ORIGINAL PAPER

Behavior of some clays on drying and wetting paths

**Assia Benchouk · Mounir Derfouf · Nabil Abou-Bekr ·
Said Taibi**

Abstract This paper presents an experimental study carried out on some clayey soils of Tlemcen region situated in the North West of Algeria. The characterization of the volumetric behavior under the effect of suction is studied on drying–wetting paths which highlight the correspondence between void ratio, degree of saturation, and water content versus suction. The initial conditions of studied material are in slurry form and compacted at different initial water contents. For the slurry form, correlations are derived to predict parameters characterizing the drying path.

Introduction

Compacted soils are commonly used in the construction of soil structures as roads, embankments, and earth dams. Several researchers highlighted the influence of compaction stress and compaction water content on the behavior of unsaturated clayey soils (Taibi et al. 2011; Fleureau et al. 1999, 2002; Abou-Bekr et al. 2006).

Volume and water content changes in soils are the consequences of environmental factors, such as drying–wetting cycles. Also, changes in the groundwater level generate the shrinkage and the swelling of the soil surface.

The parameter associated with those changes in volume and water content in soils is the negative pore water pressure (u_c) called also capillary pressure or suction. The suction is defined as the difference between the air pressure (u_a) and water pressure (u_w) in the soil:

$$u_c = u_a - u_w \qquad (1)$$

In unsaturated soils, the soil–water characteristic curve represents a constitutive relationship. In other words, the soil water characteristic curve describes the relationship between soil suction and soil water content, it also describes the changes in degree of saturation (S_r) or void ratio versus suction (u_c).

It can be used as a tool for the determination of the degree of saturation or water content changes in the soil on drying or wetting paths and to determine also the associated void ratio versus (u_c). This paper presents some experimental results obtained on drying–wetting paths on four clayey soils specimens all collected from Tlemcen region. The selected soils have different liquid limits and diverse areas of use:

– The bentonite of bental factory of Maghnia, used as drilling mud
– The bentonite deposit of Maghnia, the natural material used in the manufacturing of drilling bentonite
– The marl of Bouhennak
– The clay of Sikkak, used in the core of "Sikkak" earth dam

Materials and testing methods

Materials

Table 1 summarizes the results of the physical, chemical, and mechanical identification of the four studied soil specimens.

A. Benchouk (✉) · M. Derfouf · N. Abou-Bekr
EOLE, Department of Civil Engineering,
University of Tlemcen, BP 230 - 13000 Tlemcen, Algeria
e-mail: benchouk.assia@gmail.com

S. Taibi
LOMC, FRE CNRS 1302, Université du Havre, 53 rue de Prony,
76600 Le Havre, France

Table 1 Studied soils properties

Soil	Sikkak clay	Bouhennak marl	Maghnia bentonite	Bentonite deposit	Norm
Physical identification					
Sieve distribution					NF P 94–041
Gravel (%)	7		4		
Sand (%)	35		31		
Silt (%)	13		17		
Clay (<2 μm) (%)	45	43	48	60	
<80 μm (%)	78	73	82	87.3	NF P 94–057
Atterberg limits					
Liquidity ω_L (%)	50	47	112	130	NF P 94–051
Plasticity ω_P (%)	23	25	45	42	
Plasticity index Ip (%)	27	22	67	88	
Density of solid particles (G_s)	2.64	2.60	2.72	2.65	NF P 94–054
Chemical identification					
VB	3.6	6.67	22	42.7	NF P 94–068
SST (m²/g)	75	140	467	897	
% CaCO$_3$	11	31	6	4	
% MO	1.5	–	–	–	
Mechanical identification					
Standard proctor					NF P 94–093
$\gamma_{d\ max}/\gamma_w$	1.55	–	1.23	–	
ω_{opt} (%)	16	–	18	–	

Testing methods

The experimental study focuses on the determination of the drying–wetting paths carried on the studied materials which are in slurry and compacted forms. In the first battery of tests, each of the four investigated materials is in slurry form: on the drying path, the initial state corresponds to a saturated water content, which is equal to 1.5 times the liquid limit of the material ($w=1.5w_L$). On the wetting path, the initial soil state is considered dry. The soil in slurry form has been dried in the open air, then in an oven at 50 °C.

In the second phase of laboratory investigations, the samples of the two studied materials (Maghnia bentonite deposit and Sikkak clay) are in compacted form. The samples are compacted statically using a California Bearing Ratio loading press at a speed of 1.5 mm/min. For each material, three drying–wetting paths were performed. All samples on the three paths are compacted to the Standard Proctor maximum dry density. While the initial water content is different on each path: at the Standard Proctor Optimum (w_{SPO}) and on both sides of the optimum ($w_{SPO}-2$ % and $w_{SPO}+2$ %).

