Malaysian Journal of Civil Engineering 26(2):119-135 (2014)

EFFECT OF SODIUM CHLORIDE ON THE WETTING INDUCED COLLAPSE STRAIN OF SOILS

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Abstract: Collapsible soils are unsaturated soils which present the potential for large strains and complete change to the whole particle structure after wetting with or without loading. These soils are characterized with loose structures composed of silt to fine-sand-size particles. Collapsible soils are deposited in arid and semi-arid regions. Due to the expansion of human activities, these regions are occupied aggressively leading to the use of large quantities of water which create favorable conditions for soil collapse. The soils failure leads to severe damages and large distresses to man-made structures. The experimental study on reconstituted soil in laboratory consists of the evaluation of the effect of a saline solution of sodium chloride at different, water content and levels of compaction energy on the collapsible potential. The method used is based on oedometer tests with variation of the vertical stress. The study clearly reveals the influence of the salt concentration on the change of microstructural characteristics of the reconstituted soil and reduction of the collapse potential .

Keywords: *Collapsible soils; wetting; experimental investigation; chemical treatment*

1.0 Introduction

Important distresses to structures caused by collapsible soils and triggered by wetting effect were observed in many regions throughout the world, mainly in aride and semi-aride areas. Recently, cases in the southeastern region of Algeria are a good illustration of the extent of the problem. Collapsible soils are unsaturated soils which may undergo inter-granular rearrangement with abrupt and significant volume reduction after wetting. The large settlement resulting from the soil collapse pushed for deep studies of these types of soils. According to Dudley (1970). two types of collapse exist. In the case of cemented structures, the collapse is dependent of the level of stress rather of the level of wetting. However, if the soil elements are connected with fine particles (clay or silt) which induce high link forces caused by suction or cementation, wetting will reduce or

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cancel the suction effect resulting in substantial reduction of the shear resistance leading to favorable conditions of collapse, if high shear stresses are present. Many research studies are developed to identify and prevent failure of collapsible soils as well as the measures to insure sufficient stability of structures to be built on such soils, (Rollins *et al.*, 1994; Cui *et al.*, 1999; Le Runigo *et al.*, 2008; Abbeche *et al.*, 2009; Ayadat and Hanna, 2007).

The solutions proposed by various researchers to mitigate collapsible soils depend on the depth of soil layer in one hand, and the bearing capacity required by the structure foundation, on the other hand. Deep foundations, replacement or on-site thermo or mechanical treatment were part of the proposed solutions. Recently, chemical stabilization methods by salts were proposed (Shao-Chi *et al.*, 2009; Kaufhold and Dohrman, 2009).

However, it should be noted that there is few studies on the effect of soluble salts particularly sodium chloride (NaCl) on the mechanical behavior and microstructural characteristics of collapsible soils. It is proposed in this experimental work to study the influence of NaCl on the reduction of the potential for collapse C_p of a soil sample reconstituted from sand and kaolin. This study involves different salt concentrations, water contents, and energies of compaction based on œdometer test with different vertical stress.

2.0 Materials, Equipment and Test

The reconstituted soil sample is composed of 80% of sand and 20% of kaolin. The application of various criteria of collapse as indicated by Abbeche *et al.* (2005) and Lutenegger and Saber (1988) show that this material is collapsible.

2.1 Characteristics of Materials

The sand used in the sample reconstitution comes from the Liwa River located in the region of Biskra, Algeria screened on the 2mm sieve; and its physical characteristics are given in the Table 1.

The kaolin soil used in this study, is extracted from Debbagh area of Guelma, Algeria. The physical characteristics are given in Table 1.

Observation by scanning electron microscopy (SEM) coupled with X-ray spectrum analysis (Figures 1 and 2) reveals that the experimental material consists of quartz, kaolin and montmorillonite.

The sieve analysis of the reconstituted sample is shown in Figure 3. The geotechnical characteristics of that sample are given in Table 1.

Table 1: Characteristics of Materials

Materials	Characteristics
Sand	Sand equivalent SE = 87 %
	Coefficient of uniformity $C_u = 3.91$
	Coefficient of curvature $C_c = 0.95$
	Grain size distribution (0.08-2 mm) with 3.03% of particles < 80 µm.
Kaolin	D‹80µm
	Liquid limit LL = 67(%)
	Plastic limit PL = 39(%)
	Specific Gravity $G_S = 2.4$
Reconstituted soil (80% sand + 20% kaolin)	Coefficient of uniformity $C_u = 5.13$
	Coefficient of curvature $C_c = 1.07$
	Liquid limit LL = 28 (%)
	Plastic limit PL = 16 (%)
	Specific gravity $G_S = 2.65$
	Maximum dry density (g/cm^3) $\gamma_d = 1.93$
	Optimal water content $w_{opt} = 10$ (%)

