The Role of Porosity on the Mechanical Resistance of the Rock of a Monument: The Case of the Punic Caves in El Haouaria

Yousr Koobaa, Mehrez Jamei

Abstract: This paper aims to investigate experimentally the role of the variable internal porosity on mechanical resistance and water retention curve as a main hydraulic property. The rock, object of our study, belongs to the caves of El Haouaria are located on the seacoast of the North East of Tunisia. Actually, the caves contain series of cracks with different types, which need a technical solution to improve the caves and avoid the collapse risk. This research might have the base issue of a technical solution So, experimental study include triaxial shear experiences and unconfined compression tests. These experimental tests were carried out in the laboratory by using several samples of rock. These samples are characterized by various types of porosity ranging nearly from 30% to 50% . Completely dried and different moisture water contents were first imposed on the rock samples, and then, separately, a series of tests were performed. The test results showed a significant effect of porosity on both retention water property and mechanical properties such as stiffness, compression and shear resistance.

Moisture water content in the rock has an influence on its resistance and the successively imposed drying-wetting cycles was at the origin of porosity increase and consequently the environmental hydraulic were the main origin of the reduction of rock resistance. From this experimental investigation, the stability of the caves can only be studied through experiments. As shown above our work relied mainly on lab experiments.

The stady of the cave stability passes necessarily by the study of the rock and the convenient improvement technique might be a solution to limit the disorders.

Key words: Monument Rock, Resistance, Porosity, Moisture Content, Drying-Wetting Cycles

I. INTRODUCTION

The caves of El Haouaria are located on the coast of the Cap Bon region of northeastern Tunisia. The caves used to be sandstone quarries already in use during the Punic era, in the VIth and VIIth centuries BC, although more intensely quarried during the Roman times. During Antiquity, this sandstone was used in the construction of the coastal towns and their main monuments, in particular the capital, Carthage. Thus, the actual role is very important in the tourism activity of Cap Bon region.

The degradation of such rock originated from apparently randomly- distributed cracks in the various caves. These caves are located in a semi-arid zone - hot in summer and cold in winter, with a variable humidity between summer and winter. It can wait for saturation in the winter period of heavy rain and its water content is close to zero in the summer period.

The rocks that make up the caves are sedimentary rocks. They have high porosity, and they are composed of different minerals which are more or less brittle. Saturation and drying cycles were already at the origin of porosity growth for a long time of t life of the caves.

In order to understand the influence of moisture on the mechanical behavior of rocks, this article will focus on the study of compressing and shearing rocks in their current state, in the dry state and under different imposed suctions.

Regarding the research literature, numerous studies have already dealt with the mechanical compaction of various porous rocks [1] and carbonate rocks [2-3]. Other researchers have dealt with the mechanical behavior of soft rocks with high porosity and low mechanical resistance [4]. Besides, according to some studies, porosity has a clear influence on porous rock durability, taking into account the alteration of salt sensitivity [5,1] . Significant contributions to a general understanding of the resistance and elastic deformation of such rocks were also presented. The decrease of the unconfined compression mechanical properties were shown [6-8]. According to the author's knowledge, for monument rocks, particularly in Tunisia, few researches results have been engaged and few results were already published on the shear behavior of such porous rocks.

Unconfined compression tests were carried out and they clearly demonstrated the role of porosity. Basing on these results, an empirical mathematical relation was proposed. On the other hand, triaxial tests show that soft rocks were characterized by the effect of confinement stress on the shear behavior. A stress-strain response varying from "brittle" to ductile behavior was observed. According to new investigations, some triaxial tests were carried out considering samples prepared at initial water content, and associated to a corresponding suction. Ranges of water content were taken into account for several samples. These tests were performed on the triaxial apparatus permitting to keep a constant suction during the shear test period

This paper focuses also on the role of water moisture content in relation with the wetting and drying paths or cycles which may be related explicitly to the suction variation.

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These hydraulic cycling effects have also been linked to the dissolution phenomenon inducing porosity increase.

