International Journal of Applied Engineering Research ISSN 0973-4562 Volume 10, Number 17 (2015) pp 37973-37980
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Characterization of macro and microstructural behaviour of a compacted clay to the optimum Proctor

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Abstract

The compaction of soils is one of the most common activities in geotechnical engineering. The behaviour of compacted soils is complex due to several factors: mode of fabrication, loading conditions, and the unsaturated state of the soil. However, in recent years, the development of unsaturated soil mechanics and of technologies allowing for testing of unsaturated soils and measurement of suction have significantly improved our understanding of the behaviour of compacted soils.

The paper aims to present the results of an experimental study carrying on Boughrara clay, which used for earth dams construction. The soil is compacted statically and dynamically at standard optimum Proctor.

The purpose of what follows is to try to clarify the relationship between the macroscopic deformation of the studied soils presented by the drying wetting paths and the consequences on the microstructure behavior of the compacted soil. In addition, we used several correlations to predict characteristic of the soil at the optimum Proctor.

Keywords: **C**ompacted soil, correlations, drying-wetting path, and microstructure.

Introduction

The Compacted clayey soils are used in a wide range of geotechnical applications. In civil engineering, compacted clays are found in embankments and earth dams. In these applications, the compacted material remains essentially unsaturated over its service life [1]. However, it is usually recognised that the behaviour of compacted soils is complex.

The fabric of compacted soils has been widely studied, most often by mercury intrusion porosimetry. It has generally been observed that soils compacted on the dry side of optimum have a bimodal pore-size distribution whereas soils compacted on the wet side of optimum have a single family of pores (e.g., [2], [3]). Also, the soil fabric is directly reflected in the Soil Water Characteristic Curve (SWCC), ([4], [5]).

The aim of this article is to improving the understanding of the relation between the macroscopic and microscopic behaviours of compacted clayey materials. At the macroscopic scale, the approach consists of measuring their physical properties (void ratio, degree of saturation, water content) versus suction during drying-wetting path, which allows taking into account the relationship between shrinkage and desaturation. At the microscopic scale, study of the clay particles is carried out by environmental scanning electron microscope (ESEM) picture analysis and try to study the evolution of the porosity derived from mercury intrusion porosimetry tests.

To reach this objective, we studied a clayey soil used in the construction of core of earth dams. The Boughrara earth dams, which is located in Tlemcen, North West of Algeria.

First, we identify the material, and then we paid a particular attention to the characteristics at the optimum Proctor. We introduce various correlations, versus simple physical properties as Atterberg limits, found in the literature to predict the compaction characteristics such as maximum dry unit weight and optimum moisture content. Then we compare those predictions to the real values obtained from the laboratory compaction test.

In the second part of the article, we studied the relation between the macroscopic and microscopic properties of Boughrara compacted clay, especially on drying and wetting paths (SWCC). Finally, we focused on the microstructure of statically compacted specimen submitted to different suctions on drying path.

Materials

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

Analysing the results the material is a highly plastic clay from the USCS classification / LCPC, the soil is designated by fO-At, therefore the soil of Boughrara is a very low organic plastic clay.

TABLE.1. Identification results of Boughrara clay.

Physical identification		**Standard**
Sieve distribution:		NF P 94-041
Gravel (%)	3	
Sand (%)	10	
Silt (%)	35	
Clay (<2 μm) (%)	52	
< 80 μm (%)	97	NF P 94-057
Atterberg limits		
Liquidity ω_L (%)	54	
Plasticity ω_P (%)	26	
Plasticity index Ip (%)	28	NF P 94-051
Density of solid particles (G_s)	2.65	NF P 94-054

Chemical identification		
- VB	6.91	NF P 94-068
-SST (m^2/g)	145	
- % $CaCO_3$	20	
- % MO	6	
Mechanical identification		
Standard Proctor		NF P 94-093
$\gamma_{d\ max}$ (kN/m^3)	16.2	
ω_{opt} (%)	21	

Application of correlations on the Proctor curve of the studied material

Several authors have tried to link the characteristics at the Standard Optimum Proctor with some easily measurable parameters in laboratory ([6], [7], [8]...). Through the literature review, several relationships exist between maximum dry density and optimum moisture content with Atterberg limits parameters. Some of these equations are also function of the compaction energy. The Standard Proctor compaction test (ASTM D698-12) [9] is corresponding to an energy E of 600 kN.m/m^3.

