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Experimental Study of the Physico-Chemical Stabilization of a Loess by Sodium Silicate: Case of Southern Algeria

Ouassila Bahloul[1*], Fatima Zohra Tebbi[2], Laid Lekouara[3,4]

[1]LGC-ROI. Civil Laboratory-Risks and Structures Interactions. Faculty of Technology University of Mostepha Ben Boulaid, Batna 2, Algeria
[2]LRNAT Laboratory, Earth Sciences and Universe Institute. University of Mostepha Ben Boulaid, Batna 2, Algeria
[3]Faculty of Science and Technology, University of Abbés Laghrour Khenchela, Algeria
[4]Material and Hydrology Laboratory, University of Sidi Bel Abbes, Faculty of Technology, Algeria.
*e-mail: o.bahloul@univ-batna2.dz

Abstract

This study focuses on collapsible soil from hyper-arid regions in the south of Algeria (Zeribet El Oued, Biskra). A physical characterization of the studied soil was performed which revealed that the soil samples are loess. After this, an experimental study was done on the influence of the sodium silicate solution (Na_2SiO_3) at different doses on the collapse potential (CP) and the microstructure of the material. The microstructure investigation was made through a scanning electron microscope (SEM) observation.The main results of this study show that the treatment of collapsible soil with sodium silicate has led to a significant reduction of the collapse potential, exceeding 87%. An effective treatment is obtained with a sodium silicate solution at the optimal dose of 0.8 mol.L^{-1}. The SEM observations have revealed micro-structural transformations which are correlated to changes to geotechnical behavior.

Keywords: open structure, collapsible soil, chemical treatment, microstructure.

1 Introduction

Loess soils cover a large part of the world's land, including China, Russia, the USA, New Zealand, and other mid-latitude countries having large loess distribution areas [1-3]; Algeria too has a large loess area. Loess has poor engineering properties such as strong water sensitivity and severe collapsibility because of the inherent metastable structure [4]. Important structural disorders, caused by collapsible soils due to water, were observed in many parts of the world, especially in arid and semi-arid regions. The risk of collapse of a loess is related to several conditions such as significant porosity related to an open structure, and the binding elements that are strong enough to stabilize the contacts inter-granular and relatively weak to disappear or be weakened when water is introduced [5] and a high void ratio and an unstable arrangement of the soil particles [6]. Loess soils are the result of an accumulation of wind-blown soil particles mainly silty, clay and sand heterogeneously distributed [7]. In fact, collapsible soils are unsaturated soils that may undergo inter-granular rearrangement with a significant reduction in

their volume after having been flooded. Loess is a complex mineral with clay minerals like quartz, feldspar, and illite. Its large pores, weak cementation, and high salt content cause poor engineering characteristics, including compressibility, collapsibility, and wetting strength reduction [8]. The world's common foundation treatment methods include dynamic consolidation, replacement cushion, compaction pile, impact compaction, pre-soaked treatment, and chemical stabilization. Traditional compaction reduces loess' collapsibility, but wetting-drying and freezing-thawing cycles can affect compacted foundations, causing secondary or multiple collapse. Physical stabilization methods cannot eliminate collapsibility, leading to research on chemical stabilization methods [9]. Chemical methods involve adding stabilizing agents to soil, reacting with minerals or water, and cementing particles to make the structure denser. These methods offer rapid speed, easy construction, and stable performance. Traditional stabilizing agents like lime and cement are commonly used in engineering practice to improve loess mechanical properties [10]. Many studies performed experimental studies to illustrate that the mechanical resistance of collapsible soils can be improved by different stabilizing agents [11-14]. Recent studies concentrated on the influence of various parameters such compaction energy, initial water content and stress level, and saline solutions at different concentrations (ammonium sulfates $(NH_4)_2SO_4$, potassium chloride KCl, and sodium chloride NaCl) [15, 16]. Those studies were performed at a microstructural level to better understand the effect of salts on the treatment of collapsible soils. The results of those studies showed a favorable effect of salts on the structure of collapsible soils with a significant reduction in collapse potential [12, 17]. Gu, Lv [8] studied the effect of sodium silicate on the geotechnical parameters and microstructure of a loess. The results confirmed the effectiveness of this treatment. Siddiqua and Bigdeli [18] studied the stabilization of a collapsible soil using magnesium chloride ($MgCl_2$). The results showed that 7% $MgCl_2$ over 28 days of hardening had the best effect on stabilizing the soil collapse.
This study is a contribution to the application of chemical stabilization technique of a soil from the region of Zeribet El Oued, district of Biskra in southern Algeria, by addition of sodium silicate solution (Na_2SiO_3) at different concentrations and its effect on the collapse potential of the loess. Also, XRD and Scanning Electron Microscopy (SEM) were studied for soil samples and the treated material.