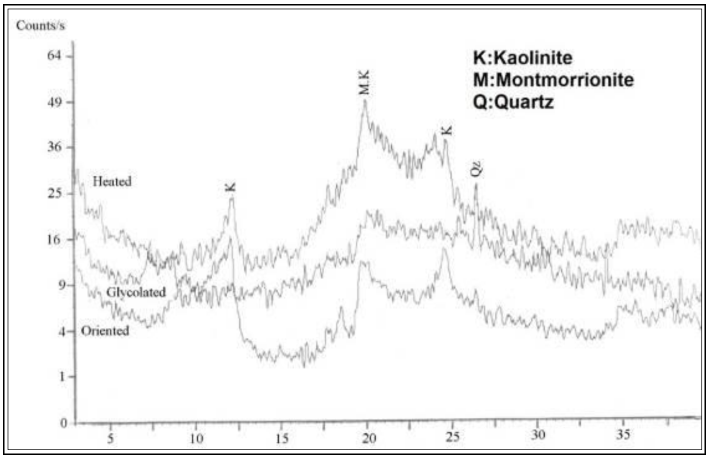
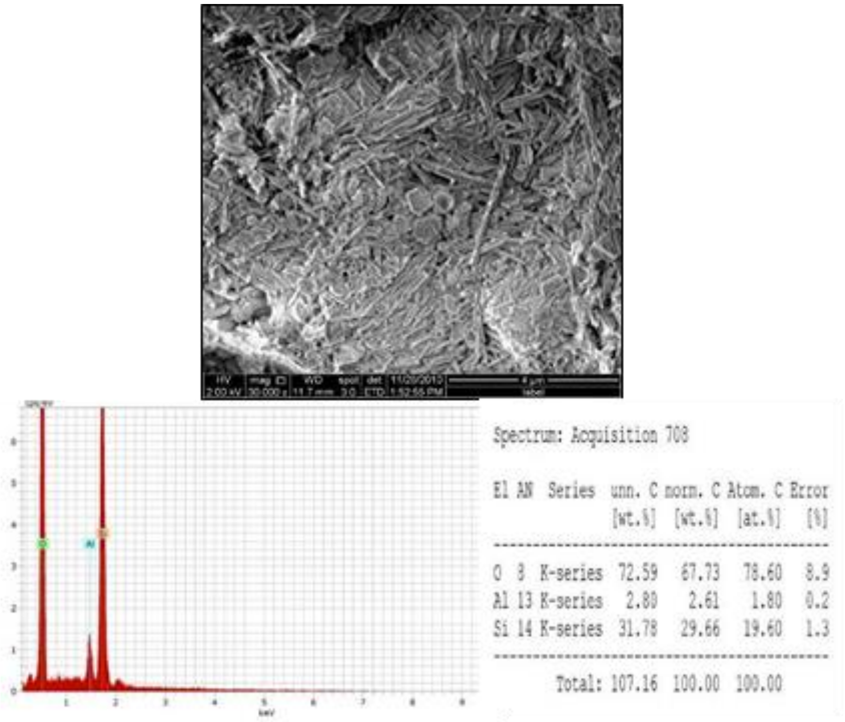


Figure 1: X-ray output spectrum of reconstituted sample (sand & kaolin)



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Spectrum: Acquisition 708

El AN  Series  unn. C norm. C Atom. C Error
               [wt.%] [wt.%]  [at.%]   [%]
--------------------------------------------
O   8  K-series  72.59   67.73   78.60  8.9
Al 13  K-series   2.80    2.61    1.80  0.2
Si 14  K-series  31.78   29.66   19.60  1.3
--------------------------------------------
          Total: 107.16  100.00  100.00
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Figure 2: Electron Photomicrograph of reconstituted sample (sand & kaolin)

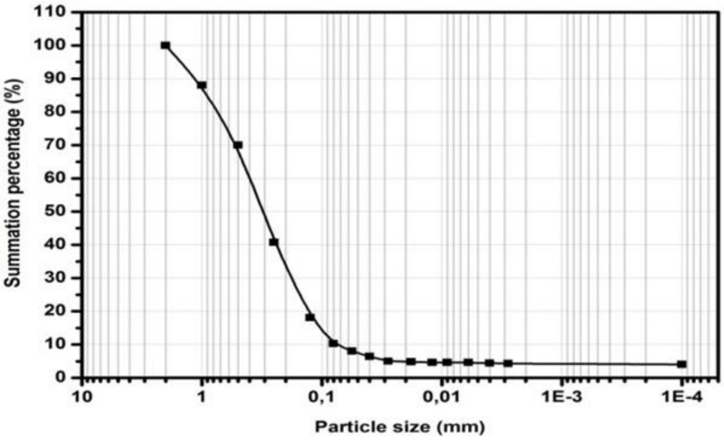


Figure 3: Sieve analysis of the reconstituted sample

2.2 *Characteristics of Consistency of the Reconstituted Soil*

The literature revealed that a soil is likely to collapse if at least one of the following criteria is verified: activity of soil ($A_c<1$), liquid index ($I_l<0$), plasticity index ($PI\leq20$), consistence index ($I_c>1$) and manageability index ($I_w\leq1$) (Abbeche *et al.*, 2005; Ayadat and Hanna, 2007). The results presented in Table 2 show that the soil of our study is likely to collapse, and that four of the five criteria mentioned above are checked, which confirms the results of Abbeche *et al.* (2010).

