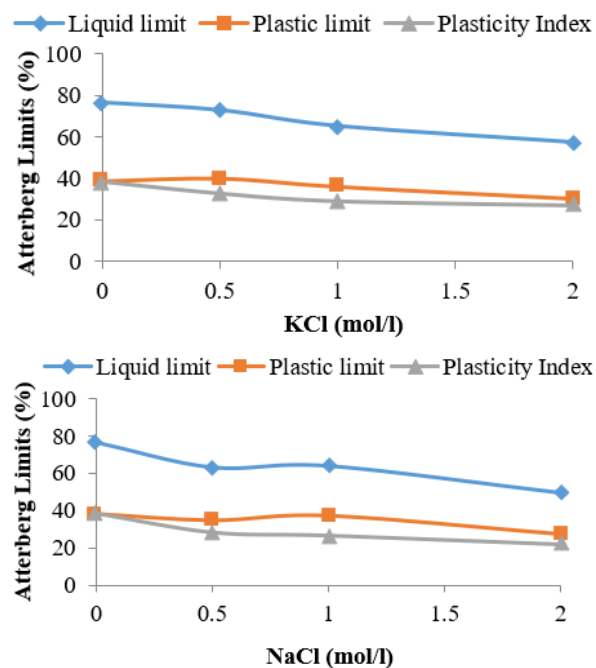


Figure 5. The effect of KCl and NaCl salts on the Atterberg limits

The variation of the samples Atterberg limits at different concentrations of KCl and NaCl is mentioned in Figure 5. It shows that adding amounts of KCl and NaCl decreased the plasticity index. The lowest values occur at 2 M of KCl and NaCl, where the plasticity index reduced by approximately 29% and 43.1% respectively compared to untreated soil. Also, a reduction in the soil liquid limit and the plastic limit was observed where the values dropped by 26% and 21% respectively for a concentration of 2 M of KCl, and by 35% and 29% respectively for a concentration of 2 M of NaCl. The noticeable difference in the effects of NaCl and KCl on reducing the liquid and plastic limits arises from the smaller ionic radius, higher hydration energy, and stronger capacity of Na⁺ to compress the diffuse double layer compared with K⁺. Consequently, sodium salts are more effective in reducing the soil's ability to absorb and retain water, which directly decreases the liquid limit, plastic limit, and plasticity index to a greater extent than potassium salts [34]. These results are in good agreement with those obtained by Schmitz and Van Paasen [35] who reported that the reduction in the liquid limit is related to the increase in the molarity of the salt. The results are also similar to previous studies carried out by: Al-Omari et al. [36] and Shukla et al. [37] which used potassium chloride (KCl) at different concentrations on an expansive soil. The authors found a decrease in plasticity properties even at high values of water content, which confirms that the addition of KCl made the soil more solid compared to the normal state. In addition, Frydman et al. [13] and Al-Omari et al. [36] found that increasing the electrolyte concentration by adding

chemicals reduces the thickness of the double layer and increases the shear strength between the soil particles which leads to a reduction in the plasticity index and the liquid limit [38].

3.2 The effect of KCl and NaCl salts on compressibility properties

Figure 6 shows the effect of KCl and NaCl salts with different concentrations on the compressibility characteristics of the studied soil. It was noted that there is a decrease in the swelling coefficient (S_c), which presents the importance of the swelling deformation induced by an unloading compared to a given stress state [35], compared to the natural state. The values of the swelling coefficient were reduced by 43% and 27% respectively for 2 M concentration of KCl and NaCl. Moreover, at low consolidation pressure and low salt concentration, the compressibility coefficient remains relatively high. Conversely, at higher consolidation pressures and salt concentrations, a pronounced reduction in C_c is observed. This confirms the inverse relationship between consolidation pressure and the compressibility coefficient [39].

On the other hand, an increase in the compressibility coefficient (C_c) was noticed by 8.3% and 28.6% for 2 M concentration of KCl and NaCl respectively. According to the obtained values of swelling coefficient and compressibility coefficient, the soil was altered from a swelling soil category to a low swelling soil category, after the addition of the highest concentration of salts. And it was changed from a moderately compressible soil to a quite highly compressible (after addition of 2 M of NaCl).