II. HYDRO-MECHANICAL ROCK BEHAVIOR

The research study was conducted following the steps: firstly, some in-situ investigations were done in order to define a monitoring scheme to follow the cracks initiation and growth. This main step was necessary to quantify the disorders using mechanical indexes. Secondly an extraction process of the samples was considered. Therefore a convenient experimental methodology was defined, including the extraction of the samples from the blocks, followed by a preparation of the samples according to French standards in this field. Series of triaxial and unconfined compression tests were then performed.

A. THE PREPARATION OF ROCK SAMPLES

Experimental laboratory campaign tests were engaged using some specific devices for the rocks. Blocks of rock removed from *El Haouaria caves* (Figure 1). They served to prepare the samples according to French standards. The samples was designed with the required dimensions.


Fig1: The Elhaouaria caves (Tourist visiting site)

Porous rock compression resistance was measured using a series of uniaxial compression tests. Two different procedures were used controlled force and controlled displacement experiments (the displacement rate was fixed at 0.5mm/mn).

A water drilling method using a cutting disc was mainly used to prepare the samples. Cylindrical samples (diameter of 10mm and samples high of 20mm) were particularly designed by the rotary coring technique. The uniaxial compression device has an ultimate 300kN capacity.

Figure 2 shows the cylindrical samples selected by the above mentioned procedure. One notes that parallelism was obtained using a water-pass and it was assured until reaching parallel end surfaces free from asperities.

(a)   **(b)**   **(c)**
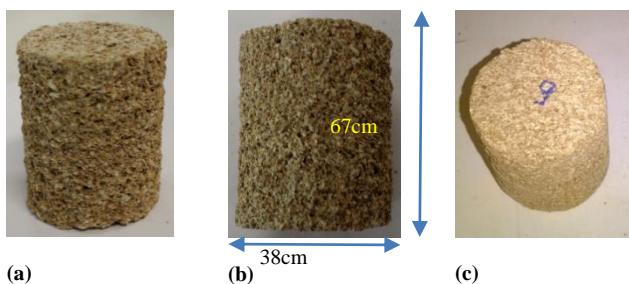
Fig 2: Samples of shape and size prepared for triaxial tests a and b porosity 50% c rock porosity 30%

B. PERFORMING EXPERIMENTS

Firstly, to perform compressive tests under a controlled displacement rate, 50 samples were designed with dimensions of (4mm diameter and 8mm high), and 9 with (10mm, of diameter and 20mm of high). Cylindrical ones were designed as it is shown in Figure3. Dry density and bulk density were measured as additional parameters to the average porosities of the samples.

To investigate the role of the saturation in parallel to the role of porosity, the uniaxial compressive experiments (UCS) were performed under extreme two conditions: completely dry samples and saturated ones. All these tests were conducted basing on the French Standard NF P 94-420.

On the other hand, some tests were also performed under a given water moisture content, corresponding to a well-defined suction. Therefore, the suction value was attributed to the water content, measured using some corresponding rock samples.

Fig 3: samples of the studied rock

Uniaxial compression experiences were performed using a device with a capacity of 300kN. The displacement rate was fixed at 0.5 mm/min (Figure 4).

Fig 4: Compression test

To study the shear behavior, a triaxle equipment designed for soft and hard rocks was used. Samples were prepared with conventional dimensions (38mm, 76mm). The triaxial device was automatically controlled by using stress controlled conditions (Figure 5). The two strains (axialε_1 and radialε_3) were determined from transducer readings. The radial deformation ε_3 response was monitored with transducers (an electro-optical laser system was mounted on two diametrically-opposite sides).

Axial (vertical) displacements were measured by means of an external LVDT including corrections *due to* cell deformability.

In fact, to control the confining and the deviatory stresses, two stepper motors using air pressure regulators were used (for more details see Romero, 1999).

To determine rock capacity to retain water or to restore it, the water retention curve as a main hydraulic property was determined using two complementary methods:
    -osmotic
    -salt solution method.

