Hydro-Mechanical Behavior of Compacted Soils with different Compaction Water content

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Abstract: The hydraulic and mechanical properties of clayey soils compacted with similar void ratio are investigated. The soil behavior in terms of swelling properties, compressibility, strength and permeability depend on its structure, which is induced by the compaction process adopted (energy and water content). This behavior is studied through the analysis of mercury intrusion porosimetry tests and scan electron microscope photographs of samples compacted at points near optimum water content increased or decreased by 2% (wet and dry side respectively). Oedometer and triaxial tests, as well as the measurement of the water retention curves are performed in the two types of samples to characterize their hydro-mechanical behavior. Experimental data allowed finding the constants of Barcelona Basic Model (BBM), an unsaturated elastoplastic constitutive model which includes suction as state parameter besides stress. The differences observed in how the soil behaves under stress or suction changes are explained by the different structures induced by the compaction process. These differences were adequately explained, demonstrating and confirming the reasons that lead a designer to prescribe different compaction conditions for road embankments or earth dams.

1. Introduction

The construction process adopted for earth dams or road or railway embankments requires special care because the material is compacted to conform to the specifications prescribed by the designer and indicated in the contract documents. The aim of the specifications is essentially to ensure, indirectly, that strength and compressibility necessary for the proper performance of the earth structure are reached. This is done through the compaction on a given interval, with a given water content and energy, which will give the soil a proper dry weight, therefore a given void ratio that affects the hydro-mechanical properties of the material.

The main purpose of this work was to analyze the hydro-mechanical behavior of the compacted clayey soil used in the construction of the core of Odelouca dam located in Algarve (South of Portugal). Samples prepared at the wet and dry side of the compaction curve were analyzed in order to study the effect of the structure induced by compaction on their hydro-mechanical behavior. Several tests, such as mercury intrusion porosimetry, electronic microscope photographs, Atterberg limits, x-ray diffraction and compaction curve using standard Proctor compaction effort were performed to characterize the material. Oedometer and triaxial tests were performed in samples compacted on the dry and wet side of optimum, therefore prepared with different structures. Structure is how the clay aggregates are disposed and how they are linked.

The results obtained from the several tests were analyzed considering the different structures induced by the compaction process. They allow finding useful conclusions that explain and allow a more rational approach of the importance of the prescription of the compaction interval. In fact, a dam earth embankment is compacted in the wet side of optimum while a road embankment is compacted in the dry side and with high compaction effort. The validity of these general prescription rules can only be performed if concepts of unsaturated soil mechanics are used for civil engineering purposes. The equations defined considering the unsaturated soil behavior are also important to settlements prediction as they describe the behavior of the material under stress and suction changes.

2. Structure induced by the compaction process

For a better understanding of the behavior of compacted clayey soils is important to consider the structure induced by the compaction process of clayey soils. The presence of water influence clay aggregates size and arrangement. This arrangement gives the name of fabric. The structure relates to fabric plus eventual links that can be formed between aggregates.

As shown at Figure 1, the soil behavior in oedometric conditions is different depending on its structure. An unstructured soil usually has larger compressibility than one with some structure. A similar correspondence can be done for strength as this value is larger for structured materials. Both mechanical characteristics will decrease as the greater is the loss of structure.

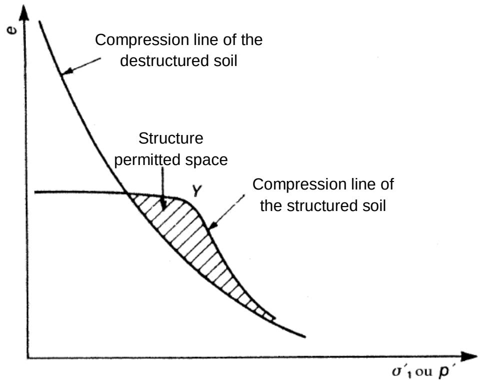


Figure 1 – Comparison between the behavior of completely unstructured soil and soil with some structure (Vaughan *et al.*, 1988)

According to Alonso (2004), the work of Proctor (1933) and microstructural interpretations offered by Lambe (1958) and Seed and Chan (1959) contributed to the creation of a basic reference model that would allow an interpretation of the behavior of compacted soils. In this way, dispersed structures are reached adopting compaction in the wet side, which are characterized by an arrangement of the clay aggregates in a preferred orientation. Otherwise, at the dry side, the clayey particles have a flocculated orientation with small pores and also relatively large pores (Lambe, 1958). The pores due to the arrangement between clayey particles form the macrostructure (large voids). The presence of the clay aggregates are the microstructure (small voids).