2 Methods and Materials

The soil in this study is loess from the region of Zeribet El Oued, district of Biskra in Algeria. In summer, the climate of this region is hyper-arid, dry, and warm but cold and wet in winter Figure 1. Part of the material was excavated by mechanical excavator at about 1.50 m below ground surface.
To characterize the physical and geotechnical parameters of the loess soil, the tests were conducted according to the standards NF P94-050 [19]. The Atterberg limits, as NF P94-051 [20] standard, were applied on soil fractions below 400 µm, which were extracted from untreated soils. The consistency limits were measured on soil- sodium silicate mixtures. Similarly, based on NF P94-048 [21] the percentage of calcium carbonate (% $CaCO_3$) was estimated by Calcimeter. Shear tests were carried out on treated and untreated samples, using direct shear apparatus according to NF P94-071-1 [22]. The soil pH was measured on the soil extract 1/2.5, using a pH meter.

The different soil properties are presented in Table 1. The fractions of sand, silt, and clay are 9%, 80%, and 11%, respectively. This material has a fraction of 12% of calcium carbonate. According to the classification of Casagrande, the material is classified as CL or low plasticity clay. The sieve analysis of the subject material is presented in Figure 2. Table 1 shows comparative index properties for Libyan, French and Algerian loess. All plasticity values for the studied soil are close to the values of different loess soil of the different regions.

Gibbs and Holland [23] classified the loess material into three types: sandy loess, silty loess and clayey loess, as shown in Figure 3. The soil sample of Zeribet El Oued has a liquid limit, LL of 31% and a plasticity index, PI of 12, so our soil sample is a silty loess. In order to assess the collapse potential, researchers used experimental and empirical approaches based on characteristics specific to such soils. Based on dry density, the studied soil is classified as moderately susceptible to settlement due to its medium density [24].

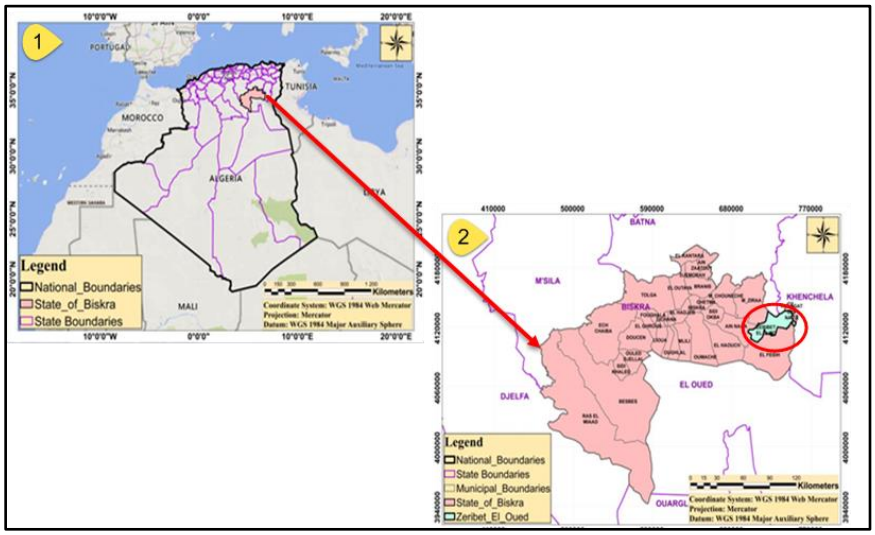


Figure 1: Location of the national and state boundaries (1) and Location of the ground site (2)