Table 2 summarizes several relationships found in the literature. In the following, these relationships will be applied on the Boughrara material. The maximum dry density and optimum water content obtained from correlations (*see last column of Table 2*) are compared to the compacted soil characteristics obtained in the laboratory test.
The results of these correlations are plotted on the Proctor curve of Boughrara material (*see. figure 1*).
By analysing the graph in *Figure 1*, we see that the best correlation, which describes the studied soil at the optimum, is the equation of Boltz (1998) [11]. This relationship is a function of the liquid limit of the soil and the compaction energy.

TABLE 2: Different correlations giving characteristics at the standard optimum Proctor.

Authors	**w_L (%)**	**Correlations**	**Results (γ_{dmax}, w_{spo})**
Popovic (1980) [10]	25 to 70	$\rho_{dopt} = \frac{2.7}{1.283 + 0.00818 w_L}$ $w_{spo} = 8.14 + 0.257\ w_L$	15.65 kN/m^3 22.02 %
Blotz (1998) [11]	17 to 170	$\gamma_{dmax} = (2.27 \log w_L - 0.94).\log E - 0.16 w_L + 17.02$ $w_{spo} = (12.39 - 12.21 \log w_L).\log E + 0.67 w_L + 9.21$	16.69 kN/m^3 21.05 %
Fleureau. (2002), [6]	17 to 170	$\gamma_{dmax} = 21 - 0.113.w_L + 0.00024\,(w_L)^2$ $w_{spo} = 1.99 + 0.46\ w_L - 0.0012\,(w_L)^2$	15.6 kN/m^3 23.33 %
Gress (2002) [12]	20 to 60	$\rho_{dopt} = 2.09 - 0.00927\,w_L$ $w_{spo} = 7.92 + 0.268\ w_L$	15.89 kN/m^3 22.39 %
Gurtung (2004) [13]	Fine soils	$w_{spo}(\%) = [1.95 - 0.38\,(\log E)].\omega_p$ $\gamma_{dmax}(kN/m^3) = 22.68\,e^{-0.0183.w_{opt}}$	14.82 kN/m^3 23.25 %
Osman (2008) [14]	Fine soils	$w_{spo} = [1.99 - 0.165\,(\ln E)].I_p$ $\gamma_{dmax} = L - M.w_{opt}$ $L = 14.34 + 1.195 \ln E$ $M = -0.19 + 0.073 \ln E$	26.17 % 14.73 kN/m^3
Sivrikaya (2008) [15]	28 to 74	$\gamma_{dmaxt} = 0.22\,(96.32 - w_p)$ $w_{spo} = 0.94.w_p$	15.47 kN/m^3 24.44 %
Nagraraj (2015) [8]	Ip = 12 to 46	$\gamma_{dmax} = 20.64 - 0.19\ w_p$ $w_{spo} = 0.84\ w_p$	15.7 kN/m^3 21.84 %

Testing methods

A. Drying wetting path

The behaviour of Boughrara clay is studied on drying-wetting path to see the influence of compaction mode (quasi static and dynamic) on the development of soil parameters (e, Sr and w).
The test consist to impose to the specimens a series of increasing suctions (defined as the difference between pore air pressure and pore water pressure) until the sample is completely dry (drying path). In the wetting path, we impose a series of decreasing suctions. At equilibrium, and for each suction, we measured the final characteristics of the samples (volume, water content), to deduce the void ratio (e), the degree of saturation (Sr) and the water content (w).

