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MICROSTRUCTURE AND GEOTECHNICAL CHARACTERISTICS OF A HIGHLY PLASTIC CLAY TREATED BY MAGNESIUM CHLORIDE

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Abstract: Chemical stabilization of soil is an effective improvement technique because it reduces the ability of the soil to swell. We added different proportions of magnesium chloride to an expansive clay and performed swelling, geotechnical characterization, and mechanical strength tests. The results show that the swelling potential and swelling pressure of the expansive soil were significantly decreased by the addition of magnesium chloride ($MgCl_2$). This treatment also improved the physical and mechanical characteristics and microstructure of the soil. The soil's plastic limit, shrinkage limit, cohesion, and internal friction angle all increased linearly with the addition of the $MgCl_2$ stabilizer. However, we observed that the liquid limit of the soil decreased as the level of magnesium chloride was increased.

Keywords: *swelling, treatment, microstructure, salt, oedometer*

1. INTRODUCTION

Soil swelling can cause the failure of both surface structures and buried structures. The failure of several buildings and other structures in the Mila region of northeast Algeria have been studied by National Laboratory of Habitat and Construction in Batna, Algeria (LNHC Batna). These studies have shown that the soils on which these struc-

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tures have been built are expansive soils that undergo significant variation in volume when subjected to changes in humidity.

The mineralogical composition of the expansive soil, its density, its structure, its water content, and its shrinkage limit all influence the extent of swelling. Several soil treatment techniques have been developed by different researchers. These include the addition of lime, cement, sand, fly ash, puzzolan and salts (Abou-Bker, Sidi Mohamed 2004; Al-Rawas et al. 2005; Louafi, Bahar 2012; Minglei 2013; Turkoz et al. 2014; Bourokba et al. 2015; Gangadhara et al. 2015; Johson et al. 2016; Bekhouche et al. 2018). The majority of these methods are based on the use of hydraulic binders such as cement or lime to improve the physical and mechanical characteristics of expansive soils (Derriche, Lazzali 1997; Djelloul et al. 2018). Khemissa et al. (2017) used combinations of cement and lime in different proportions in the treatment of M'Sila inflationary clay and reported that this treatment significantly reduced the swelling potential and swelling pressure of this clay, thus improving its suitability for supporting structures.

Salts are also used to decrease soil swelling because they act on the balance of osmotic pressure to stabilize inflating soils. The effectiveness of a salt in reducing the swelling of clay may be related to the exchange capacity of the soil and the valence, nature, and size of the cations that play a major role in the ion substitutions that occur during clay slips (Didier 1972; Abou-Bker, Sidi Mohamed 2004; Hachichi, Fleureau 1999).

Azzouz (2015) and Barry et al. (1991) showed that soils' swelling can be reduced and their geotechnical properties improved by the addition of salts combined with polymers. Breen 1999 demonstrated that the interaction of polymers with clays depends on the type of clay, the size of its grains, and the nature of the exchangeable cations present in the clay. Polymers are often used in combination with other additives.

In this work, we studied the stabilization of expansive clay extracted from a site in Mila, Algeria. Identification tests such as consistency limits, compaction, and free swelling tests were performed on untreated soil and soil treated with 1, 2, 3, 4 and 5% magnesium chloride. We performed a microstructural analysis of untreated soil and soil treated with magnesium chloride at the previously specified dosages using a scanning electron microscope (SEM) and analyzed the chemical composition of the soil by energy-dispersive X-ray analysis (EDAX).

2. METHODS AND MATERIALS

2.1. SOIL SOURCES

The clay we studied was extracted from a region of eastern Algeria called Mila. The study site is composed of clay formations or marl-rich formations with clay-marl rocks of various colors that are blended with sand, limestone, gypsum or silt. We chose to study the clay from this area because damage to structures in this area has been attributed to the swelling behavior of the clay as shown in Fig. 1. For this study, we mixed the clay with varying proportions (1, 2, 3, 4, and 5%) of magnesium chloride ($MgCl_2$). Samples were taken from depths between 2.00 and 4.50 m and consisted of intact clay or marl with gypsum crystals present. The samples were yellowish with whitish zones (Fig. 2).

