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Hydromechanical behavior of a natural swelling soil of Boumagueur region (east of Algeria)

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Abstract. This work presents an experimental study of the hydromechanical behavior of a natural swelling soil taken from Boumagueur region east of Algeria. Several pathological cases due to the soil shrinkage / swelling phenomenon were detected in this area. In a first part, the hydric behavior on drying-wetting paths was made, using the osmotic technics and saturated salts solutions to control suction. In The second part, using a new osmotic oedometer, the coupled behavior as a function of applied stresses and suction was investigated. It was shown that soil compressibility parameters was influenced by suction variations that an increase in suction is followed by a decrease in the virgin compression slope. On the other hand, the unloading slope of the oedometric curves was not obviously affected by the imposed suction. The decrease in suction strongly influences the apparent preconsolidation pressure, ie during swelling of the samples after wetting.

Keywords: clay swelling soil; suction; shrinkage-swelling; drying-wetting; hydromechanical behavior; compressibility

1. Introduction

Algeria, as many countries in the arid climate, is fully concerned by the problem of shrinkage / swelling of clay soils. This phenomenon is linked globally to unsaturated clays and strongly influenced by variations of soil hydric state.

This hydric difference related to these over consolidate clays, can cause annually shrinkages and swellings, which are sometimes very detrimental (Houmadi *et al*. 2009, Lamara *et al.* 2010, Mohanty *et al.* 2017, Zhao *et al*. 2018).

In Algeria, and particularly in Boumagueur region (Located at 85 km west of the town of Batna, east of Algeria), significant damages and degradations were found in the different building elements (foundations, structures, masonry...), sewage pipes (rupture) and civil engineering works (deformation of the roadways).

Many authors have studied in a first part the behavior of unsaturated soils on drying-wetting paths (which the principal parameter is the negative pore pressure, in absence of external stress), due to his great importance in the comprehension of suction role in soil deformations and many real phenomena follow, as a first approximation, drying-wetting paths (Fleureau *et al*. 2002, Goual *et al.* 2011, Benchouk *et al*. 2013, Seiphoori *et al*. 2014, Sun *et al*. 2014, Al-Mahbashi *et al*. 2015, Estabragh *et al*. 2015, Sun *et al.* 2016, He *et al*. 2017).

These changes in soil hydric state during drying-wetting paths, can also affect the hydromechanical properties of soils in a significant way (Tang *et al*. 2016, Wang *et al*. 2016, Bendahgane *et al*. 2017). To study these properties, it is necessary to determine the coupled behavior of these soils as a function of applied stresses and suction. For this, many techniques allowing the control and the imposition of suction were developed and adapted to mechanical tests as the oedometer and triaxial tests (Sun *et al*. 2004, Estabragh *et al*. 2012, Favero *et al*. 2016, Zhang *et al*. 2016).

On loading-unloading paths with suction controls, results show an increase in the apparent preconsolidation pressure and stiffness of the material with increase in suction (Collin *et al*. 2002, Medjo Eko 2002, Lloret *et al*. 2003, Alonso *et al*. 2005).

Several authors have noted a decrease in the virgin compression slope l(s), with increase in suction (Alonso *et al*. 2005, Qin *et al*. 2015, Estabragh *et al.* 2017, Li *et al*. 2018). A non-monotonic variation of the slope l(s) was observed by Cuisinier (2005); it is almost constant in the range of low suction (between 0 and 2 MPa) then the compressibility of the material increases between 2 and 4 MPa. However, for suctions higher than 4 MPa, a decrease in l(s) was observed. The same observations was obtained from a compacted loam by Geiser (1999).

In the case of unloading slope k(s), several author have observed no significant influence of suction on this parameter (Alonso *et al*. 1990). Almost, some authors noted an increase in k(s), (Rampino *et al*. 2000), or a decrease with suction increase (Futai *et al*. 2002).

In this paper, an experimental study was made to study the suction effect on shrinkage and swelling of a natural swelling soil of Boumagueur region. First, on drying-wetting cycles without mechanical external stress, then in

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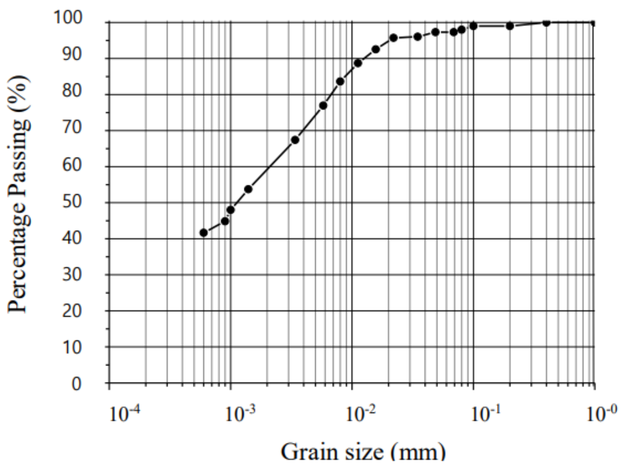