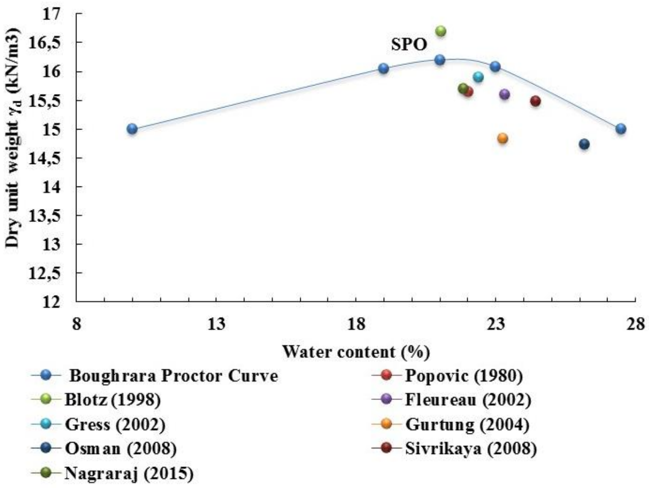


Fig.1. Boughrara Proctor curve with the results of correlations of different authors to standard optimum Proctor

The drying-wetting path is determined by using two techniques to control the suction in the soil specimen. The two techniques are osmotic and saturated salt solution.

The first used method is the osmotic technique, which used in geotechnical engineering by [16], [17], [18]. In this technique, the soil specimen is placed in contact with a semi-permeable membrane behind which a solution of macromolecules of polyethylene glycol (PEG) is circulated. The semi-permeable membrane is permeable to water molecules but impermeable to the PEG molecules [19].

The relationship between suction (s) and PEG concentration (c) is well defined. [18] found that the suction value is equal to: $s = 11\ c^2$.

In this study, the osmotic technique was used to impose soil suction between *0.05* and *2 MPa* by using the PEG 6000 and PEG 20000.

The second method is applied to achieve high suctions, between *4* and *392 MPa*, this method controls the suction in specimen by salt solutions it is called vapour equilibrium technique (VET). The suction is controlled, in a closed system, by migration of water molecules through the vapour phase from the soil pores to a saturated salt solution, until equilibrium is achieved ([20], [21]).

B. Microstructural analysis

The microstructure analysis was carried out following two approaches:

- The first qualitative based on microscopic observation with an Environmental Scanning Electron Microscope (ESEM).
- The second quantitative based on mercury porosimetry.

If the first method (ESEM) did not require specific preparation to the different studied samples. However, the second method require that samples must be completely dry before being introduced into the mercury porosimeter.

Microstructural investigations of the original and final fabrics under suction were carried out using a mercury intrusion porosimeter (MIP). The samples were freeze-dried to remove all pore fluid and vapours whilst preserving the original fabric [22]. Then, the lyophilized samples were tested in the mercury intrusion porosimeter.

Initial conditions

Drying wetting path

Two initial conditions are considered:

- First, samples are compacted at standard Proctor optimum (using static compaction).
- Second state, samples are compacted at standard Proctor optimum (using dynamic compaction).

The samples were prepared as follows:

- First, the studied soil is mixed at the optimum moisture content (21 %) then, placed in plastic bags for 24 hours for homogenization.
- For static compacting: Compacting was carried out in the CBR press at a speed of 1.5 mm / min. The compacted samples were made in cylindrical moulds in order to obtain the dimensions of 1 cm diameter and 1 cm height.

For dynamic compaction: We use a normal Proctor mould to compact the soil to the maximum dry density of 1.62. After demoulding cubic, samples of approximately 1cm^3 were cut; this is in order to speed up the time to reach equilibrium. In fact, [23] have shown that the equilibrium time is reduced by 50% (decreases from 30 to 15 days) when the sample size is reduced by 75% (25.4 mm to 6.35 mm). Soil specimen sizes can be small or quite large. [24] said that larger the specimen size, the longer the time that is required to attain equilibrium conditions. Specimen sizes ranging from 1 to 5 g are sufficient for purposes of measuring the water content corresponding to high-total-suction values on the SWCC.

Results and discussions

A. Drying wetting path

The values of the initial suctions in the compacted soil, statically and dynamically at optimum, are determined by the filter paper method (ASTM D5298-94) [25]; they are presented in the *figure 2* and reported in *table 3*. 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.

