Experimental and modelling investigate on the behaviour of a partially saturated mine chalk

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EXPERIMENTAL AND MODELLING INVESTIGATE ON THE BEHAVIOUR OF A PARTIALLY SATURATED MINE CHALK

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ABSTRACT: Due to seasonal environmental changes (i.e. water table, hygrometry) the pillars of mines in chalk are often submitted to variations of the degree of water saturation. These changes could affect the short and long term stability of pillars in the underground quarries. Experimental investigations have been conducted on saturated, partially saturated and dry chalk. In this context, the concepts and the methods of mechanics unsaturated soils have been applied to partially saturated chalks. Water retention properties and a series of high pressure controlled suction odometer compression tests were carried out on the samples of the chalk from the pillars of the abandoned Estreux mine (France). These results show that the yield stress of chalk increases when the water saturation decreases. They have been simulated by means of the Barcelona Basic Model – BBM (Alonso et al., 1990) allowing to account the swelling and collapse under wetting at constant vertical load.

KEYWORDS: chalk, quarries, suction, water retention, oedometer

RÉSUMÉ: En raison du changement saisonnier environnemental (i.e. niveau d'eau, hygrométrie), les piliers des carrières sont soumis régulièrement aux variations du degré de saturation. Ces changements ont donc une grande influence sur la stabilité des piliers à court terme et aussi à long terme dans les carrières souterraines. Des investigations expérimentales ont été menées sur la craie saturée, non saturée et sèche. Dans ce contexte, les concepts et les méthodes de sols non saturés ont été appliquées pour ces études. Les caractéristiques de rétention de la craie et une série d'essais d'oedomètre haute pression à succion contrôlée ont été réalisés. La craie est prélevée des piliers dans la carrière abandonnée d'Estreux (France). Les résultats montrent que la surface de charge se développe lors de la diminution de saturation. Ils ont été simulés par le modèle de Barcelone – BBM (Alonso et al, 1990) permettant de rendre compte de l'effondrement et aussi du gonflement sous remouillage avec une charge constante.

MOTS-CLEFS: craie, carrières, succion, rétention d'eau, oedomètre

1. Introduction

In the context of research into the stability of abandoned subsurface cavities in chalk by INERIS (Institute National de l'Environnement Industriel et des Risques), the abandoned Estreux mine (Northern France) has been conducted. In relation with the regular environmental changes (i.e. water table, hygrometry) induce a variation of degree of water saturation in the pillars in the mine, the study of the behaviour of the Estreux chalk under unsaturated states was found necessary.

Various investigations have been carried out on the collapse phenomena for mineworking (Raffoux, 1980; Bonvallet, 1979; Bell et al. 1999; Talesnick et al. 2001; Sorgi, 2004; Priol, 2005). There are two main factors to create these collapses on the geomaterial, which are external (environmental conditions) and internal (intrinsic). This is certainly related to the water weakening effects, described specially for the oil reservoir chalk in the North Sea (Newman, 1983; Andersen, 1995; Schroeder et al., 1998; Gutierrez et al., 2000; De Gennaro et al., 2003 and 2004). Delage et al. (1996) showed that the mechanics of unsaturated soils could be used to investigate the behaviour multiphase chalks.

In this page, using the methods and the concepts of the mechanics unsaturated soils investigate the determination of the water retention properties of Estreux Chalk. From these results, the compressibility of a partially saturated mine chalk is investigated through running the controlled suction odometer. These results have been simulated by means of the Barcelona Basic Model – BBM (Alonso at al., 1990).

2. Experimental investigation

2.1. Material characterisation

The study was carried out on the Estreux chalk specimens extracted from the Estreux abandoned underground mine in Northern France, 10 km East of Valenciennes in the vicinity of the A2 highway relied on Valenciennes and Brussels. Blocks of Estreux chalk were retrieved at 20 meters in depth. The Estreux chalk formation belongs to the late Cretaceous geological period, which dated from 89 to 94 Ma years ago. One square pillar (side 1.4 m and 1.8 m in height) has been continuously monitored in relationship with the research programme conducted by INERIS on "ageing phenomena" in geomaterials since 2003 (Sorgi 2004, Auvray et al. 2004). These measurements show the relative humidity inside the mine included between 80 and 100% and the temperature is almost constant 11°C.