Table 2: Characteristics of consistency of the reconstituted soil

w_0*	A_c	PI	I_l	I_c	I_w
2	2.60	12	-1.17	2.17	0.16
4			-0.67	2.00	0.33
6			-0.83	1.83	1.50

*Initial water content

2.3 *Physico-Chemical Characteristics of the Reconstituted Soil*

It was found that the Cation Exchange Capacity (CEC) of the sample is low according to Table 3 with a saturated adsorption complex. The CEC is essentially determined by the nature and content of the clay fraction, which in our case consists of kaolin mixed with smectites impurities. The pH indicates that the material is alkaline and the electrical conductivity (EC) is low.

Table 3: Characteristics of consistency of the reconstituted soil

Adsorption complex			Solution soil		
Ca^{++}	0.21	meq/ 100g	pH	7.36	
Mg^{++}	0.10	meq/ 100g	EC	1.2	ms/cm
K^{+}	0.13	meq/ 100g	CO3H	3.88	meq/ l
Na^{+}	2.07	meq/ 100g	SO4--	2.5	meq/ l
CEC	2.51	meq/ 100g	Cl-	5.52	meq/ l
			Ca++	4.50	meq/ l
			Mg++	3.70	meq/ l
			Na+	3.00	meq/ l
			K+	2.80	meq/ l

2.4 *Equipment*

The experimental equipment and tests are the same as those reported by Abbeche *et al.* (2010); only the saline solution is different. The equipment used is shown schematically in Figure 4. It is composed of a disc having a diameter slightly smaller than that of the oedometer ring, fixed at a guidance rod and a hammer in the shape of a disc. The 152g hammer falls along the rod with a drop of 15 cm and contacts the fixed disc resulting in the compaction of sample in the oedometer ring, with the following compaction energy:

$$E_c = n.m.g.h/v \qquad (1)$$

where E_c is the compaction energy, n is the number of drops, m is the mass of hammer disc, h is the drop height, g is the acceleration of gravity and v is the volume of material before compaction.

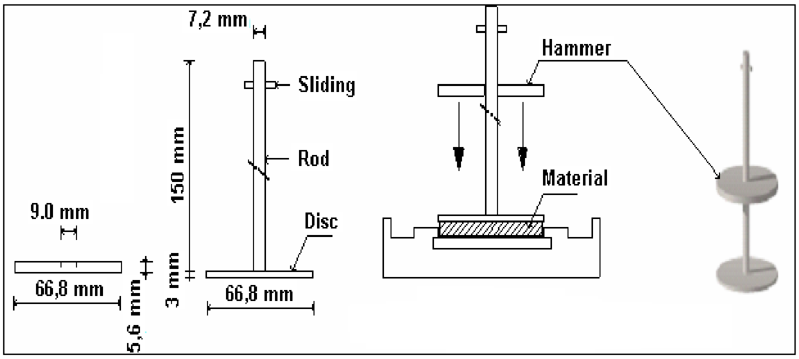


Figure 4: Experimental equipment (compaction device)

2.5 *Test and Procedure*

The object of this study is to reconstitute the soil in an oedometer mold with specific water content and dry density. The material is compacted in one layer because of the low thickness of the ring. Reconstituted soil exhibits good mechanical characteristics when it is compacted with a low initial water content (w_0=2, 4 and 6%). However, if higher moisture is introduced, even without additional load, the structure collapses and significant deformations occur.

Jennings and Knight (1975) proposed a procedure to estimate the collapse potential of a soil. That potential is evaluated by loading in an oedometer device two undisturbed soil samples at natural moisture content. One sample is then flooded for saturation. These tests provide the void ratios (e_1 and e_2) before and after flooding at a specific loading. This behavior can be observed in Figure 5 representing a typical curve of a double consolidation method for such soil. The collapse potential, C_p is calculated as the vertical strain similar to an abrupt settlement and thus can be expressed as

$$C_p\,(\%) = \Delta H/H_0\ 100 = \Delta e_c/(1+e_0)\ 100 \qquad (2)$$

Where ΔH is change in height of the sample upon flooding, H_0 is original height of the sample, $\Delta e_c = (e_1 - e_2)$ is the change in void ratio of the sample up on flooding, e_1 is the void ratio at dry state, e_2 is the void ratio upon of flooding and e_0 is the initial void ratio before loading.