TABLE 3: Results of the determination of initial suctions by filter paper method.

Initial conditions	*Suction (kPa)*
OPN quasi statique	900
OPN dynamique	990

The results of drying-wetting paths for Boughrara material prepared by static and dynamic compaction are shown in the *figure2*.

From this representation to five plans, one can draw the following conclusions:

- There is a slight dispersion in the results but the points seem close to an average line, independently of the initial mode of compaction (static or dynamic).
- In the [w, e] plane, compacted samples statically and dynamically, following the saturation line $e = (\gamma_s/\gamma_w).w$ and the horizontal asymptote of the curve when *w* tends towards *0*. The corresponding value of the suction is s_{sL} called shrinkage suction (*see figure 2.B*).
- In terms of void ratio function of suction, compacted samples are below the normally consolidated line NC so they follow an overconsolidated path. The NC line is defined from the correlation with liquid limit proposed by [26]:

$w = w_L$ or $e = (\gamma_s/\gamma_w)/w_L$ for $s = 7$ kPa

$w = w_P$ or $e = (\gamma_s/\gamma_w)/w_P$ for $s = 1000$ kPa

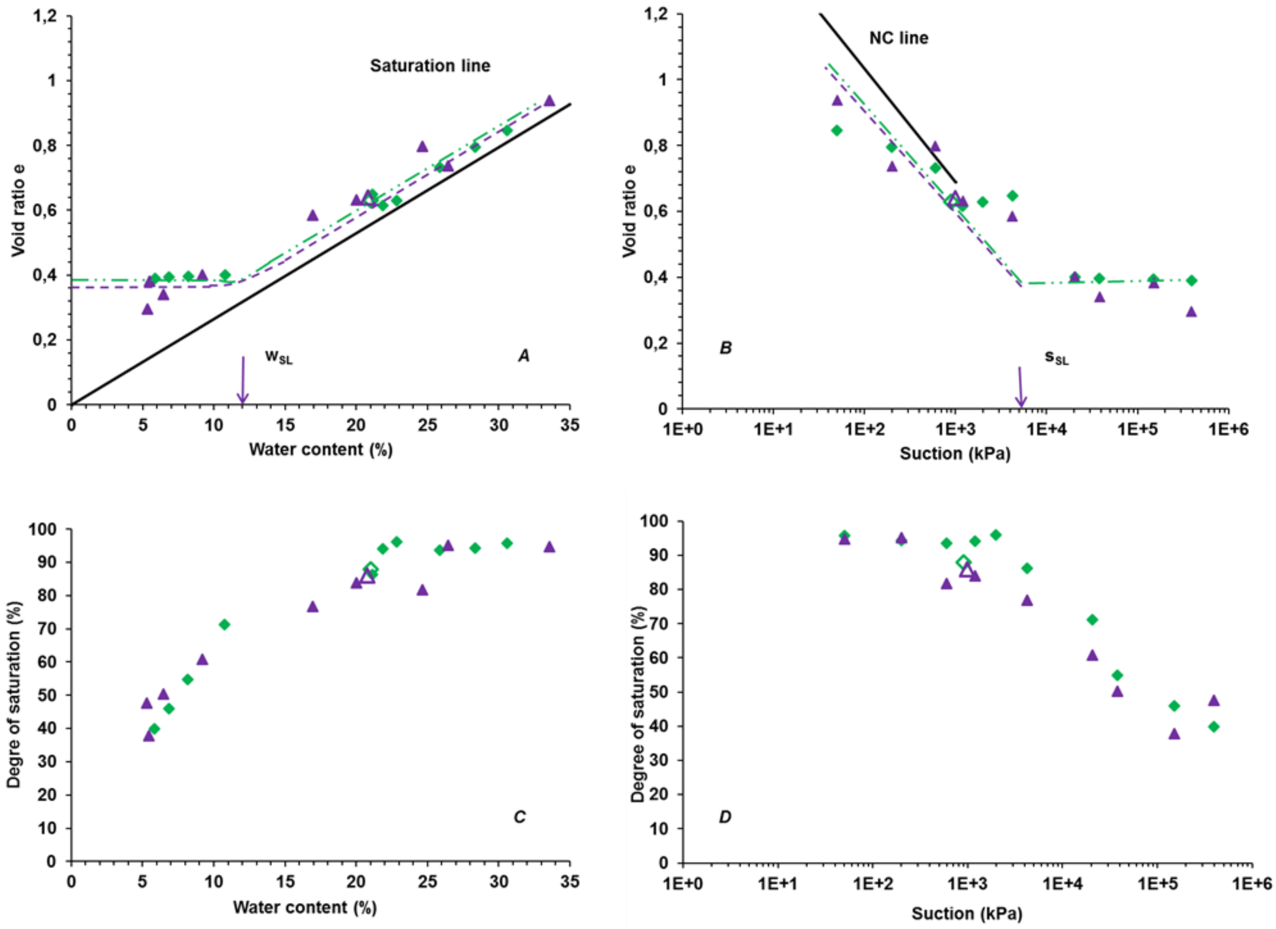
- Drying-wetting paths are substantially reversible.