The drying–wetting path is determined by using two techniques to control the negative pore water pressure in the soil specimen: osmotic and saturated salt solution techniques. The first used method is the osmotic technique which was initially developed by biologists (Lagerweff et al. 1961 in Blatz James et al. 2008) and later introduced in geotechnical engineering by Kassif and Ben shalom (1971), Fleureau et al. (1993), Delage et al. (1992, 1998). In this technique, the soil specimen is placed in contact with a semipermeable membrane behind which a solution of macro molecules of polyethylene glycol (PEG) is circulated. The semipermeable membrane is permeable to water molecules but impermeable to the PEG molecules.

The relationship between suction (u_c) and PEG concentration (c) is well defined for two molecular weights: the PEG 6000 and PEG 20000. Delage et al. (1998) found that the suction value is equal to:

$$u_c = 11c^2 \qquad (2)$$

In this study, the osmotic technique was used to impose soil suction between 0.05 and 3 MPa by using both the PEG 6000 and PEG 20000. The second method is applied to achieve high suctions, between 4.3 and 392 MPa, this method controls the suction in specimen by salt solutions it's called vapor equilibrium technique.

Vapor equilibrium technique is implemented by controlling the relative humidity of a closed system. The suction is controlled by migration of water molecules through the vapor phase from the soil pores to a saturated salt solution, until equilibrium is achieved (Fredlund and Rahardjo 1993; Delage et al. 2008).

Several salt solutions were used to control the relative humidity of the atmosphere in the desiccators containing the samples, and hence the matric suction in the samples (Taibi et al. 2011). The salts used in the tests presented in this paper are: K_2SO_4; KH_2PO_4; KNO_3; $ZnSO_4$, $7H_2O$; Na_2SO_3, $7H_2O$; $(NH_4)_2$ SO_4; NaCl; $NaNO_2$; CH_3COOH; $CaCl_2$, $2H_2O$, and H_2SO_4.

Results and discussion

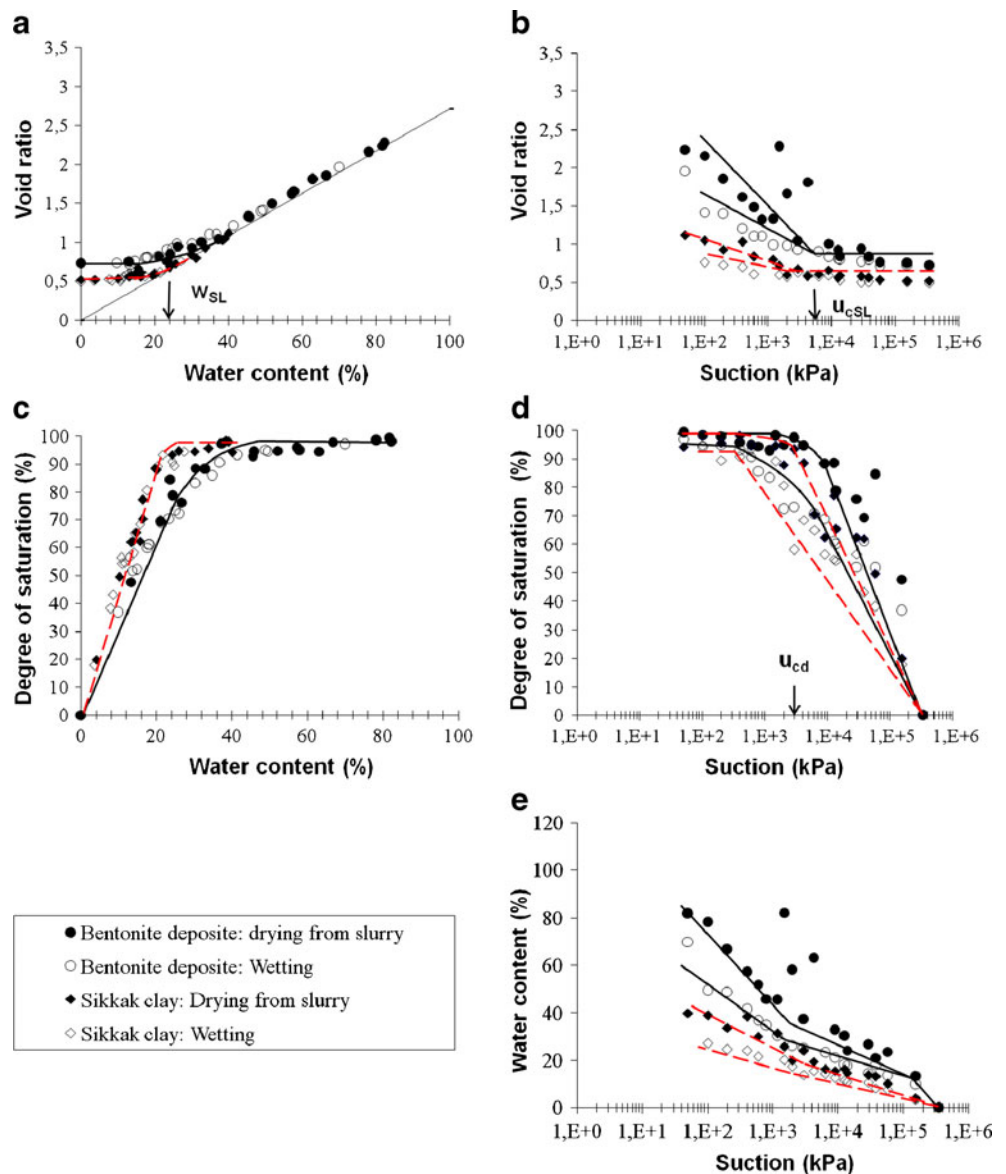### Drying–wetting path of clays in slurry form