Fig. 1 Granulometric analysis of the studied soil

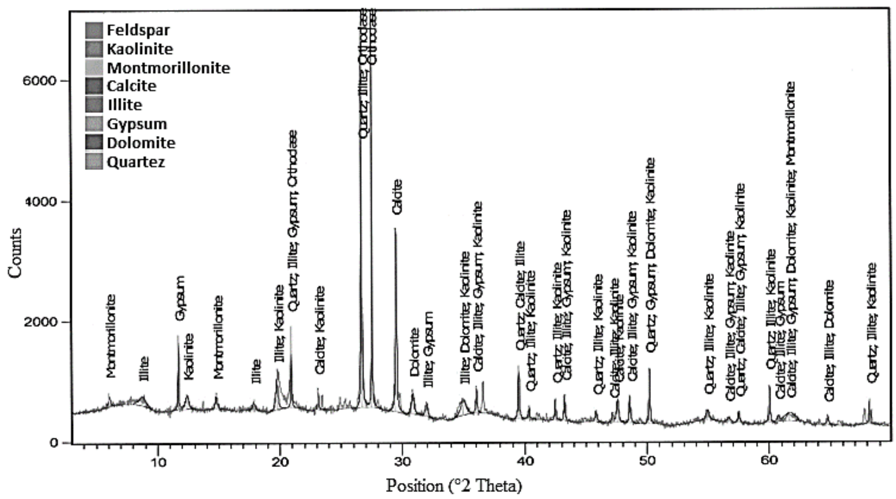


Fig. 2 X-ray diffraction of the studied material (Boumagueur site)

coupled behavior, as a function of suction and of applied stresses using a new oedometer with suction controls.

2. Studied material

The study was performed on undisturbed samples from the Boumagueur clay taken at a depth of 2.5 to 7 m. Grain size distribution shows a high percentage of fine particles (> 95%), with a clay fraction (<2µ) greater than 60% (Figure. 1)

The main physical and chemical properties as well as the initial characteristics of the material are presented in Tables 1 and 2.

The mineralogical composition of studied soil was determined by X-ray diffraction (Fig. 2). The soil contains 19% quartz and 60% of the clay minerals including 40% of the montmorillonite, 5% of illite and 15% of the kaolinite. Table 3 shows the percentage of each mineral component of the studied material.

The filter paper method (ASTM D5298) was used to determinate the initial matrix suction, which is about 20 MPa. The free swelling method based on standard ASTM 4546-0, method A, was used to measure swelling potential (ΔH / H) and swelling pressure (Ps), which have successive values of 33% and 1000 kPa. In free swelling method, a specimen is inserted into a classical oedometric cell, then submitted to the load of the piston (1.5 kPa) and finally saturated by immersion. Its vertical strains are measured; the maximum strain related to initial height is the swelling

Table 1 Physical characteristics of the studied material

Liquid limit LL (%)	Plastic limit PL (%)	Plasticity index PI (%)	Density of solid grains g_s (kN/m^3)	Dry unit weight g_d (kN/m^3)	Initial water content w_0 (%)	Initial degree of saturation Sr_0 (%)	Initial void ratio e_0
61.5	29.3	32.2	26.5	18.5	14	86	0.43

Table 2 Chemical properties of the studied material

$CaCO_3$ content (%)	Blue methylene value	Specific surface area (m^2/g)	Organic matter content (%)
46	7.2	150.69	8.5

Table 3 Mineralogical composition of the studied soil

Quartz	Calcite	Gypsum	Dolomite	Feldspar	Montmorillonite	Illite	Kaolinite
19%	16.5%	0.1%	2%	2.4%	40%	5%	15%

potential (ΔH / H). After this step, the loading is started and swelling pressure (Ps) is defined as the load which cancels the maximum strain due to swelling.

3. Experimental methods

3.1 Imposition suction methods

3.1.1 Osmotic technic

The osmotic method is a technique of imposition of suction in order of 0 kPa up to a value of 8500 kPa. Its principle consists to put soil sample into contact with a solution of organic macromolecules of polyethylene glycol PEG, via a semi-permeable membrane allowing only water to pass. This solution is at an osmotic pressure set by concentration of PEG, and at equilibrium, the interstitial pressure of water in sample corresponds to this osmotic pressure. The commonly used macromolecule is polyethylene glycol (PEG) having a molecular weight of 20000 or 6000 Dalton. The report between solution concentration and suction is independent of the type of PEG and can be approximated by a parabolic equation (Delage *et al*. 1998) of form

$$s = 11C^2 \quad (1)$$

where, s is the suction expressed in MPa and C is the concentration of PEG expressed in g of PEG per g of water.

3.1.2 Saturated salt solutions (vapor phase control technique)

This technique is generally used for imposition suction from some MPa to hundreds of MPa. It is based on the kelvin law

$$s = (\rho_w R.T/M_v)\ln(RH) \quad (2)$$

s: total suction (MPa), r_w : The density of water at temperature T (g/cm^3), R : Perfect gas constant (R = 8.314 J/mol.K), T : Temperature (K), Mv : Molecular weight of water vapor (Mv = 18.01 g/mol), RH : Relative humidity (%).

The principle of this method consists in placing a sample of soil in a hermetic enclosure (desiccator), were the relative humidity is controlled by a saturated salt solution

The value of RH depends both on solution used (salt and concentration) and on temperature. For our tests at ambient temperature, the desiccators were placed in an environment thermostated at 20°C.

3.2 Measuring suction method

3.2.1 Filter paper methods (ASTM D5298)

This method of measuring suction is based on the fact that at the moisture equilibrium, the soil water potential and the water potential of filter paper in contact with soil are identical. The time required to reach the water potential equilibrium is 10 days. The suction range accessible by this technique is between a few kPa and several hundreds of MPa.