In [w, Sr] and [s, Sr] planes, it is noted that the samples compacted at static and dynamic optimum Proctor reached a degree of saturation of about 95% for a suction of about 50 kPa.

The following table summarizes the main obtained characteristics.

TABLE 4: Principal characteristics for Boughrara clay on drying-wetting path.

Initial condition	**Water content shrinkage limit W_{SL} (%)**	**Suction shrinkage limit S_{SL} (MPa)**	**Final void ratio**
SPO Static	12	5	0.39
SPO Dynamic	12	5	0.38



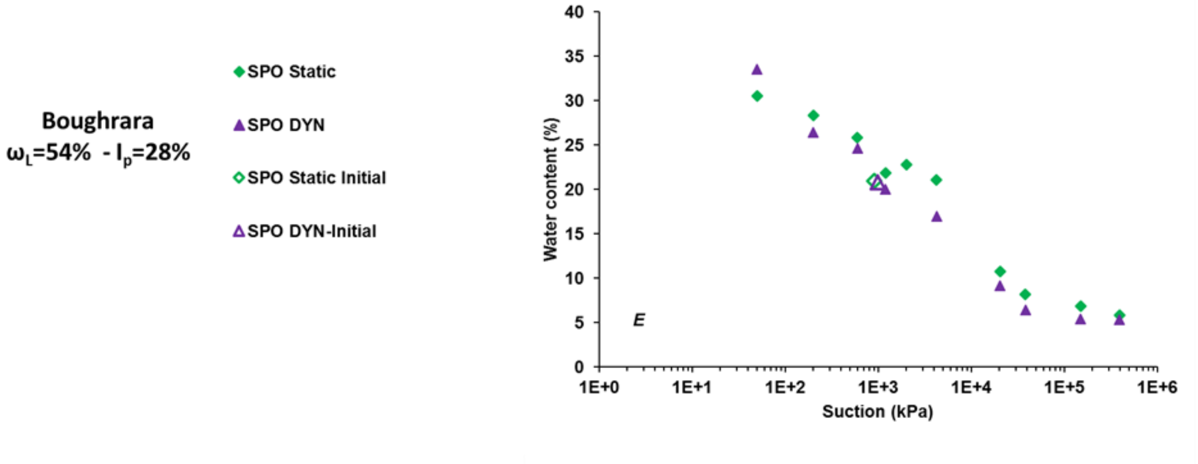


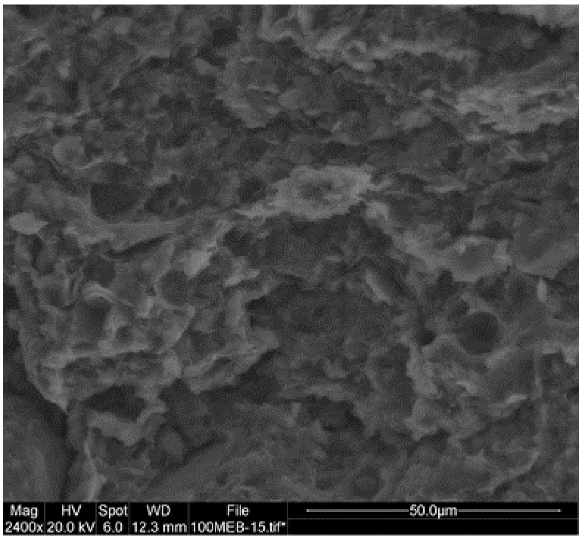
Fig.2. Drying-wetting paths for samples compacted at studied initial conditions.

B. Microstructure analysis

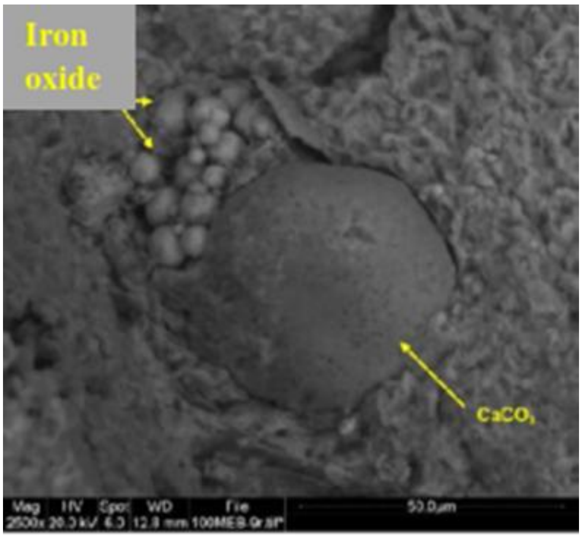
The soil sample, which is compacted statically at the optimum Proctor, is subjected to observations in the ESEM (see *figure 3*), the results have led to the following findings:

- *Figure 3.A* show a very flaky clay area.

In *Figure 3.B*, we note the presence of calcium carbonate $CaCO_3$ and the iron oxide particles thus confirming the results of the chemical analysis and identification tests on the material (presence of $CaCO_3$) (see *table 1*).