Alonso (2004), citing Lambe (1958), states that at the wet side of compaction are reached dispersed structures characterized by an arrangement in a preferred orientation. Otherwise, at the dry side, the clayey particles have a flocculated orientation. The effect of the water content at the particles arrangement is due to the interaction between the electrical charges of water and minerals in the soil. The effect of the compaction in the soil structure is shown at Figure 2.

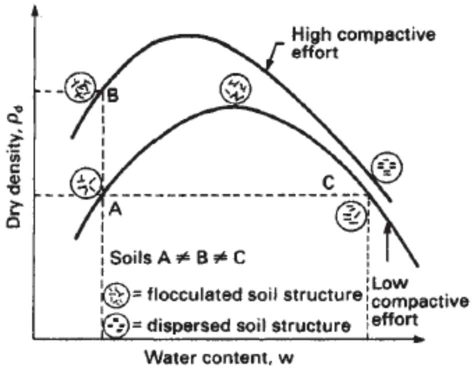


Figure 2 – Compaction effect on soil structure (Lambe, T. W., 1958)

According Mitchell and Soga (2005) there are some engineering principles that relate the soils fabric, their structure and their mechanical properties. Those are the ones who explain the different behaviors of compacted soils at the wet or dry side of the compaction curve. It’s from these characteristics of compacted clayey soils that can be made comments about its mechanical and hydraulic behavior.

3. Hydro-mechanical properties of soils compacted in the dry and wet side of the curve

Compressibility, strength and permeability are extremely important properties and are the main aspects to consider in the design of embankments built with fine soils. The knowledge of the water retention properties is also important to solve transient flow problems. Settlement prediction and long term behavior, in particular, require the knowledge of the swelling properties of the soil as water is exchanged with the atmosphere even if water percolation is not predicted inside the earth structure.

Starting with strength, capillary forces play an important role. They are due to suction, which is large for the soils compacted at the dry side.

Relatively to the compressibility, according to the last paragraph, it’s easy to understand that the soil compacted at the dry side will be more rigid and less deformable than the soil compacted at the wet side. Moreover, for the same suction, yielding stress is larger for the soil compacted at the dry side than for the wet side. This behavior is partly explained by the different structures.

In terms of permeability, this value is slightly larger for the soils compacted in the dry side due to the large voids present induced by compaction. The water retention curve measured in samples compacted at the dry or wet side of the compaction curve is different also due to the structural differences. In fact, at the dry side, due to the biggest amount of large pores, the curve usually goes above the curve for the wet side. In the other side, as the microstructure is almost the same because it is related with the clay aggregate and not its arrangement, the curves for the two sides of the compaction curve are identical for the lower water contents.

Concerning the swell potential of the clayey soil, this property is related with the nature of the clayey minerals, as well as specific surface, cation exchange capacity, ion exchange nature, organic material content and the presence of cementation agent between particles (Mitchell and Soga, 2005). For the compacted materials, the overconsolidation ratio is also important, as well as the void ratio and suction.

Even the low expansive clayey soils like those commonly used in the construction of embankments may suffer volume changes. The amplitude of these deformations depends on the conditions of compaction and on the applied stress suction before wetting. Volume changes can be classified as swelling (increase in volume under low stress) or collapse (decrease in volume under high stress).

It’s understood that the swelling and the collapse are convenient names for a complex process that is controlled by the dry weight and applied stress, which controls voids ratio and soil structure and suction. For high levels in water content the initial suction is very small and the saturation does not introduce significant changes therefore small swell deformations are expected.