3.3 Oedometer suction controlled path

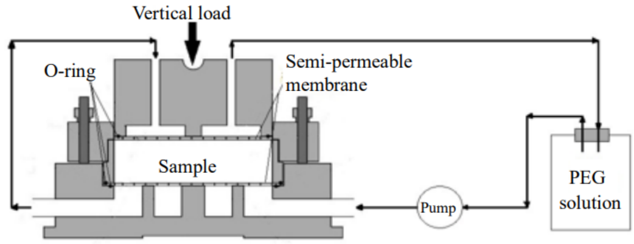


Fig. 3 Schematic representation of a modified osmotic odometer

According to Derfouf *et al.* 2017, an osmotic oedometer was developed allowing the imposition of suction using the osmotic technique (Fig. 3). The circulation of PEG solution (i.e., suction imposition) through the base and the top of sample was assured along the tests using a peristaltic pump. The solution circulates through the bottom and the piston of oedometric enclosure, which was made to permit solution to flow through the entire lower and upper area of soil sample. Between sample and PEG solution, a semi-permeable membrane (Spectra / Por® No. 3) was introduced to prevent passage of PEG macromolecules to the sample. In the modified oedometer, the maximum accessible vertical stress and suction are 2000 kPa and 8000 kPa, respectively. The initial height and the diameter of soil sample are 2 and 7 cm, respectively. When a given suction was applied, it took approximately twelve days to reach equilibrium of deformations.

4. Testing program and samples preparing

4.1 Behavior of Boumagueur clay on drying-wetting path

In the study of the soil behavior on drying-wetting path, the osmotic and the saturated salt solution techniques were used. The tests were realized at a remolded and undisturbed soil.

For drying path, different increasing suctions were imposed on samples. On the other hand and for wetting path, different decreasing suctions were imposed.

When equilibrium is reached for each imposed suction, the state parameters of samples are then measured (void ratio, water content, dry density…)

4.1.1 Behavior of remolded soil

Two initial states of samples are prepared:

• A slurry is prepared with an initial water content equal to 1.2 LL.

• Normally consolidated soil is prepared from slurry consolidated under a vertical stress of 100 kPa.

For drying path, initial saturated samples (slurry and consolidated soil) are submitted to different increasing imposed suctions.

For wetting paths, initial saturated samples (slurry and consolidated soil) are first dried in open air during one week and then in an oven at 50°C during 24hr. This procedure prevents the occurrence of microcracks. Dried samples are then submitted to different decreasing imposed suctions, starting from 500 MPa.

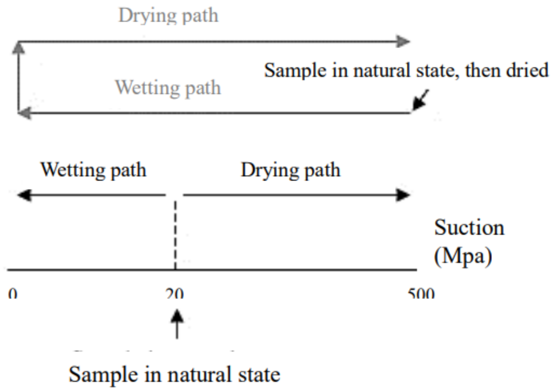


Fig. 4 Drying-Wetting paths followed for undisturbed soil

When equilibrium is reached for each imposed suction, the state parameters of samples are then measured (void ratio, water content, dry density…).

4.1.2 Behavior of undisturbed soil

To study the variation effect of suction on soil in natural state, it is necessary to calculate initial suction of samples. The determination of this value will mark the limit between the two paths in such a way that, if imposed suction values are higher than initial suction, a drying path is followed and, if lower values are imposed, a wetting path is followed. The initial matrix suction of samples was determined by filter paper method (ASTM D5298), which is about 20 MPa.

In this part, the initial states of samples are presented in the form:

• Samples in natural state (w_0=14%; S_{r0}=86%; see table 1).

• Samples in natural state, dried in open air and then in an oven at 50°C.

For drying-wetting path, samples in natural state are submitted to different imposed suctions. If imposed suction values are higher than initial suction, a drying path is followed and, if lower values are imposed, a wetting path is followed.

For wetting paths, samples in natural state are first dried in open air during one week and then in an oven at 50°C during 24hr. This procedure prevents the occurrence of microcracks. Dried samples are then submitted to different decreasing imposed suctions, starting from 500 MPa.

At the end of the wetting path, samples were resubmitted to a drying path by submitting samples to different increasing imposed suctions, until a suction of 500 MPa.

When equilibrium is reached for each imposed suction, the state parameters of samples are then measured (void ratio, water content, dry density…).

Fig. 4 shows drying-wetting paths followed for undisturbed samples.

4.2 Behavior of Boumagueur clay on oedometric path with controlled suction

For characterization of behavior on oedometric path with controlled suction, the tests were realized at an undisturbed soil. Before using oedometer, the initial matrix suction of samples was determined by filter paper method (ASTM D5298), which is about 20 MPa.

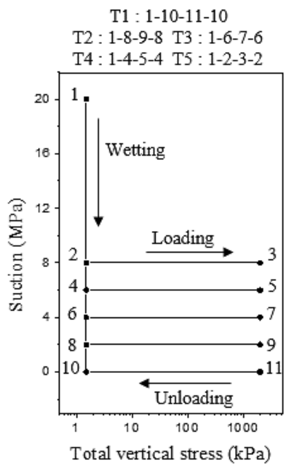


Fig. 5 Suction-stress paths followed

Fig. 5 shows suction-stress paths followed by different samples. The initial state of all samples corresponds to point “1” corresponding to a low vertical stress of about 1.5 kPa and an initial suction of about 20 MPa. First, each sample is submitted to a given imposed suction on wetting path. When the equilibrium is reached, sample was loaded and then unloaded under constant suction.

5. Results and discussions

5.1 Behavior of Boumagueur clay on drying-wetting path

5.1.1 Behavior of remolded soil

The curves obtained are presented in 5 planes, marked from (a) to (e), (Fig. 6). Those on the left connect void ratio and saturation degree with water content, while those on the right connect void ratio, saturation degree and water content with imposed suction.

Concerning drying-wetting test of material prepared initially in the form of slurry with w = 1.2 LL.