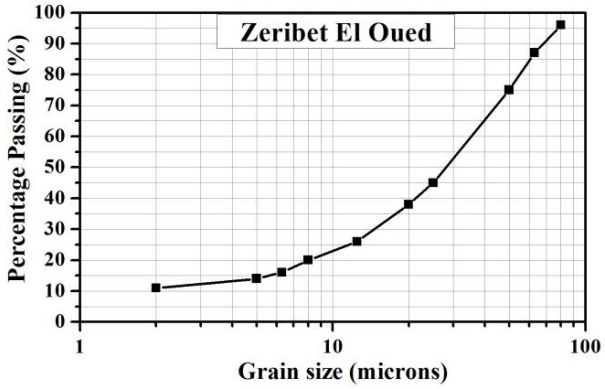


Figure 2: Sieve analysis of the subject material (Zeribet El Oued)

Figure 4a shows an open structure that is poorly cemented between the different elements of the loess, with the appearance of pores with different shape and opening with loose areas.

The X-ray dispersive energy microanalysis (EDAX) of untreated soil allows to observe the presence of the feldspar group (Potassium Aluminium Silicate $K(Si_3Al)O_8$), and (Calcium magnesium Carbonate $(CaMg(CO_3)_2)$, this type of analysis was reported by [3], (Figure 4b).

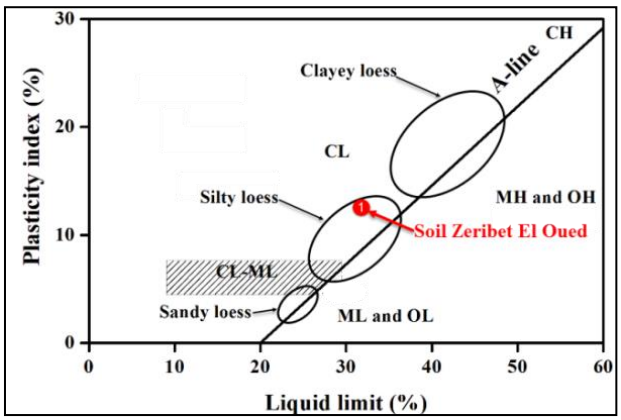


Figure 3: Plasticity properties of Zeribet El Oued Soil as compared with loess types defined by [23]

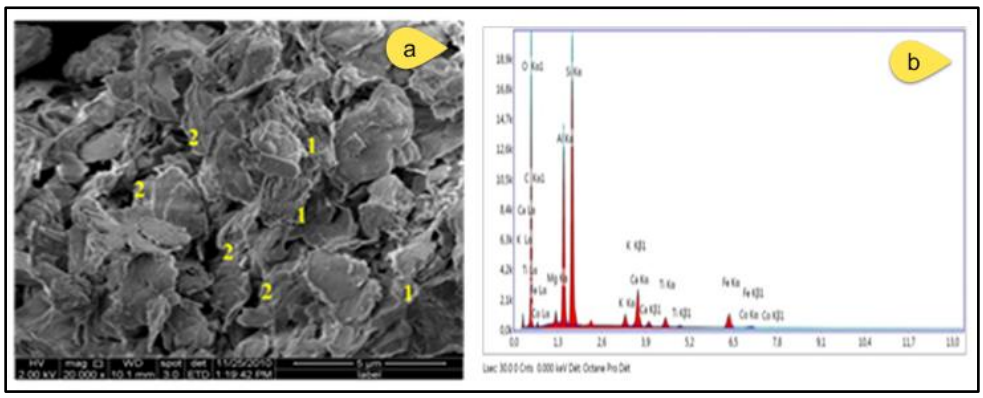


Figure 4: (a) SEM Observation of a loessic soil (Aggregations of grains of silt (1), (2) pores); (b) X-ray dispersive energy microanalysis (EDAX) of untreated soil

Table 1: Index properties of Libyan, Algerian, French and Loess of present study [3, 25, 28]

Soil parameters	**Method or standards**	**[25]**	**[25]**	**[3]**	**[3]**	**[1]**	**Zeribet ElOued Loess Algeria**
Natural water content, *w* (%)	NF P94-050 [19]	6.0	3.0	5.0	6.0	14.0	**13.8**
Void ratio, *e*	/	0.87	0.84	0.89	0.91	0.84	**0.88**
Natural dry unit, γ_d kN/m^3)	NF P94-050 [19]	13.6	14.0	14.2	14.3	14.5	**14.2**
Specific gravity,Gs	/	2.66	2.68	2.68	2.73	2.67	**2.67**
< 2 µm fraction of clay (%)	NF P94-056 [26], NF P94-057 [27]	11	13	9	12	16	**11**

