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Volumetric behavior of natural swelling soil on drying-wetting paths. Application to the Boumagueur marl -Algeria-

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Abstract: This article presents the results of experimental work carried out both in situ (coring; pressuremeter test) and in the laboratory (drying-wetting and oedometric tests) to describe the volumetric behavior on drying-wetting path of a swelling clayey soil of eastern Algeria. In order to perform drying-wetting tests the osmotic technique and saturated salts solutions were used. These suction-imposed methods have gained widespread acceptance as reliable methods for imposing suction on soil specimens. They allowed to sweep a wide range of suctions between 0 and 500 MPa. The ability to impose suction on soil specimens allows for drying and wetting stress paths to be applied to evaluate resulting changes in state parameters (void ratio, degree of saturation and water content). These paths were carried out on specimens with different initial states. Slurries of soil were used to characterize the reference behavior, while the undisturbed soil samples allow to describe the behavior of material under in situ conditions. In the last part of this article and to specify the behavior observed in the saturated domain, a comparison between the resulting deformations of the drying-wetting test and those resulting from the oedometric test was made.

Keywords: Suction; Shrinkage; Swelling; drying-wetting; undisturbed soil; slurry; volumetric behavior.

1 Introduction

A large number of geotechnical problems such as shrinkage-swelling phenomena linked to the presence of partially saturated clayey soil zones, especially in arid or semi-arid zones, such as in Algeria, where unsaturated soil conditions dominate. Under natural conditions, unsaturated soils are inevitably subjected to drying-wetting paths due to environmental factors such as changes in the ground water table level, and fluctuations of relative humidity caused by, for example, moisture changes under rainy and drought conditions. This phenomenon plays a major part in many problems affecting geotechnical structures, for instance, settlement or crack of foundations during drying, swelling or collapse of embankments during wetting and so on.

In the absence of external mechanical stress, free drying or wetting leads to changes in soil volume, water content as well as degree of saturation, and that may result in settlements or heave of structures. This hydric difference related to these over consolidate clays, can cause annually shrinkages and swellings, which are sometimes very detrimental (e.g., Houmadi et al.,[17] Lamara et al.,[20] Medjnoun et al.,[26] and Mohanty et al.[29]). The main parameter that causes these changes in volume and water content of unsaturated soils is suction which plays a vital role on soil volumetric behavior. It is defined as the difference between the pore-air pressure and the pore-water pressure in the soil. It is an important parameter, which makes the difference between the behavior of saturated and unsaturated soils (e.g., Fredlund and Rahardjo[13]).

Starting from the water-saturated condition, as suction increases, soil gets desaturated as a result of water transfer from the porous medium to the environment, which, at the same time, results in volume change (shrinkage). On the contrary, in the case of an air-saturated sample, with the decrease in suction, water enters the soil, leading to

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an increase in degree of saturation and volume (swelling). The cyclic variations of volume, water content and degree of saturation on drying–wetting paths are of considerable importance in soil mechanics applied to shallow foundations and were investigated both experimentally and numerically over the last decades.

The study of drying-wetting paths is a necessary step in the study of unsaturated soils behavior. Indeed, it has a double interest, on the one hand because it makes it possible to highlight the role of the suction to which the soil is subjected and to understand this important aspect of its behavior, on the other hand, many real phenomena follow, as a first approximation, drying-wetting paths (e.g., Al-Mahbashi et al.,[2] Bendahgane et al.,[5] Estabragh et al.,[10] He et al.,[15] Goual et al.,[18] Seiphoori et al.,[31] Sun et al.,[33] Sun et al.,[34] Tang et al.,[35] and Wenjing et al.[41])

These drying-wetting tests also show the interest of a global representation of the soil state during drying-wetting cycle. This representation makes it possible, in particular, to follow the saturation evolution of the soil and to relate the shrinkage – swelling or water retention behavior to suction (e.g., Alonso et al.,[3] Derfouf et al.,[9] Fleureau et al.,[12] Tripathy et al.,[36] Vanapalli et al.,[37] Wang et al.,[39] and Zhao et al.[43]). The enriching experimental data permitted the determination of compressibility (e.g., Maria et al.[25]), permeability (e.g., Van Genuchten[38]) as well as shear strength (e.g., Fredlund et al.[14] and Linchang et al.[23]) of different soils, in particular expansive clay. Several parameters affecting drying-wetting curves such as temperature (e.g., Laloui et al.[19] and Salager et al.[30]), stress history (e.g., Lu and Likos.[24] and Zhong et al.[44]) and mineralogy (e.g., Wei et al.[40]) were highlighted and well-illustrated.

In terms of volume change, another interesting aspect is the analogy between the effect of mechanical stress and that of suction. By comparing the results of mechanical consolidation and drying tests, some authors (e.g., Benchouk et al.,[4] Biarez et al.,[7] Fleureau et al.,[11] Li.[21] and Li et al.[22]) found that the drying curve of saturated slurry was equivalent to an oedometric consolidation curve, provided that suction was smaller than the air-entry value, that is, the soil remained quasi-saturated.

The article does not address the problem of shrinkage-swelling observed in situ but aims to study the volumetric behavior of the natural clay in an unsaturated state, taken from Boumagueur region (East of Algeria), where several pathological cases due to the soil shrinkage-swelling phenomenon were detected.

Table 1: Lithology of the site.

Depth $^{(*)}$	Soil description
0 - 0.5 m	Topsoil, surface clayey sands
0.5 - 2.5 m	Clay + Sandy clay
2.5 - 10 m	Compact greenish marl with traces of sand, clay, gypsum and carbonate concretions.

$^{(*)}$: all drillings not exceeding the depth of ten meters.

2 Materials

2.1 Lithology of the site

The soil was taken from the Boumagueur study site located in the east of Algeria; this site is generally flat. A rock material, materializes most of the geological evolution of the region. It is essentially composed of:

- Recent alluvial deposits (clays, silts) and limestone sediment (Quaternary). This clayey layer covers the most region of Boumagueur.
- Marl, sandstone and clay (Tertiary). This marly layer outcrops in several places in the study area.

The geological formations encountered according to the three core drillings in the site (Figure 1), were summarized in three categories in Table 1.