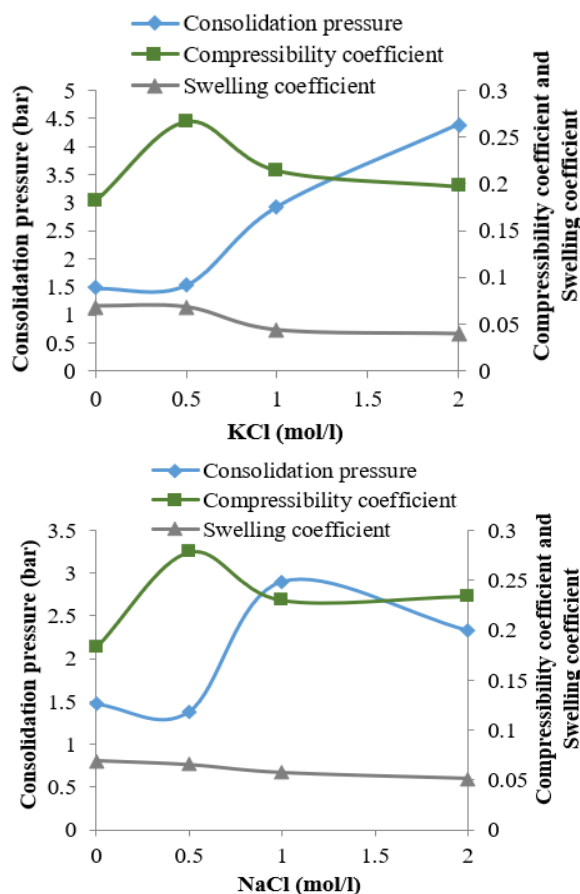


Figure 6. The effect of KCl and NaCl salts on compressibility properties

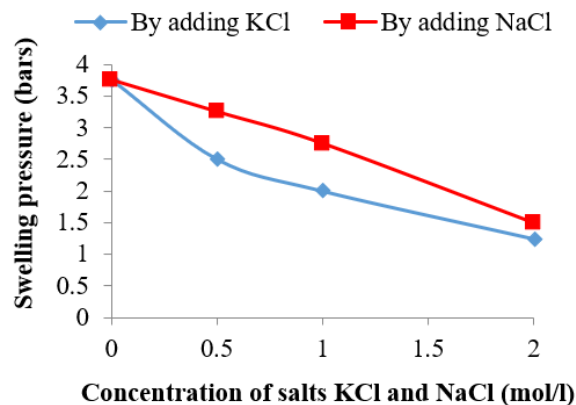


Figure 7. The effect of KCl and NaCl salts on the swelling pressure

From the oedometer free swelling test. The obtained results are summarized in Figure 7. The greatest improvement occurred at a concentration of 2 M of KCl and NaCl where the swelling pressure decreased by approximately 66% and 60% respectively compared to untreated soil. These results are similar to those obtained by Al-Omari et al. [36] and Gueddouda et al. [15]. They found that the addition of KCl and NaCl had a very important role in reducing the swelling pressure. In addition, the free swelling for the expansive soil is reduced linearly with the increase in the percentage of chemical substances added up to an optimal value; after this value the reduction in free swelling is negligible. This is probably explained by the fact that the further addition of salts no longer produces noticeable effects, since the main adsorption sites are already saturated, the compression of the diffuse double layer has reached its limit, and the particles have attained a more stable arrangement (floculated or aggregated) [40].

3.3 The effect of KCl and NaCl salts on the CBR

Figure 8 shows the results of the CBR values for the samples tested.

Remarkably, the maximum CBR value was reached by adding the highest concentration 2 M of KCl which leads to an increase of 252%. In contrast, the CBR values under NaCl values under NaCl effects reached a plateau at around 0.75M concentration, and stayed constant up to 2 M. The induced increase is of 113%.

The action of KCl and NaCl salts on the swelling potential differs from one clay to another. It is due to the mineralogical nature of clay. In addition, chemical solutions have a positive effect on swelling reduction and in most cases optimal swelling reduction is achieved with the use of high salt concentrations [8].