Figure 3 shows that volume changes depend on the dry weight induced by compaction process and the applied stress as in points A, B and C, having the same water content but different void ratio. For the same medium confinement stress under which wetting was applied, swell occurs for the denser point A and collapse occurs for the loser point C.

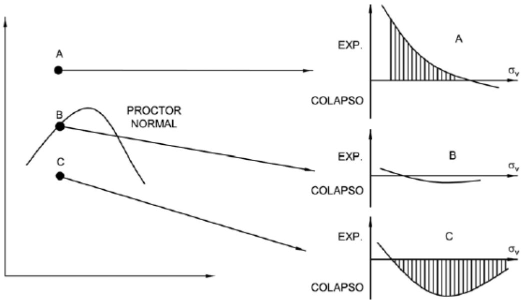


Figure 3 – Volume variation tendency at the soil wetting, according to the dry weight and applied stress (Alonso, 2004)

4. Experimental characterization of the compacted material

4.1 Physical characterization of the material and samples preparation

The material studied in this work consists in the clayed soil used at the Odelouca dam core. The main characteristics of the soil are presented for a better comprehension of its behavior when compacted at the dry or wet side of the compaction curve and subjected to stress and suction changes.

X-ray diffraction showed that Kaolinite is the predominant clay mineral, non-expansive and responsible for the plastic properties of the material (LL=53%, IP=22%). The compaction curve was determined in order to settle de maximum volumetric dry weight and the corresponding optimum water content (Figure 4). In spite of all cautions taken during the setup of the oedometer tests, the points obtained are not those intended initially (optimum ± 2%) (Figure 4). The justification is given by Reis (2010).

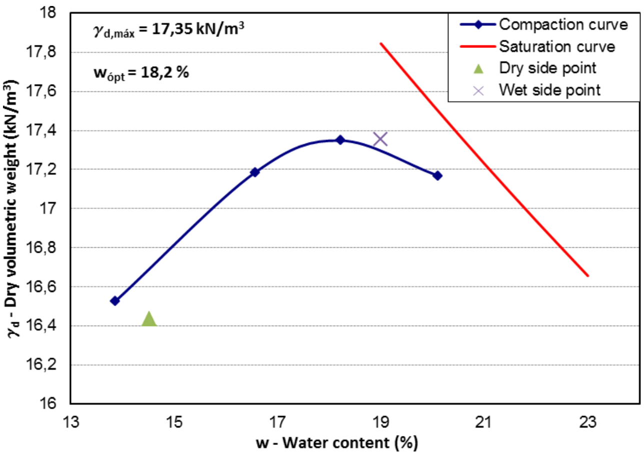


Figure 4 – Soil compaction curve and points studied in the oedometer tests

4.2 Structure for the compacted samples

Several laboratorial tests were performed to analyze the effects of structure induced by the compaction procedure on the hydro-mechanical behavior of the compacted material. As mentioned before, the samples were compacted at points near optimum water content increased or decreased by 2% (wet and dry side respectively). Mercury intrusion porosimetry tests (figure 5), scanning electron microscope (SEM) photographs (Figures 6 and 7) and water retention curves (Figure 8) were performed in order to get important information about the soil structure.

The porosimetry tests results (Figure 5) show that the soil compacted at the wet side (with a dispersed structure) has only peak at small diameters. On the other hand, the soil compacted at the dry side (flocculated structure) has two peaks, one for dimensions next for those found in the wet side and other for larger pores. This result is consistent with a soil having double structure. Finally, the porosimetry performed on a destructed sample (prepared with water content $w = 1.5 \times \mathrm{LL}$), shows only one peak near the dimension of the small pores found for the other two samples. This confirms that the small peak diameter is the dimension of the pore of the clay aggregates. Structural differences are evident in the comparison between the SEM photographs for samples compacted at the wet (Figure 6) or dry side (Figure 7).