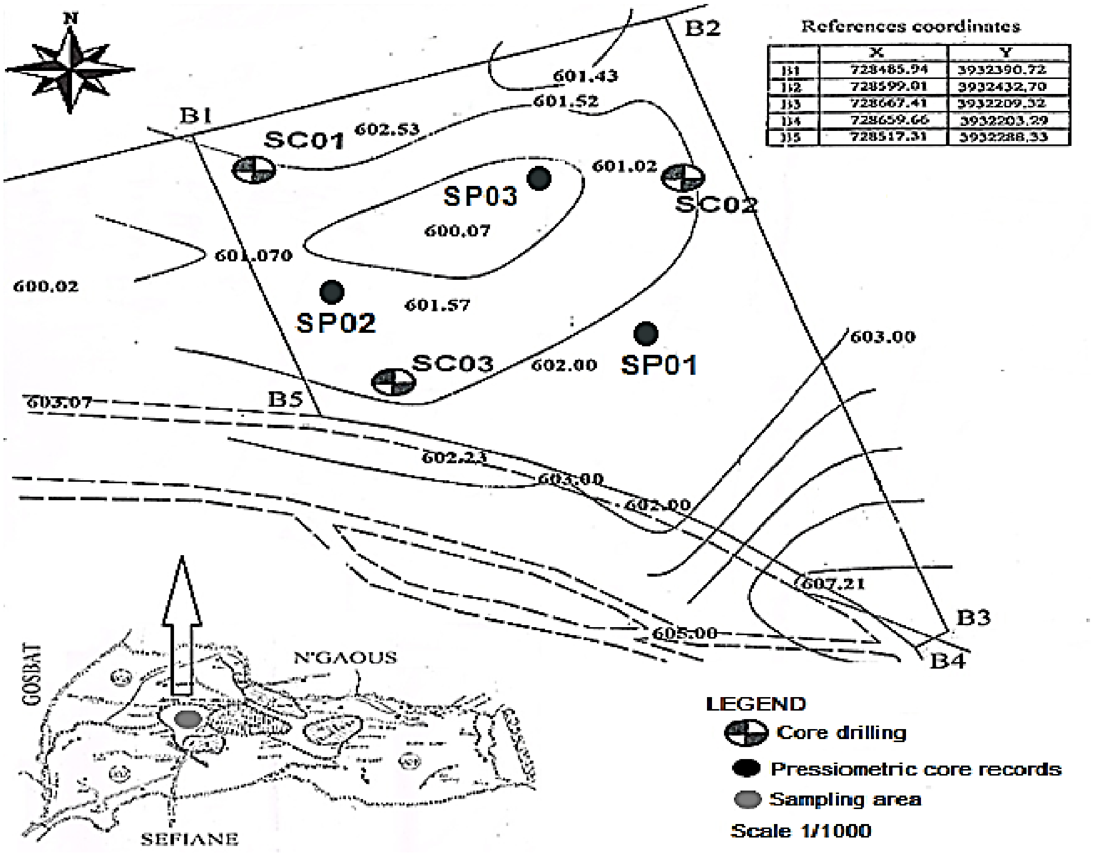
2.2 Studied material

The study was performed on the Boumagueur marl taken at a depth of 3 to 4 m in the form of intact samples in the natural state. The main physical and chemical properties are presented in Table 2. According to the USCS/LPC classification, this marl is designated as follows:

CH: highly plastic clay with low organic matter

The results of the X-ray fluorescence analysis (Table 3) show the high proportion of silica of about 49% compared to that of alumina, which is about 14.5%, these two chemical elements being the main components of clays.

The mineralogical composition of the studied soil was determined by X-ray diffraction (Figure 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 4 shows the percentage of each mineral component of the studied material.



References coordinates

	X	Y
B1	728485.94	3932390.72
B2	728599.01	3932432,70
B3	728667.41	3932209,32
B4	728659.66	3932203,29
B5	728517.31	3932288,33

Figure 1: Study area topography and location of core drillings.

Table 2: Physical and chemical properties of the studied material.

Physical identification		
▪ Particle size		
Gravel	(%)	-
Sand	(%)	5
Silt	(%)	35
Clay	(% < 2µm)	60
	(% < 80µm)	98
▪ Atterberg limit		
Liquid limit LL	(%)	61.5
Plastic limit PL	(%)	29.5
Plasticity index PI	(%)	32
▪ Solid grains density		2.65
Chemical identification		
▪ Value of methylene blue		7.2
▪ Specific surface area	(m^2/g)	150.7
▪ CaCO3 content	(%)	46
▪ Organic matter content	(%)	8.5
▪ Clay activity		0.53

3 Experimental methods

3.1 Oedometric tests

Standard oedometric tests according to ASTM 4546-03 method A, so-called free swelling method, and XP P 94-090-1 standard, was carried out on cylindrical specimens of saturated soil at different initial states. The maximum applied stress is about 2000 kPa. The initial height and the diameter of soil samples are 2 and 7 cm, respectively. The mechanical loading-unloading is carried out in several stages. At the end of each test, the samples are carefully removed and its thickness and water content are measured.

3.2 Pressuremeter tests

The pressuremeter test (Pressuremeter Menard Standard NF P 94-110) is a loading test carried out in situ in a borehole. An inflatable cylindrical probe is set at the testing depth in a predrilled borehole within soil. Once in place, the membrane is expanded against the surrounding

Table 3: Chemical composition of minerals.

Silica	Alumina	Ferric oxide	Calcium	Magnesium	Potassium	Sodium	Sulfur	Chlorine
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	Cl
49.00%	14.34%	5.43%	10.87%	2.86%	1.81%	0.52%	1.96%	0.02%