To assure the drying condition, the samples were kept for 24 hours in an oven at 105° C [9].

Fig 5: Controlled suction in a triaxial apparatus

Ten drying-wetting cycles were applied, starting from completely drying state (samples were preserved in an oven at 100C° for 48 hours) to reach a saturation sate. The saturation state was reached by imbibing water at a constant temperature.

III.   DISCUSSION OF THE RESULTS

A. PHYSICAL PROPERTIES

Table 1 gives the physical properties of rock samples. As it was expected, a low dry unit weight and high porosity values were obtained proving the high porosity character of the rocks of the El Haouaria monuments.

Table I: Physical properties of the tested rocks

Physical characteristics	
bulk density (g/cm3)	1.5-2.5
solid density(g/cm3)	2.73
Porosity	25%-55%

B. WATER RETENTION CURVE

Figure 6 gives the water retention curves under both drying and wetting paths. It clearly demonstrates the hysteretic behavior of the rocks, certainly due to the dimensions and connected or not connected internal porosities. On the other hand the role of the average porosity on the retention property was quantified by the wetting-cycles dependency on porosity.

The hydraulic hysteresis behavior was also signaled in relation with the rock microstructure and therefore with the internal porosity. This phenomenon is observed for many other types of materials such as compacted soils and rocks [10-13]. The average air-entry value suction was deduced separately for the drying and wetting paths. It was of 50 kPa at drying and 30 kPa for the humidification path. However, considering a given hydraulic path (wetting or drainage), from the measurements, the air-entry suction decreases with porosity increase.
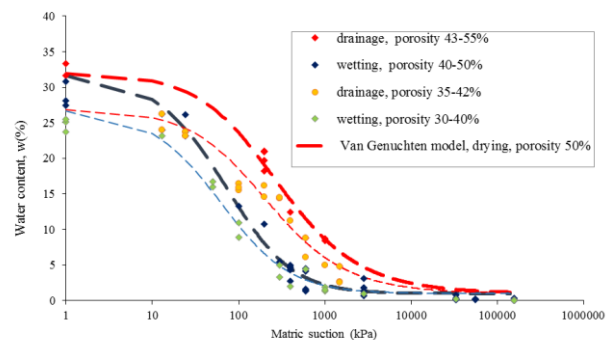

Fig 6. Water retention curve of El Haouaria rock

This result is in agreement with the equivalent results obtained already in the geotechnical field. In fact, micro-structure and void ratio well affects the water storage capacity of a given soil. This fact has been highlighted in several experimental investigations, in the sense that water retention curve is much dependent on compaction and consequently on porosity distribution [14-15]

C. EFFECT OF HYDRAULIC CYCLES

Some wetting-drying tests were performed. Table 2 presents the dependency of total porosity on the hydraulic cycles based on the10 hydraulic cycle features. Porosity was measured in the range between 6% and 14%. Such obtained variation was more important for the case of samples having low porosity. In fact, due to the cementation of grains, average porosity decreases and then the air entry suction value increases. Under wetting, a part of cementation vanishes. Consequently, hydraulic cycles induce a porosity variation during the weather time across the life of the studied monument.

TableII: Porosity variation after 10 hydraulic cycles

sample	Initial porosity Φ_1 (%)	Porosity after 10 wetting-drying cycles, Φ_2 (%)	$\Phi_1 - \Phi_2$
1	41%	48%	7%
2	38%	46%	8%
3	29%	39%	10%
4	30%	42%	13%
5	40%	46%	6%
6	40%	48%	8%
7	36%	47%	11%
8	31%	43%	12%

9	35%	44%	10%
10	28%	41%	13%
11	28%	42%	14%
12	35%	47%	12%

D. UNIAXIAL COMPRESSIVE STRENGTH (UCS) AND ITS DEPENDENCY ON POROSITY

Figure 7 shows the results of the uniaxial compression experiments performed on 6 different samples with similar porosity variation between 0.3 and 0.46.