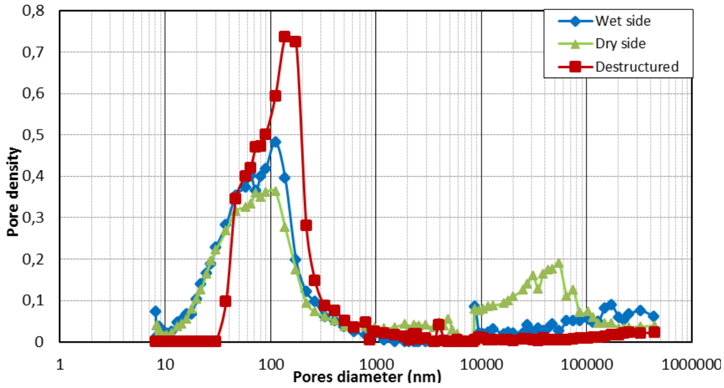


Figure 5 – Comparative analysis of the porosimetries

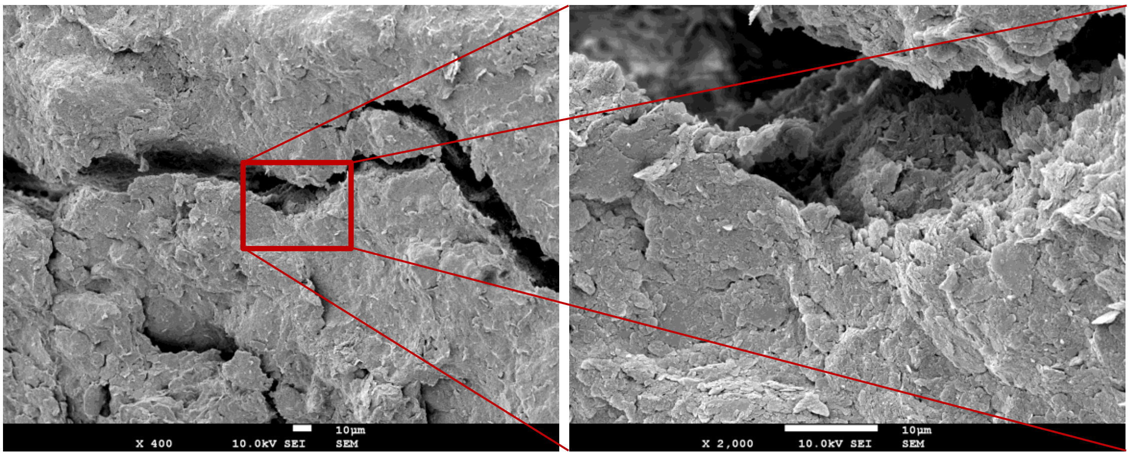


Figure 6 – Wet side electronic microscope picture

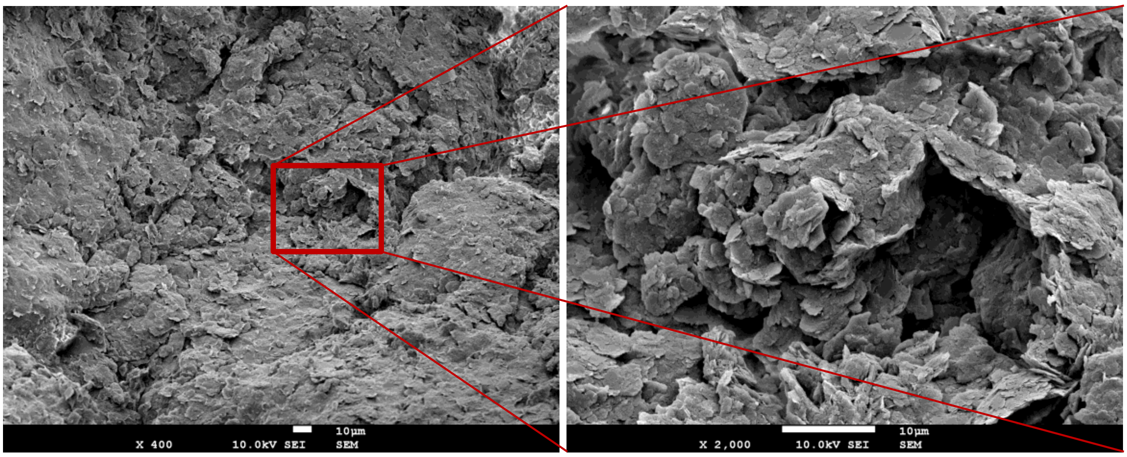


Figure 7 – Dry side microscope picture

Finally, the differences on the water retention curves allow to conclude the investigation on the different soil structures. As shown at Figure 8 the retention curves geometry are different for the two cases. As expected due to the larger pores, the saturation water content (Table 1) is higher for the sample compacted at the dry side. For the low water contents the retention curves are similar for both cases. This is because the shape of the curve depends on the water retained in the micropores for the high suctions and for the low suctions it depends on the water retained in the macropores (Romero et al., 1999).