Table 1 presents the index properties of Estreux chalk. By using a helium picnometer, the specific gravity G_s of the Estreux chalk is obtained 2.74. As compared to the specific gravity of pure calcite (G_s = 2.71), this higher value is related to the presence of the glauconite fraction (with G_s = 2.99 for glauconite), which is often presented in the northern French chalk (Masson 1973, Bonvallet 1979, Hazebrouck & Duthoit 1979). It explains the high value of specific surface measured using methylene blue absorption (S_s = 13 m²/g, as compared to 9 m²/g for a pure chalk as Lixhe chalk). The average porosity *n* about 37% shown as a good agreement with the values proposed in the literature (Masson, 1973; Bonvallet, 1979). The high value of degree of saturation S_{rw} = 97% presents probably the chalk completely saturated in the mine, which could indicate a loss of water during testing.

Table 1. Index data of Estreux chalk

Properties	
Specific gravity, G_s	2.74
Degree of Saturation, S_{rw} (%)	97
Intact dry density, g_s (Mg/m^3)	1.73
Porosity, n (%)	37
Natural water content, W_{sat} (%)	20.7
Specific surface, S_s (m²/g)	14

2.2. Retention properties of Estreux chalk

The water retention properties of Estreux chalk were determined by cylindrical samples of 20 mm in diameter and from 20 mm to 25 mm in height. Because the relative humidity changes in the mine from 80 to 100%, we carry out for the suction value between 0 and 24.9 MPa by using 3 methods: the osmotic methods applied for the low suction (from 0 to 1.5 MPa) (Williams & Shaykewich, 1969;

Delage et al., 1998; Marcial, 2003), the vapour equilibrium method with high suction (from 2 to 24.9 MPa) (Delage et al., 1998; Cui & Delage, 2000; Marcial, 2003) and the filter paper method with contact for intact sample (Fawcett & Collis-George, 1967; Chandler & Gutierrez, 1986; Houston et al., 1994, Bulut et al., 2001).

The water retention curve of Estreux chalk is described in Figure 1, in terms of changes in degree of saturation (S_{rw}) as the function of the logarithm of suction (lg(s)). As compared to the wetting path, a small discrepancy of the dry path is related to a rather slight hysteresis. In fact, this is often associated to a variability of the porous network (inkbottle effect) interpreted by the capillary interaction, drop effect (different of contact angle between fluid and solid for wetting path and dry path) (Cui & Delage, 2000) and the presence of diverse nature in the material (physico-chemical interaction), which regularly produce reduce hyteresis. Priol (2005) also found the small hysterisis in Lixhe chalk on the system air – water. This is related to the similar porous media of Estreux chalk, suggested by the Environmental Scanning Electron Microscope observation carried out (Sorgi & De Gennaro, 2007) and the presence of the clay fraction (illite) in the Estreux chalk. Measurements of paper weights have made after 15 and 30 days; the average matrix suction of the intact sample equal to 40 kPa with the high value of degree of saturation (S_{rw} = 97%) shown as the intact chalk in the mine remained saturated. The air entry value of Estreux chalk can be estimated at approximate 1.5 MPa. This is a suction level required to throw out water and reduce degree of saturation following a dry path. Desaturation starts above 1 MPa and the degree of saturation at suction of 2.5 MPa is 10%. It means that along the wetting path or the dry path, the starting of saturation or desaturation produces rather brutally which is caused by changes of few percentage points in the relative humidity. At the highest suction (s = 24.9 MPa) as the lowest relative humidity (hr = 83.5%), the degree of saturation equals to 2 – 5 %, the chalk is nearly desaturated. Thus, with the changes of the relative humidity in the Estreux mine between 80% and 100% can generate important changes of the state of saturation of the Estreux chalk, at least in the surface of the pillar in contact with the relative humidity of atmosphere. Consequently, it is related to affect the stability of the mine. The effects of these changes are quantified by running the controlled suction oedometer.