The [log (u_c), e] diagram (Figs. 1b and 2b), represents the compressibility behavior of the soil under the effect of suction, the drying path shows two distinct phases:

– A first phase: there is an important variation of void ratio with the capillary pressure. This variation is similar to behavior of saturated soil, by the parallelism between the drying path and the oedometric one on saturated soil

– A second phase: where the soil becomes quasi-rigid and behaves elastically

The [w, e] diagram (Figs. 1a and 2a), represents the shrinkage behavior of the soil. The shrinkage limit w_{SL} corresponds to the intersection between the saturation line $e=(\gamma_s/\gamma_w)\cdot w$ and the horizontal asymptote of the curve when w tends towards 0. The corresponding value of the negative pore water pressure is u_{csL} called shrinkage suction.

The graphs Figs. 1c, d and 2c, d show the changes in the degree of saturation as a function of the two

Fig. 1 Drying–wetting path on bentonite deposit of Maghnia and Sikkak clay in slurry form at $w_i=1.5w_L$

● Bentonite deposite: drying from slurry
○ Bentonite deposite: Wetting
◆ Sikkak clay: Drying from slurry
◇ Sikkak clay: Wetting

Fig. 2 Drying–wetting path on Bouhennak marl and Maghnia bentonite in slurry form at w_i= $1.5\,w_L$
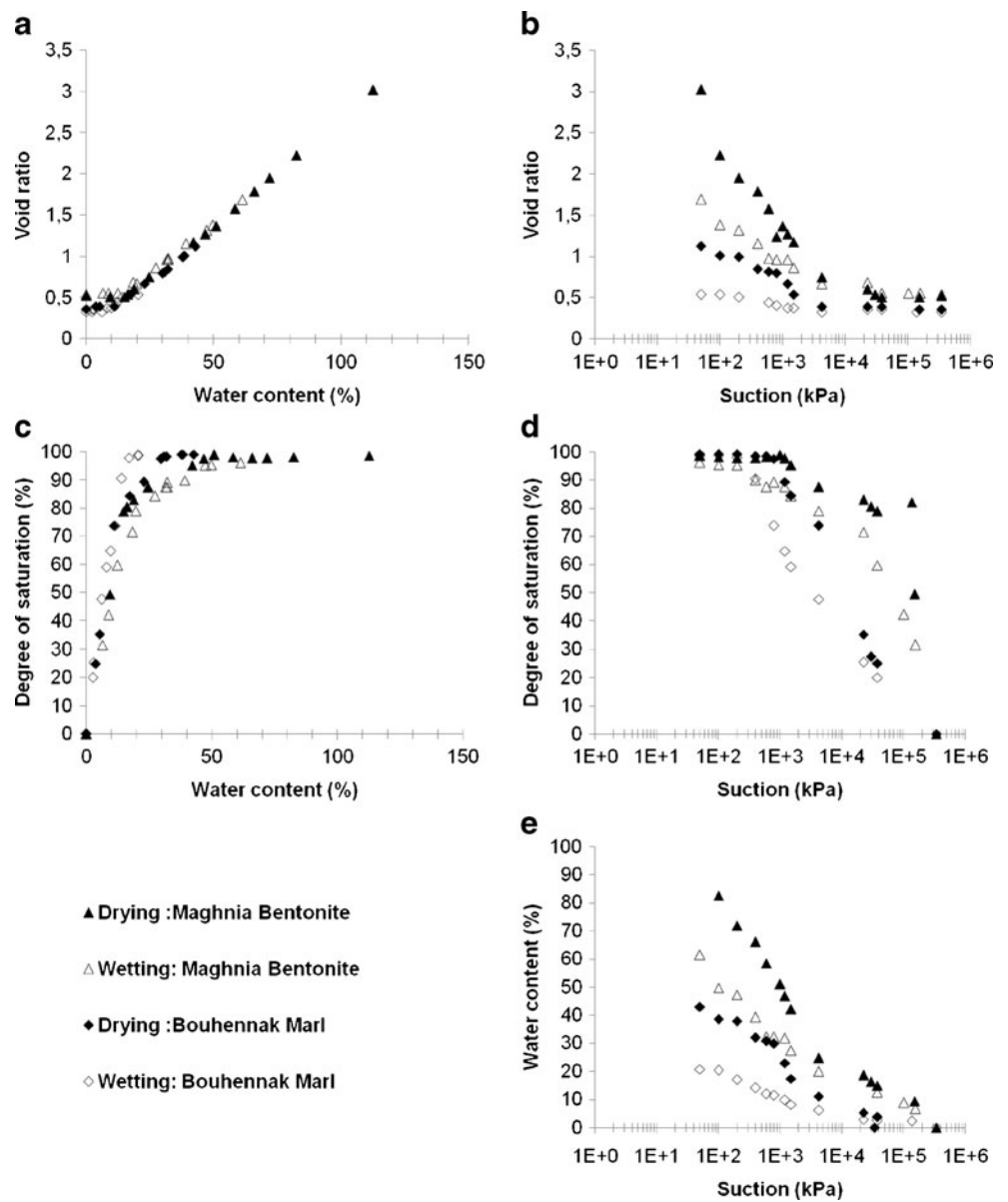
variables w and S_r. The two curves show two distinct behavior: on the one hand, an approximately linear variation corresponding to a degree of saturation close to 1, and on the other hand, a very rapid desaturation of the soil associated with a small change in void ratio. The intersection between the two lines corresponds to the air entry point, which corresponds to the "desaturation suction"