The potassium chloride reduces the swelling of soils thanks to the fixing of cations between the sheets, and the swelling remains to be reduced and its speed is rapid even at low concentrations [40]. In this study, the swelling potential was reduced by 74.58% and 69.50% for a concentration of 2 M of KCl, NaCl, respectively compared to the untreated soil. The results are presented in Figure 9. The higher efficiency of KCl compared to NaCl can be explained by the ability of K^+ ions to better penetrate the interlayers of clay minerals, replacing exchangeable cations and reducing the amount of absorbed water between the layers. This mechanism leads to the formation of stronger interparticle bonds and greater

stabilization of the soil structure [33]. These results are similar with the results obtained by Hachichi and Fleureau [8], Belabbaci et al. [40], and Srinivas et al. [41].

According to Zhao et al. [1], increasing the salt concentration leads to compression of the thickness of the clay double layer.

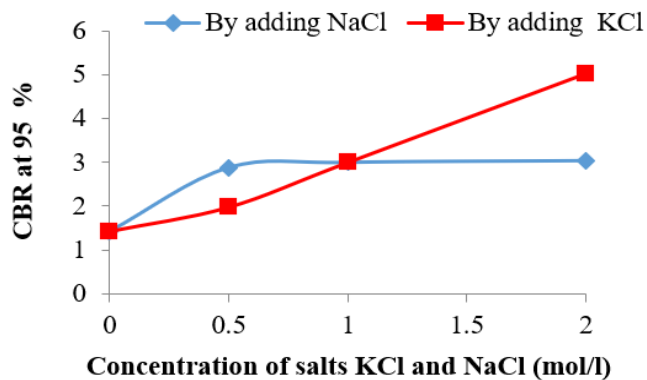


Figure 8. The effect of KCl and NaCl salts on CBR

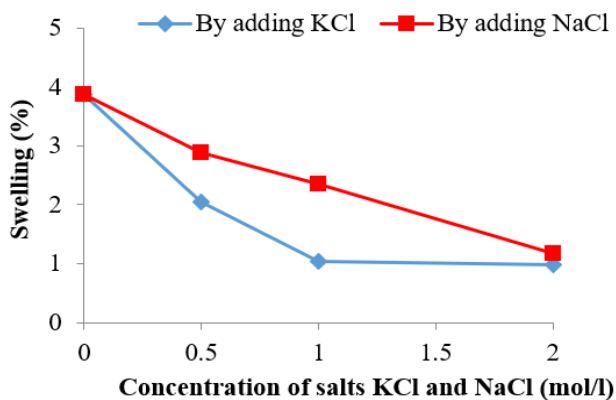


Figure 9. The effect of KCl and NaCl salts on swelling potential

3.4 The effect of KCl and NaCl salts on compaction properties

The effect of KCl and NaCl on the relationship between dry density and moisture content is shown in Figure 10. The results of the compaction tests revealed a change in the compaction characteristics after adding salts. Increased KCl or NaCl concentration caused an increase in dry density and a decrease in soil moisture content. This observation would probably be due to the reduced thickness of the double layer of diffuse water [36, 40].

The results show that the dry density of the soil without any mixing is 1.53 t/m³. With the addition of 0.5 M, 1 M and 2 M KCl, it reached 1.56 t/m³, 1.58 t/m³ and 1.68 t/m³ respectively. And with the addition of 0.5 M, 1 M and 2 M NaCl, the obtained values were 1.61 t/m³, 1.63 t/m³ and 1.64 t/m³ respectively.

By adding 2 M of KCl and NaCl the dry density was increased by 9.8% and 7.8% respectively. Similar observations were also made by Al-Omari et al. [36], Shukla et al. [37], Afrin [42], El Kady et al. [43] and Durotoye and Akinmusuru [44]. Test results show that the addition of salts significantly improves compaction characteristics where sodium and potassium chlorides react with calcium oxides and hydroxides in the soil to form calcium chloride, which has a

very important role for soil hardening and increased dryness [45, 46].