Fig. 1. Structural damages on building caused by expansive soil in Mila region

Fig. 2.Untreated soil lithology

2.2. PREPARATION OF SOIL SPECIMENS

Soil samples were finely crushed soils to 80 μm sieve size after drying at 105 °C for 24 hours. The samples were then mixed with dry $MgCl_2$ in different proportions (1, 2, 3, 4, and 5%) for 10 min in a mixer to obtain satisfactory homogeneity. The mixtures were then moistened with distilled water to reach the optimum water content, Wopt, as determined by Proctor's tests. An oedometric test for free swelling (ASTM D 4546-96) was then performed: the wet soil-$MgCl_2$ mixtures were statically packed into a cylindrical mold with a diameter of 70 mm and a height of 20 mm, and then vertically compressed at a constant deformation speed of 1 mm/min. The sample in the cell was subjected to an imbibition process that caused free swelling constrained by the piston pressure. Vertical deformations were measured until equilibrium was achieved.

The maximum deformation, which occurs at the initial height, reflects the potential for soil swelling. This is called the "swelling potential" of the soil. After the free swelling process under low load (piston weight) had come to equilibrium, the load on the almost-saturated sample was increased in steps until the sample volume returned to its initial value. The stress required to return the sample to its initial height is the inflation pressure. The rate of swelling is defined as the percentage increase in height:

$$S\ (\%) = \frac{\Delta H}{H_i} \times 100\,, \qquad (1)$$

S – swelling potential (%),
ΔH – change in sample height,
H_i – initial sample height.
The reduction in swelling rate is given by the relationship:

$$\frac{\Delta S}{S} = \frac{S_0 - S_a}{S_0} \times 100\,, \qquad (2)$$

$\Delta S/S$ is the percentage reduction in swelling,
S_0 – swelling without additive content,
S_a – swelling with additive content.

Shear tests were performed on treated and untreated samples using a direct shear device according to French standard (NF P94-071, 1994). The samples were prepared in the same way as for the swelling tests, in rings 60 mm in diameter and 20 mm in height.

3. RESULTS AND DISCUSSIONS

3.1. GEOTECHNICAL CHARACTERIZATION AND CLASSIFICATION OF UNTREATED SOIL

The main physical and geotechnical characteristics of the untreated soil, as determined from the standard tests, are given in Table 1. The granulometric curve of the clay shows that 45% of the clay particles are less than 2 μm in size and 95% are less than 2 mm (Fig. 3).

The main minerals detected by X-ray diffraction analysis of the soil are montmorillonite ($MgOAlO_35SiO_2H_2O$), quartz (SiO_2) and kaolinite ($Al_2Si_2O_5(OH)_4$) (Fig. 4).

Table 1. Geotechnical characterization of natural intact soil (γ_s = 27 kN/m^3)

Parameters of untreated soil	Methods	SM
Natural water content w_{nat} (%)	NF P94-050 (1995)	13.60
Natural dry unit weight γ_d (kN/m^3)	NF P94-053 (2014)	16.1
Natural void ratio *e*	/	0.67
Porosity *n* (%)	/	0.40
Natural wet unit weight γ_h (kN/m^3)	/	18.3
Degree of saturation S_r (%)	/	54.07
Saturation water content (%)		25.15
Optimum water content w_{opt} (%)	NF P94-0093 (2014)	22.31
Maximum dry density $\gamma_{d,\ opt}$ (kN/m^3)		16.5
Degree of saturation at Proctor optimum S_r (%)	/	88.97
Saturation water content at w_{sat} (%)	/	25.05
Liquid limit LL (%)	NF P94-051 (1993)	80.70
Plastic limit PL (%)		25.22
Plasticity index PI (%)		55.48
Shrinkage limit W_r (%)		11
Shrinkage index IR (%)		69.7
≤2 mm fraction (%)	NF P94-056 (1996)	95.25
≤80 μm fraction (%)		80,55
≤2 μm fraction (%)	NF P94-057 (1992)	45
Activity of clay (A_c)		1.23
Methylene blue value VBS (g/100 g)	NF P94-**68** (1998)	11.66
Specific surface SSA (m^2/g)	/	244.86
$CaCO_3$ content (%)	NF P94-048 (1996)	17