Table 4: 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%

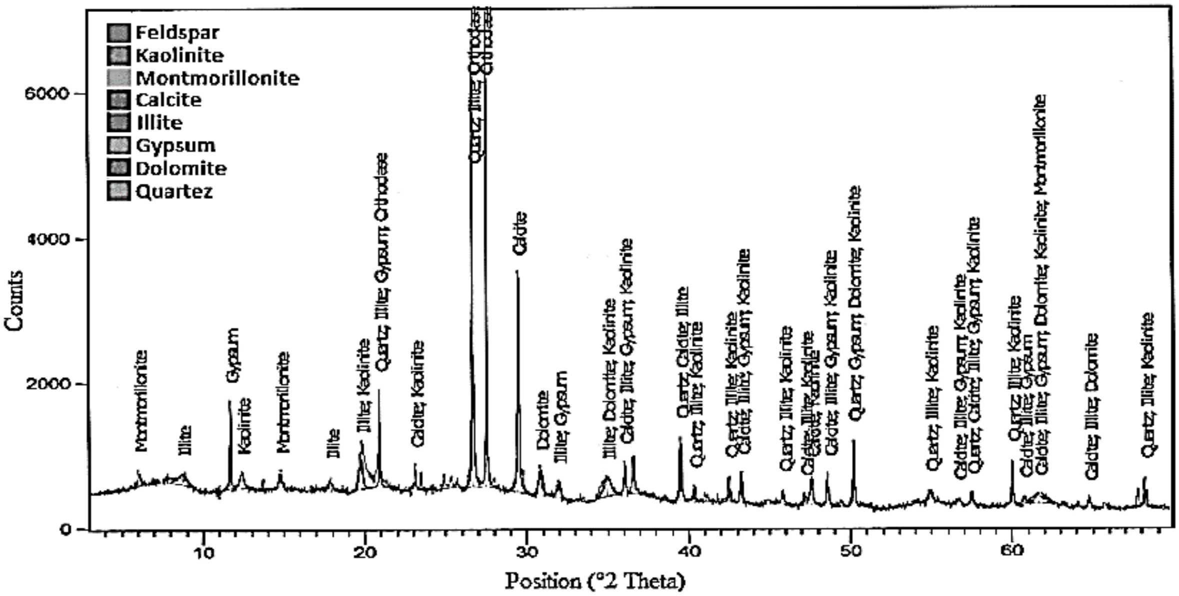


Figure 2: X-ray diffraction of the studied material (Boumagueur site).

soil by means of water, gas or oil under pressure. The probe is submitted to increments of volume or pressure. These pressuremeter tests make it possible to obtain the characteristics of deformability and rupture of the soil.

3.3 Measuring suction method

The suction measurement was carried out by the filter paper method (ASTM D5298). This method of measuring allows to measure the matric suction of soils. It is based on the fact that at the hydric equilibrium, the soil water potential and the water potential of the filter paper in contact with the soil are identical. The time required to reach the water balance is 10 days. The suction range accessible by this technique is between a few kPa and several hundreds of MPa.

3.4 drying-wetting tests

3.4.1 Osmotic method

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. For each solution of PEG, we used the adequate semi-permeable membrane (Spectra Por N° 3 for PEG 6000 and Spectra Por N° 4 for PEG 20000).

The ratio between solution concentration and suction is independent of the type of PEG and can be approximated by a parabolic equation (e.g. Delage et al.[8]) given by the following relation:

$$s = 11\ C^2 \tag{1}$$

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

3.4.2 Saturated salt solutions (vapor phase control technique)

This technique is generally used for the imposition of suction from some MPa to hundreds of MPa. It is based on the ''Kelvin'' law given by the Eq. (2):

$$s = (r_w.R.T\ /\ Mv)\ \ln\ (RH) \tag{2}$$

s: total suction (MPa), r_w: The density of water at temperature T (kg/m^3), R: Perfect gas constant (R = 8.314 J/mol.K), T: Temperature (K), Mv: Molecular weight of water vapor (Mv = 18.01×10^{-3} kg/mol), RH: Relative humidity (%).

The principle of this method consists in placing a sample of soil in a hermetic enclosure (desiccator), where 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.

3.4.3 Determination of the state parameters

The presentation of drying-wetting paths requires knowledge of the state parameters of the different samples, namely water content (w), dry density (γ_d/γ_w), void ratio (e) and degree of saturation (Sr). The method for determination external (total) volumes of samples after equilibrium is based on a hydrostatic measurement in an oil used to fill the pores without swilling the sample (Tessier, 1975, cited in Derfouf et al.[9]). This oil, which is generally kerdane with density g_k / g_w of about 0.785, is not miscible with water and evaporates at 105 ° C.

When the equilibrium is reached, the sample is weighed to define the humid weight Ph then immersed in kerdane to fill the pores and after four hours, the sample is removed from the kerdane and weighed again to have the humid and the absorbed kerdane weight Ph_k. Thereafter, a hydrostatic weighing in the kerdane was made in order to obtain the immersed weight P_{imm}. The drying weight P_s is obtained after drying the sample at 105 °C. The total volume of the sample (V) is calculated by the Eq (3), and the other state parameters (w, e, Sr) are easily deduced.

$$V = (Ph_k - P_{imm})\ /\ (\gamma_k/\gamma_w) \tag{3}$$

4 Testing program and samples preparation

The experimental program includes oedometric loading-unloading, pressuremeter and drying-wetting tests.

4.1 Oedometric tests

4.1.1 Remolded soil

Two standard oedometric tests (XP P 94-090-1 standard) were carried out on remolded samples prepared initially in the form of:

- Slurry with an initial water content $w_i \geq 1.2$ LL.
- Normally consolidated soil prepared from slurry and consolidated under a vertical stress of 100 kPa.

Oedometric tests consist of applying increasing loads in several stages. After the maximum load is reached, unloading is performed. The test ends with an unloading with at least four mechanical loads, the last of which corresponds to the load of the oedometer piston. At the end of the test, samples are carefully removed and its thickness and water content are measured.

4.1.2 Undisturbed soil

Three other oedometric tests were performed according to ASTM 4546-03 method A, the so-called free swelling method on saturated undisturbed soil. In this 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. After deformations stabilization, its vertical strains are measured; the maximum strain related to the initial height is the swelling potential (ΔH / H). After this step, the loading-unloading is started in several stages and the swelling pressure (P_s) is defined as the load that cancels the maximum strain due to swelling. At the end of the test, samples are carefully removed and their thickness and water content are measured.

4.2 Pressuremeter tests

Three pressuremeter tests were carried out in situ to see the homogeneity and the degree of consolidation of the studied soil. These pressuremeter tests allow determining the soil resistance characteristics, namely the pressuremeter modulus E_p and the limit pressure P_l.

4.3 Drying-wetting tests

The tests series was completed by drying-wetting tests on samples at different initial states. In the study of the soil behavior on drying-wetting path, the osmotic and the saturated salt solution techniques were used. The tests were carried out on 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, degree of saturation...)

4.3.1 Remolded soil

Two initial states of samples are prepared:

- Slurry with an initial water content $w_i \geq 1.2$ LL.
- Normally, consolidated soil prepared from slurry and 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. On the other hand and for wetting path, 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. Dried samples are then submitted to different decreasing imposed suctions, starting from 500 MPa. When equilibrium is reached for each imposed suction, the state parameters of samples are then measured (void ratio, water content, degree of saturation ...).

