Influence Of Initial Compaction Conditions On Shrink-Swell Behavior During Drying Wetting Paths.

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Abstract

This paper presents an experimental study carried out on clay used in the core of Boughrara dam (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 correspond to statically compacted specimens at different initial water contents and dry densities. The test results showed that at constant water content, the drying wetting path was independent of the initial dry density. On the other hand, the drying wetting path was found greatly influenced by initial water content. On drying path, specimens with high initial water content, tend to shrink more, and for suction higher than 30MPa, the drying path was found to be independent of initial conditions. On wetting path, the swelling potential was found dependent on the dry density more than the water content.

Keywords: Compaction, Drying, Wetting, Soil suction, Shrinkage, Swelling.

1. Introduction

Unsaturated soils are usually defined as mixture of tree phases: solid liquid and gaz. In such soils, the contractile skin would be subjected to the water pressure \( u_w \), which is lower than the air pressure \( u_a \). The difference pressure \( u = u_a - u_w \), is referred to as suction, or more precisely: matric suction.

For these soils, the soil–water characteristic curve (SWCC) represents a constitutive relationship. In other words, the soil water characteristic curve describes the relationship between soil suction (S) and soil water content (w), or degree of saturation (Sr), on drying or wetting paths. Knowing the specific density of the soil \( G_s = \gamma_s/\gamma_a \), the associated changes in void ratio \( e \) versus suction can be determined. Various properties of unsaturated soils can be derived from the SWCC curve: shear strength, hydraulic conductivity, volume changes, ([25], [7], [18]). Also, parameters like the air entry value \( S_a \), shrinkage limit, can be obtained from the SWCC (figure 1), and used to obtain fitting parameters to model the SWCC curve ([20], [6]).

As the soil moves from a saturated state to drier condition or vise versa, soil volume changes by shrinking on drying path or swelling on wetting path. As a result, many problems and damages can be caused the existing constructions ([11], [1]).

For compacted soils, because of their large using in construction of different soil structures such as roads, railroad embankments, earth dams, many researches were undertaken in other to better understand their behavior on drying wetting path. These studies have highlighted the influence of compaction stress, compaction water content and dry density, clay mineralogy on such paths ([28], [16], [27], [30], [10], [29]).

The shrinkage curve (drying path) of a soil specimen shows different phases of deformation. From a progressive drying of natural saturated soil, [29] distinguished two phases: (i) normal shrinkage, and (ii) residual shrinkage. [4]and [12], add a third phase at the begin of shrinkage curve called structural shrinkage. Figure 1 shows a general form of the shrinkage curve in diagram [e-w], where we have also localized the position of the air entry value, the shrinkage.

Similar to the multiphase shrinkage behavior of a soil specimen, the swelling of desiccated soils also occurs in three different phases ([26]), namely primary swelling, secondary swelling, and no swelling. In this paper, we propose to study the behavior of Boughrara clay dam compacted at the optimum Proctor conditions (SPO), on drying wetting path, and to bring out the influence of variations in the initial compaction conditions in terms of water content and dry density on such path.
2. Material and methods

Tested material was taken from the deposit soil used for the construction of Boughrara core Dam, located in the North West Algeria, at about 60 km for Tlemcen city. The identifications test results are shown in tables 1 and 2. These results showed a predominance of the clay fraction. 70% of the elements are less than 2 μm, and the methylene blue index (MBI) is 10.11. This material is characterized by high plasticity and little activity (Ac). From the calcium carbonate content (CaCO₃) value and the specific surface area (SST), we can deduce that this is marly clay composed mainly of Kaolinite and Illite. According to the USCS/LPC classification, this clay is designated: CH: highly plastic clay with low organic percentage.

2.1. Osmotic technique for control of suction

This technique is based on the osmotic principle. The difference between two solutions having different concentrations and separated by a semi-permeable membrane induces a difference between the pressures of the two solutions. This difference is the osmotic pressure. The sample is made in contact within an aqueous solution of polyethylene glycol (PEG) by semi-permeable membrane which is characterized by a specific value of MWCO (Molecular Weight Cut Off). Since PEG molecules cannot cross the semi-permeable membrane, suction is applied to the water through the membrane by osmosis and its value is controlled by the concentration of the PEG solution.