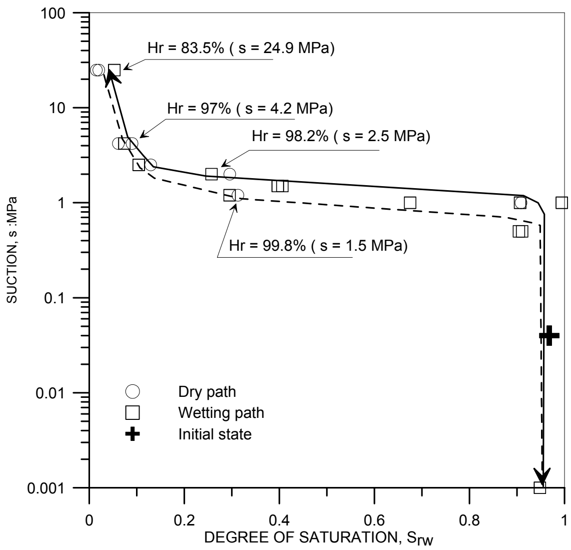


Figure 1: Water retention curve of Estreux chalk

2.3. Odometer tests

A high stress double lever arm odometer equipped with a suction control system was used (see Marcial et al. 2002) to investigate the compressibility of a partially saturated Estreux chalk samples. The control of the suction was carried out either by using the osmotic method (suctions smaller than

1.5 MPa) (see Kassiff & Benshalom, 1971; Delage et al., 1992; Dineen and Burland, 1995; De Gennaro et al., 2003; Priol, 2005). The same cell was also used at higher suctions with the vapour equilibrium method (Esteban, 1990; Oteo-Mazo et al., 1995; Oldecop & Alonso, 2001; Marcial, 2003) for suctions higher than 4.2 MPa. In this case, air with controlled RH was circulated in the odometer cell under the bottom of the sample (see Figure 2).
Samples of 38 mm in diameter and 19mm ± 2mm in height were reshaped on a lathe. A dry sample was obtained after a period of 48 hours in an oven at 60°C following the recommendations of the International Society of Rock Mechanics.
Based on the experimental results from the determination of the water retention properties, four oedometer compression tests were carried out as follows: two tests in dry conditions (T1 & T2), one test in controlled suction (T3: s = 4.2 MPa with vapour equilibrium method, K_2SO_4) and one test in saturated conditions (T4). We considered that the suction of the saturated sample equals to 0 MPa and its dry sample can be estimated at 30 MPa.

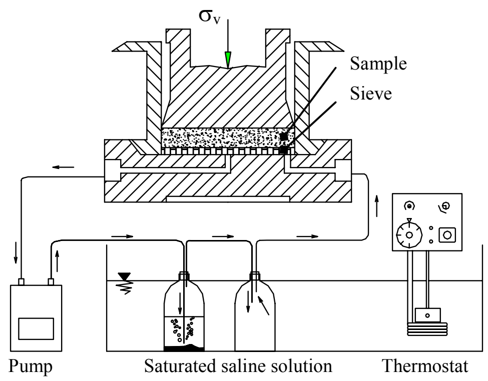
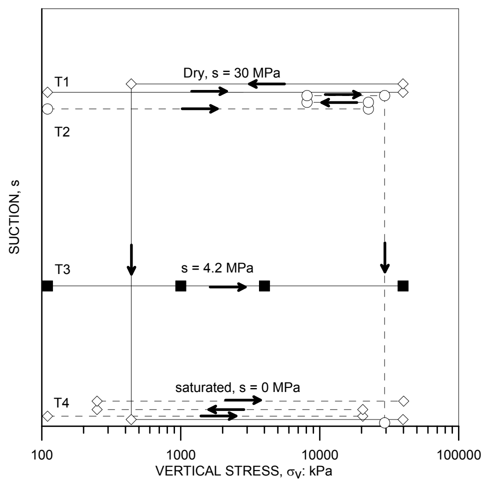


Figure 2. Scheme of the vapour equilibrium oedometer.