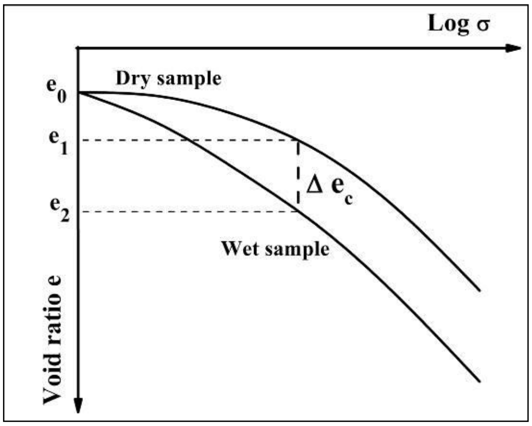


Figure 5: Typical oedometer curve for a collapsing soil (Jennings and Knight, 1975).

Also, Jennings and Knight (1975) correlated the collapse potential C_p to the severity of foundation disorder (Table 4).

Table 4: Foundation disorder level based on collapse potential C_p (Jennings and Knight, 1975)

C_p (%)	Severity of disorders
0-1	Minor disorders
1-5	Moderate disorders
5-10	Disorders
10-20	Severe disorders
› 20	Very severe disorders

In order to obtain samples with different degrees of compaction, those samples are moistened at different water contents, then they are subject to different compaction energies (20, 40 and 60 drops) (Abbeche *et al.*, 2005). The samples thus prepared were tested using an oedometer by saturating them with solutions at different salt concentrations.

Generally, work treating the effect of salts on the microstructural characteristics and hydraulic behaviour of clay materials use concentrations up to 1 mol/L (Tessier and Berrier, 1979; Halitim, 1985).

The salt solution used for the soil treatment is sodium chloride (NaCl) with various concentrations (0.5, 1.0, 1.5 and 2 mol/L). The test program for this study is given in Table 5.

Table 5: Test program

Test	Used parameters	Number of tests	Observation
oedometer tests	Water content 2, 4 and 6%. Compaction energy 20, 40 and 60 drops Salt (NaCl) Concentration (0.5, 1.0, 1.5 and 2.0 mol/L).	09 (Control) + 36 (Treated)	Prepared according to Jennings and Knight (1975)

For this study, two collapse potentials C_p, before and after treatment, will be determined by Equation 2 based on the concept indicated in Figure 5.

3.0 Results and Analysis

3.1 Oedometer Results: Untreated Soils

From the results obtained in this study, summarized in Figures 6 and 7 for the highest collapse potential, and presented in Figures 8 to 16, it is clear that the collapse of the sample without treatment correlates with collapsible soil which can cause disorders to foundation of structures (Jennings and Knight, 1975). Indeed, for various vertical stresses σ as well as for various compaction energies E_c, the collapse potential C_p varies from 0.98 to 12.40% for initial water content w_0=2%, from 0.82 to 10.64% for initial water content w_0=4%; and from 0.66 to 8.79% for an initial water content w_0=6%. These results correspond to minor to severe disorders (Table 4). It should be noted that the potential of collapse C_p decreases when initial water content or initial compaction energy increase. That is attributed to the reduction of the suction forces when the initial water content increases and denser structure when the energy increases. The wetting of the reconstituted sample induces a total suppression of the suction forces; which soften the material and reducing the shear resistance leading to an abrupt collapse. The collapse potential C_p is at its maximum for a vertical stress in the range of 400 kPa. Figures 6 and 7 show that the potential C_p decreases almost linearly when the water content or the compaction energy increase, for vertical stress of 400 kPa. This result reflects that there is a total re-arrangement of the soil skeleton under that loading, which results in the reduction of the voids This behavior is the same regardless of the vertical stress. These results agree with those of Lawton *et al.* (1989) and Abbeche *et al.*, (2007, 2009 and 2010). Thus, a reconstituted soil sample has a behavior similar to those undisturbed natural collapsible soils.

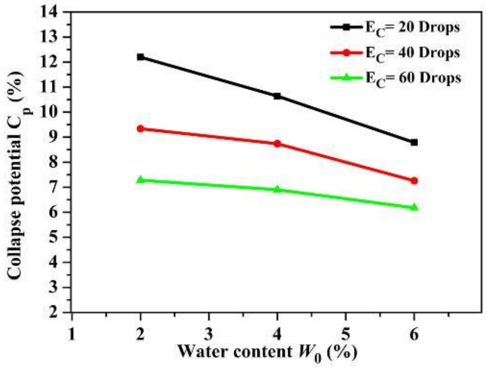


Figure 6: Variation of the collapse potential C_p with respect to water content for untreated soil at a vertical stress of 400 KPa

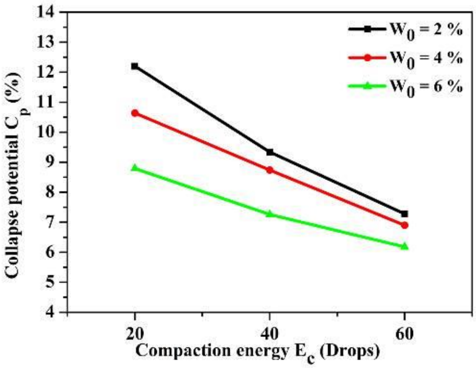


Figure 7: Variation of the collapse potential C_p with respect to energy of compaction for untreated soil at a vertical stress of 400 KPa

3.2 Oedometer Results: Soil Treated by Salt (NaCl)

Results shown on figures 8 to 16 reveal a substantial reduction of the collapse potential C_p for soil samples treated with as sodium chloride (NaCl) at various ionic concentrations. Also, we note that the collapse potential C_p is at its maximum for a vertical stress in the range of 400 kPa. As stated before, this result reflects that there is a total re-arrangement of the soil skeleton under that loading, which results in the reduction of the voids.