4.3.2 Undisturbed soil

To study the effect of suction variation 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 15 MPa. In this part, the samples were prepared from undisturbed soil, which was trimmed into small soil blocks of one to two cubic centimetres in volume, the initial characteristics of the undisturbed soil are ei = 0.43; wi=14%; Sri=86%.

5 Results and discussion

5.1 Behavior of Boumagueur marl on oedometric path

Five saturated oedometric tests were carried out on slurry with $w_i \geq 1.2$ LL; normally consolidated soil prepared from slurry and consolidated at a vertical stress of 100 kPa and on an undisturbed soil (samples in natural state).

The set of curves obtained for the slurry and the consolidated soil are shown in figures 3. The correlation of *Biarez and Favre,* (1975)[6] established for oedometric path, was added on the same diagram. These authors have shown that the Normally Consolidated coefficient of compressibility C_c is correlated to Liquid Limit LL (Eq 4 and 5) and the Normally Consolidated line corresponds in loading-void ratio diagram to 2 points:

- A loading of P = 7 kPa gives a void ratio corresponding to the liquid limit LL (e = (γs/ γw) LL),
- A loading of P = 1 MPa gives a void ratio corresponding to the plastic limit PL (e = (gs / gw) PL).

$$C_c = 0{,}009\ (LL - 13)\ \text{avec}\ (LL\ \text{in}\ \%) \qquad (4)$$

$$C_c/C_s \approx 4 \qquad (5)$$

During the loading phase of the slurry, the material is in a normally consolidated state (NC), it follows a line in the [log (P), e] diagram, with a slope C_c.

For the consolidated soil at 100 kPa, the material follows first an over consolidated path with a slope C_s up to the value of the preconsolidation pressur (P_0 = 100 kPa). Beyond this value, the material joins the normally consolidated path of the slurry. It follows a line of a slope C_c parallel to those of the slurry and the oedometric path given by the correlation of *Biarez and Favre,* (1975).

Figure 4 groups in the [log P, e] diagram, oedometric tests of three undisturbed samples taken at a depth of 3 to 4 meters from each borehole. A first analysis suggests that these oedometric paths show an over consolidated behavior up to an apparent preconsolidation pressure value ranging from approximately 150 – 200 kPa. The corresponding apparent compression and swelling indexes values are respectively of about 30 and 8 %. The swelling potential value $\Delta H / H$ ranges between 29% and 34.5% and the swelling pressure which is defined as the load which cancels the maximum strain due to swelling is of the order of 800 to 1200 kPa.

These values of apparent preconsolidation pressure are very low with respect to the state of the specimens and the geology of the site. For this reason, it was necessary to assess these values on the basis of the correlations of the literature using the correlation of *Biarez and Favre* (1975).

Figure 4 shows the location of this correlation line of slope of $C_c = 0{,}009\ (LL - 13) = 0.43$ in the same graph as the experimental oedometric tests. Extending the correlation line and the experimental results with dashed lines, we can see that their intersections give preconsolidation pressures ranging approximately from 2 to 2.5 MPa. Therefore, in the field of tested stress in the laboratory, the samples are still over-consolidated and the preconsolidation pressures determined experimentally do not seem accurate. In situ tests presented in the following paragraph will substantiate this result. The results of all oedometric tests performed on remolded and undisturbed samples are summarized in Table 5.

5.2 Pressuremeter tests

Three in situ pressuremeter tests were carried out in the site of study. Figure 5(a) shows the variation in pressiometric modulus with depth and Figure 5(b) the change in the limit pressure.

We note homogeneity of the soil conditions for the three pressuremeters cores. The pressuremeter modulus stabilizes at the depth of about 5 m around a value of between 55 and 65 MPa. The same observation can be made for the limit pressure which reaches a maximum value of 2.2 MPa at 5 m depth.

The analysis of these results shows that all the values of the E_p / P_1 ratio are superior to 15 allowing to classify these soils as highly over consolidated clays (Ménard.[27]). This statement confirms the analysis of the oedometric results in terms of high preconsolidation pressure values deduced from the *Biarez and Favre* correlations.

5.3 Behavior of Boumagueur marl on drying-wetting path

5.3.1 Behavior of remolded soil

The curves obtained are presented in 5 diagrams, marked from (a) to (e), (Figure 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.

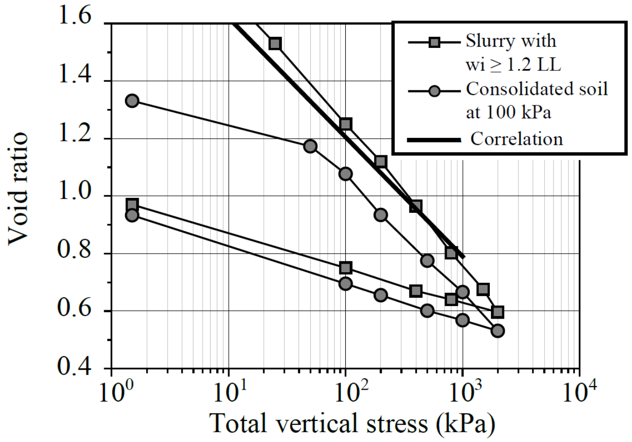


Figure 3: Oedometric test on slurry with wi ≥ 1.2 LL (Test: OT1) and on Consolidated soil at 100 kPa (Test: OT2).

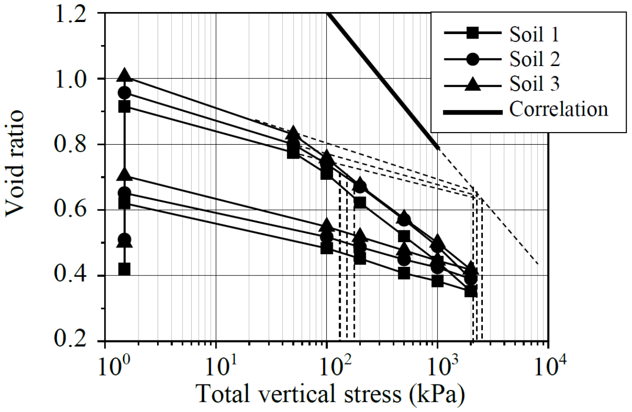


Figure 4: Oedometric test on undisturbed soil (Test: OT3) and extrapolation of correlation line and oedometric paths.

Regarding the drying-wetting test, the soil sample was initially prepared in the form of slurry with $w_i \geq 1.2LL$.

The [w, e] diagram (Figures 6(a)) shows the change of void ratio as a function of water content (shrinkage curve) of soil. The saturation of soil is expressed by 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}.