According to the French classification of fine grain soils (NF P 11-300, 1992), the soil tested belongs to subclass A4 (PI > 40 or VBS > 8), with the presence of very plastic clays or marly clays. To classify soil sensitivity to swelling, liquid limits (LL) and soil plasticity index (PI) (Dakshanamurthy, Raman 1973; Chen 1988) were overlaid on the Casagrande diagram as suggested by (Khemissa, Mahamedi 2014) (Fig. 5). The untreated soil is classified as a highly plastic clay with high to very high swelling potential. The results are consistent with those of (Khemissa, Mahamedi 2014). Note that the three soils treated with 3, 4 and 5% $MgCl_2$ have low to medium swelling potential.

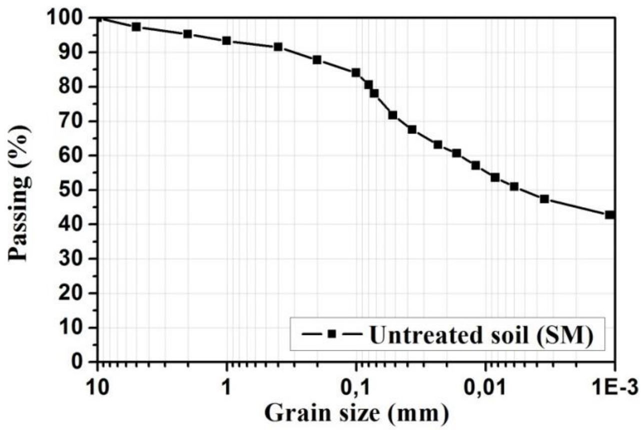

Fig. 3. Grain size distribution curve of untreated soil

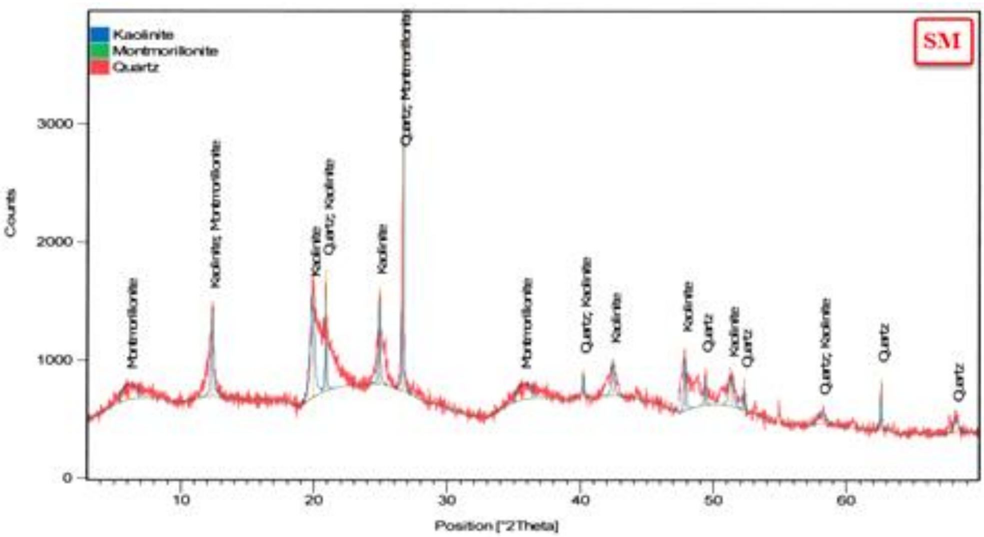

Fig. 4. X-ray diffraction of the untreated soil

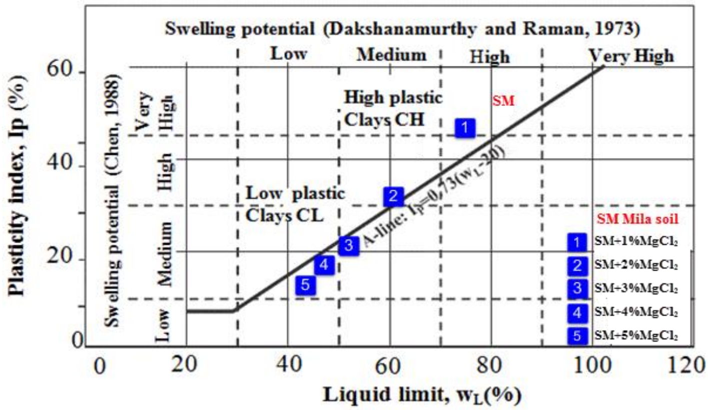

Fig. 5. Soil classification and swelling based on (Dakshanamurthy, Raman 1973; Chen 1988)

3.2. CHEMICAL COMPOSITION BY SOIL EDAX BEFORE AND AFTER TTREATMENT

The main components of the soil are clay and feldspar, with some quartz present. As shown in Table 2, Al, Si, and Fe are the predominant elements. Mg and Ca are also present in small amounts, but the low content of K indicates that illite and muscovite are not present in significant quantities. The control soil was similar to the clay soils studied by (Bekhouche et al. 2018; Khemissa et al. 2017; Khoudir, Messaoud 2018). The magnesium content of the soil increased in proportion to the quantity of $MgCl_2$ added for treatment. The proportions of Si and Al decreased because of dilution by the addition of magnesium chloride, which also introduced Cl into the system. The quantities of other chemical elements remained constant before and after treatment.

Table 2. Chemistry of the soil before and after addition of $MgCl_2$

Atomic (%) (EDS)	SM 0%	SM 1%	SM 2%	SM 3%	SM 4%	SM 5%
C	19.03	19.18	19.22	18.69	16.58	16.62
O	60.19	58.23	59.95	54.78	52.52	49.30
Mg	1.04	2.26	3.73	5.98	8.53	14.25
Al	6.56	6.41	5.52	6.21	5.66	4.98
Si	9.66	9.28	8.14	8.54	9.56	7.44
K	0.43	0.45	0.37	0.28	0.18	0.35
Ca	1.99	1.85	0.86	1.02	0.98	0.88
Fe	1.10	1.14	1.08	1.00	1.12	0.98
Cl	/	0.98	1.14	3.38	4.70	5.21

3.3. EFFECT OF MAGNESIUM CHLORIDE ON CONSISTENCY CHARACTERISTICS AND VALUE OF METHYLENE BLUE

Figure 6 illustrates the effect of the magnesium chloride assay on the soil properties. The soil's consistency, liquid limits, plastic index, and shrinkage index are inversely proportional to the percentage of $MgCl_2$ salt added, but its plastic limit and shrinkage limit increase with $MgCl_2$ content.

Incorporating the salt into the soil leads to the release of Mg^{2+} ions, which cause rapid aggregation of the soil particles. This aggregation effect explains the change in plastic index shown in Fig. 6.