It should be noted that for a collapse potential at a vertical stress of 400 kPa, and for a low salt concentration (0.5 mol/L), the reduction ratios of C_p vary from 15% to 35%. However, for high concentrations (2 mol/L), the reduction ratios of C_p vary from 65% to 70%. The collapse reduction ratio is related to the applied vertical stress, knowing that for low concentrations (0.5 mol/L), this collapse reduction ratio varies from 15% to 25% for a vertical stress of 200 kPa, and it varies between 10% to 40% for a vertical stress of 800 kPa. For high salt concentrations (2 mol/L), the collapse reduction ratio varies between 60% to 70% for a vertical stress of 200 kPa. On the other hand for a vertical stress of 800 kPa, the values of the collapse reduction ratio vary between 30% to 65%.Thus, the behavior of a treated soil by saline solution NaCl is on one hand, affected by the initial water content and the compaction energy and on the other hand by the ionic concentration.

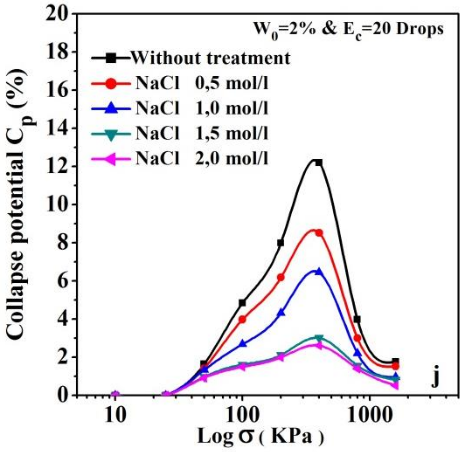


Figure 8: Variation of the collapse potential C_p with respect to vertical stress for treatment by salt NaCl (W_0=2% & E_c=20 drops)

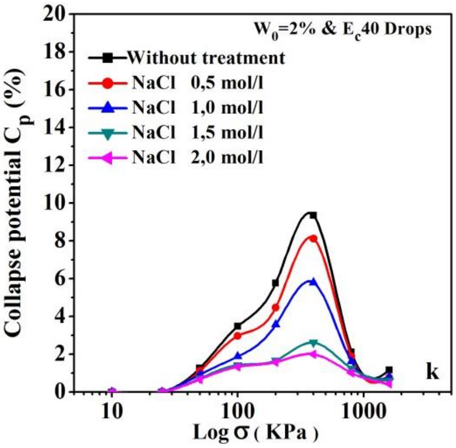


Figure 9: Variation of the collapse potential C_p with respect to vertical stress for treatment by salt NaCl (W_0=2% & E_c=40 drops)

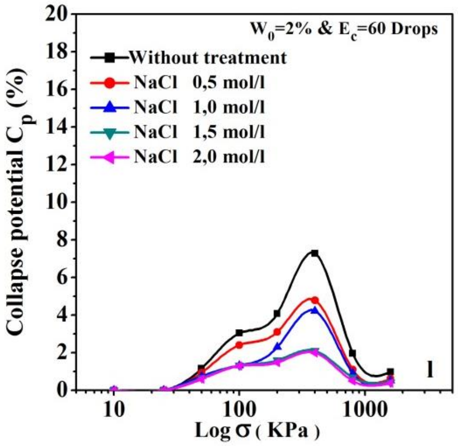


Figure 10: Variation of the collapse potential C_p with respect to vertical stress for treatment by salt NaCl (W_0=2% & E_c=60 drops)

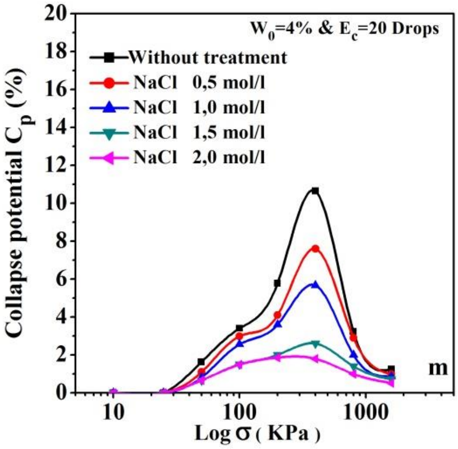


Figure 11: Variation of the collapse potential C_p with respect to vertical stress for treatment by salt NaCl (W_0=4% & E_c=20 drops)