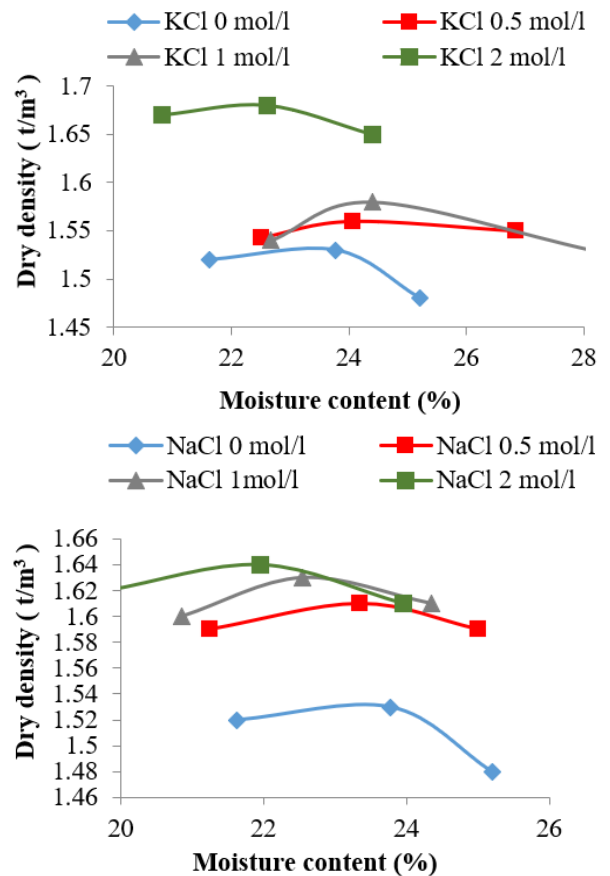


Figure 10. The effect of KCl and NaCl on the relationship between dry density and moisture content

3.5 The effect of KCl and NaCl salts on compressive strength

The results of a series of unconfined compression tests were reported to study the effect of KCl and NaCl at different concentrations (0.5 M, 1 M and 2 M) on the compressive strength of the sample. The values of compressive strength are presented in Figure 11. It can be noticed that clay soil has a higher compressive strength with the addition of salts than with water alone. This is because clay soil has several layers and sheets of silica with a hydrogen bond connecting these sheets [40].

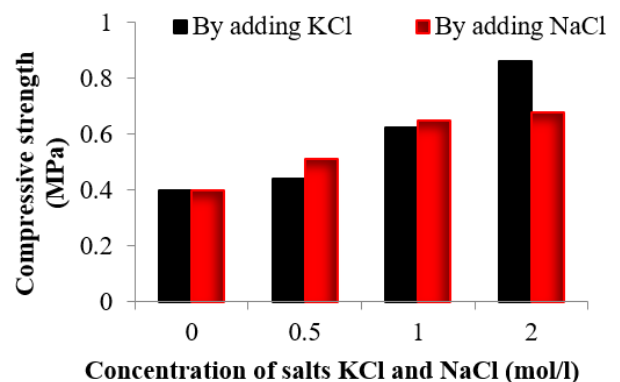


Figure 11. The effect of KCl and NaCl salts on compressive strength

The maximum increase in the compressive strength of soil was achieved by adding 2 M concentration of salts. The strength increased by 114.5% and 70%, respectively for KCl and NaCl, compared to untreated soil. This shows another positive contribution of salts in improving the mechanical characteristics of the studied soils. The same trend of results was found by Xiang et al. [34] and Shukla et al. [37].

3.6 The effect of KCl and NaCl salts on friction angle and cohesion (UU triaxial shear test)

To evaluate the effects of salt concentration on shear strength parameters, such as cohesion and the angle of internal friction, soil samples were subjected to a UU test. These parameters are influenced by the composition, arrangement, bonding and micro-effects of soil particles, they also varied according to the type and content of the additives [47]. From Figure 12, the results indicated that KCl and NaCl salts had a significant effect on the shear strength parameters. The cohesion and friction angle were increased with increasing salts concentration. But the tendency for increase in internal friction angle and cohesion by the addition of NaCl was higher than that found by the addition of KCl, indicating that concentration and solution type had a great influence on the soil shear strength parameters. The best improvement occurred at 2 M concentration of KCl and NaCl where the cohesion values were augmented by about 289.2% and 413.5% respectively. And, the values of the angle of internal friction were increased by about 174.4% and 569.2% respectively. These results are in good agreement with those of Dubey and Jain [48] which noticed an increase in internal friction angle and cohesion values by the addition of salt (NaCl).