denoted u_{cd}. We also define a "resaturation suction" denoted (u_{cSAT}) on the wetting path.

– When comparing the drying–wetting cycles of the four investigated soils, one observes the same tendencies of variation of the different parameters, the differences lies in the characteristic parameter of each material (see Table 2):

Table 2 Principal characteristics of the studied materials

Material specimen	w_L (%)	I_p (%)	u_{cd} (kPa)	u_{cSL} (kPa)	w_{SL} (%)
Bouhennak marl	47	22	1,000	5,000	14
Sikkak clay	50	27	1,000	3,500	18
Bentonite deposit	112	67	3,000	5,500	24
Maghnia bentonite	130	88	3,000	7,000	20

Table 3 Characteristics value of some clay prepared at 1.2–1.5w_L

Studied materials					
Materials	Authors	w_L (%)	I_p (%)	u_{cd} (kPa)	u_{cSL} (kPa)
Bouhennak marl		47	22	1,000	5,000
Sikkak clay		50	27	1,000	3,500
Bentonite deposit		112	67	3,000	5,500
Maghnia bentonite		130	88	3,000	7,000
Others materials in literature and their authors					
Sterrebeek loam	Biarez et al. (1988)	27	20	26	
Vieux pré clay	Indarto (1991), in Taibi (1994)	32	13	800	1,400[a]
Orly loam	Taibi (1994)	33	13	100[a]	1,500[a]
Red marl	Biarez et al. (1988)	36	13	500	1,300[a]
Jossigny loam	Fleureau et al. (2002)	37	21	800	2,000
Silty clay 90P300/5RF/5S	Sayad-Gaidi (2003)	38	19	200	1,200
Yellow clay	Indarto (1991), in Taibi (1994)	40	20	800[a]	1,000[a]
Mers El Kebir clay	Bourokba et al. (2007)	49	30	1,500	4,000
White clay	Zerhouni (1991)	61	31	900	2,000

[a] Data estimated from the experimental curves of their authors

– The Maghnia bentonite and the bentonite deposit present the largest saturated domain compared to the other soils. This can be explained by the fact that highly plastic clays are finer.

Behavior prediction in the saturated domain

Zerhouni (1991) tried to establish correlations based on a simple linear regression between the liquid limit and desaturation capillary pressure, the regression coefficient R^2 was about 0.836.