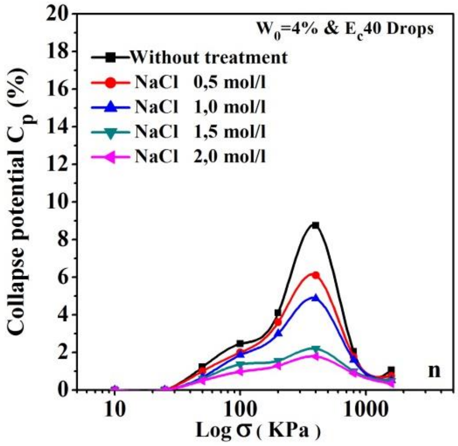


Figure 12: Variation of the collapse potential C_p with respect to vertical stress for treatment by salt NaCl (W_0=4% & E_c=40 drops)

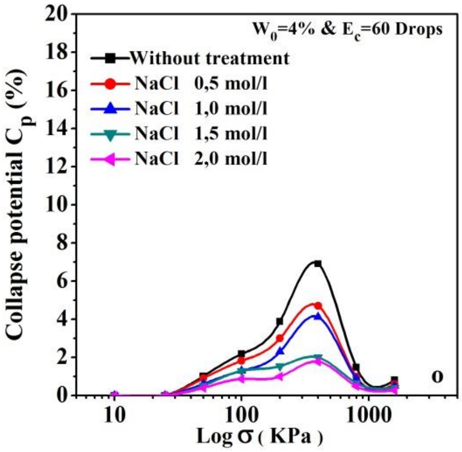


Figure 13: Variation of the collapse potential C_p with respect to vertical stress for treatment by salt NaCl (W_0=4% & E_c=60 drops)

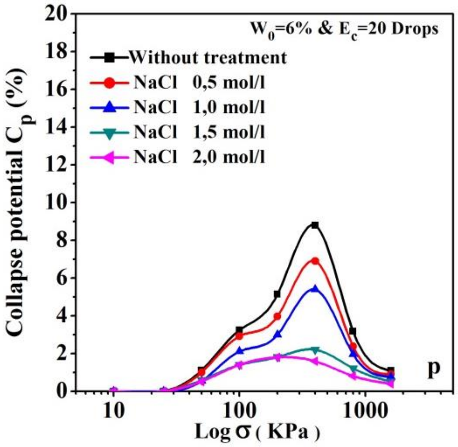


Figure 14: Variation of the collapse potential C_p with respect to vertical stress for treatment by salt NaCl (W_0=6% & E_c=20 drops)

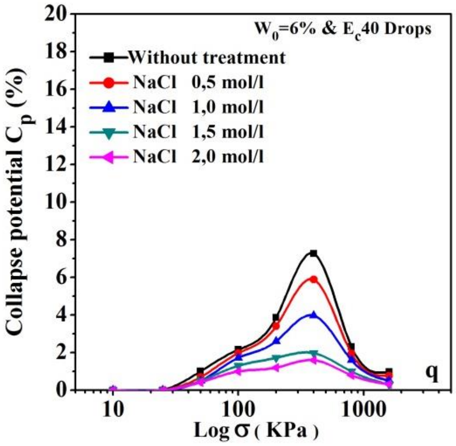


Figure 15: Variation of the collapse potential C_p with respect to vertical stress for treatment by salt NaCl (W_0=6% & E_c=40 drops)

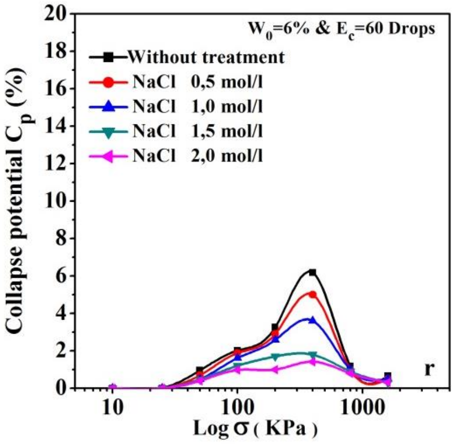


Figure 16: Variation of the collapse potential C_p with respect to vertical stress for treatment by salt NaCl (W_0=6% & E_c=60 drops)

4.0 Observation Under the Scanning Electron Microscope (S.E.M.)

4.1 Quartz Structure: Case of the Untreated Soil

In the case of the untreated soil under compacting force 20 drops, we notice a loose contact between kaolinite crystallites and the quartz crystals (Figure 17). Kaolinite crystallites do not present any preferential orientation compared to the quartzose skeleton (Figure 17). This type of microstructure was reported by various authors (Rollins *et al.*, 1994; Grabowska, 1975; Tessier and Berrier, 1979; Lawton *et al.*, 1989).