For salt concentrations at zero, the values of cohesion and angle of internal friction were 0.222 bars and 3.90° respectively.

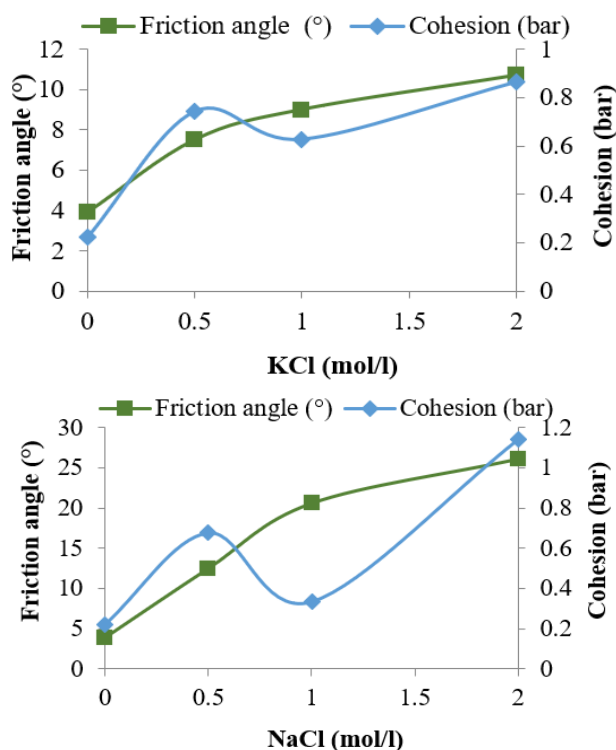


Figure 12. The effect of KCl and NaCl salts on friction angle and cohesion

After addition of 0.5 M of KCl and NaCl, a linear increase of cohesion and the angle of internal friction were noticed. At additional 1 M of KCl and NaCl, the cohesion decreased due to the longer distances and weaker attraction forces between the clay particles [49]. In this case, the double layer can increase the distances between the clay particles, limiting the additional adsorption capacity of the soil particles. Also, at 2 M concentration of salts, an increase in shear strength parameters was found. In general, it can be concluded that the salts make the clay more cohesive, which was modified from a soft untreated soil to a firm treated one.

4. CONCLUSIONS AND FUTURE WORKS

This research aims to characterize the mechanical behavior of an expansive clay soil treated with chemical solutions (KCl and NaCl) at three concentrations 0.5 M, 1 M and 2 M, to reduce expansibility and improve soil strength. The choice of the study site was justified by its extension to dangerous areas, where significant damage has been recorded in road infrastructure, buildings and light civil works.

Through the tests carried out, it can be concluded that the treatment of clay with KCl and NaCl salts have a significant influence on its mechanical characteristics. However, clay processing significantly affects its plasticity parameters, consolidation pressure, CBR index, swelling index, compaction parameters, compressive strength and shear strength. The main conclusions drawn from this work are as follows:

- Potassium chloride and sodium chloride decrease liquid limit, plasticity index, swelling coefficient, swelling pressure and swelling potential. The optimal benefit occurs at 2 M KCl and NaCl, where the plasticity index is reduced by a factor of about 29% and 43% respectively.
- The swelling pressure is reduced by a factor of approximately 66% and 60% respectively.
- Swelling is reduced by a factor of approximately 74.58% and 69.5% respectively.
- Potassium chloride and sodium chloride increase the CBR index. It is concluded that the best improvement occurs at 2 M KCl and NaCl where the CBR is increased by about 252% and 113% respectively.
- Potassium chloride and sodium chloride increase maximum dry density and decrease optimum moisture content. Adding 2 M of KCl and NaCl gives the highest value of maximum dry density as it increased by about 9.8% and 7.8% respectively.
- Potassium chloride and sodium chloride increase the compressive strength, by 114.5% and 70% respectively for a 2 M concentration.
- The highest concentration of KCl and NaCl reverses the shear properties from decrease to increase knowing that cohesion and angle of internal friction are augmented by a factor of about 289.2% and 174.4% (for 2 M KCl); and 413.5% and 569.2% (for 2 M NaCl).

Future research will focus on combining geotextile reinforcement with the use of salts (KCl and NaCl) at the same concentrations as in this study, to assess whether this approach further improves swelling control, strength, and soil stability compared to salt treatment alone.