Plane (a), e = f (w): This graph shows the change of void ratio as a function of water content (shrinkage curve) of soil. The saturation of soil results in a straight line passing through the origin of the axis system, with the equation:

$e = (\gamma_s / \gamma_w)\, w$, (with g_s / g_w: solid grains density). The intersection of this line with the horizontal asymptote of the curve when water content tends to zero corresponds to shrinkage limit of material w_{SL}. (Fleureau *et al*. 1993).

The shrinkage limit w_{SL} is of the order of 14% corresponding to a voids ratio e_{SL} of the order of 0.41. When the water content decreases lower than the shrinkage limit, the void ratio tends to a constant value.

By way of comparison, the values of liquid limit LL and plastic limit PL were reported on axis of water contents.

On the second plane b, e = f(s): We observe a very large change in void ratio with suction, which resembles to the oedometric curve of a normally consolidated saturated soil. Unlike the latter, it has a quasi-horizontal plateau when

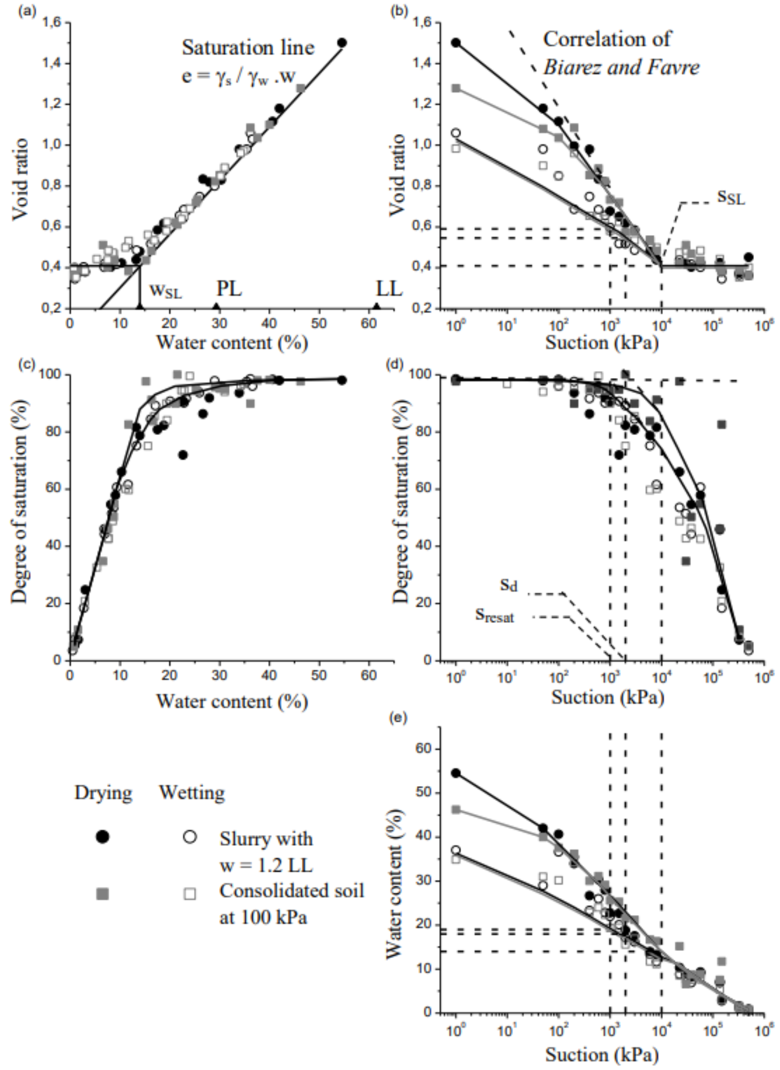


Fig. 6 Drying-wetting path on the Boumagueur clay in the form of slurry with w = 1.2 LL and consolidated soil at 100 kPa

suction becomes greater than a threshold value corresponding to the shrinkage limit suction. For drying and wetting paths, there is a strong irreversibility before the plateau and a quasi-reversibility on the plateau.

In this plane, it is thus possible to distinguish two domains of variation in void ratio, the first one being characterized by large deformations, while the second are quasi-zero. The limit between these two domains corresponds to the point at the beginning of the line of nearly constant void ratio (shrinkage limit void ration e_{SL}). The corresponding suction is the shrinkage limit suction (s_{SL} = 10 MPa) corresponds to the void ratio e_{SL} = 0.41.

The correlation of isotropic line of Biarez and Favre, 1975, was added on the same plane.

Biarez and Favre (1975) have shown that the Normally Consolidated coefficient of compressibility C_c is correlated to Liquid Limit LL as follows: $C_C = 0.009\ (LL - 13)$ (LL in %), and corresponds in loading-void ratio plane to 2 points:

- A loading of p′=7 kPa gives a void ratio corresponding to the liquid limit LL ($e = (\gamma_s / \gamma_w)$ LL),

- A loading of p′=1 MPa gives a void ratio corresponding to the plastic limit PL (e = (g_s / g_w). PL).

During drying path, and before desaturation of soil (suction less than the suction of desaturation), Fleureau *et al*. 1993, showed that there is equivalence between mechanical isotropic loading p′ and suction. Then p′ can be replaced by suction

$$w = LL, \text{ or } e = (\gamma_s / \gamma_w)\ LL, \text{ for } p' \text{ (or s)} = 7 \text{ kPa} \quad (3)$$

$$w = PL, \text{ or } e = (\gamma_s / \gamma_w)\ PL, \text{ for } p' \text{ (or s)} = 1000 \text{ kPa} \quad (4)$$

$$C_C = 0.009\ (LL - 13)\ \ (LL \text{ in } \%) \quad (5)$$

The plane (c), Sr = f (w): Highlights the water contentrange in which the soil remains saturated. When water content becomes lower than shrinkage limit (w_{SL}), the saturation degree diminishes very rapidly, almost linearly with water content.