The relationship between suction (S) and PEG concentration (Cₚₑ₉) was firstly established by [17], and completed by [23] up to 10MPa. This relationship was found independent from the type of PEG, and it can be approached by a parabolic equation: S=11Cₚₑ₉², where the suction is expressed by (MPa), and the concentration of PEG by (g/g water). In this study PEG 20000 and 6000 were used to impose soil suction between 50kPa to 8000kPa by using respectively a semi permeable membrane with MWCO 12000 Da and 3500 Da.

Figure 2 shows a photo of the device performed for this technique. It is to set the semi-permeable membrane into a beaker containing PEG solution through a PVC O-ring. This last, is then slipped on to the walls of the beaker until the contact between the solution and the membrane is perfect (no air bubbles trapped under the membrane). The beaker is then covered by parafilm membrane to prevent evaporation from samples.

However, it is necessary to note certain points that have to be carefully taken in uses this technique:

- The temperature intervenes in the calculation of the osmotic potential which is the suction developed by the solution. It is, therefore, necessary to work at constant temperature (20°C in our case).
- The volume of osmotic solution may increase (on drying path), or decrease (on wetting path); this induces the variation of the solution concentration. In order to avoid this effect, we must use a great deal of solution.
Table 1. Physical properties of Boughrara clay.

<table>
<thead>
<tr>
<th>Granulometry</th>
<th>Plasticity</th>
<th>Specific density</th>
<th>Optimum Proctor</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;80µm</td>
<td>&lt;2µm(2)</td>
<td>D60</td>
<td>D30</td>
</tr>
<tr>
<td>97%</td>
<td>72%</td>
<td>1µm</td>
<td>0.7µm</td>
</tr>
</tbody>
</table>

Table 2. Chemical properties of Boughrara clay.

<table>
<thead>
<tr>
<th>CaCO_3</th>
<th>MBI</th>
<th>SST</th>
<th>Organic Content</th>
<th>Ac (1/2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>10.11</td>
<td>212 m²/g</td>
<td>5-6.5%</td>
<td>0.39</td>
</tr>
</tbody>
</table>

- The chemical instability of cellulosic membrane results in its decomposition in acidic environment or under the bacterium effect in soil. To solve this problem, one can add to the osmotic solution some drops of antibiotic (penicillin), or a spoon of Benzoic acid.
- According to [31], it is necessary to wait two days between the preparation and use of solution, in order to allow stabilization of solution density.

The device of osmotic technique

By measuring the variation of the sample mass, the time of stabilisation is obtained. The equilibrium is reached when the sample mass remains constant. With this method, we have estimated that the time equilibrium for vapour equilibrium technique exceed 50 days, where, for the osmotic technique it range between 15 and 20 days.

2.4. Experimental program and Samples preparation

The experimental program consist of two types of tests: Drying and wetting tests and oedometer free swell tests. The preparation of the test specimens was carried out in three steps as follows:

- In the first step, natural soils were air-dried, and the aggregates were carefully crushed.
- In the second step, the required quantity of water was added to the soil and both were carefully mixed (by spraying). The soil-water mixture was kept in a sealed plastic bag for at least 24 h to achieve uniform moisture conditions.
In the third step, the materials were statically compacted at desired dry density and water content.

For samples used in drying wetting tests, a special mould was used. The obtained specimens were 22 mm in diameter and 12 mm in height. Immediately, they were put in the different devices used for these tests. In this case, each point corresponds to a different specimen, which can offer the advantage of shorter test duration.