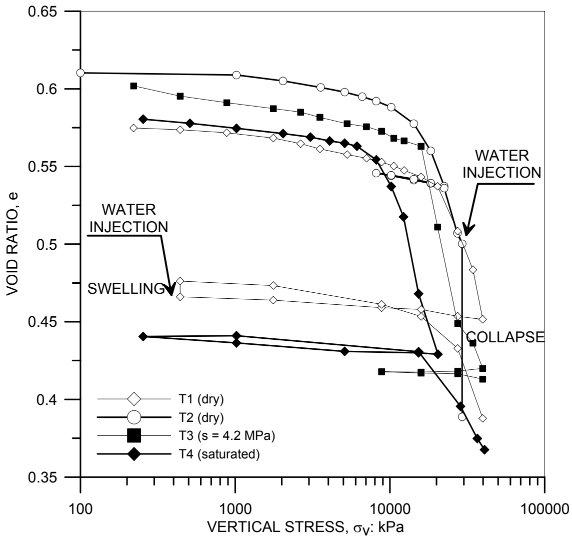
The experimental results of the odometer compression tests are presented in the Figure 3 as follows:

(a): Loading paths in a vertical stress suction (σ_v: s) plan

(b): Compressibility curves of Estreux chalk in [lg(σ_v): e]



(a)



(b)

Figure 3. Loading path (a) and compressibility curve odometric tests (b).

The compressibility curves of Figure 3 shown some responses are compatible with these of unsaturated soils:

- increase in yield stress with increased suction
- increase in compressibility with decreased suction
- slight suction dependency of pseudo-elastic compressibility module
- slight swelling due to suction release in the elastic zone
- significant collapse when soaking under high stress when the sample is located on the LC curve. Interestingly, the position of the collapsed sample is close to the saturated compression sections of tests T2 and T4.

The corresponding numerical values are given in Table 2.

Table 2. Compressibility data taken from odometer tests.

State	Stiffness		Yield stress (MPa)
	Elastic	Plastic	
Dry (T1)	0.0022	0.1082	16
Dry (T2)	0.0055	0.094	13.5
Suction controlled (T3)	0.0095	0.1137	11.4
Saturated (T4)	0.0039	0.135	7.5

These trends illustrate the sensitivity of the mechanical response of the Estreux chalk. They are in good agreement with the water weakening effects described by Matthews and Clayton (1993) and with earlier observations on reservoir chalks (with water and oil as pore fluids) by De Gennaro et al. (2004) and Priol (2005). Water sensitivity is denoted by the swelling observed in test T1 (soaking under 441 kPa) and by the collapse observed in T2 when soaking under 29.28 MPa. The increase in compressibility and decrease in yield stress with increased degree of saturation (decreased suction) are two other manifestations of the water weakening effect.

3. BBM Modelling

3.1. General framework

Alonso et al. (1990) have proposed the Barcelona Basic Model (BBM), an elasto–plastic constitutive model describing the stress–strain behaviour of partially saturated soils. This model is formulated in the framework of hardening elastoplasticity and extends the modified Cam-Clay model for an anisotropic stress state.
Two independent sets of stress variables used in the investigation of the mechanical behaviour of partially saturated soils: the net stress ($p = p_{total} - u_a$ where p_{total} and u_a are the total mean stress and the air pressure respectively) and the suction ($s = u_a - u_w$ where u_w is the water pressure).

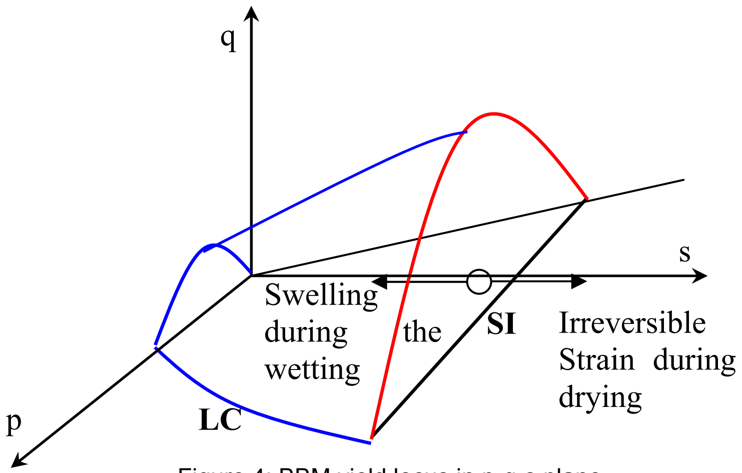


Figure 4: BBM yield locus in p-q-s plane

The formulation related to suction and to pressure is performed following:

- The volumetric deformation is partioned in an elastic part and a plastic one. Each contribution is composed of a mechanical component and of a suction one:

$$d\varepsilon_v = d\varepsilon_v^e + d\varepsilon_v^p$$
$$d\varepsilon_v = d\varepsilon_{vp}^e + d\varepsilon_{vs}^e + d\varepsilon_{vp}^p + d\varepsilon_{vs}^p \tag{1}$$

with the elastic part is given by:

$$d\varepsilon_v^e = \frac{\kappa}{v}\frac{dp}{p} + \frac{\kappa_s}{v}\frac{ds}{s + p_{atm}} \tag{2}$$

where κ, v, κ_s and p_{atm} are the elastic stiffness parameter for changes in net mean stress, the specific volume, the elastic stiffness parameter for changes in suction and atmospheric pressure. and the plastic part can be proposed by hardening laws:

$$d\varepsilon_v^p = \frac{\lambda(0) - \kappa}{v}\frac{dp_o^*}{p_o^*} + \frac{\lambda_s - \kappa_s}{v}\frac{ds_o}{s_o + p_{atm}} \tag{3}$$

where $\lambda(0), \lambda_s, p_o^*$ and s_o are the stiffness parameter for changes in net mean stress for saturated state, the stiffness parameter for changes in suction foe virgin states of the soil, the preconsolidation stress for saturated conditions and the hardening parameter of the suction increase yield curve.

- The elliptic yield surface takes into account the effect of suction by introducing an additional net stress ($p_s = ks$) which defined the difference of compression strengths between saturated and unsaturated specimens. It can be formulated as:

$$F_1 = q^2 - M^2(p + p_s)(p_o - p) \tag{4}$$

where M is a slope of critical state lines.

- The loading collapse (LC) and suction increase (SI) controlling the irreversible deformation are expressed by:

$$\text{LC: } \frac{p_o(s)}{p_c} = \left(\frac{p_o^*}{p_c}\right)^{\frac{\lambda(0)-\kappa}{\lambda(s)-\kappa}} \tag{5}$$

with $\lambda(s) = \lambda(0)\left[\left(1-r\right)\exp(-\beta s) + r\right]$

where $r = \lambda(s \to \infty)/\lambda(0)$ and β is a parameter that controls the rate of increase of soil stiffness with matrix suction s.

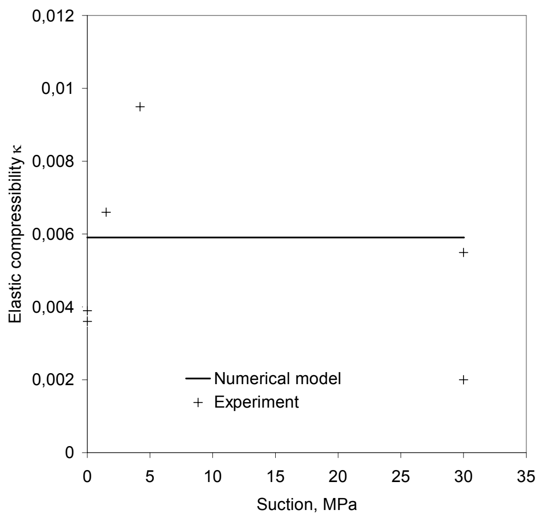
$$\text{SI: } s = s_o \tag{6}$$

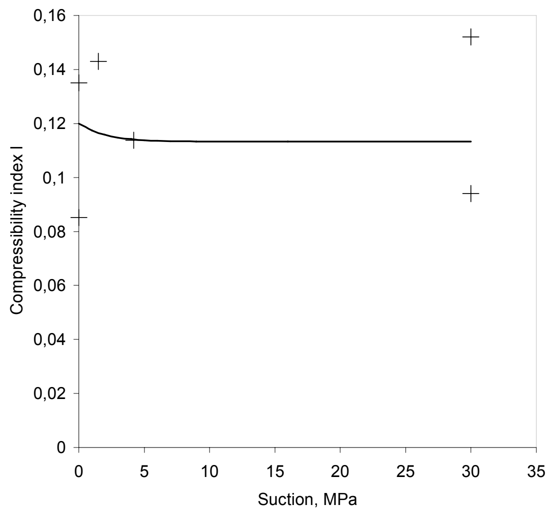
- Introducing a parameter α which assume that the flow rule predicts zero lateral strain for odometric path, to avoid the shortcoming, a non- associated flow rule is given by:

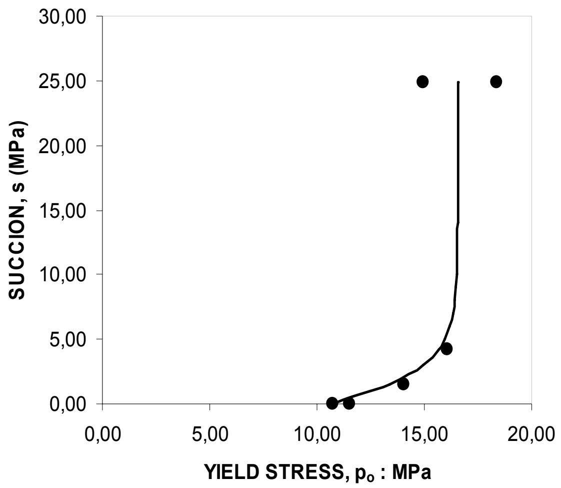
$$\frac{d\varepsilon_s^p}{d\varepsilon_{vp}^p} = \frac{2q\alpha}{M^2(2p + p_s - p_o)} \tag{7}$$

3.2. Modelling

Using the experimental results, Figure 5 shows the determination in a manner of the parameters $\kappa, \lambda, \lambda(s)$. For the Estreux chalk studied the model parameters are given in Table 3.







$$\frac{p_o(s)}{p_c} = \left(\frac{p_o^*}{p_c}\right)^{\frac{\lambda(0)-\kappa}{\lambda(s)-\kappa}}$$

Figure 5: Suction controlled oedometer tests

Table 3: Model parameters

λ(0)	κ	β(1/MPa)	r	p_c (MPa)	$p_o(0)$ (MPa)	k	φ'
0,120	0,006	0,500	0,944	0,010	10,700	0,185	27

E (MPa)	ν	κ_s	λs	M
2399,4	0,19	0,01	0,002	1,069

The BBM response for an odometer test with suction constant is depicted in the Figure 6.

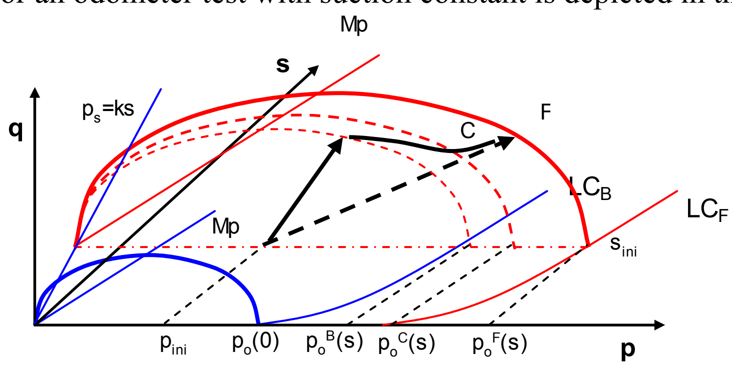


Figure 6: Loading path in p-q-s plane

In the elastic state, the loading path of the odometer tests is considered as linear between p and q by the lateral stress ratio at rest (K_o). From the plastic region, the slope (p,q) of loading path tends to way asymptotic towards the one of virgin consolidation odometer. Thus, this slope can be proposed by:

$$q = \left[\eta_{oed} + \left(\eta_{elas} - \eta_{oed}\right)\exp(-Ax)\right]p \qquad (8)$$