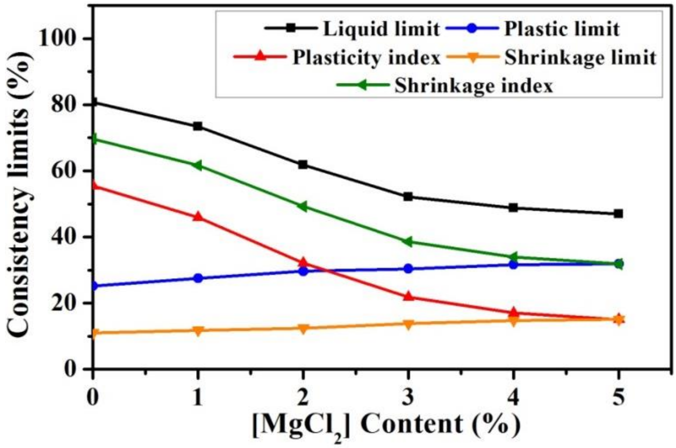

Fig. 6. Consistency limits measured on untreated and $MgCl_2$ treated soil

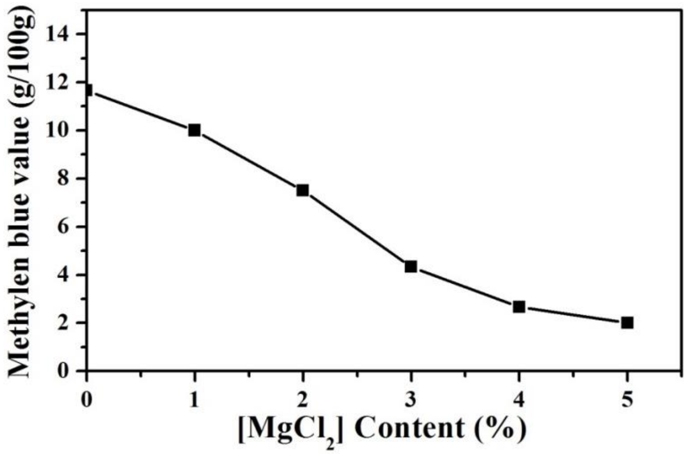

Fig. 7. Methylene blue values measured on untreated and $MgCl_2$ treated soil

The results of the methylene blue test on untreated soil and $MgCl_2$-treated soil are shown in Fig. 7. The VBS values vary inversely with the $MgCl_2$ dosage. This occurs because magnesium chloride incorporated into wet clay soil acts on the electrical charges of fine particles and changes the structure of the soil, resulting in flocculation.

The consistency-limit values for soil treated with 4% $MgCl_2$ and soil treated with 5% $MgCl_2$ were almost identical.

3.4. EFFECT OF MAGNESIUM CHLORIDE ON PROCTOR OPTIMUM

The standard Proctor compaction test was performed on pure soil sieved to 20 mm and dried at 40 °C and on all the mixtures tested. The dry unit weights were determined immediately after compaction at each water content. The untreated soil had a maximum dry density of 16.5 kN/m^3 with an optimal water content of 22.31%. The untreated soil treated with 5% of the $MgCl_2$ stabilizer showed a decrease in its maximum dry density to 15.5 kN/m^3, and an increase in its optimal water content to 26.28% (Fig. 8).