REFERENCES

- [1] Zhao, H., Ge, L., Petry, T.M., Sun, Y.Z. (2014). Effects of chemical stabilizers on an expansive clay. *KSCE Journal of Civil Engineering*, 18(4): 1009-1017. <https://doi.org/10.1007/s12205-013-1014-5>
- [2] Mutaz, E., Dafalla, M. (2014). Utilizing chemical treatment in improving bearing capacity of highly expansive clays. *Characterization, Modeling, and Evaluation of Geotechnical Engineering Systems*, pp. 74-82. <https://doi.org/10.1061/9780784478486.010>
- [3] Azam, S., Abduljawwad, S.N. (2000). Influence of gypsification on engineering behavior of expansive clay. *Journal of Geotechnical and Geoenvironmental Engineering*, 126(6): 538-542. [https://doi.org/10.1061/\(ASCE\)10900241\(2000\)126:6\(538\)](https://doi.org/10.1061/(ASCE)10900241(2000)126:6(538))
- [4] Nagaraj, H., Munnas, M., Sridharan, A. (2010). Swelling behavior of expansive soils. *International Journal of Geotechnical Engineering*, 4(1): 99-110. <https://doi.org/10.3328/IJGE.2010.04.01.99-110>
- [5] Bekkouche, S.R., Benzerara, M., Zada, U., Muhammad, G., Ali, Z. (2022). Use of eco-friendly materials in the stabilization of expansive soils. *Buildings*, 12(10): 1770. <https://doi.org/10.3390/buildings12101770>
- [6] Zada, U., Jamal, A., Iqbal, M., Eldin, S.M., Almoshaogeh, M., Bekkouche, S.R., Almuaythir, S. (2023). Recent advances in expansive soil stabilization using admixtures: Current challenges and opportunities. *Case Studies in Construction Materials*, 18: e01985. <https://doi.org/10.1016/j.cscm.2023.e01985>
- [7] Xiang, G., Ye, W., Xu, Y., Jalal, F.E. (2020). Swelling deformation of Na-bentonite in solutions containing different cations. *Engineering Geology*, 277: 105757. <https://doi.org/10.1016/j.enggeo.2020.105757>
- [8] Hachichi, A., Fleureau, J.M. (1999). Characterization and stabilization of a few expansive soils from Algeria. *Revue Française de Geotechnique*, 86: 37-51. <https://doi.org/10.1051/geotech/1999086037>
- [9] Bekkouche, S.R., Boukhatem, G. (2016). Experimental characterization of clay soils behavior stabilized by polymers. *Journal of Fundamental and Applied Sciences*, 8(3): 1193-1205. <https://doi.org/10.4314/jfas.v8i3.30>
- [10] Idoui, I. (2018). Utilisation des Bio-Polymères dans l'amélioration du comportement des sols. Thèse de Doctorat, Faculté des Sciences de la Nature et de la Vie, Département des Sciences de la Terre, Université de Jijel.
- [11] Fondjo, A.A., Theron, E., Ray, R.P. (2021). Stabilization of expansive soils using mechanical and chemical methods: A comprehensive review. *Civil Engineering and Architecture*, 9(5): 1295-1308. <https://doi.org/10.13189/cea.2021.090503>
- [12] Al-Ashou, O., Al-Khashab, M.N. (1993). Treatment of expansive clay soil with potassium chloride. *Al-Rafidian Engineering Journal*, 1(2): 17-31.
- [13] Frydman, S., Ravina, I., Ehrenreich, T. (1978). Stabilization of heavy clay with potassium chloride. *Geotechnical Engineering*, 8(2): 95-107.
- [14] Zhang, S., Zhu, T., Zheng, P., Ye, L. (2024). Evaluation and prediction of swelling properties of bentonite under the action of salt solution. *Applied Clay Science*, 258: 107453. <https://doi.org/10.1016/j.clay.2024.107453>