As it was observed from these results, the compressive strength decreased from 13MPa to 4MPa. Hence, the role of porosity on the compressive strength was very significant. The feature of the rocks under a uniaxial loading was typically described by a non-elastic behavior followed by a plastic one with strain hardening.

Likewise, for saturated specimens, an important reduction in compression strength was observed.

On the other hand, suction effect (or the water content) was quantified based on the same uniaxial compression tests (Figure 8). In fact, suction was applied using salt and the osmotic solutions (the choice between the two techniques depended on the corresponding valuable range of suction corresponding to each technique). The results show that the compression strength depends on porosity largely more than on the suction or water content.
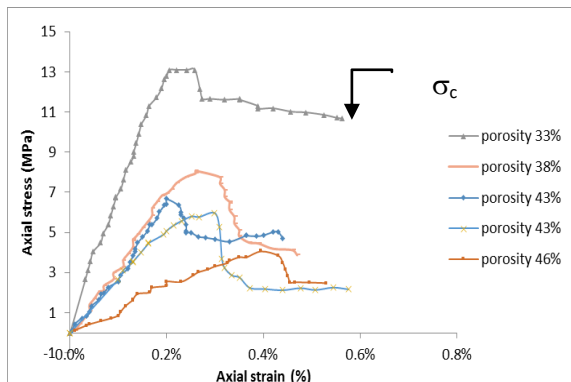

Fig7: Compression Stress-strain versus axial strain *in dry state* for different porosity values

At the same level, it was shown that the compression strength of samples under a 300 kPa suction tends to approach the value at a completely dried state. Obviously, this comparison is valuable for the samples with a similar porosity (Figure 8).

Figure 9 gives compression strength versus porosity. A reduction of the compression strength was approached by an empirical equation which indicates an exponential function decrease.

As it was introduced by Prick [16], hydraulic softening of rocks can be defined as a rate between the difference between UCS at dry state and UCS at saturated state and UCS at dry state (taken as a reference state).
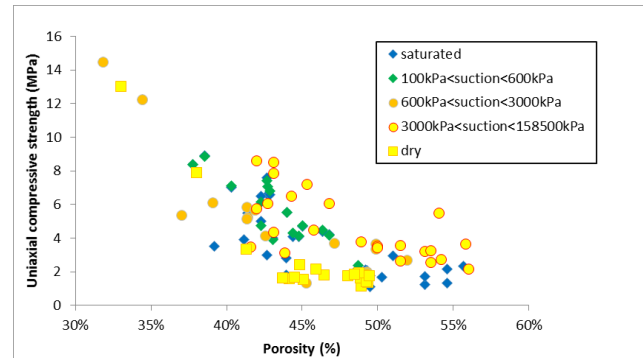

Fig 8. Compressive strength (peak stress) versus total average porosity for different applied suctions

Equation 2 shows the hydraulic softening coefficient. As it was indicated by several authors such coefficient was used to give an estimation of the rock durability [17].

$$\alpha_s = \frac{UCS_{dry} - UCS_{saturated}}{UCS_{dry}} \qquad (2)$$

In fact, the lower the coefficient is, the higher rock durability is. It means that the lower value of hydraulic softening coefficient corresponds to an absence of saturation. This coefficient can be affected to each hydraulic cycle in order to quantify the role of the cycles on the resistance of the rock.
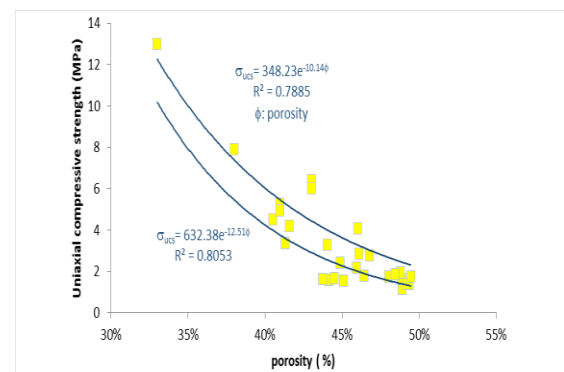

Fig 9. Uniaxial compression strength versus total average porosity (dry state)

According to this criterion, El Haouaria rock can be classified as moderately durable (the average value αs of 0.5).