Liquid limit, LL (%)		27	31	30	33	28	**31**
Plastic limit, PL (%)	NF P94-051	19	20	23	22	19	**19**
Plasticity index, PI (%)	[20]	8	11	7	11	9	**12**
$CaCO_3$ content, (%)	NF P94-048 [21]	/	/	/	/	6	**12**

2.1 Methods

Jennings [29], proposed an experimental approach to the collapse potential of soils based on the oedometer tests. That approach was followed by a theoretical study formulated by [30]. The oedometer approach is based on the concept of a single point oedometer test according to ASTM standard on an as is soil sample at its natural moisture content. Then the sample is flooded after a specific vertical stress is applied, As illustrated in Figure 5 from [31], a direct estimation of the collapse potential is obtained from the deformation the soil sample.

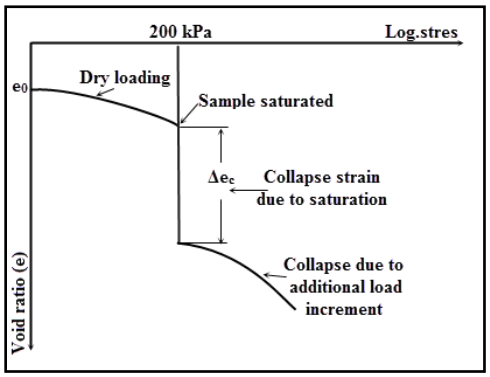


Figure 5: Simple Oedometer Curve [31]

The test program was conducted on undisturbed soil sample with different flooding liquids such as distilled water, saline solution of the sodium silicate (Na_2SiO_3) at different doses (0.2, 0.4, 0.6, 0.8 and 1.0 $mol.L^{-1}$). For this purpose, two collapse potentials, before and after treatment, will be determined by the following formula:

$$CP = \left(\frac{\Delta e_c}{1+e_0}\right) 100\% \quad (1)$$

with: $\Delta e_c = e_1$ (200 kPa) - e_2 (200 kPa, flooded).
e_0: initial void ratio.

The most used concept to estimate the consequence of collapsible soils to supported structures was proposed by [31] and is based on the degree of the collapse potential resulting after the introduction of water to a soil sample under a specific stress of 200 kPa and that correlation is presented in Table 2.

Table 1: Identification of collapse associated structural problems [31]

Collapse potential (CP)	**Severity of problem**
0%-1%	No problem
1%-5%	Moderate problem

5%-10%	Trouble
10%-20%	Severe trouble
>20%	Very severe trouble

3 Results and Discussion

3.1 The Effect of Silicate Sodium Treatment on pH

To explain the results of the tests of compressibility and change of the- microstructure, it has proved very important to analyze the physico-chemical change and particularly the pH level of the solution after addition of sodium silicate (Na_2SiO_3) with a density of 1.38 g/cm^3 at different concentration (0.2, 0.4, 0.6, 0.8, and 1 mol.L^{-1}).
Figure 6 shows that the pH increases with the concentration of silicate of sodium until 0.8 mol.L^{-1}, beyond that; there is a very small change in that parameter. This result can be explained by the pH of the pure solution of the sodium silicate, which is 12.