Compaction parameters were determined by Standard Optimum Proctor (SPO). For the present study, five compaction conditions were chosen. These are:

- **Maximum dry density and optimum moisture content** (SPO, $\gamma_d=16.2$ kN/m$^3$, w=21%),

- **Maximum dry density and 3% of optimum moisture content** (SPO-3, $\gamma_d=16.2$kN/m$^3$, w=18%),

- **98% of maximum dry density and 3% of optimum moisture content** (98%SPO-3, $\gamma_d=15.88$kN/m$^3$, w=18%),

- **98% maximum dry density and 3% wet of Optimum moisture content** (98%SPO+3, $\gamma_d=15.88$kN/m$^3$, w=24%).

Compaction curve and the compaction conditions are shown in Figure 3. Table 3 present the soil state parameters of these initial conditions.

The initial suction of compacted materials were determined by using the filter paper method ([2]). The calibrated filter papers (Whatman42) were placed in the specimens during compaction, protected on both sides by ordinary filter papers, between two soil layers. Measured values are also presented 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.

For the same initial conditions (table 3), a free swell oedometric tests were undertaken, according to the ASTM norms ([3], method A). In this test, the specimen is lowered to swell under token pressure (1kPa, in our case) by submerging the specimen in distilled water. After attaining an equilibrium condition, the soil specimen is then loaded and unloaded following the conventional oedometer test procedure. Samples were compacted directly in the oedometer ring, to a height of 15mm and 50mm in diameter.
Table 3. Compaction conditions of soil specimens

<table>
<thead>
<tr>
<th>Initial conditions</th>
<th>Initial Suction $S_0$ (kPa)</th>
<th>$w_i$(%)</th>
<th>$γ_d$(kN/m3)</th>
<th>$e_0$</th>
<th>Sr(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPO (*)</td>
<td>700</td>
<td>20.68</td>
<td>16.36</td>
<td>0.62</td>
<td>88.49</td>
</tr>
<tr>
<td>SPO (**)</td>
<td>757</td>
<td>21</td>
<td>16.2</td>
<td>0.636</td>
<td>87.5</td>
</tr>
<tr>
<td>SPO-3(*)</td>
<td>1045</td>
<td>18.07</td>
<td>16.27</td>
<td>0.629</td>
<td>76.12</td>
</tr>
<tr>
<td>98%SPO-3(*)</td>
<td>870</td>
<td>18.07</td>
<td>15.92</td>
<td>0.665</td>
<td>72.06</td>
</tr>
<tr>
<td>SPO+3(*)</td>
<td>237</td>
<td>23.7</td>
<td>16.31</td>
<td>0.625</td>
<td>100</td>
</tr>
<tr>
<td>98%SPO+3(*)</td>
<td>93</td>
<td>24.2</td>
<td>15.98</td>
<td>0.658</td>
<td>97.46</td>
</tr>
</tbody>
</table>

(*) Static compaction, (**) Dynamic compaction-Proctor test-

3. Results and discussion

Figure 5 and 6 represent drying wetting path on compacted Boughrara clay. The three graphs in the right-hand side (B, D, E) show the changes in void ratio, degree of saturation and water content with logarithm of suction. On the left-hand side, the void ratio (A) and degree of saturation (C) are plotted versus water content. This presentation was chosen in other to highlight the correspondence between the curves and the different phases in the behavior of the soil. A suction of 1 kPa, correspond really to null suction.

3.1. Drying wetting path for SPO specimens

In figure 5, the first graph (A) is the usual shrinkage-swelling curve, with the void ratio as a measure of the external volume.

On the drying path, the void ratio decreases as the water is extracted from soil. When the water content reaches shrinkage limit $w_{SL}$, the void ratio tends to a constant value, noted $e_{SL}$. The value of $w_{SL}$ is about 12% and $e_{SL}$ is 0.37. In this case, we can identify two phases in the shrinkage path: normal shrinkage and residual shrinkage (figure 1). The absence of the structural shrinkage phase is due to the fact that the soil is initially unsaturated (The initial point is located to the left of saturation line, $Sr<90$ %). According to [Fredlund and Rahardjo, 1993], in this state, water phase is continuous and air phase is occlude in bubbles.