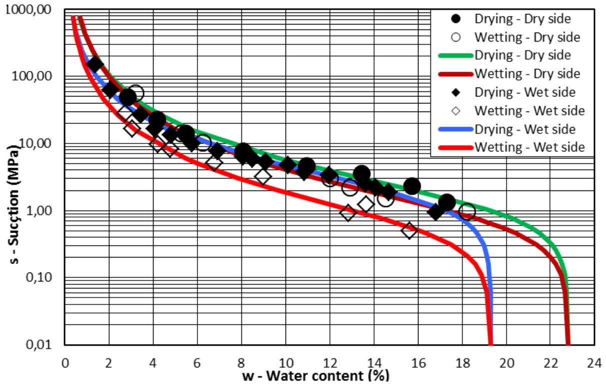


Figure 8 – Dry and wet side retention curves

Equation (1) was used (Van Genuchten, 1980) to fit the retention curves, where S_r is the saturation, s is suction and P and λ are fitting parameters presented in Table1.

$$S_r = \left[1 + \left(\frac{s}{P}\right)^{\frac{1}{1-\lambda}}\right]^{-\lambda} \tag{1}$$

Table 1 – Retention curve adopted parameters

	Drying		Wetting		Saturation water content (%)
	P (MPa)	λ	**P** (MPa)	λ	
Wet side	1,99	0,40	0,65	0,36	19
Dry side	1,40	0,36	0,87	0,34	23

4.3 Oedometric tests

The volumetric behavior and the constants for BBM calibration were obtained from data from the oedometric tests performed. Suction was controlled during the tests by using vapor equilibrium technique (Reis, 2010). The samples were compacted at points near the optimum water content ± 2% (Figure9) (approx. void ratio $e = 0.53$) but, due to the preparation process, higher ratio voids were obtained as shown later at Table 2. Figures 9 and 10 illustrate the results of the oedometers tests at the $(e, \log \sigma)$ plane for the wet and dry side of optimum, respectively. As explained at Reis (2010), probably the intermediate suction of 39 MPa, corresponding to 75% relative humidity, is a high value and near the maximum value applied which was 85 MPa (55% relative humidity). For these two suctions the soil is very stiff and eventually the yielding stress was not reached during loading process. As simplification it was assumed that the yielding surface in the (s, p) plane between the suctions corresponding to these two relative humidities is vertical. This way, the three samples tested were treated as saturated or unsaturated. The compressibility index Cc, the swelling index Cs and the yielding stress found are presented in Table 2. The average void ratio from the specimens' preparation is also in this table.

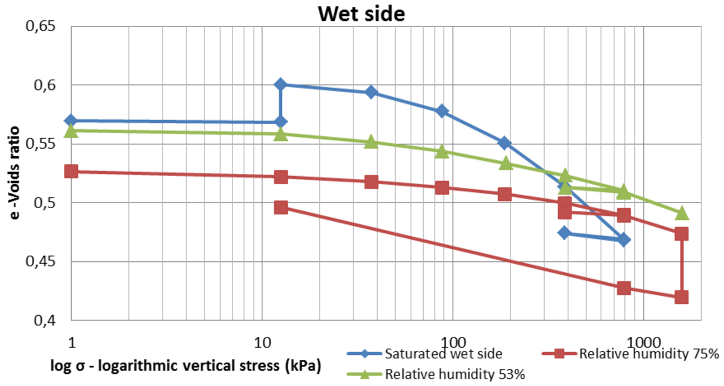


Figure 9 –Oedometers test at the plane ($e, \log \sigma$) plane – wet side of optimum