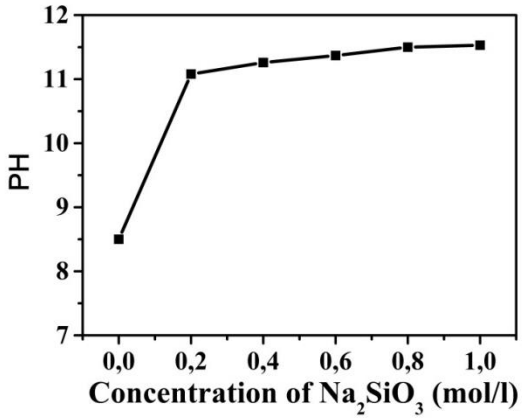


Figure 6: Effect of Sodium Silicate (Na_2SiO_3) on PH

3.2 The Effect of Sodium Silicate Treatment on Atterberg Limits

Regarding the influence of the used solution on other geotechnical properties of the studied soil, Figure 7 clearly shows that the liquid limit decreases when the concentration of the stabilizer (Na_2SiO_3) increases. For measurements of 0.8 and 1 mol.L^{-1}, it is noted that the liquid limit values obtained are close and consisted of 26.7 and 25.3%, respectively. However, the plasticity limit increased slightly, leading to a remarkable effect on the reduction in the plasticity index regardless of the percentage of the stabilizer.

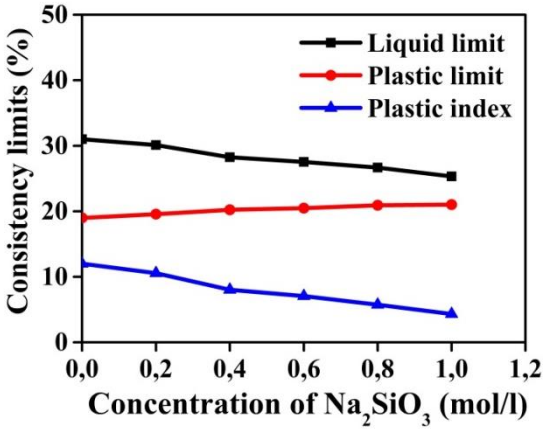


Figure 7: Atterberg Limits Measured on Untreated and Sodium Silicate Treated Soil

3.3 Collapse Tests

Figure 8a shows the change in the collapse potential based on the concentration (0.2, 0.4, 0.6, 0.8 and 1.0 mol.L^{-1}) of the sodium silicate solution (Na_2SiO_3), for loess. The collapse potential of the untreated sample is 6.42%. Based on the classification of [31], the untreated soil may lead to trouble. We also notice that the soil sample has an important collapse potential because it has a percentage of 12% of $CaCO_3$, which is a cementing agent that dissolves once water is introduced, creating an unstable soil structure, due to a flocculation of the material with high porosity. However, there is a significant reduction in the collapse potential for soils treated with the sodium silicate solution (Na_2SiO_3) when the concentration increases This can be explained by the cementing effect of the sodium silicate solution (Na_2SiO_3), which forms layers that lead to new formations by covering the particles, creating a smooth surface. As sodium silicate is injected, it fills voids, forming independent structural aggregates. The stiff skeleton and silicate gel have different physicomechanical properties, with the stiff skeleton having elasticity and absorbing stresses, while the gel component has viscous properties. these results corroborate those of Beketov and Seleznev [32]. The review of the curve of Figure 8b highlights the considerable influence of the sodium silicate solution (Na_2SiO_3) on the collapse potential. The treated soils with 0.8 and 1 mol.L^{-1} develop the same collapse potential of about 0.78%. The stabilization of the values of the collapse potential beyond 0.8 mol.L^{-1}, can be explained by the lack of variation of the alteration of the material due to the low variation of pH at concentrations of the sodium silicate at 0.8 and 1.0 mol.L^{-1}. Thus, the dose of 0.8 mol.L^{-1} of the sodium silicate solution can be considered as an optimal concentration because an additional amount would not improve further the properties of the collapse.