The shrinkage limit w_{SL} is about 14% corresponding to a voids ratio e_{SL} of about 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.

Table 5: Compressibility parameters of oedometric tests.

Test		C_c	C_s	C_c/C_s	P_0 (kPa)	P_s (kPa)	DH/H (%)
Correlation		0.43	0.11	4	2000-2500 (*)	—	—
OT1		0.42	0.11	3.81	—	—	—
OT2		0.41	0.11	3.77	100	—	—
OT3	**Soil 01**	0.30	0.08	3.75	150	1200	34.5
	Soil 02	0.30	0.08	3.75	170	800	29
	Soil 03	0.28	0.075	3.73	180	1000	33

(*) value of the apparent preconsolidation stress assessed from the intersection of the correlation line and the experimental results of the undisturbed soil.

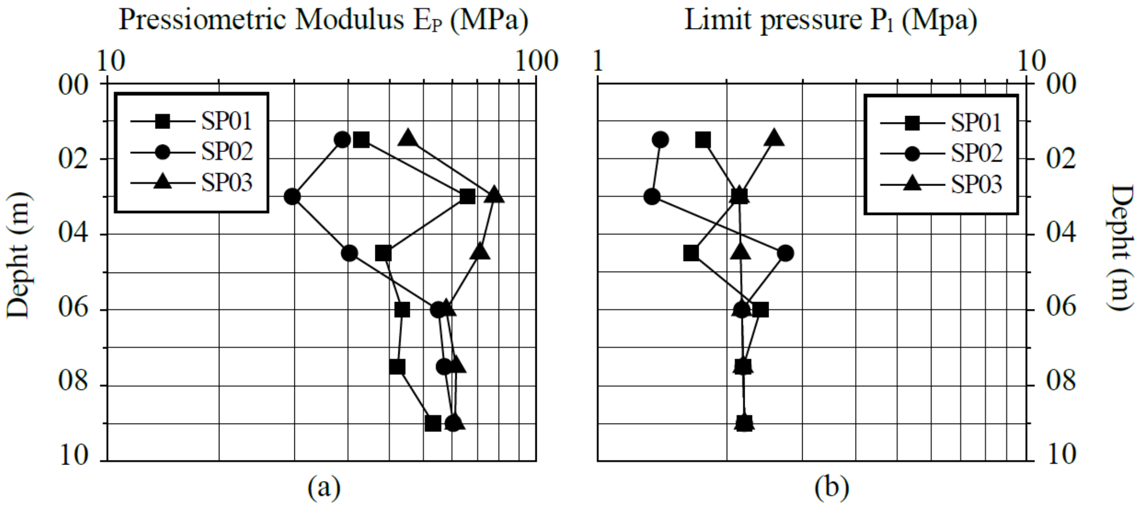


Figure 5: Pressuremeter test results.

The [log s, e] diagram (Figures 6(b)) shows the compressibility behavior of the soil under the effect of suction. We observe a very large change in void ratio with suction, similar to the oedometric curve of saturated soil. Unlike the latter, void ratio tends to an asymptotic value when suction becomes greater than a threshold value corresponding to the shrinkage limit suction.

In this diagram, it is therefore possible to distinguish two domains of variation in void ratio. In the first domain, the soil remains saturated and characterized by large deformations of about 48.5 % (Table 6). In the second domain, deformations are negligible and the soil becomes quasi-rigid and elastic. 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.

This transition suction (shrinkage limit succion) between these two domains represents a characteristic point in this diagram and plays an important part in modelling the behavior of the soil as it corresponds to a drastic change in its properties (Abou-Bekr.[1] and Modaressi and Abou-Bekr.[28]).

For drying and wetting paths, there is a strong irreversibility in the first domain whereas there is quasi-reversibility in the second domain. When the value of the suction is between the suction of desaturation s_d and the shrinkage limit suction s_{SL}, there is a small desaturation of the soil (85% < Sr < 100%) but this does not affect its compressibility, the void ratio continuing to decrease linearly with the logarithm of the suction as in the case of a saturated soil.

The correlation of *Biarez and Favre* (1975) was added on the same plane. During drying path, and before desaturation of soil (suction less than the suction of desaturation), Fleureau et al.[11], showed that there is equivalence between mechanical isotropic loading p′ and suction. Then p′ can be replaced by suction

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

$$w = PL, \text{ or } e = (\gamma_s/\ \gamma_w)\ PL, \text{ for } p' \text{ (or s)} = 1000 \text{ kPa} \quad (7)$$

The [w, Sr] diagram (Figures 6(c)) highlights the water content range 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 [log s, Sr] diagram (Figures 6(d)) 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) from which the soil begins to re-saturate 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 [w, e] diagram (Figures 6(e)) 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 find that there is a hysteresis between wetting and drying paths, which is a fundamental characteristic of the behavior of unsaturated porous media (Fleureau et al.[11] and Hillel.[16]).

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 the following features. 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 re-saturated and presents a strong irreversibility characterized by the overall variation in volume of soil. For suctions, lower than re-saturation suction, soil is almost saturated and the hysteresis remains in the two diagrams [log s; e] and [log s; w].

The drying-wetting path of consolidated soil is similar to that of the slurry. However, there are some differences. In the [log s, e] diagram, drying path of consolidated soil begins with a lower void ratio (consolidated soil is denser 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 it follows the same path as 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 the 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.

Tables 6 and 7, include for the drying-wetting paths of the D-W1 and D-W2 tests, the variation of different parameters: void ratio, water content and saturation degree according to the suction domain.

On the drying path (table 6) and for a suction less than s_d we observe a decrease in the water content and degree of saturation (ΔSr = 4%, Δw = 31.5% for the test D-W1, ΔSr = 3.5%, Δw = 23 % for test D-W2) accompanied by a very large change in the voids ratio. A shrinkage of about 34% for the D-W1 test and 27.5% for the D-W2 test was noted.

For suction values between s_d and s_{SL}, the soil slightly desaturates (decrease in the degree of saturation and the water content: ΔSr = 3.5%, Δw = 9%), but this does not affect the compressibility of the latter because a shrinkage of about 14.5% was noted.

For suction greater than s_{SL}, and despite the very rapid decrease in the degree of saturation (ΔSr = 86.5%), the material no longer deforms (Δe = 0%).

On the wetting path (table 7) and for a suction higher than s_{SL}, and despite the large increase in the water content and the degree of saturation (ΔSr = 72%, Δw = 13%), deformations are quasi-zero (Δe = 0).