E. SHEAR TESTS

Deducing from the above presented tests, the most significant role of porosity compared to suction and the saturation, triaxial tests were focused on dry samples with significant different porosities. Deviatory stress–strain–curves have been obtained at different confining stresses between 0.5 MPa and 1.2 MPa.

(a)

(b)

(c)

(d)
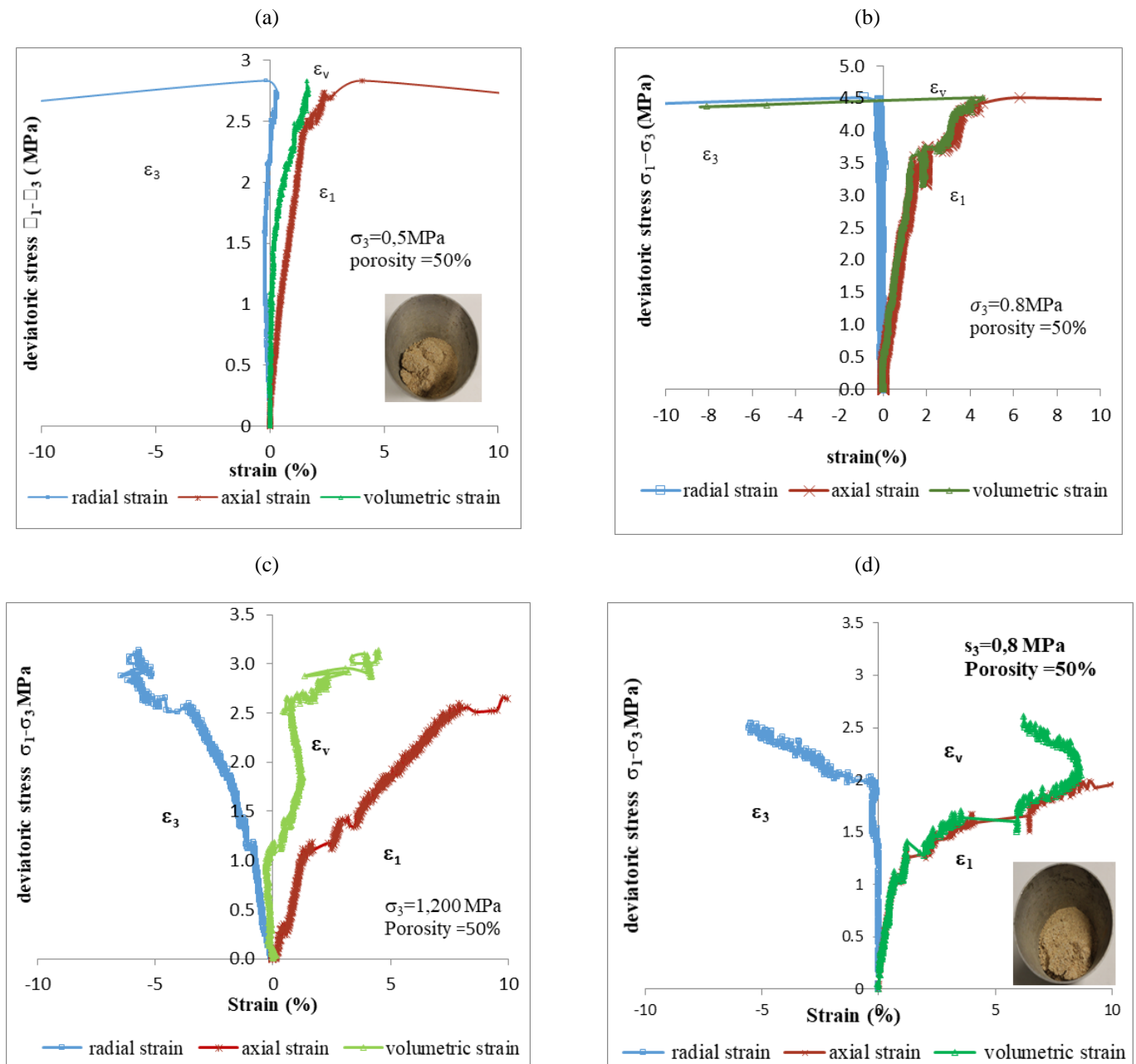
Fig 10: A deviatory stress versus different strains (axial, volumetric and deviatoric strains) under confining stress ranges from 0.5 MPa (a), 0.8 MPa (b), 1.2 MPa (c), 0.8 MPa (d)