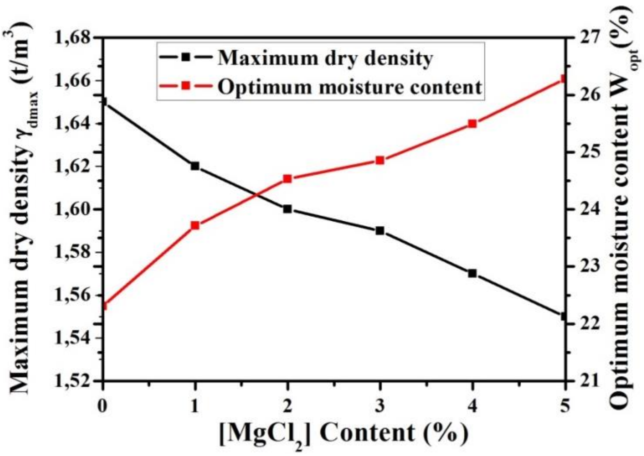

Fig. 8. Effect of $MgCl_2$ content on Proctor water content and dry density

3.5. EFFECT OF MAGNESIUM CHLORIDE ON FREE SWELLING

As can be seen in Fig. 9, treatment with $MgCl_2$ substantially reduces the swelling potential and swelling pressure of the soil. Swelling potentials were reduced by 22% to 80%, and swelling pressures by 29% to 86%. The behavior of the soil treated with $MgCl_2$ is influenced by the concentration and nature of the cations adsorbed on the soil exchange complex. Mg^{2+}, because of its high valence, is strongly attracted by negatively charged clays. This compresses the diffuse double layer and effectively increases the stability of the material. The behavior we observed corroborates the results of (Belabbaci et al. 2012). Treatment with 4 and 5% dosages of $MgCl_2$ causes similar levels of improvement. We therefore recommend treatment 4% $MgCl_2$.

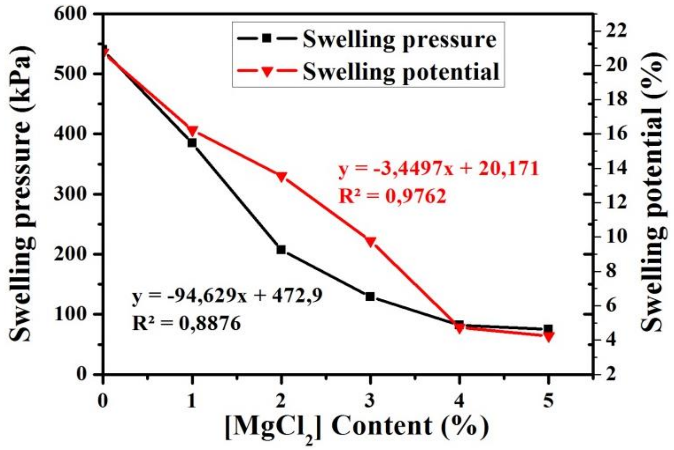

Fig. 9. Effect of the addition of $MgCl_2$ content on the potential and swelling pressure

3.6. EFFECT OF MAGNESIUM CHLORIDE ON COHESION AND FRICTION ANGLE

Figure 10 clearly illustrates that the cohesion, *C*, and friction angle, *φ*, of the soil samples were altered by the addition of $MgCl_2$. This increased the soil carrying capacity and improved the soil resistance.

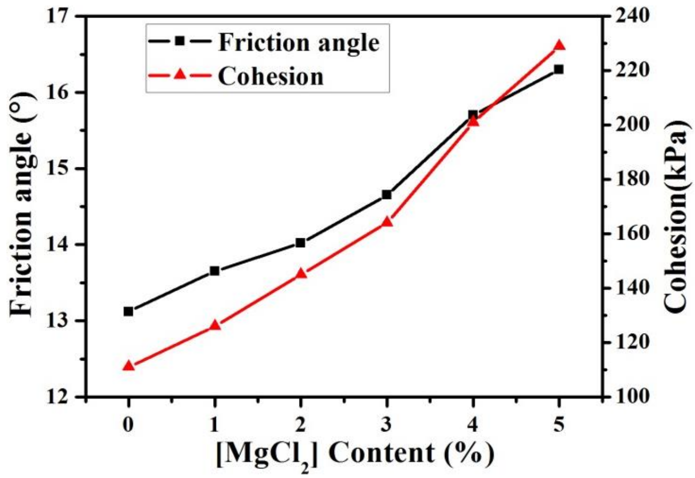

Fig. 10. Effect of the addition of magnesium chloride content on the shear parameters of soil

3.7. INFLUENCE OF MAGNESIUM CHLORIDE ($MgCl_2$) ON THE MICROSTRUCTURE

We used scanning electron microscopy (SEM) to analyze changes in the soil microstructure resulting from the addition of $MgCl_2$. Figure 11a shows that in untreated soil, the contact between kaolinite crystallites and quartz crystals is loose. The clay particles in this sample are slightly more separated than in the treated samples, and the inter-aggregate pores are larger, resulting in an open structure in which the different soil particles are poorly cemented. Also, in Fig. 11b we notice the presence of both montmorillonite and quartz crystals. SEM observation of the sample treated with $MgCl_2$ shows the presence of salt crystals coated with clay packets. The presence of magnesium ions in exchangeable form results in the electrostatic compression of clay slips and inhibits their dispersion, thus improving the structural stability of the soil.