For suction values between s_{SL} and s_{re}, the soil re-saturates (increase in the degree of saturation and water content: ΔSr = 16%, Δw = 5%), and a swelling of about 13% was noted.

For suction greater than s_{re}, and despite the slight increase in the degree of saturation (ΔSr = 7%), the soil behaves like a saturated soil and shows this time a swelling of about 28.5%.

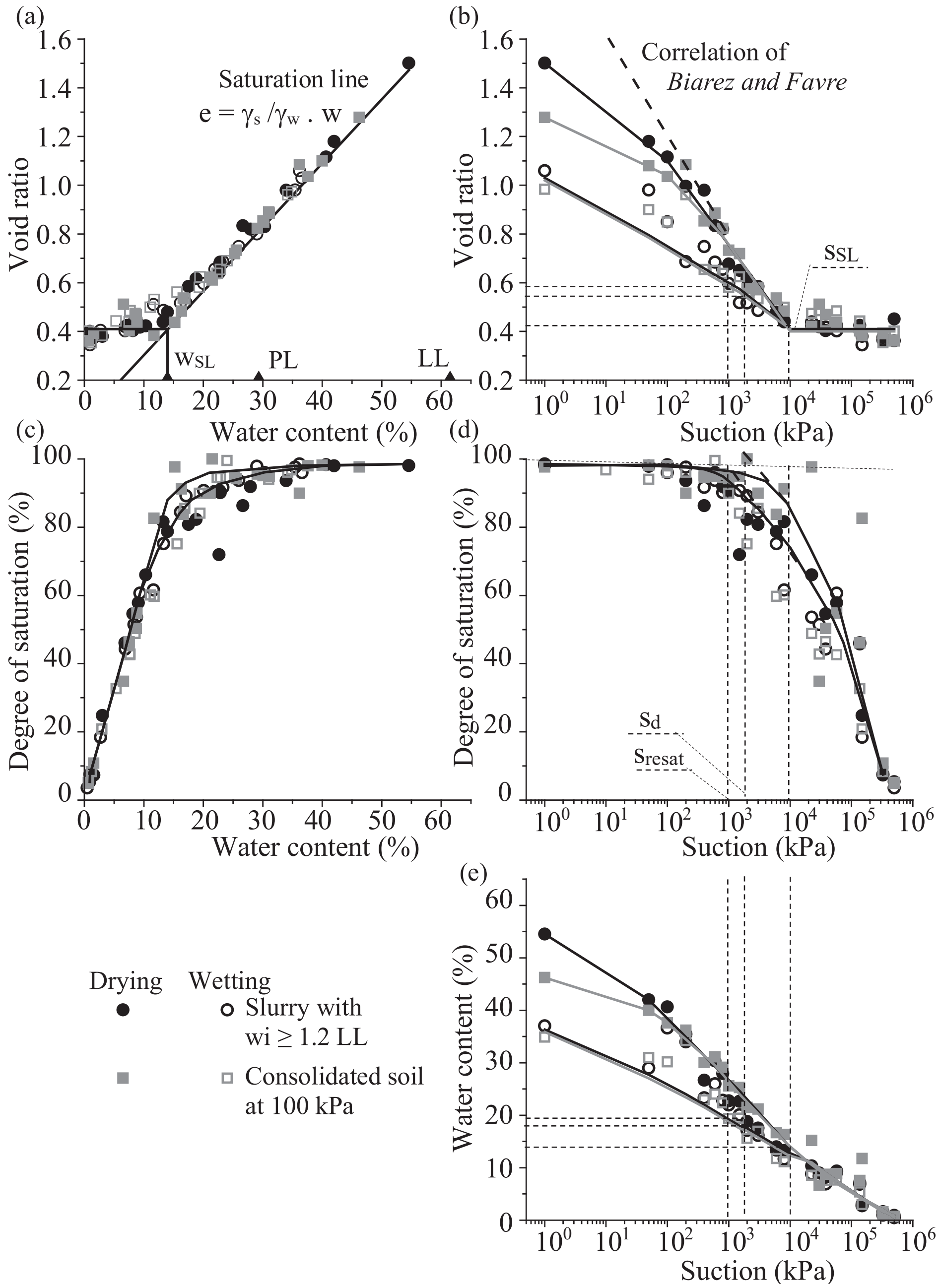


Figure 6: Drying-wetting path on the Boumagueur marl in the form of slurry with $w_i \geq 1.2$ LL (Test D-W1) and consolidated soil at 100 kPa (Test D-W2).

Table 6: Variation of the state parameters as a function of suction domain on drying path.

Test	Suction domain	Δe	Δe / (1+e_0) (%)	ΔSr (%)	Δw (%)
D-W1	$s \leq s_d$	0.85	-34	4	31.5
	$s_d \leq s \leq s_{SL}$	0.24	-14.5	3.5	9
	$s \geq s_{SL}$	0	0	86.5	13
D-W2	$s \leq s_d$	0.63	-27.5	3.5	23
	$s_d \leq s \leq s_{SL}$	0.24	-14.5	3.5	9
	$s \geq s_{SL}$	0	0	86.5	13

Table 7: Variation of the state parameters as a function of suction domain on wetting path.

Test	Suction domain	Δe	Δe / (1+e_0) (%)	ΔSr (%)	Δw (%)
D-W1	$s \geq s_{SL}$	0	0	72	13
	$s_{SL} \leq s \leq s_{resat}$	0.18	13	16	5
	$s \leq s_{resat}$	0.45	28.5	7	18
D-W2	$s \geq s_{SL}$	0	0	72	13
	$s_{SL} \leq s \leq s_{resat}$	0.18	13	16	5
	$s \leq s_{resat}$	0.45	28.5	7	18

Table 8: Comparison of compressibility parameters of drying-wetting and oedometric tests.

Test	C_c or I_d (I)	C_s or I_w (II)	(I/II)
Correlation	0.436	0.110	4
OT1	0.420	0.110	3.81
OT2	0.415	0.110	3.77
D-W1	0.394	0.120	3.28
D-W2	0.394	0.120	3.28

5.3.2 Behavior characterization in the saturated domain

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 (Eq 6 and 7).