The deviatory stress q is defined as q = σ1 −σ3 (compressive stresses and contraction strains are positive).

The terms σ1and σ3 represent the total maximum and minimum principal stresses. Test results are given in figures 10 and 11 in terms of deviatory stress (q= σ1 − σ3) versus strain (three kinds of strain were measured: axial strain ε1, volumetric strain εv and radial strain ε3). Each curve is identified by its corresponding strain.

Rocks are dried at 50% porosity. For confinement stress 0.8MPa, two kinds of rock samples were tested. Figure 11 show the results for lower porosity of 30%.

Two conclusions can be drawn from the trends indicated in figures 10 and 11:

(1) The results show that, in figures 10(a) and 10(b), the curves are respectively characterized by a very linear elastic deformation. A maximum deviatory stress is observed around 2.5 MPa and 3.5 MPa, and it is associated to 2% and 4 % axial deformations for σ3=800 kPa and σ3= 500 kPa, respectively.

Moreover, these tests show that an elastic behavior followed by a plastic one for relatively lower confinement stresses was identified. Besides, a hardening behavior for higher confining stresses were noticed.

2) In figure 11, both samples display strain hardening, large strains and no stress drop. Beyond these stress levels, the deviatory stress provides a significant contribution to the compact strain, and no shearing is observed. On the other hand, no shearing localization was observed on the samples.

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In fact, because high confining stresses tend to stop the initiation of cracks and their growth. From a volumetric strain evolution, dilatation appears after some contractive volume values. It reoccurs much later (for higher axial strain) with an increasing lateral confining stress.

(a)