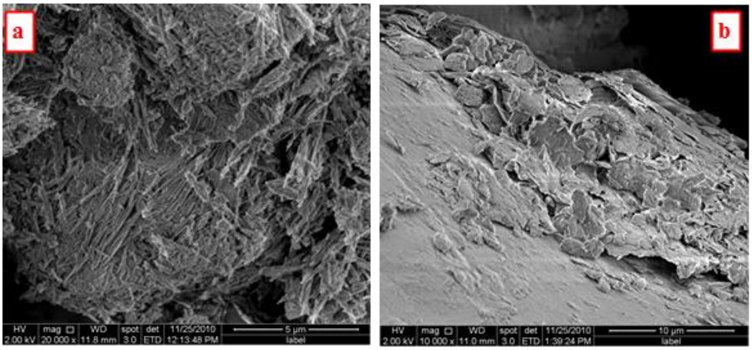

Fig. 11. Observation SEM of untreated soil

Figure 12 shows an oriented structure without cracking of the clay packets. This is probably due to the flocculation of colloids, which occurs when the ionic strength of the interstitial solution is increased because of an increase in the quantity of exchangeable Mg^{2+} present.

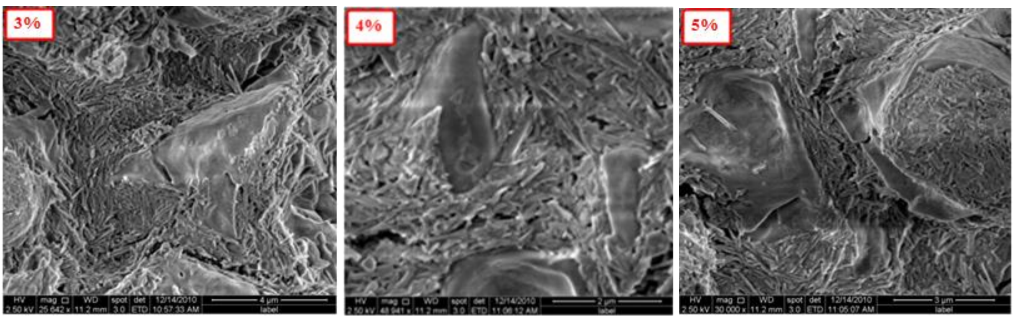

Fig. 12. Observation SEM of soil treated by different dosages of $MgCl_2$

5. CONCLUSION

We studied the behavior of a clay soil mixed with different percentages of magnesium chloride. We observed:

- An improvement in consistency parameters. The addition of $MgCl_2$ resulted in a decrease in the value of methylene blue (VBS), an increase in optimum water content, and a reduction in maximum dry density, confirming that Mg^{2+} improves the swelling behavior of the soil.
- The reduction in swelling and swelling pressure increases with the addition of $MgCl_2$. An 80% reduction in the swelling rate and an 86% reduction in the swelling pressure were achieved with the addition of 4% $MgCl_2$.
- Increased cohesion and friction angle resulted in improved soil bearing capacity and resistance in treated soil.
- S.E.M and EDAX analyses showed significant changes in the material resulting from the addition of magnesium chloride.
- Magnesium chloride treatment results in an oriented microstructure without cracking of the clay packets. This probably occurs because the ionic strength of the interstitial solution increases thanks to the increase in the concentration of exchangeable Mg^{2+}, causing the flocculation of the colloids in the sample.
- We recommend the addition of no more than 4% $MgCl_2$ because further addition of $MgCl_2$ treatment would slightly alter geotechnical properties.

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