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

$$P' = (\sigma'_1 + \sigma'_2 + \sigma'_3)/3 = (\sigma'_1 + 2\,\sigma'_2)/3 \qquad (8)$$

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

$$P' = (\sigma'_1 + 2\,K_0\,\sigma'_1)/3, \text{ with } K_0 \approx 0.5$$

$$P' = \sigma'_1\,(1 + K_0)/3 \qquad (9)$$

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

It is observed that, in the saturated domain, the drying-wetting curves have the same shape that oedometric curves. We note that as long as the samples remain saturated ($s \leq s_d$), the paths of drying and oedometric tests and the correlation line 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 ($s \leq s_d$ = 2 MPa). It can be concluded from these observations that identical increments of suction or mechanical stress produce the same change in void ratio (volume) as long as the material remains saturated. This joins the results of many authors such as: Benchouk et al.,[4] Biarez et al.,[7] Derfouf et al.,[9] Li et al.,[22] Lu et al.[24] and Zerhouni.[42].

The comparison in the saturated domain between the compression coefficients C_c and C_s on one hand, and the drying (I_d) and wetting (I_w) indexes which are defined as being respectively the slope of the drying and wetting paths in the saturated domain (Table 8), shows that the compression coefficient C_c and the drying index I_d are almost of the same order. The same applies to the elastic compression coefficient C_s and the wetting index I_w. It follows that the correlations of *Biarez and Favre, 1975*, established for C_c and C_s, remain applicable for I_d and I_w. (e.g., Benchouk et al.,[4] Biarez et al.[7] and Derfouf et al.[9])

5.3.3 Behavior of undisturbed soil

The drying-wetting path carried out on 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. It is noted that the initial state of intact sample is slightly below the Normally Consolidated line because undisturbed samples are in a denser state. The drying path followed from initial state tends at first to join the Normally Consolidated line, before reaching shrinkage limit level. 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

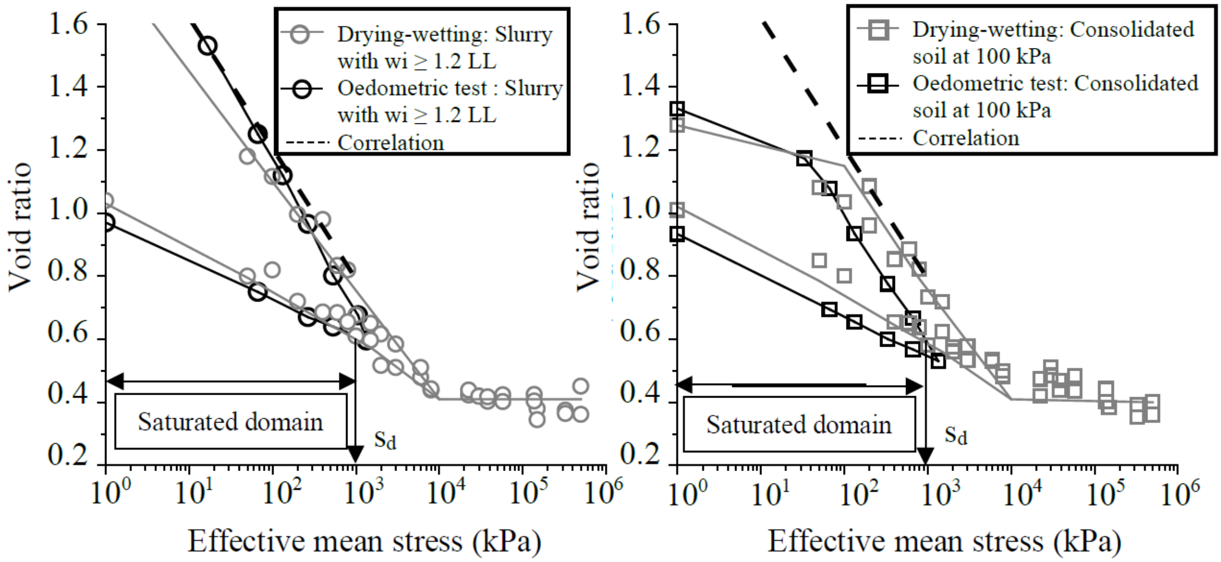


Figure 7: Comparison between drying-wetting and oedometric paths.

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.

The samples in natural state exhibit an extremely different behavior. The characteristics of paths on slurry and on an undisturbed soil are very different in all planes. For instance, 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 value in the [log s; e] diagram is approximately 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. (e.g., Fleureau et al.[11] and Sidoroff et al.[32]).

Different shrinkage limit levels are then observed, that of natural sample being below that of the slurry, that is to say that the material is in a denser 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.

All these differences likely associated with the consolidation pressure of undisturbed soil are due (i) to physico-chemical bonds existing between grains and (ii) to mechanical overloads that material has undergone in geological time.

For comparison purposes, we superposed the results of the classical oedometric test on the saturated undisturbed soil and the test of the drying-wetting path on the same undisturbed material. In addition, we also superposed the correlation line of *Biarez and Favre* (1975). We note that the oedometric path tends to join the drying wetting path.

The intersection of the drying-wetting paths of the undisturbed soils with the *Biarez and Favre* correlation line (Figure 9) allows estimating a preconsolidation suction value.

Consequently, the preconsolidation suction is analogous to the preconsolidation pressure determined from oedometric tests. The value of this preconsolidation suction is about of the same order of magnitude as the oedometric preconsolidation pressure (Figure 9), it has a value of 25 to 30 MPa.

This shows the equivalence between the hydric and mechanical behaviors (equivalence between the effect of suction and that of the total mechanical stress) in the suction domain where the soil remains quasi-saturated. On the other hand, the state of over consolidation of the material is confirmed by means of two different methods (mechanical tests and hydric tests).

6 Conclusion

The soil of Boumagueur study region is clayey in nature characterized by high plasticity. The high values of the swelling potential and the swelling pressure determined from saturated oedometric tests on undisturbed samples showed the swelling character of the studied soil.