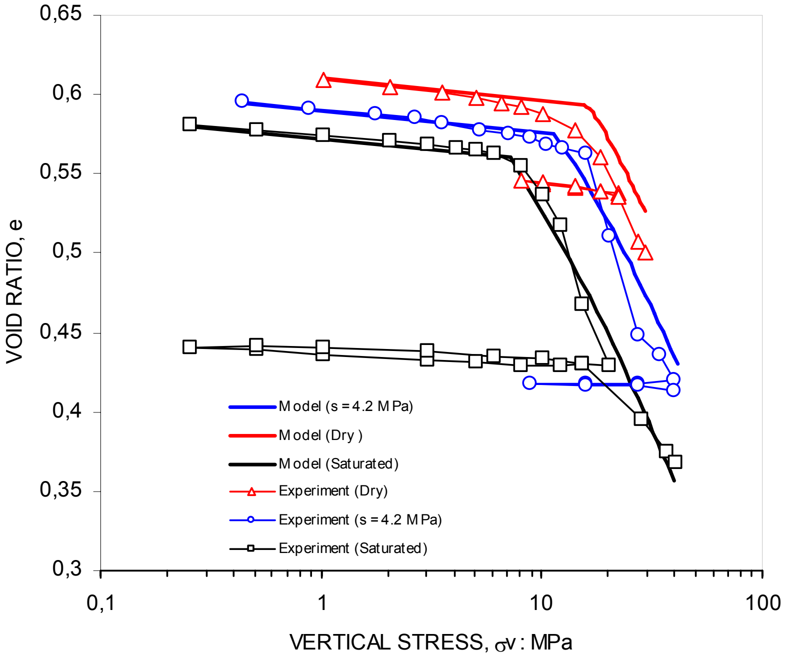
with $\eta_{elas} = \dfrac{3(1-2\nu)}{1+\nu}$

where ν is a Poisson coefficient, A is a parameter which controls the rate of slope of loading path and x is a loading increment.

According to the LC yield curves and the hardening laws, a decrease in suction within the plastic region will result in the volumetric strain to account the swelling and the collapse under wetting at constant vertical loading in the odometer tests:

$$d\varepsilon_v^p = -\ln(\frac{p_o}{p_c})\frac{\lambda(0)\beta(1-r)}{v}\exp(-\beta s)ds \tag{9}$$

In the Figure 7, the experimental results are compared to the numerical simulation at three states (saturated - s = 0MPa, suction at 4,2 MPa and dry – s = 30 MPa). At dry states, the water injection is also modelled. A qualitative good agreement between experimental and numerical results is obtained.



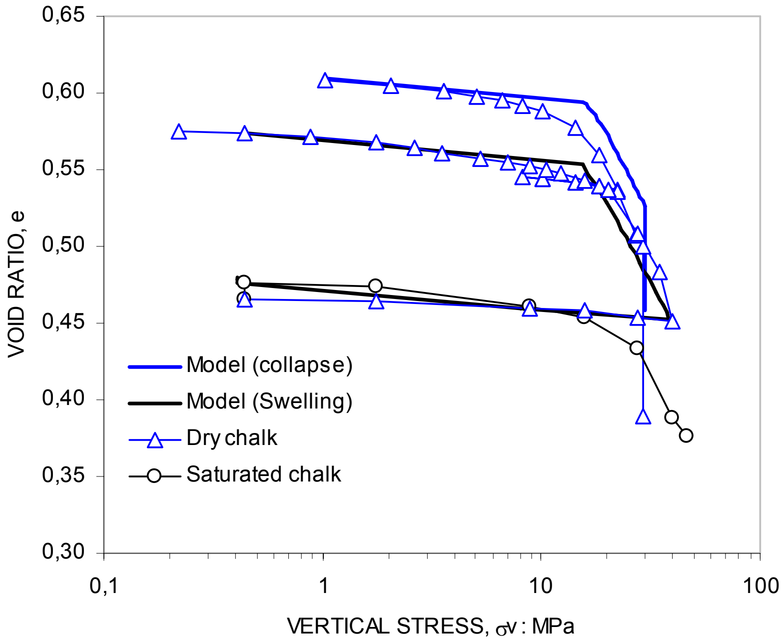


Figure 7 : Modelling compressibility curve odometric tests

4. Conclusion

In this paper, the water retention properties and compression behaviour of partially saturated chalks from an abandoned underground were investigated in relation with the long term stability of abandoned underground quarries.
The water retention properties of Estreux chalk confirmed the changing values of the ambient relative humidity in the quarry (between 80% and 100%) can definitely lead to significantly unsaturated states, at least the surface of the pillar directly in contact with the ambient relative humidity.
Four tests on odometer tests shown the compressibility of the chalk depends on the suction: chalk strength is increased by increasing suction; the water weakening effects in the chalk is examined in more details by the presence of swelling and collapse in water injection.
The comparison between experimental and numerical results using BBM were confirmed the application of the methods and concepts of mechanics of unsaturated soils for analyse the compressibility in chalks.

5. Acknowledgements

The results on Estreux chalk have been obtained during the French National Project BCRD coordinated by INERIS.

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