Following the same approach and considering that the materials have the same initial conditions, correlations were established between the liquid limit and the properties that characterize the extent of saturated area (desaturation negative pore pressure and shrinkage suction). Table 3 summarizes the different characteristics of the four studied soils as well as others reported in the literature. These characteristics are plotted in the (w_L, u_{cd}) and (w_L, u_{cSL}) plans (Fig. 3).

It is seen that the experimental points seem gathered around the regression lines which are expressed by the following equations:

$$u_{cd} = 28.6(w_L) - 474.05 \left(R^2 = 0.89\right) \tag{3}$$

$$u_{cSL} = 52.73(w_L) + 27.85 \left(R^2 = 0.70\right) \tag{4}$$

The obtained values of regression coefficients are relatively insufficient, especially for the suction of shrinkage. The work should be pushed to improve these correlations. In other words, a great part of the drying path could be estimated in an approached way using the established correlations.
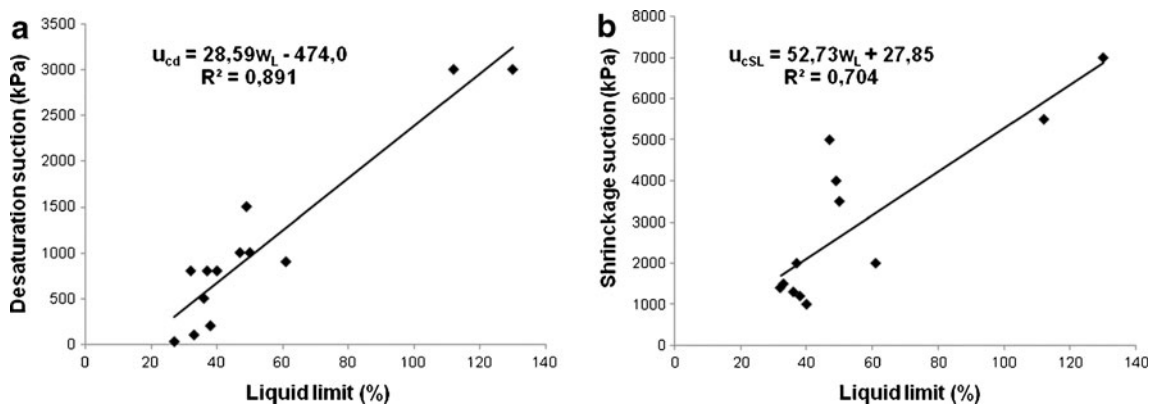
Fig. 3 Correlation of suction of desaturation and shrinkage with the liquid limit, clays prepared as a paste to 1.2w_L and 1.5w_L

Fig. 4 Comparison between drying–wetting cycles and oedometric paths
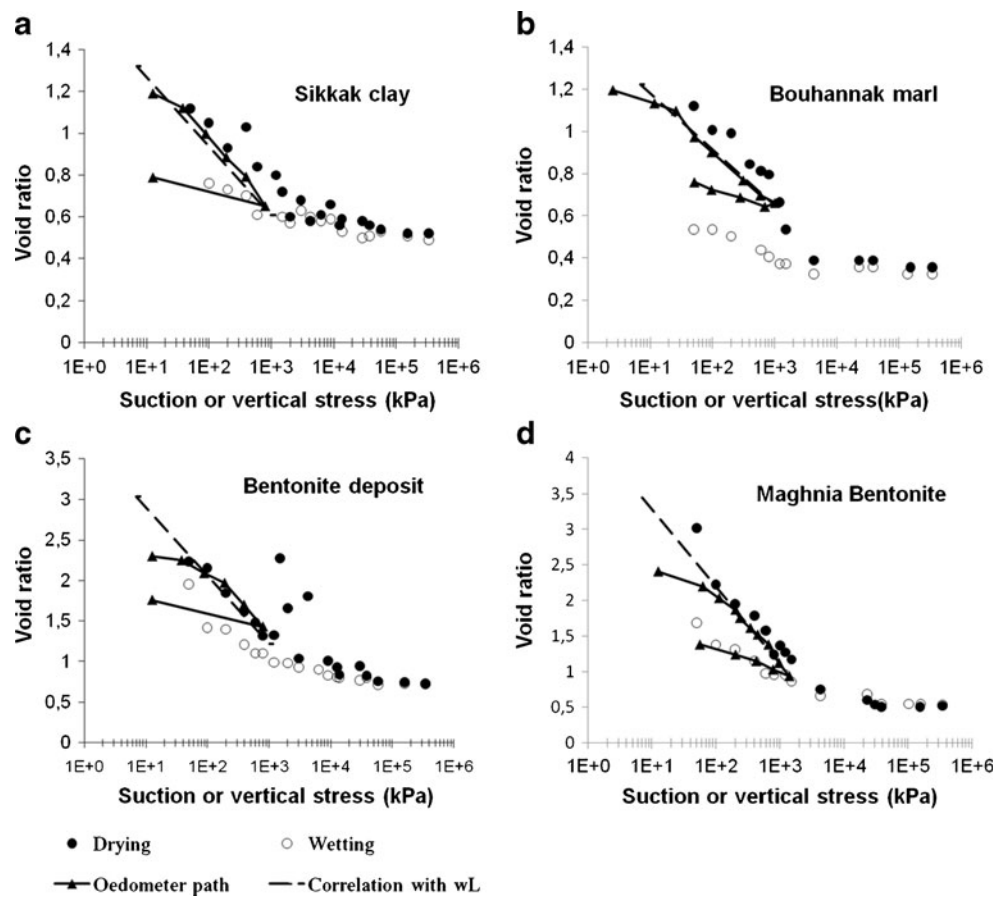
In Fig. 4, on the same graph, the curve of drying and wetting path of slurry materials and oedometer curve of the four studied materials in addition to the correlation with liquid limit proposed by Biarez and Favre (1975) is presented:

$$w = w_L \text{ or } e = (\gamma_s/\gamma_w)/w_L \text{ for } u_c = 7 \text{ kPa} \tag{5}$$

$$w = w_P \text{ or } e = (\gamma_s/\gamma_w)/w_P \text{ for } u_c = 1,000 \text{ kPa} \tag{6}$$

It is noted that the drying path of these saturated samples is parallel to the compression line of oedometer curve and the correlation line of isotropic compression path.

The comparison between the coefficients of compressibility (C_c) and swelling (C_s), on one hand, and drying (C_d) and wetting (C_h) indices on the other hand (defined by Biarez et al. 1988), shows that the indices of compressibility

and drying are almost equal, as well as the indices swelling and wetting.

It follows that the correlations of Biarez and Favre (1975) established for C_c and C_s stays always valid for C_d and C_h (see Table 4):

$$C_d = 0.009(w_L - 13) \tag{7}$$

$$C_d/C_h \approx 4 \tag{8}$$

It should be noted that these correlations can be applied only for drying paths of normally consolidated soils.

So, in the area where the samples are saturated, identical increments of capillary pressure or mechanical stress produce the same volume change, the drying path can be deduced naturally from the correlations of isotropic compression path, which confirms the conclusion of several

Table 4 Measured parameters

Materials	C_C	C_d	C_s	C_h	C_C/C_s	C_d/C_h
Bouhennak marl	0.311	0.286	0.08	0.073	3.88	3.92
Maghnia bentonite	0.975	1.097	0.263	0.251	3.71	4.37
Sikkak clay	0.323	0.315	0.076	0.076	4.25	4.14
Bentonite deposit	0.866	0.880	0.196	0.229	4.41	3.84

researchers (Biarez et al. 1988; Zerhouni 1991; Fleureau et al. 2002).

Drying–wetting paths of compacted soils

The initial states of compacted materials were determined by measuring the suction using the filter paper method (ASTM D5298-94); they are presented in the Figs. 5b and 6b and reported in Table 5. From the initial suction, the sample follows a drying path if imposed suction is higher than the initial one, in the opposite case, it follows a wetting path.