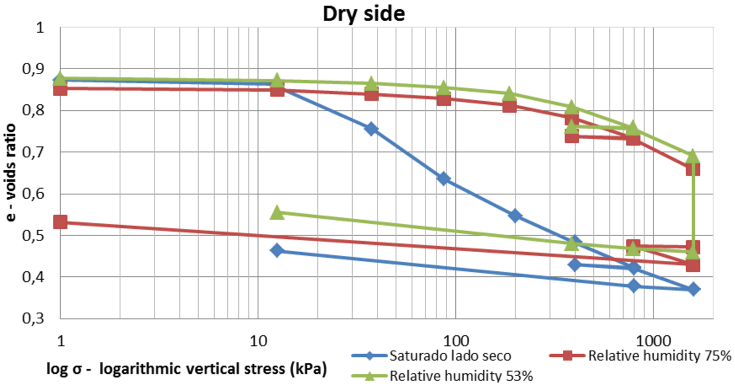


Figure 10 – Oedometers test at the plane ($e, \log \sigma$) plane – dry side of optimum

Table 2 – Assumed oedometer tests parameters

	Wet side (e = 0,552)			Dry side (e = 0,867)		
	C_S	**C_C**	σ_y (kPa)	**C_S**	**C_C**	σ_y (kPa)
Saturated soil	0,020	0,15	121	0,030	0,24	14
Unsaturated soil	0,010	0,05	203	0,015	0,22	270

For each side of the curve, as expected, the compressibility increases with the increment of the water content because higher values were found for the saturated specimens when compared with those of the unsaturated The comparison between the results of the two sides of the curve is not straightforward as it is affected by the high void of the samples prepared at the dry side of the curve. For these last, collapse was measured on full saturation under low vertical stress and is explained by the destruction of the aggregates arrangement. This mechanism explains the higher compressibility of these samples when compared with the values measured for the samples compacted in the wet side. The loss of structure induced by full saturation is confirmed in the comparison of the behavior of the saturated samples with the one observed in a destructed sample (Reis, 2010).

The high void ratio of the samples compacted at the dry side also explains the small yielding stress measured in full saturated conditions. For the unsaturated samples the results are the expected as higher yielding stress was measured for the specimens compacted in the dry side. For this reason the elastic domain is higher at the dry side.

Finally, the permeability was measured indirectly (Reis, 2010) from the oedometric results. Lower values were found for the specimen compacted at the wet side, which is explained by its disperse structure (only micropores).

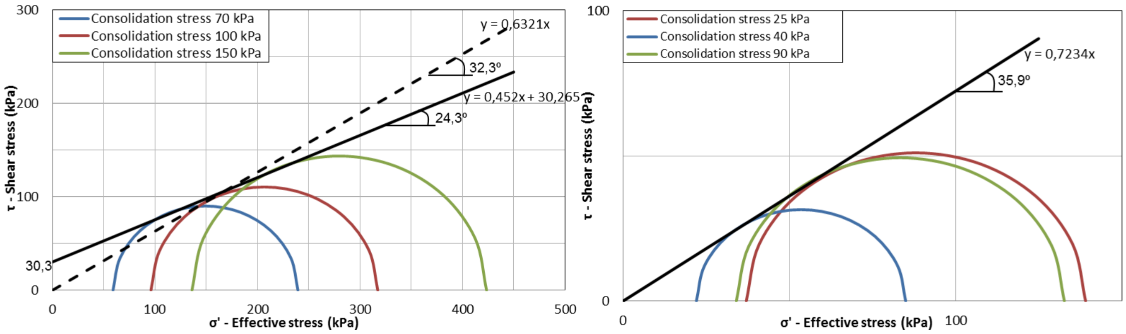
4.4 Triaxial tests

The saturated shear strength parameters of samples compacted at the wet or dry side of the compaction curve (optimum ±2%) were measured in undrained consolidated triaxial tests.

Ductile behavior was observed, as shown in Figure 11. This way, the shear surfaces of the samples were corrected to give a better value of the applied stresses.