The curve of the plane d, Sr = f(s) shows on drying path, two substantially linear parts corresponding, on the one hand, to a saturation degree close to 100 % and, on the other hand, to the very rapid desaturation of material. The intersection between the two lines characterizes the point of air entry, to which corresponds suction of desaturation denoted s_d and equal to 2 MPa. On wetting path, suction of re-saturation s_{resat} = 1 MPa, was determined using the same method.

It will be noted that soil remains quasi-saturated for suctions less than suction of desaturation, once the suction exceeds this value, saturation degree decreases rapidly to a residual value of the order of 1.5%.

The plane (e), w =f(s) corresponds to the soil water retention curve (SWRC). As long as suction is lower than s_{SL}, changes in water content correspond to changes in void ratio. When suction increases, there is a sharp decrease in water content. After the shrinkage limit, the slope of the curve decreases slightly.

If we consider wetting path, we finds that there is a hysteresis between wetting and drying paths, which is a fundamental characteristic of the behavior of unsaturated porous media (Hillel 1980, Fleureau *et al.* 1993).

Depending on suction range considered and in the three right-hand planes (void ratio, saturation degree and water content as a function of suction), we note that:

For suctions higher than shrinkage limit suction ($s>s_{SL}$), drying and wetting paths are reversible and merged.

In the intermediate domain where suction is between suction of re-saturation and shrinkage limit suction, the material is resaturated and this time presents a strongirreversibility characterized by the overall variation in volume of soil and filling of pores.

For suctions less than re-saturation suction, soil is almost saturated and the hysteresis remains in the two planes: e = f (s) and w = f (s).

The drying-wetting path of consolidated soil is similar to the path of the slurry. However, there are some differences:

In plan b, drying path of consolidated soil begins with a lower void ratio (consolidated soil is more dense than the slurry). It first follows an over consolidated path, and then joins the normally consolidated path of the slurry, for suction of about 200 kPa, then follows a single path, that of the slurry. Therefore, the consolidated soil has the same parameters w_{SL}, s_{SL}, s_d, as those of the slurry.

On wetting paths, we note that the slurry and the consolidated soil follow the same path throughout wetting, in other words, before and after shrinkage limit suction, despite the dispersion of some experimental points related to measurement uncertainties. This can be explained by the fact that drying in an oven has erased the initial mechanical Over-consolidation of consolidated soil, and consequently, the initial state of the slurry and the consolidated soil after drying in oven is almost the same.

5.1.2 Comparison between drying and oedometric paths

On the drying path, as long as the suction remains lower than the air entry value ($s < s_d$), the soil remains saturated, and suction is an isotropic pressure, and equal to the mean pore pressure, then

$$w = LL,\ \text{or}\ e = (\gamma_s / \gamma_w)\ LL,\ \text{for}\ p'\ (\text{or}\ s) = 7\ \text{kPa} \qquad (6)$$

On the saturated oedometric path, the mean stress is calculated as follows

$$p' = (\sigma'_1 + \sigma'_2 + \sigma'_3)/3 = (\sigma'_1 + 2\,\sigma'_2)/3 \qquad (7)$$

As $\sigma'_2 = K_0\,\sigma'_1$ (with $K_0 = 1 - \sin\varphi'$ "*Jacky Formula*", and j′ is the effective friction angle of the soil), the mean effective stress becomes

$$p' = (\sigma'_1 + 2\,K_0\sigma'_1)/3,\ \text{with}\ K_0 \approx 0.$$

$$\mathbf{p' = \sigma'_1(1 + 2\,K_0)/3} \qquad (8)$$

To compare the effects of suction and mechanical loading on the volume change, we have plotted on the same graph (Fig. 7) in [log p′; e] plane, the drying and oedometric paths.

We note that the paths of drying and oedometric tests are parallel. It can be considered that the suction on drying path (expressed in term of effective stress p′) and the effective mean stress p′ on oedometric path, have the same effect on void ratio variation as long as the material remains saturated ($s \leq sd = 2$ MPa). This is consistent with the results of Biarez *et al.* 1988, Zerhouni (1991), Fleureau *et al.* 1993, Lu *et al.* 2006; Benchouk *et al.* 2013 and *Li et al.* 2018.

5.1.3 Behavior of undisturbed soil

The samples in natural state exhibit an extremely different behavior. The drying-wetting path performed on the undisturbed soil is illustrated in figure 8, where drying-wetting path of slurry of the same material, which is approximately coincident with normally consolidated compression path, is also shown.

The characteristics of paths on slurry and on an undisturbed soil are very different in all planes, for example:

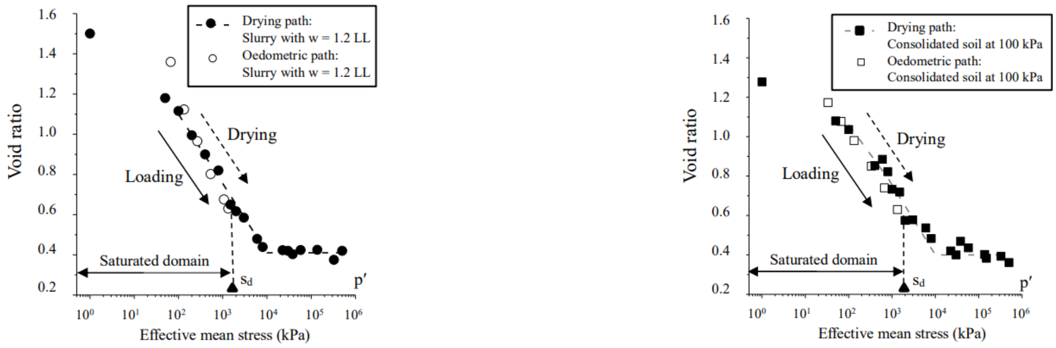
On the shrinkage curve e = f (w), it is noted that the value of shrinkage limit of sample in natural state is 10% corresponding to a void ratio of 0.31 and the shrinkage limit suction in plane e = f (s) is of the order of 40 MPa.