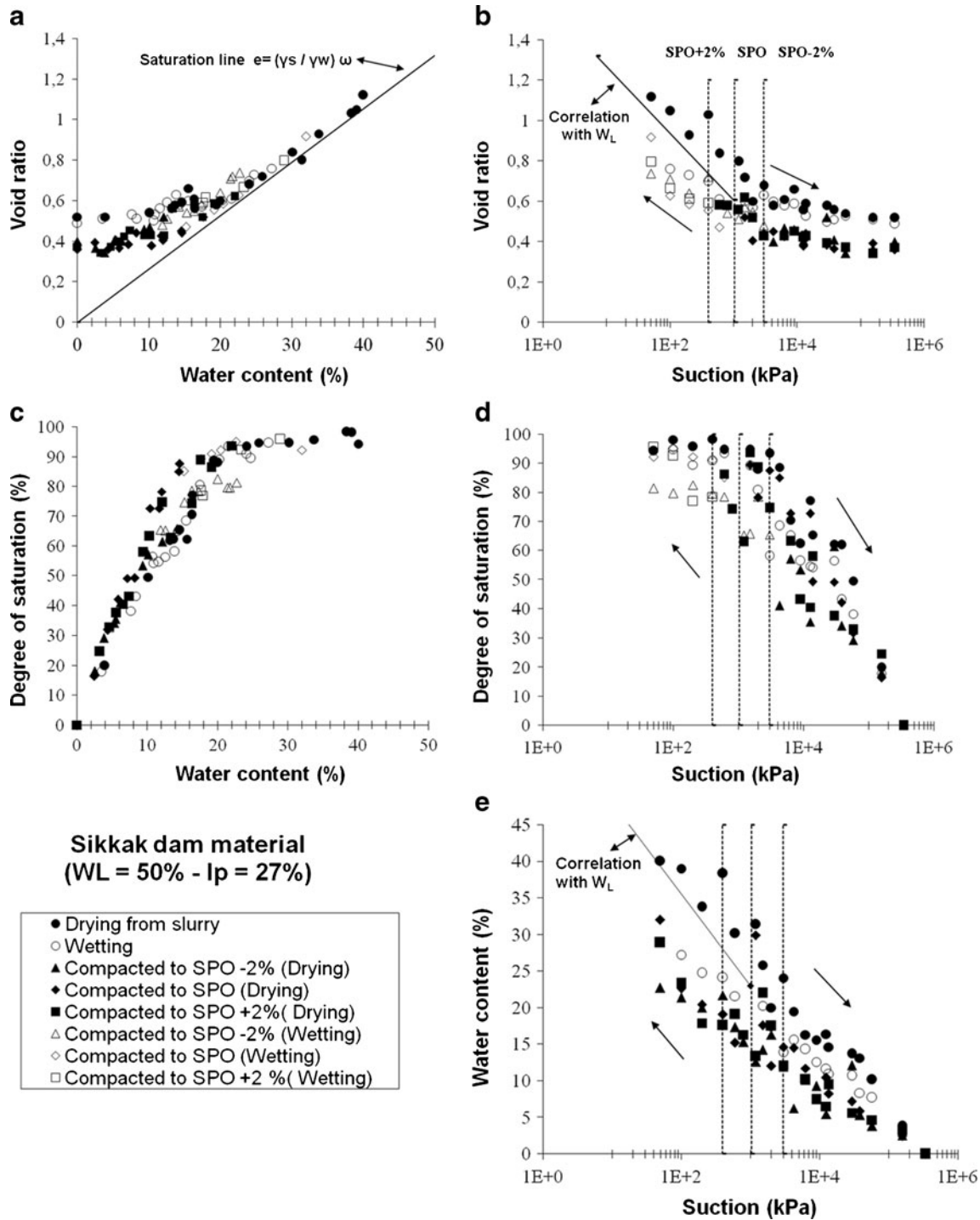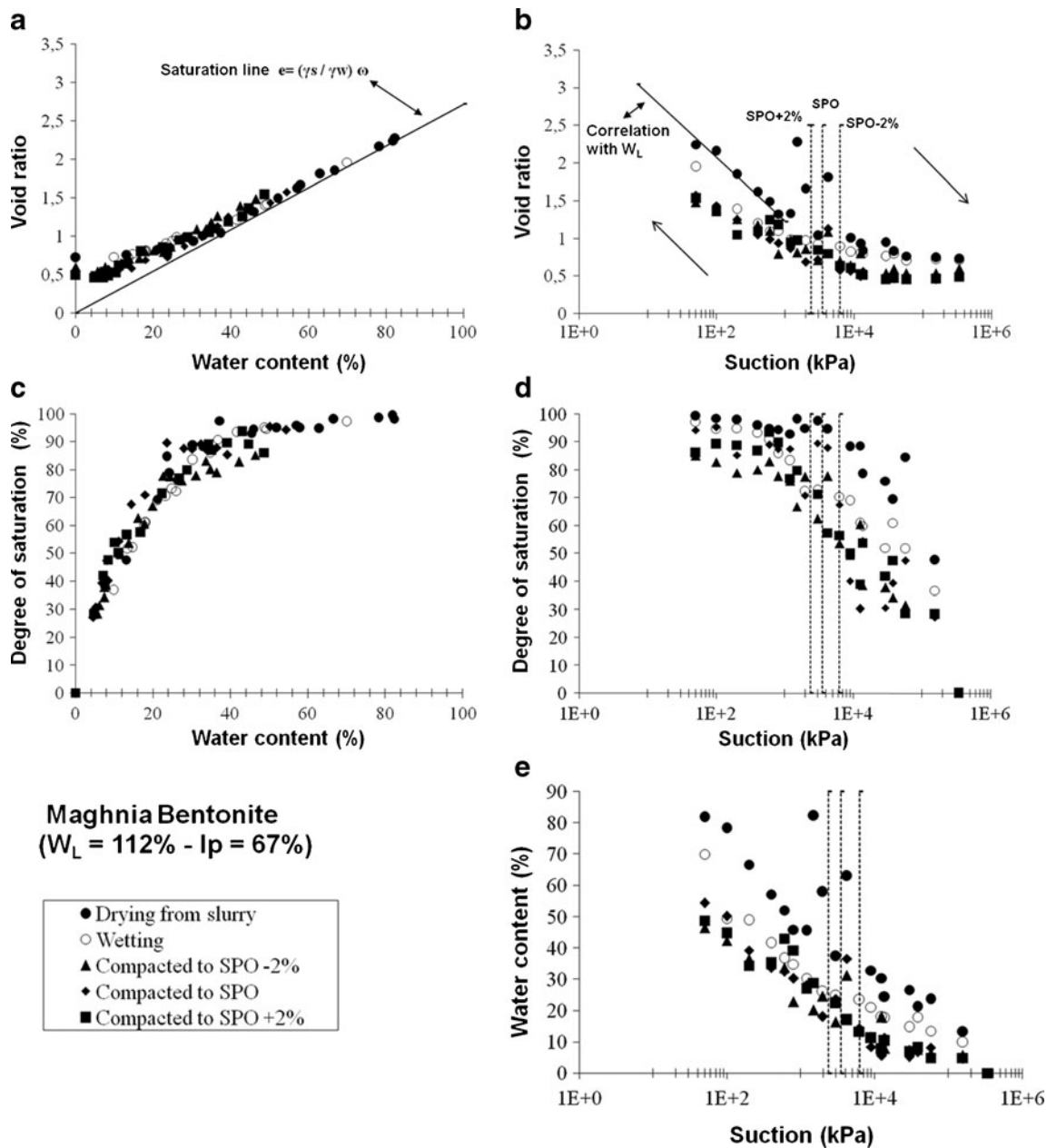The drying–wetting cycles for compacted soils show the following results:

Fig. 5 Drying–wetting paths at different initial states for the Sikkak material

Fig. 6 Drying–wetting paths at different initial states for the bentonite deposit material

– There is a slight dispersion in the results but the points seem close to an average line, independently

Table 5 Measured suctions for each initial states of studied materials

Materials	Initial states	Suction (kPa)
Sikkak marl	SPO−2 %	3,004.6
	SPO	1,032.4
	SPO+2 %	398.3
Bentonite deposit	SPO−2 %	6,292.71
	SPO	3,506.08
	SPO+2 %	2,369.17

of the initial water content, especially in the Figs. 5b and e.

– The compacted samples, with any initial water content, behave like over consolidated samples. Their deformability is much less than that of the slurry material on a drying path.

– The drying–wetting paths are practically linear and reversible.

– The desaturation curve of the compacted samples on the dry side of optimum (SPO, −2 %) is noticeably different from those compacted to the optimum or on the wet side. Vanapalli et al. (1999) found similar results.

– For a given value of suction, the degree of saturation of the compacted samples on the dry side of the optimum is somewhat lower than that of the two others. Vanapalli et al. (1999) showed that the desaturation curve of a specimen compacted dry of optimum is noticeably different from that of a specimen compacted at optimum or wet of optimum. At the same suction, the degree of saturation of the specimen compacted dry of optimum is somewhat lower than that of the two others.

Comparison between drying–wetting paths of slurry and compacted soils

By comparing the results obtained from slurry and compacted material of Sikkak and bentonite deposit, (see Figs. 5 and 6), one can say what follows:

– The minimum void ratio of compacted samples is lower than that of slurry material (see Figs. 5a and 6a).
– The shrinkage suction is higher when the shrinkage limit (water content) is lower for the compacted samples compared to those of the slurry. This goes in accordance with the conclusions of Fleureau et al. (1993) who state that the shrinkage limit is not an intrinsic parameter of the material but depends on its initial state. The compacted material does not present hysteresis and its deformability is much lower than that of the paste material on a drying path.

Conclusions

Through this paper, the volumetric behavior on drying–wetting path was characterized for different materials, with various initial states (slurry and compacted at different water contents).

The following conclusions have been obtained:

– Materials in slurry form:

Drying wetting tests of soils show the presence of a large domain where the soils remain saturated despite the increases of capillary pressure. The width of this domain depends on the soil's plasticity index and the percentage of fine particles.

Correlations were used to obtain the capillary pressure. The result gives an acceptable relation versus liquid limit.

– Compacted soils:

On drying paths applied to compacted materials, the samples behave as over consolidated materials. The drying wetting paths in this case are nearly linear and reversible. The shrinkage limit suction is higher for the compacted samples compared to the samples prepared in the slurry form.

Little variations in initial water content do not affect the behavior of the material on drying wetting path.

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