(b)
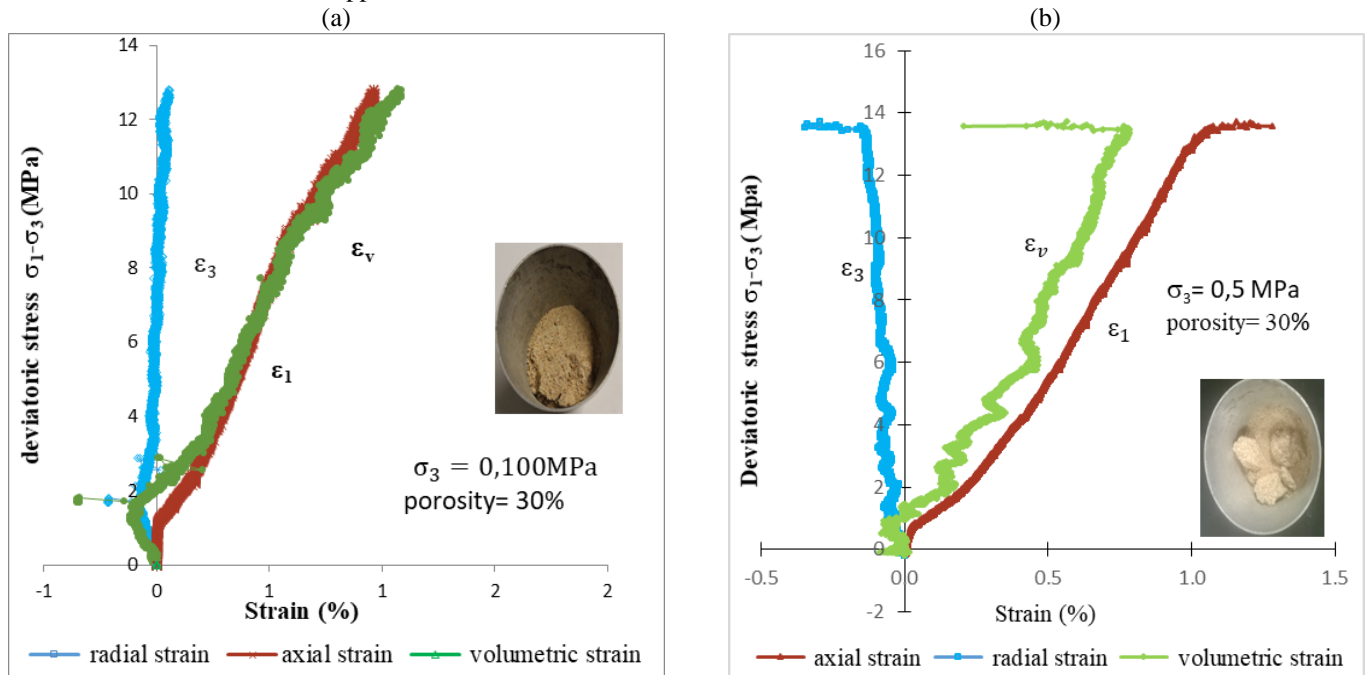
Fig 11: A deviatory stress versus strains (axial, volumetric and deviatory strains) for dry rocks under confining stress 0.1 MPa (a) and 0.5 MPa (b). Rock samples are dried with a 30% porosity

IV. CONCLUSION

The hydro-mechanical behavior of El Haouaria rock was established from the quantitative variables expressed by the relationship between:
- Water content and suction evolution,
-compression strength and porosity.

The role of porosity was dominant compared to suction effect. Naturally, we notice a degradation of the rock under wetting-drying cycles during a long period of the monument's life. Porosity grows inside the rock randomly. Porosity growth was affected progressively by the strength of the rock and it caused disorders such as the development of cracks in the monument. Shear strength was quantified again for the two types of porosity and the hardening behavior was highlighted for a lower porosity. Then, the increase of porosity was retained as a key parameter to affect rock resistance.

From the water retention curve, it has been shown that the suction air entry value was very low. Water retention curves obtained under drying and wetting paths show the hysteretic behavior which moves according to the porosity change. Moreover the saturation water content was naturally affected by the variation of porosity. For the studied range of porosity, the presence of a hysteresis between wetting and drainage was observed.

Concerning the volumetric behavior determined across the measured principal strains, the role of porosity was clearly highlighted. For example, the contractive behavior is noted for porosity 50%. For different confining stresses. The contractive volumetric behavior was addressed, giving a response similar to the response of the loose sands under shear action.

Finally, the mechanical behavior of the rock of El Haouria caves depends mainly on the porosity growth. Rock porosity was well affected by the wetting drying cycles which obviously were related to the marine environmental conditions of the archeological monuments constructed sine the Punic era.

Some added experiments are required to deeply investigate the effect of environmental cycles. These experimental results will be the basis to propose an improvement technique of the cave stability.

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Yousr Koubaa, is a Tunisian researcher in the geotechnical engineering field. She graduated from the National Engineering School of Tunis as a civil engineer and finished her master's degree at the same School. She started her research experiment with the master's project in the National Engineering School of Tunis where she studied the crushing of a very soft material. Currently she directed urban planning and urban mobility projects at Urban Planning Agency of "Grand Tunis", Tunisia. Her research mainly focuses on studying the behavior of rocks of El Haouaria caves to give protocol of caves monitoring.

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