A



B

Fig.3. ESEM image of Boughrara's sample compacted statically to the optimum.

Chemical analysis carried out by ESEM (see figure 4), realized with a probe coupled to the ESEM-EDX, showed the presence of several elements such as: Si (silicates, quartz), Al (clay feldspar), Ti (titanium oxide) and presence of carbonate (CaCO3 ...).

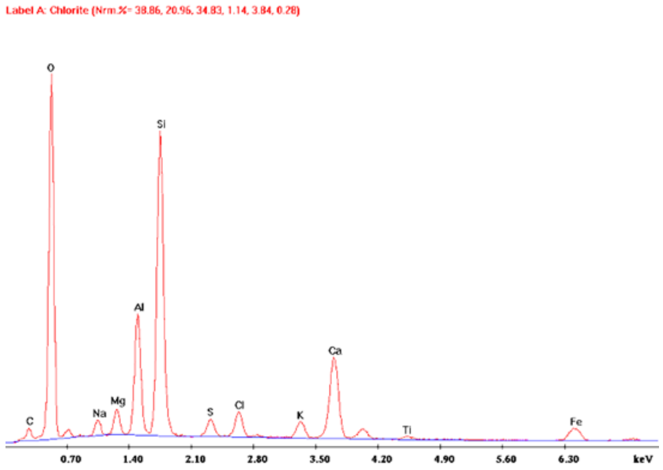


Fig.4. ESEM-EDX of the compacted sample at optimum Proctor compacted statically

The measurement of the pore size distribution by mercury intrusion in Boughrara's soil, compacted statically at the optimum, is shown in *figure 5*.
The sample shows a peak in the microstructural elements (small diameter pores) and a certain homogeneity in sizes for large pores (macrostructure). This is due to the fact that after compacting the sample becomes more homogeneous at the optimum, representing a unimodal pore distribution; this joins the results found in the literature ([27], [28]).