If we compare these values with those of the slurry and consolidated soil, we note that the shrinkage limits void ratio and water content are lower and shrinkage limit suction is higher. This difference is probably due to the initial microstructure anisotropy of undisturbed soil, compared to the slurry. (Fleureau *et al.* 1993, Sidoroff *et al.* 1993).

Different shrinkage limit plateau are then observed, that of natural sample being below that of the slurry, that is to say that the material is in a more dense state. The shrinkage limit suction is higher and the shrinkage limit water content is lower for natural sample. This confirms that the shrinkage limit of soil is not an intrinsic parameter, but depends on its initial state (Fleureau *et al.* 1993).

All these differences can be attributed to the consolidation pressure of not remolded soil; it is due in partly to physic-chemical bonds created between grains and partly to mechanical overloads that material has undergone in geological time.

It is also noted that drying-wetting path from initial state of intact sample shows an inflection point when approaching the shrinkage plateau. The initial state of intact sample is slightly below the Normally Consolidated line. The drying path followed from initial state tends at first to join the Normally Consolidated line, before reaching shrinkage limit plateau, hence the existence of this



(a) Slurry with w = 1.2 LL (b) Consolidated soil at 100 kPa

Fig. 7 Comparison between drying and oedometric paths

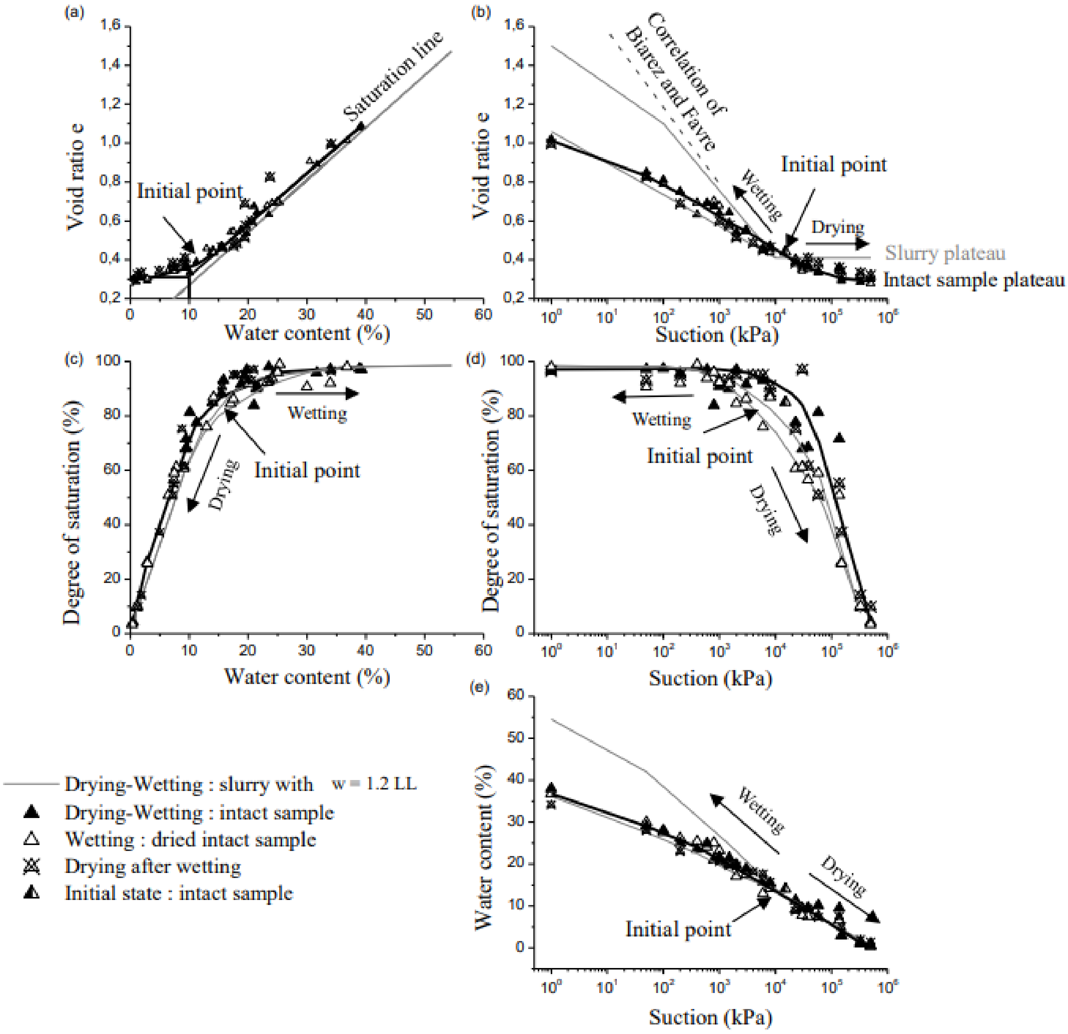
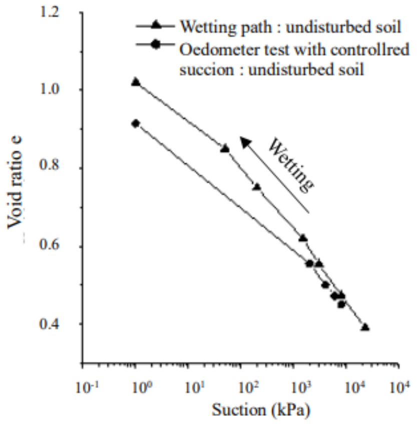