- [15] Gueddouda, M.K., Goual, I., Lamara, M., Smaida, A., Mekarta, B. (2011). Chemical stabilization of expansive clays from Algeria. *Global Journal of Researches in Engineering*, 11(5): 1-7.
- [16] Zhang, K.Y., Li, F. (2003). Grouting-test study on expansive soil of Hefei area. *Geotechnical Engineering Technique*, 8(2): 102-115.
- [17] Fattah, M.Y., Salman, F.A., Nareeman, B.J. (2010). A treatment of expansive soil using different additives. *Acta Montanistica Slovaca*, 15(4): 290-297. <https://doi.org/10.4028/www.scientific.net/amr.243-249.2973>
- [18] Lan, T.N. (1977). Un nouvel essai d'identification des sols-l'essai au bleu de methylene. *Bull Liaison Lab Ponts Chauss*, 88: 136-137.
- [19] Bigot, G., Zerhouni, M.I. (2000). Retrait, gonflement et tassement des sols fins. *Bulletin-Laboratoires des Ponts et Chaussées*, 105-114.
- [20] ASTM D2216-10. (2010). Standard test methods for laboratory determination of water (moisture) content of soil and rock by mass. *Annual Book of ASTM Standards*. PA, USA, 2010. <https://doi.org/10.1520/D2216-10>
- [21] ASTM D4318-17e1. (2010). Standard test methods for liquid limit, plastic limit, and plasticity index of soils. *ASTM International*. PA, USA, 2017. <https://doi.org/10.1520/D4318-17E01>
- [22] ASTM C837-09. (2024). Standard test method for methylene blue index of clay. PA, USA. <https://doi.org/10.1520/C0837-09R24>
- [23] ASTM-D7928-16e1. (2017). Standard Test method for particle-size distribution (gradation) of fine-grained soil using the sedimentation (hydrometer) analysis. *ASTM International: West Conshohocken, PA, USA*. <https://doi.org/10.1520/d7928-16>
- [24] ASTM D4373-96. (2017). Standard test method for rapid determination of carbonate content of soils. *ASTM International*. PA, USA. <https://doi.org/10.1520/d4373-96>
- [25] ASTM-D2850-15. (2025). Standard test method for unconsolidated undrained triaxial compression test on cohesive soils. *ASTM International: West Conshohocken, PA, USA, 2015*. <https://doi.org/10.1520/d2850>
- [26] ASTM-D3080. (2023). Standard test method for direct shear test of soils under consolidated drained conditions. *ASTM International: West Conshohocken, PA, États-Unis*. https://doi.org/10.1520/d3080_d3080m
- [27] ASTM-D2435-04. (2011). Standard test methods for one-dimensional consolidation properties of soils using incremental loading. *ASTM International: West Conshohocken, PA, USA*. <https://doi.org/10.1520/D2435-04>
- [28] ASTM-D2166-06. (2010). Standard test method for unconfined compressive strength of cohesive soil. *ASTM International: West Conshohocken, PA, USA*. <https://doi.org/10.1520/D2166-06>
- [29] ASTM-D1557-12. (2021). Standard test methods for laboratory compaction characteristics of soil using modified effort (56,000 Ft lbf/ft³ (2700 kN-m/m³)) 1. *ASTM International: West Conshohocken, PA, USA*. <https://doi.org/10.1520/D1557-12R21>
- [30] ASTM-D1883-16. (2010). Standard Test Method for California Bearing Ratio (CBR) of Laboratory Compacted Soils. *ASTM International: West Conshohocken, PA, USA*. <https://doi.org/10.1520/d1883-07e01>