The second graph (B) is the compressibility plot, where the effective stress is replaced by suction. Two phases are distinguished. The first is characterized by large variation of the void ratio when suction is increased, and in the second, this variation becomes negligible. The transition suction between the two domains, $S_{SL}=4$MPa, is termed the “shrinkage limit suction”; and correspond to $w_{SL}$ in graph (A). Beyond this value, the liquid phase becomes mainly discontinuous, and is located in the menisci around the contact points. At microscopic level, this behavior is explained by the changes in the obliquity of intergranular forces with respect to the normal to the contact between the grains, ([13], [16]).

The evolution of the degree of saturation with water content is represented in the graph (C). The normal and the residual shrinkage phase are also identified in this plane. The evolution of the degree of saturation in these two phases can be approached by straight lines with two different slopes. There intersection, correspond to shrinkage limit, $w_{SL}$.

The two last graphs (D and E) represent respectively the SWCC curve. It appears that the effect of suction on the void ratio is widely related to the saturation of the material. The maximum compressibility is occurs when the water content is less than the shrinkage limit, $w_{SL}$ (i.e., normal shrinkage phase). Beyond this value, the degree of saturation falls below the value of 75% to reach about 40 % at a suction value of 500 MPa. In this interval, the decrease in water content is approximately 7 %.

The wetting path of specimens compacted to the SPO conditions, shows a linear variation in all graphs. Corresponding to graph A, C and D, the final degree of saturation is about 97 %. The final point is positioned left on saturation line. In these conditions, the measured final void ratio and water content are respectively 0.76 and 28 %. This later is close the value of plastic limit (i.e., $w_p=26$ %).

3.2. Drying wetting path for specimens compacted at dry and wet side of SPO

Drying wetting paths of compacted specimens on dry or wet side of optimum Proctor are represented in figure 6. The drying wetting paths of SPO specimens have also been plotted in the same graphs for comparisons purposes.
By viewing the figure, it’s difficult to distinguish between curves, especially in \([e, \log(S)]\) and \([w, \log(S)]\) diagrams. The main differences are observed in the others diagrams (i.e., \([e, w]\), \([Sr, \log(S)]\), \([Sr, w]\)). For this diagrams, the Drying wetting paths of SPO specimens, is generally positioned between the curves of specimens compacted on the dry and wet side of optimum Proctor.

Figure 5. Drying wetting paths on specimens compacted to SPO.
Furthermore, the specimens compacted on the same side of the optimum proctor (i.e., same water content), shows that drying wetting paths are nearly superimposed. This result confirms in part the dependence of the drying wetting paths of compacted soils to the initial water content, and indicates that for a difference of 2% in dry density, no significant different behavior is observed.

This difference can be explained by the fact that the samples compacted on the dry side have a more open

![Figure 6. Drying wetting paths on specimens compacted at dry and wet side of SPO.](image-url)
microstructure characterized by a bimodal porosity: inter-aggregate and intra-aggregate, contrary to the samples compacted at optimum Proctor or wet side of optimum Proctor, where their microstructure is dominated by a unimodal porosity: intra-aggregate, ([22], [24], [21]).

[8], as mentioned by [14], showed that in most clays, except smectite, the mechanism of filling or emptying of pores is obeying to a phenomenon of capillary type, governed by the law Laplace. This leads to that the samples compacted at dry side, desaturate quickly compared to the samples compacted at SPO or the wet side conditions (Diagram [Sr, log(S)], figure 6).

In the table 4, we have summarized the main characteristics on drying path, in terms of: shrinkage suction, suction of desaturation: $S_e$ (i.e., air entry value), water content, void ratio and degree of saturation. The suction $S_e$ is determined in the diagram [Sr-log(S)]. It corresponds to the intersection between the line corresponding to Sr=100% and the asymptote of drying path [27]. This value was defined just for specimens compacted on the wet side of the optimum Proctor (i.e., Sr>97 %).

Table 4. Soil state parameters as function of suction for different initial conditions.