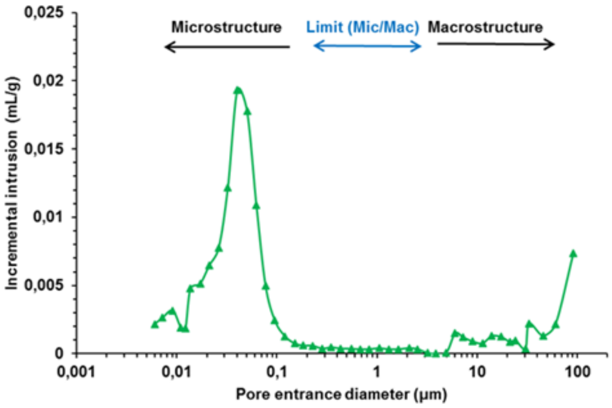


Fig.5. Porosimetry curves of sample compacted statically at the optimum.

The figure 6 shows the results of two samples statically compacted and subjected to drying wetting path under 2 and 4.23 MPa of imposed suction. After equilibrium, the mercury intrusion test gives the following results:

- The initial suction of compacted soil at the optimum Proctor, measured by filter paper, is 900 kPa (see *Table 3*). Consequently, the analysed samples follow a drying path because the imposed suctions (2 and 4.23 MPa) are greater than that of the initial condition.
- The graph shows that when the suction increase from 2 to 4.23 MPa there is a slight reduction in the macroporosity (the boundary between macro and micro porosity is about 0.5µm). The sample subjected to 2 MPa of suction present a peak of 10 µm, while for a greater suction of 4.23 MPa, the peak decrease to 6 µm.
- Regarding microporosity (diameter <0.5 microns), we obtain substantially the same peak (0.03 microns), although the prevalence is slightly pronounced for the suction of 4.23 MPa, may be this is due to the fact that we approach the shrinkage limit which is of the order of 5 MPa (see *table 4*). Although both studied suctions are close, the results are similar to those found in the literature [29].

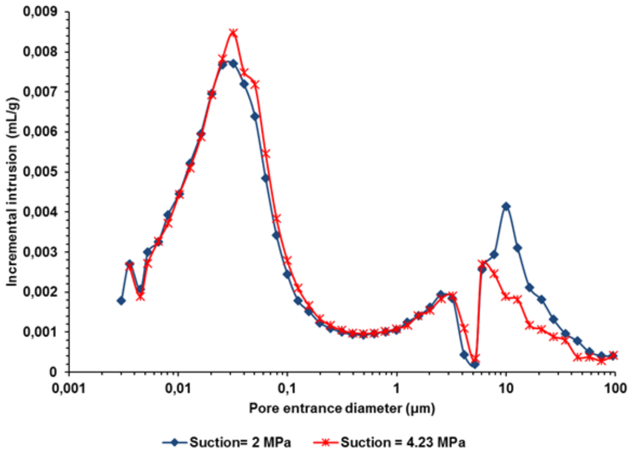


Fig.6. Pore distribution of samples compacted statically under different suctions.

Conclusion

The aim of this paper was to give an overview of the behaviour of compacted clay from an earth dam of the western north of Algeria. Some interesting features have been highlighted:

- The correlation of Blotz [11], which takes into account the compaction energy, gives the best prediction of the characteristics at the optimum proctor of Boughrara material.
- The drying wetting path carried out on Boughrara clay compacted at the optimum proctor, static and dynamic, show that samples follows an overconsolidated path in drying and have substantially the same shrinkage bearing.
- We find the same behaviour for compacted samples statically and those compacted dynamically (in Proctor mould), this result joined those found in the literature. This result is in favour of using statically compressed samples for research on compacted embankments that are implemented in situ by dynamic compaction.
- Regarding the microstructure of the samples compacted statically, which follow the drying path, have a dual porosity. With imposed increases of

suctions, the macrospores are reduced in favour of an increase of the microspores when the suction is approaching the shrinkage limit.

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