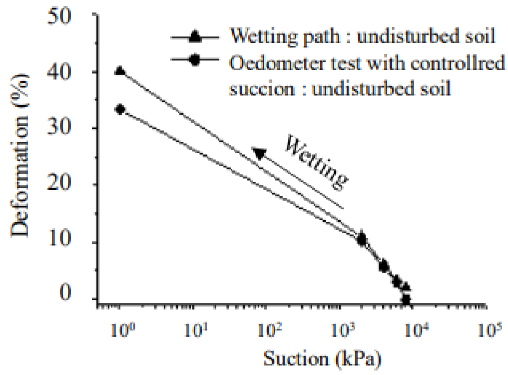
Fig. 8 Drying-wetting path on the Boumagueur clay in his natural state

inflection point. The wetting path followed from initial state is an over-consolidated unloading path. The continuity of drying and wetting paths clearly shows the typical behavior of an over-consolidated soil, whose preconsolidation stress can be estimated, as a first approximation, by the intersection of intact soil path with the Normally Consolidated line

On wetting path from a dry state, it is noted for suctions greater than initial suction of intact sample, wetting path coincides with drying path. This can be explained by the fact that the soil being strongly desaturated, water is in form of menisci at contact points between particles of soil. These menisci generate the capillary forces that are normal to the contact planes and therefore do not cause rearrangement of particles, either on drying or wetting path. This also explains the presence of this shrinkage plateau in plane e = f (s). When suction becomes lower than initial suction, the wetting saturates sample progressively and capillary forces



(a)



(b)

Fig. 9 Comparison of: (a) wetting and oedometric curves of undisturbed soil and (b) final deformations obtained at the end of the suction imposition phase and the deformation of wetting path

Table 4 Hydromechanical parameters determined from curves of controlled-suction oedometric tests

Tests	Stress paths followed	Imposed suction (MPa)	Initial water content wi (%)	Final water content wf (%)	Initial saturation Degree Sri (%)	Final saturation Degree Srf (%)	Swelling potential ΔH/H (%)	Unloading slope *k (s)*	Virgin compression slope *l (s)*	Apparent preconsolidation pressure *(kPa)* P_0 *(s)*
T1	1-10-11-10	0	14	31	85	100	33.2	0.1	0.26	75
T2	1-8-9-8	2	13.6	22	86	100	10.2	0.02	0.19	295
T3	1-6-7-6	4	13.5	17	85	100	5.6	0.04	0.17	412
T4	1-4-5-4	6	13.8	15	85	100	3	0.04	0.15	481
T5	1-2-3-2	8	14	14.6	86	100	1.3	0.04	0.15	641

are no longer normal to contact planes between particles, hence their rearrangement, then an increase in voids ratio.

At the end of wetting path, samples were resubmitted to a drying path. It is noted that this drying path coincides with wetting path of intact soil. It is an over-consolidated, volumetric quasi-elastic path, and reversible, similar to mechanical loading and unloading paths of over-consolidated saturated soils.

5.2 Behavior of Boumagueur clay on oedometric path with controlled suction

For characterization of behavior on oedometric path with controlled suction, the tests were realized at an undisturbed soil (w_0=14%; S_{r0}=86%; see Table 1). During the first phase, which is imposition suction phase and for each test, different suction was imposed. Samples were loaded and then unloaded under constant suction in the second phase.

5.2.1 Suction imposition suction phase

During suction imposition phase, we will have a wetting path of samples, knowing that initial suction of samples is higher than imposed suction. The following relation calculates the values of deformations

$$\varepsilon_s = (e_s - e_i)/(1 + e_i) \qquad (9)$$

e_s: Strain due to suction (%), e_s : Voids ratio after suction imposition phase, e_i : Initial void ratio

The values of final deformations and of void ratio obtained at the end of imposition suction phase are shown in Fig. 9. For comparison, we have plotted on the same graph some representative points of wetting path of drying-wetting tests of samples in natural state, plotted in terms of void ratio and deformations as a function of suction.

The obtained curve of oedometric test with controlled suction has a similar appearance that of wetting path of natural samples, characterized by a strain which is all the greater as suction decreases and is positioned below it. This displacement between these two curves is due to the fact that:

-Samples subjected to a “free” wetting path (without mechanical stress), strain freely in the 3 directions, which can be assimilated to an isotropic strain.

-On the other hand, samples subjected to a wetting path in an oedometer cell with controlled suction and under mechanical stress (even if this one remains weak = 1.5 kPa), strain in only one direction only imposed by the oedometer (path K_0), the lateral strain being zero, thus anisotropic strain.

This may explain why isotropic “free” wetting gives a final void ratio a little greater than anisotropic wetting.

5.2.2 Sample loading / unloading phase

Fig. 10 shows the variation of void ratio as a function of total vertical stress for all tests. The hydromechanical parameters determined from these curves are presented in Table 4.