<table>
<thead>
<tr>
<th>Initial conditions</th>
<th>Suction (MPa)</th>
<th>e</th>
<th>Sr (%)</th>
<th>w (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPO</td>
<td>$S_{SL}=4$</td>
<td>0.37</td>
<td>82</td>
<td>12</td>
</tr>
<tr>
<td>SPO-3</td>
<td>$S_{SL}=6$</td>
<td>0.41</td>
<td>70</td>
<td>10.5</td>
</tr>
<tr>
<td>98%SPO-3</td>
<td>$S_{SL}=3$</td>
<td>0.46</td>
<td>97</td>
<td>17</td>
</tr>
<tr>
<td>SPO+3</td>
<td>$S_{SL}=10$</td>
<td>0.35</td>
<td>89</td>
<td>12</td>
</tr>
<tr>
<td>98%SPO+3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The influence of the water content can be seen on the values of shrinkage suction, and the corresponding void ratio. For specimens compacted on dry side of optimum Proctor, the $S_{SL}$ is about 6 MPa with $e_{SL}=0.4$, against $S_{SL}=10$ MPa and $e_{SL}=0.35$ for specimens compacted on the wet side. The optimum Proctor values range between these later. For shrinkage limit, $w_{SL}$, the obtained values stay close one to the other (i.e., 10.5 % to 12 %).

We have also examined the influence of the initial dry density and water content on the drying and wetting index, (i.e., $I_D$ and $I_w$), defined in the diagram [e-w], and the shrinkage and swelling potential, (i.e., $\varepsilon_{sh}$ and $\varepsilon_{sw}$). The formula used to calculate these parameters are:

$$I_D = \frac{e_0 - e_{SL}}{w_0 - w_{SL}}$$  \hspace{1cm} (1)

$$I_w = \frac{e_f - e_0}{w_f + w_0}$$  \hspace{1cm} (2)

$$\varepsilon_{sh} = \frac{e_0 - e_{SL}}{1 + e_0} \times 100\%$$  \hspace{1cm} (3)

$$\varepsilon_{sw} = \frac{e_f - e_0}{1 + e_0} \times 100\%$$  \hspace{1cm} (4)

Where, $w_f$ and $e_f$ are respectively the final water content and void ratio obtained on wetting path.

On drying path, the drying index ranges between 0.024 to 0.033 and the shrinkage potential varies between 14.06 % to 22.81 % (table 5). Also, from the data given in table 5, it appears that specimens with higher initial water content expected to shrink more (low drying index and higher shrinkage potential). We note that in this case, the influence of initial dry density is not very clear. However, the normal and the residual shrinkage phases are identified on drying path for all compacted specimens, (figure 6, diagram [w-e]).

On wetting paths, the obtained wetting index range from 0.014 to 0.027, and the swelling potential from 9.37 % to 12.33 % (table 5). The highest values of wetting index are associated to specimens compacted on the wet side, and the lowest are observed on dry side. On the other hand, no tendency is observed between initial water content and swelling potential. However, this last, tends to increase when initial dry density increase.

Table 5. Values of drying index, wetting index, shrinkage and swelling deformation for different initial conditions.

<table>
<thead>
<tr>
<th>Initial conditions</th>
<th>$I_D$</th>
<th>$I_w$</th>
<th>(\varepsilon_{sh}) (%)</th>
<th>(\varepsilon_{sw}) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPO</td>
<td>0.028</td>
<td>0.021</td>
<td>15.43</td>
<td>8.64</td>
</tr>
<tr>
<td>SPO-3</td>
<td>0.032</td>
<td>0.019</td>
<td>14.06</td>
<td>12.33</td>
</tr>
<tr>
<td>98%SPO-3</td>
<td>0.03</td>
<td>0.014</td>
<td>14.8</td>
<td>9.37</td>
</tr>
<tr>
<td>SPO+3</td>
<td>0.024</td>
<td>0.027</td>
<td>16.30</td>
<td>11.38</td>
</tr>
<tr>
<td>98%SPO+3</td>
<td>0.025</td>
<td>0.024</td>
<td>22.81</td>
<td>10.98</td>
</tr>
</tbody>
</table>