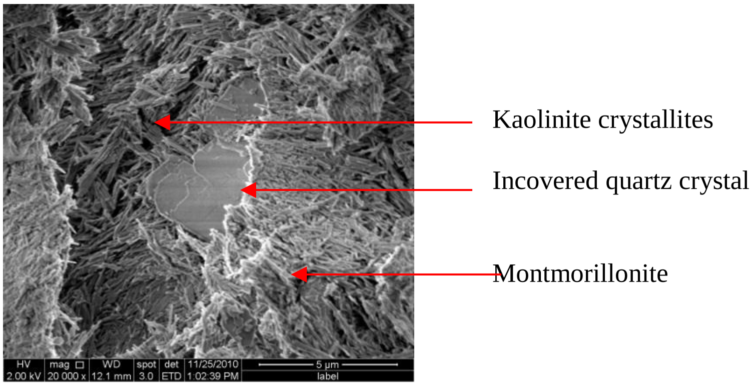


Figure 17: Electron photomicrograph of reconstituted untreated soil sample (20 drops)

Figure 18 shows that the material compacted with 40 drops is a little more packed than the sample subjected to a compacting force of 20 drops. Quartz crystals are coated with crystallites of kaolinite with more coverage than the sample that has undergone slight compaction energy (20 drops).

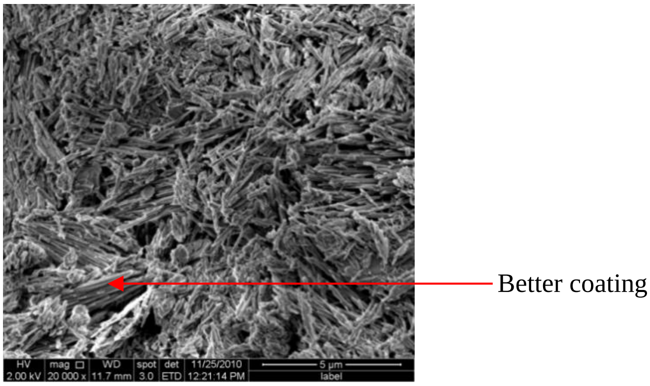


Figure 18: Electron photomicrograph of reconstituted untreated soil sample (40 drops)

Figure 19 shows that the material compacted under the effect of a force of 60 drops has a denser coating than the previous samples compacted under 20 and 40 drops and has a low porosity. The crystallites of kaolinite without define boundaries cover the quartz crystals.

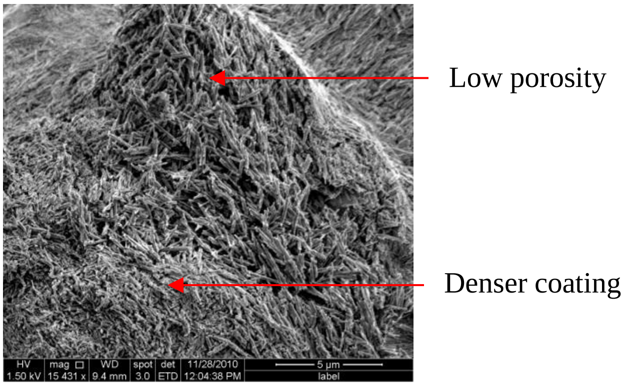
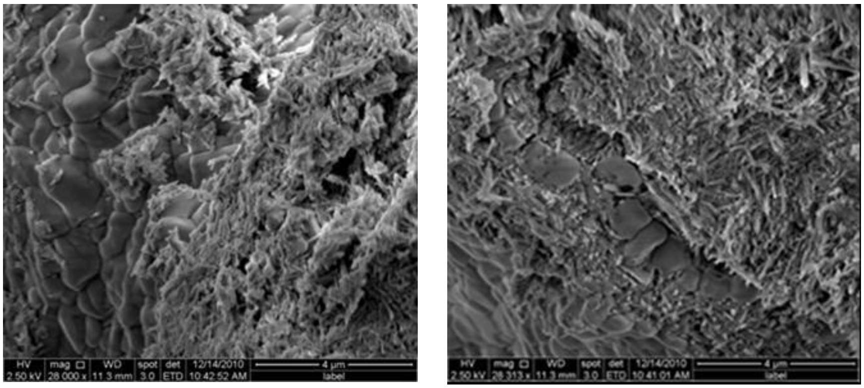


Figure 19: Electron photomicrograph of reconstituted untreated soil sample (60 drops)