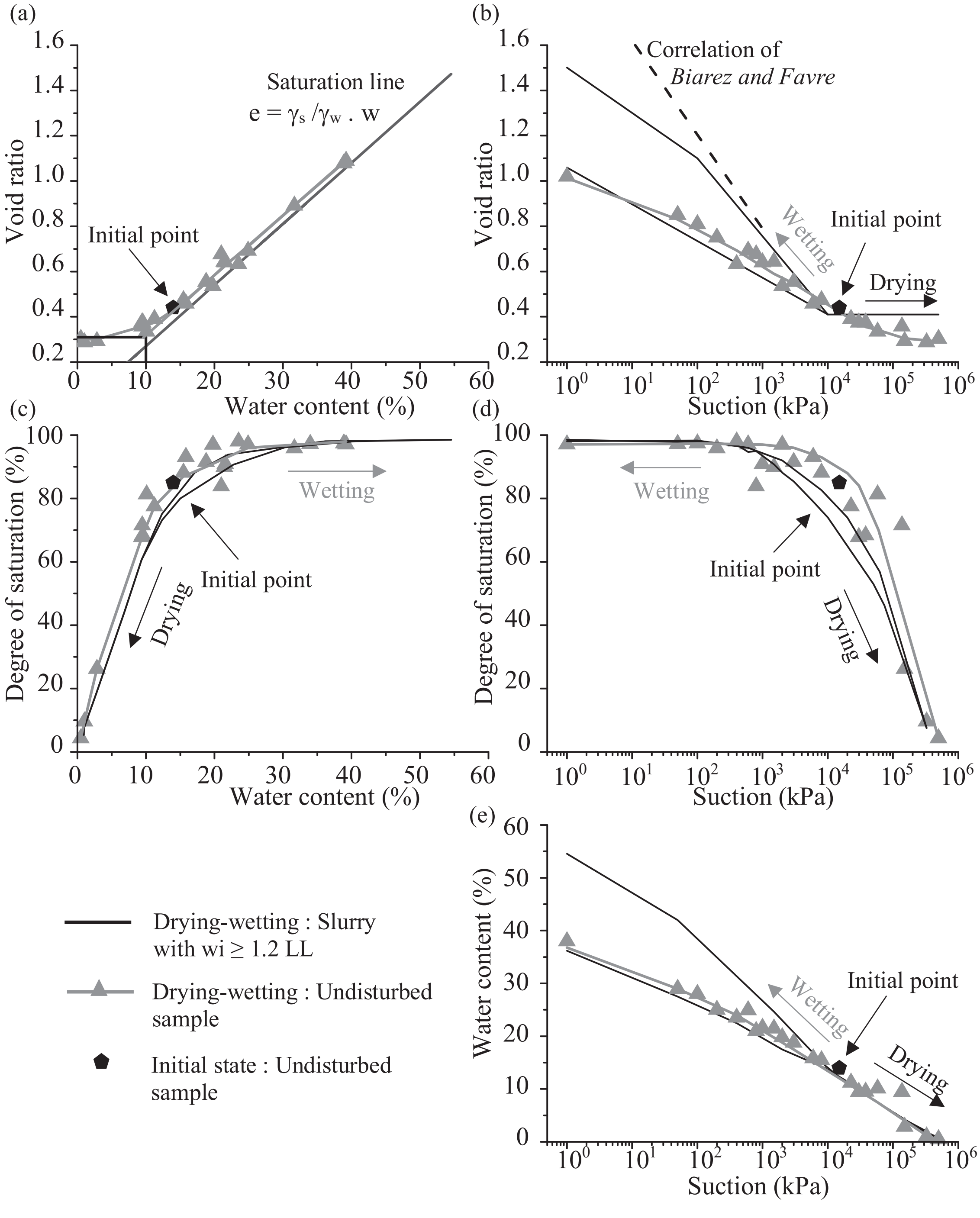


Figure 8: Drying-wetting path on the Boumagueur marl in his natural state (undisturbed samples).

Saturated oedometric tests carried out on slurry and consolidated soil at 100 kPa can be used as a reference state.

The characterization of the hydric behavior in the absence of external mechanical stress of the studied material, show the interest of a global representation of material state during a drying-wetting cycle. This representation makes it possible in particular to follow the evolution of the saturation of the soil and to connect the shrinkage characteristics to the drying and wetting characteristics. From the drying-wetting tests, it was found that a variation in suction is followed by a variation

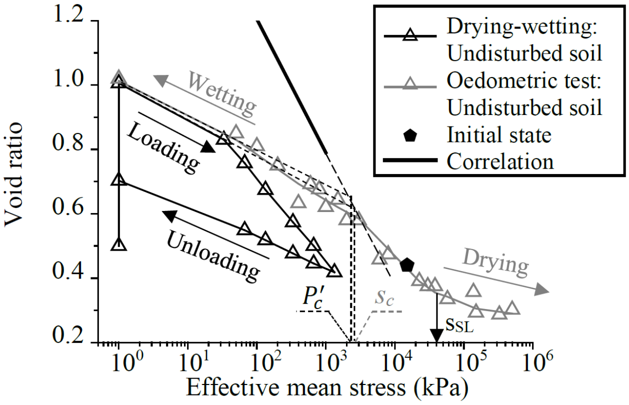


Figure. 9: Comparison between drying-wetting, oedometric compressibility and Biarez and Favre correlation on undisturbed soil samples of Boumagueur marl.

in the soil hydric state and thus significant variations in the void ratio (volume of sample).

The role of initial state was studied by comparing behavior of the slurry with $w_i \geq 1.2$ LL, consolidated soil at 100 kPa and of natural samples which exhibit extremely different behavior. Different asymptotic behaviors with respect to shrinkage are observed. The shrinkage limit with regard to void ratio and water content of sample in natural state is lower than those of the slurry. The shrinkage limit with regard to suction of undisturbed sample is higher than that of the slurry. This confirms that the shrinkage characteristics of soil are not an intrinsic characteristics but depend on the preparation of samples. All these differences likely associated with the consolidation pressure of undisturbed soil are due to physico-chemical bonds existing between grains and to mechanical overloads that material has undergone in geological time.

To determine the behavior observed in the saturated domain, the deformations resulting from the suction can be compared with those resulting from an external isotropic stress applied to a saturated sample. It is noted that, as long as the samples remain saturated, the drying path is parallel to the compression oedometric and isotropic line. It can be concluded from these remarks that identical increments of suction or mechanical stress produce the same variation in void ratio as long as the material remains saturated.

The use of correlations helped to clarify the interpretation of oedometric tests. Indeed, the classical determination of consolidation parameters led to conclude that the soil studied had a low apparent compressibility index (of 0.30) and was slightly over consolidated. The use of *Biarez and Favre* (1975) correlations rather led to conclude that the material was highly compressible (C_c = 0.43) and highly over consolidated.

This last statement was confirmed by the comparison between laboratory (drying-wetting and oedometric tests), in situ tests (pressuremeter tests) and also by the geological history of the site that showed that eroded layers overlying the marl caused a strong decompression of that marly clay layer. The compressibility parameters thus obtained are therefore more credible and can be used to a more realistic modelling.

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