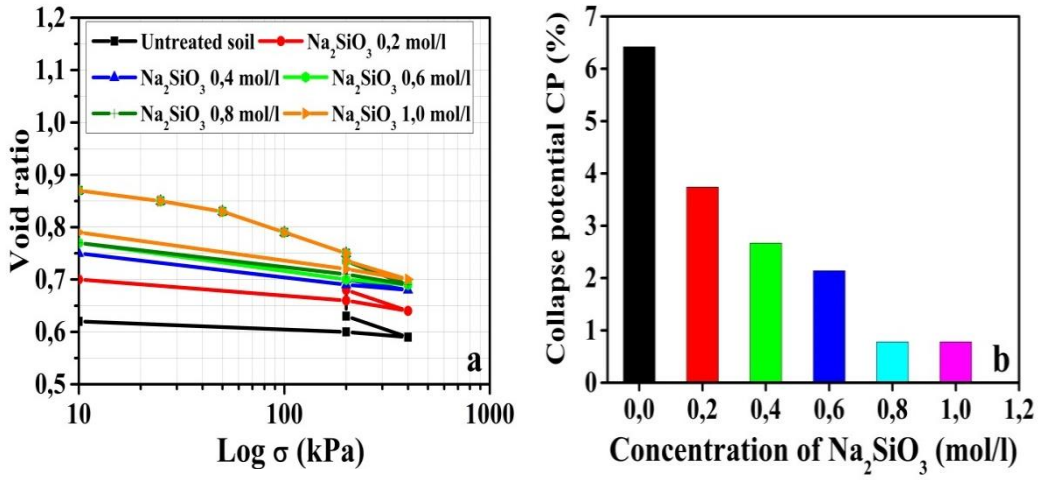


Figure 8: a- Effect of sodium silicate (Na_2SiO_3) on oedometric tests, b- Effect of sodium silicate (Na_2SiO_3) on the collapse potential

3.4 Effect of Sodium Silicate on Cohesion and Friction Angle from Shear Test

The results in Figure 9 show that cohesion C and friction angle φ increase when the percentage of concentration of the treatment increases. Sodium silicate treatment has led to an increased resistance to shear of the treated soil, resulting in an improved soil carrying capacity. The treatment of the soil by sodium silicate has highlighted its stabilizing role on the geotechnical behavior of the loess.

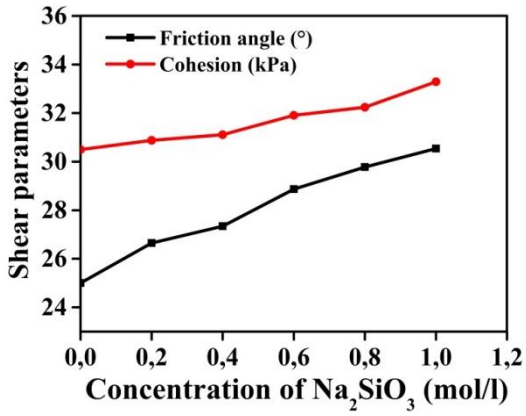


Figure 9: Effect of the addition of sodium silicate (Na_2SiO_3) on the shear parameters of soil

3.5 Effect of Sodium Silicate on the Microstructure

To better appreciate the change and reduction of the collapse potential by addition of sodium silicate solution (Na_2SiO_3) to loess soils, soils, there has been an analysis of the changes of the microstructure from the scanning electron microscope (SEM) observation. That analysis was performed to compare treated and untreated samples.
Figure 4 shows that reference loess soil has a high concentration of fine silt and clay with a high porosity between aggregates of relatively large size. After flooding, the collapse occurs creating

loose areas and an unstable structure. This structure was already observed in the loess in France [6, 33]. The samples treated with the sodium silicate solution (Na_2SiO_3) have a relatively stable microstructure and low sensitivity to collapse compared to untreated samples. Figure 10 a, b and c, show disappearance of the aggregation because of the presence of sodium silicate salt which is very alkaline. The material appears smooth, cemented without porosity. The sodium silicate strengths the micro-structural body with a dense and compact material. It is the result of the chemical effect of silicate (alteration and dissolution) on the material. In addition to strengthening the existing bonds in loess, silicate injection creates new, stronger, and more water-resistant bonds as a result of the adsorption of silicic acid on the solid phase of calcium hydroxide. The original structure of the material disappears because of the destructive effect on the siliceous components of the sodium silicate due to its strong alkalinity on silicates components (clay and quartz) and release of silica and alumina leading of a formation of a precipitate consisting of an amorphous material or gel without any micro-structural organization filling the voids around aggregates. The EDAX analysis for soil treated with 0.8 and 1 $mol.L^{-1}$ of sodium silicate on Figure 10d indicates the presence of higher concentration of silicon (Si), aluminum (Al) and sodium (Na), as well as zones of low concentration in in potassium (K), magnesium (Mg) and trace of iron (Fe).