The comparison made in table 6 between the swelling index $C_{sw}$, defined as the slope of wetting path in diagram [e-log(S)], calculated for different interval of suction and the swelling index $C_s$, defined as the slope of unloading curve obtained from the free swell oedometer tests, indicate that for suction over than 50kPa, the values of $C_{sw}$ are much lower than the $C_s$ values. Approaching saturation ($S\leq50kPa$), an increase in $C_{sw}$ is observed, but in the most cases, they still be inferior to $C_s$ values. This indicates that the swelling of each sample has not reached its maximum amplitude,
due to the formation of cracks during the processes of hydration (figure 7).

### Table 6. Comparison between Cws and Cs.

<table>
<thead>
<tr>
<th>Initial conditions</th>
<th>Cws</th>
<th>Cs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Suction interval (kPa)</td>
<td>Stress interval (kPa)</td>
</tr>
<tr>
<td>Wetting path</td>
<td>oedometric path</td>
<td></td>
</tr>
<tr>
<td>Si-50</td>
<td>0.0262</td>
<td>0.0647</td>
</tr>
<tr>
<td>SPO</td>
<td>0.0689</td>
<td>0.0647</td>
</tr>
<tr>
<td>SPO-3</td>
<td>0.0363</td>
<td>0.0589</td>
</tr>
<tr>
<td>98% SPO-3</td>
<td>0.0666</td>
<td>0.0824</td>
</tr>
<tr>
<td>SPO+3</td>
<td>0.0193</td>
<td>0.0765</td>
</tr>
<tr>
<td>98% SPO+3</td>
<td>0.0193</td>
<td>0.0765</td>
</tr>
</tbody>
</table>

In other words, following to [9], at this level of suction, the drying path is mainly depends on the specific surface of the clay (mineralogical composition).

![Figure 7. Example of the formation of cracks during wetting.](image)

### 3.3. Drying wetting paths in the high suction range

For all the initial conditions, the drying path appears to be similar at suctions higher than 30 MPa, (w≤10 %), especially in the diagram [w- log (S)], (figure 6). The same result was obtained by other authors: [27], [9] In this range, the changes in water content as a function of the suction can be approximated by a linear equation:

$$ w = -8.10^{-6}S + 9.58 \quad (5) $$

Where S is the suction given in kilopascals . The obtained regression coefficient R, is about the 0.88 (figure 9). Through this, we can say that part of the drying curve of compacted Boughrara clay can be directly deduced by simple measurement of the water content on the dry side of the optimum Proctor. The extrapolation of this conclusion to other materials requires more experimental results.

According to [27], the independence of drying path of initial conditions at low water content, means that the specimens have the same inter-aggregate structure.

![Figure 8. Adjustment of drying path of compacted specimens for suction up to 30 MPa.](image)

### 4. Conclusion

The aim of this paper is to give a simplified overview of the behavior of compacted Boughrara clay on drying wetting paths, and to examine the influence of initial conditions of compaction in terms of water content and dry density in such paths. Some interesting features have been highlighted.

- The shrinkage of compacted clay occurs in two distinct phases: normal shrinkage phase and residual shrinkage phase. The transitions between the two phases correspond to shrinkage limit: $w_{SL}$.
- The linearity of drying and wetting paths was observed, especially in [w-Sr] diagram.
- For the range of water content and dry density studied, the drying wetting paths was found more influenced by initial water content than the initial dry density.
- Specimens with high initial water content tend to shrink more (i.e., high shrinkage deformation, and low drying index).
- On wetting path, the influence of dry density was not clearly defined, and the swelling potential seems to increase with the increase of initial dry density.
- The drying path appears to be independent for initial condition of compaction for high suction range (≥30MPa). At this level of suction, drying path depends mainly on adsorption property of the clay (specific surface).
References