- [31] Kebede, D., Khan, A., Asha, A., Benti, C.G. (2022). Combined effect of marble dust and waste paper sludge in improving engineering properties of black-cotton soil of Gelan area, Ethiopia. *Journal of Engineering Research and Reports*, 22(8): 80-88. <https://doi.org/10.9734/jerr/2022/v22i817556>
- [32] Medjnoun, A. (2014). Analyse, caractérisation, prévision et modélisation du comportement des argiles gonflante. Doctoral dissertation, Tizi Ouzou. <https://doi.org/10.1051/mateconf/20141103004>
- [33] Chen, W.L., Grabowski, R.C., Goel, S. (2022). Clay swelling: Role of cations in stabilizing/destabilizing mechanisms. *ACS Omega*, 7(4): 3185-3191. <https://doi.org/10.1021/acsomega.1c04384>
- [34] Xiang, G., Ye, W., Jalal, F.E., Hu, Z. (2022). Shear strength of bentonite saturated with saline solutions exhibiting variety of cations. *Engineering Geology*, 298: 106537. <https://doi.org/10.1016/j.enggeo.2022.106537>
- [35] Schmitz, R.M., Van Paassen, L.A. (2003). The decay of the liquid limit of clays with increasing salt concentration. *Ingeokring Newsletter*, 9(1): 10-14.
- [36] Al-Omari, R., Ibrahim, S., Al-Bayati, I. (2010). Effect of potassium chloride on cyclic behavior of expansive clays. *International Journal of Geotechnical Engineering*, 4(2): 231-239. <https://doi.org/10.3328/IJGE.2010.04.02.231-239>
- [37] Shukla, R.P., Parihar, N.S., Gupta, A.K. (2018). Stabilization of expansive soil using potassium chloride. *Stavební Obzor-Civil Engineering Journal*, 27(1): 25-33. <https://doi.org/10.14311/CEJ.2018.01.0003>
- [38] Shukla, S.K. (2025). *An Introduction to Geosynthetic Engineering*. CRC Press. <https://doi.org/10.1201/b21582>
- [39] Hasan, H., Dang, L., Khabbaz, H., Fatahi, B. (2017). Swelling pressure and consolidation of soft clay stabilized with bagasse ash and lime. In *Bearing Capacity of Roads, Railways and Airfields*, pp. 1069-1075. <https://doi.org/10.1201/9781315100333-143>
- [40] Belabbaci, Z., Mamoune, S.M.A., Bekkouche, A. (2013). Laboratory study of the influence of mineral salts on swelling (KCl, MgCl₂). *Earth Science Research; Published by Canadian Center of Science and Education*, 2(2): 135-142. <https://doi.org/10.5539/esr.v2n2p135>
- [41] Srinivas, M., Raju, G.V.R.P., Prasada, G. (2010). Effect of strong chemicals on the swell properties of an expansive clay. In *Proceedings of IGC-2010: GEOTrendz, IIT Bombay*, pp. 613-616.
- [42] Afrin, H. (2017). Stabilization of clayey soils using chloride components. *American Journal of Civil Engineering*, 5(6): 365-370. <https://doi.org/10.11648/j.ajce.20170506.18>
- [43] El Kady, A., Bakr, M.A., Gad, S.A. (2020). Evaluation of salt water effect on the physical properties and compaction characteristics of expansive soil. *International Journal of Civil Engineering and Technology*, 11(11): 49-64. <https://doi.org/10.34218/ijciet.11.11.2020.005>
- [44] Durotoye, T.O., Akinmusuru, J.O. (2016). Effects of sodium chloride on the engineering properties of expansive soils. *IJRET: International Journal of Research in Engineering and Technology*, 5(9): 11-16. <https://doi.org/10.15623/ijret.2016.0509002>
- [45] Otoko, G.R. (2014). The effect of salt water on the physical properties, compaction characteristics and unconfined compressive strength of a clay, clayey sand and base course. *European International Journal of Science and Technology*, 3(2): 9-16.
- [46] Ramadhan, R.N., Jassam, M.G., Jasim, F. (2024). Engineering properties of gypseous soils improved with natural and industrial fibers. *Mathematical Modelling of Engineering Problems*, 11(6): 1393-1402. <https://doi.org/10.18280/mmep.110601>
- [47] Han, Y., Wang, Q., Wang, N., Wang, J., Zhang, X., Cheng, S., Kong, Y. (2018). Effect of freeze-thaw cycles on shear strength of saline soil. *Cold Regions Science and Technology*, 154: 42-53. <https://doi.org/10.1016/j.coldregions.2018.06.002>
- [48] Dubey, P., Jain, R. (2015). Effect of common salt (NaCl) on engineering properties of black cotton soil. *IJSTE-International Journal of Science Technology & Engineering*, 2(1): 64-68.
- [49] Al-Shayea, N.A. (2001). The combined effect of clay and moisture content on the behavior of remolded unsaturated soils. *Engineering Geology*, 62(4): 319-342. [https://doi.org/10.1016/S0013-7952\(01\)00032-1](https://doi.org/10.1016/S0013-7952(01)00032-1)