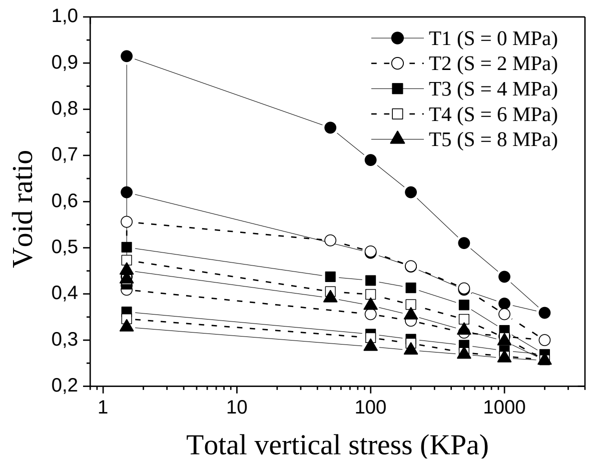


Fig. 10 Consolidation curves of oedometric tests with controlled suction

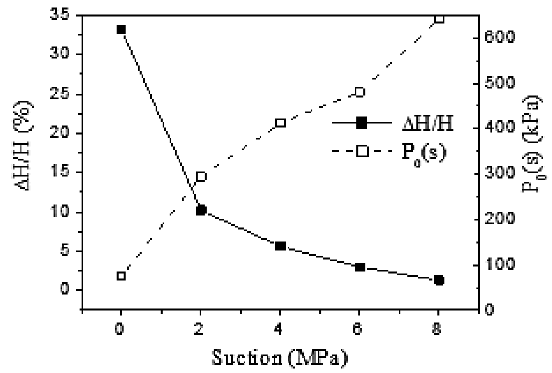


Fig. 11 Variation of the swelling pressure and the apparent preconsolidation pressure as a function of the suction

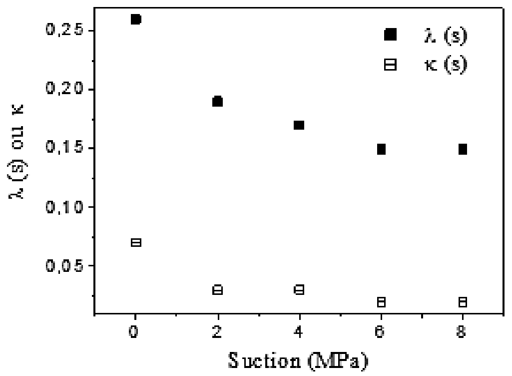


Fig. 12 Variation of l(s) and k(s) as a function of suction

Table 4, shows that the final values of saturation degree for all tests are close to 100% because, the soil remains in quasi-saturated domain, since the suction remains lower than suction of desaturation which is about 10 MPa (figure 8.d, Sr = f(s)).

5.2.3 Effect of suction on compressibility

The values of the apparent preconsolidation pressure P_0(s) obtained were plotted as a function of imposed suction in Fig. 11. The apparent preconsolidation pressure decreases when suction is decreasing. This indicates that the apparent preconsolidation pressure of a swelling soil is not only dependent on its density, but also depends on imposed suction to the soil.

The variations of swelling potential ΔH/H as a function of imposed suction were also reported in the same graph (Fig. 11), where all imposed suctions are less than initial suction of samples, which corresponds to wetting of samples. It is well known that swelling of clays occurs in several stages. During wetting, it was noticed that with the decrease in suction, an increase in swelling potential up to a maximum value for suction close to zero, corresponding to a quasi-saturated material. For this maximum value of swelling potential, Cuisinier and Masrouri (2005) explain the in this case, the major part of macropores of sample was occupied by swelling clay particles.

The variation of l(s) and k(s) slopes is shown in Fig. 12. It is noted that the discharge slope k(s) was not significantly influenced for suctions greater than 2 MPa except for test T1 where suction is zero, we observe that the parameter k(s) takes its maximum value. On the other hand, there is a decrease in the virgin compression slope l(s) with increase in suction. For suction values greater than 4 MPa, the value of l(s) stabilizes.

6. Conclusions

The soil of Boumagueur study region is clayey in nature characterized by high plasticity. It is sensitive to phenomenon of shrinkage / swelling, causing many damages and degradations in different building elements (foundations, structures, masonry...). Indeed, the grain size distribution of studied soil shows a high percentage of fine particles (> 95%), with clay fraction (<2μ) greater than 60%. The mineralogical composition was determined by X-ray diffraction. The soil contains 60% clay minerals including 40% montmorillonite.

In the first part of this article, the representation of material state during drying-wetting cycle makes it possible to follow the soil saturation evolution and to connect shrinkage characteristics to drying and wetting characteristics.

To determine the behavior observed in saturated domain, the deformations resulting from suction were compared with those resulting from an external isotropic applied stress to a saturated sample. It is noted that, identical increments of suction or mechanical stress produce the same variation in void ratio as long as the material remains saturated.

The role of initial state was studied by comparing behavior of the slurry with w = 1.2 LL, consolidated soil at 100 kPa and of natural samples. Samples in natural state exhibit extremely different behavior. Different shrinkage plateaus are observed, that of sample in natural state being below that of the slurry. The shrinkage limit void ratio and water content are lower and shrinkage limit suction is higher. This confirms that the shrinkage characteristics of soil are not an intrinsic characteristics but depends on the preparation of samples.

In the second part of the article, an osmotic oedometer was developed allowing the imposition of suction using osmotic technique. A study of swelling during wetting was made as function of the imposed suction. It was observed that with decrease in suction, an increase in swelling potential up to a maximum value for a suction close to zero.

The compressibility of studied soil is greatly influenced by any variation in suction. The virgin compression slope l(s), decreases with increase in suction. The apparent preconsolidation pressure decreases with decrease in suction. This indicates that the apparent preconsolidation pressure of a swelling soil is not only a function of its density, but also depends on imposed suction.

In the case of unloading slope k(s), it found that this parameter is not strongly influenced by suction but it takes its maximum value for suction close to zero.

Our results demonstrate the extreme sensitivity of hydromechanical behavior of a natural swelling soil to any variation in suction.

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