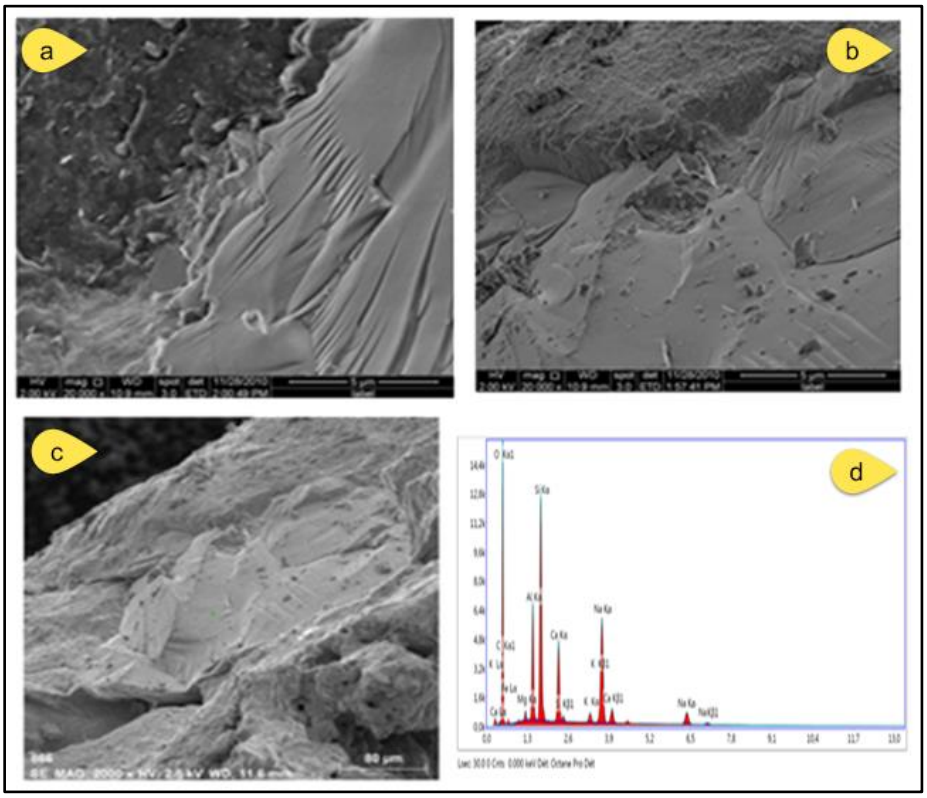


Figure 10: Observation SEM of Soil Treated by Na_2SiO_3, X-ray Dispersive Energy Microanalysis (EDAX) of Soil Treated with 1.0 $mol.L^{-1}$of Na_2SiO_3

4. Conclusion

This study is part of the chemical stabilization of a collapsible soil. The results obtained in this study have led to the following conclusions:
The liquid limit and the plasticity limit have gone slight increases with the added percentage of sodium silicate. Therefore, the plasticity index PI has gone an important reduction with the treatment. In addition, the treatment has increased the mechanical characteristics such as cohesion C and friction angle φ, leading in an improved soil carrying capacity.
It is clearly demonstrated that the treatment of collapsible soil with the addition of the sodium silicate solution (Na_2SiO_3) at doses ranging from 0.2 to 1.0 mol.L^{-1}, greatly improves the parameters of compressibility and decreasing the collapse potential over 87%. These improvements are caused by a strong alteration of the loess soil causing structural changes. It appears that for the concentration 0.8 mol.$L^{-1}$of the sodium silicate, the collapse potential remains relatively constant, which could be explained by the maximum amount of alteration of the material obtained by this dose. The analysis by the scanning electron microscope of the untreated loess soil indicates a loose structure; however, the treated soil by sodium silicate has highlighted its stabilizing role on the geotechnical behavior of the loess.The dominant mechanism and its effect on the reduction of collapse potential is chemical in nature by an alteration and dissolution of silicates components of the loess soil with consequences on the reduction of the porosity and of a consolidated microstructure. Based on this study, the dose of 0.8 mol.L^{-1} of Na_2SiO_3 is the optimal value for treatment of collapsible soil. The mechanism of loess reinforcement by sodium silicate is reinforcement of the bond strength of cement in microstructure and formation of new strengthened material. This treatment technique is applied by injecting a chemical solution.

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