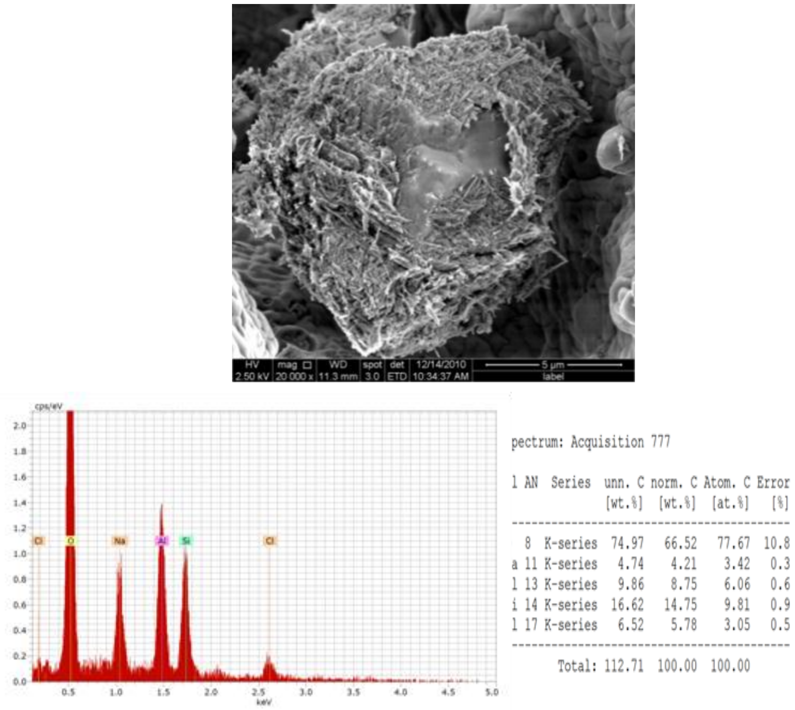
4.2 Relation Salt-Fine particules: Case of NaCl

The treated sample presents cubic NaCl crystals (halite) relatively crystallized, coated with clay in the form of sticks or rods in mixture with a smectite and quartz crystals. Figure 20 indicates that a space exists between the clay fraction and the NaCl crystals with certain fracture porosity. X-rays analysis reveals a higher concentration of silicon (Si) versus aluminum (Al) due to the presence quartz and kaolin, which reveals the presence of three-layer clay beside the Kaolin. Halite is highlighted in the X-ray analysis by peaks of sodium (Na) and chlorine (Cl) (Figure 21).



(a) **(b)**

Figure 20: Electron photomicrograph of treated soil by NaCl (a) Smectite and quartz crystals, (b) fracture porosity



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pectrum: Acquisition 777

l AN  Series   unn. C norm. C Atom. C Error
               [wt.%]  [wt.%]  [at.%]   [%]
-------------------------------------------
  8  K-series  74.97   66.52   77.67  10.8
a 11 K-series   4.74    4.21    3.42   0.3
l 13 K-series   9.86    8.75    6.06   0.6
i 14 K-series  16.62   14.75    9.81   0.9
l 17 K-series   6.52    5.78    3.05   0.5
-------------------------------------------
        Total: 112.71  100.00  100.00
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Figure 21: X-ray output spectrum of treated soil by NaCl

5.0 Discussion

The mechanical behavior of the reconstituted sample in the presence of soluble salts is attributed to the effects of the salts on the interstitial solution of the soil and the modification of the exchange complex ionic structure of the clay.

First of all, because of the increase in the ionic force of the solution of the soil, the diffuse double layer of clays is compressed, which results in a flocculation of the material and its stabilization compared to reference material (untreated soil). As for the effects of the adsorbed cations, their nature plays an important part in the physical and mechanical behavior of the cohesive material. The alkaline cation monovalent Na^+ compresses the diffuse double layer particularly when the solution of the soil presents a weak ionic force; thus supports with high water content the swelling and the dispersion of the clay particles (Halitim *et al.*, 1984). That has as a consequence in obstructing the pores of the material and its densification.

An important characteristic of the electrostatic forces is their instability in connection with the water content. Indeed, when the material is very wet, the distance between the particles increases and the electrostatic force decreases. At the extreme, the electrostatic forces disappear; thus, a repulsion of the elementary particles occurs. Therefore, the sodic materials (rich in adsorbed sodium) with low hydric potential retain water
Figures 8 to 16 show clearly that the collapse potentials in the presence of the solution NaCl at a concentration of 1.5 mo/L are close to those of 2 mol/L. As a result, we opt for an effective treatment with the saline solution at an optimal concentration of 1.5 mol/L.

6.0 Conclusions

The collapse of soils is a very complex phenomenon involving a large number of intrinsic and environmental parameters. It is mainly due to the rearrangement of the soil particles after flooding. However, a collapsible soil can be reconstituted in the laboratory by mixing fine particles with sand at water content below optimum Proctors and compacted under different energies of compaction. The characteristics of compressibility and consistencies confirm that these prepared soils have a behavior of collapsible soils.

The main observations of this study are:

- The collapse potential is reduced with increase of initial water content and increase of energy of compaction;
- The treatment by salt (NaCl) reduced the collapse potential and subsequently the damage associated with it to structures;
- The increase in salt concentration beyond certain value (1.5 mol/L) has no significant benefit.

Thus, the physical and mechanical behavior of the reconstituted collapsible soil is related, to one hand, to the energy of compaction (E_c), the initial moisture content (w_0), vertical stress (σ), and the crystalo-chemistry of its constituents; and on the other hand to the physico-chemical properties in relation with the composition of pore solution and the ion structure of the exchange complex.

7.0 Acknowledgements

We would like to thank the members of CGI Technical Services for their contributions to this study.

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