Figura 11 – Samples after consolidated undrained tests

Figure 12 shows the results found for the specimens compacted in the wet (a)) or dry (b)) side of optimum (Reis, 2010). Shear strength angles and apparent cohesion found to define Mohr Coulomb envelope are in Table 3.



a) **b)**

Figure 12 – Mohr-Coulomb envelope (critical state line, CSL) of the wet (a)) and dry (b))side compacted samples

As shown in Table 3, the apparent cohesion of the wet samples is considerable. In fact, due to the critical state theory, it should be zero because, at critical state, all links between particles are broken. In other words, this theory says that at shear failure the structure induced by compaction process is destructed. Therefore, this apparent cohesion corresponds to the tests error (more details in Reis (2010)). Assuming that the cohesion doesn't exist, the shear strength angle is approximately the same and its value is also in Table 3.

Table 3 – Shear strength parameters for the compacted samples, considering area correction

	Envelope not passing in the origin		Passing in the origin
Area correction	c' (kPa)	ϕ'(º)	ϕ' (º)
Wet side	30,3	24,3	32,3
Dry side	0,8	35,3	35,9

However, Wheeler and Sivakumar (2000) refer that structure affects shear strength parameters. The authors refer that the destructuration may not be complete or maybe different to samples compacted at the wet or dry side of the compaction curve. The authors also say that at the dry side, due to the double structure, the macro pores are easily destroyed while the micropores may not reach a critical state. Only the micropores are destroyed in the samples compacted at the wet side therefore the differences observed are explained. For this reason the authors say that the same soil compacted with different water contents must be studied separately, in other words, dry or wet side compacted samples behave differently and should be considered different materials. Further details can be found in Reis (2010).

5. Calibration of the BBM

Barcelona Basic Model, BBM, is an elastoplastic constitutive model, formulated to consider the suction at soils behavior (Alonso, et al., 1990)

The oedometric tests performed allowed finding the parameters of the loading collapse curve of the Barcelona Basic Model (Eq. 2): isotropic yielding stress saturated and unsaturated p_0^* and p_0, respectively, the reference isotropic stress pc, the saturated and unsaturated compressibility indexes in isotropic loading $\lambda(s)(s = 0$ for the full saturated case, given by Eq. 3 where r and β are constants) and the elastic compressibility κ. The parameters are in Table 4 and the curves are in Figure 14.

$$\left(\frac{p_0}{p^c}\right) = \left(\frac{p_0^*}{p^c}\right)^{\frac{\lambda(0)-\kappa}{\lambda(s)-\kappa}} \qquad (2)$$

$$\lambda(s) = \lambda(0)\left[(1-r)e^{-\beta s} + r\right] \qquad (3)$$

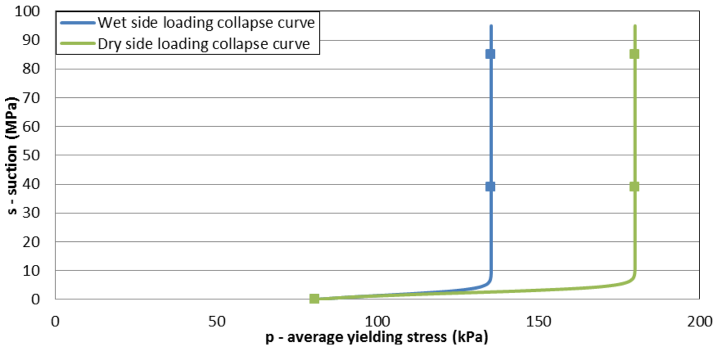


Figure 14 – Barcelona Basic Model estimated loading collapse curves

As shown by Reis (2010), adopting to the dry side the same average saturated yielding stress used to the wet side, the curve has parameters values more realistic that correspond to the ones presented at bibliography (Alonso & Pinyol, 2008).

Finally, the saturated triaxial tests allowed finding the slope of the critical state line, which depend on the shear strength angle ϕ'. No tests were performed to find the rate of increase in tensile strength with suction.

Table 4 – Adopted values to Barcelona Basic Model calibration

	Wet side	Dry side
$\boldsymbol{\kappa}$	0,0044	0,0065
$\boldsymbol{\lambda(0)}$	0,0652	0,1044
$\boldsymbol{p_0^*}$(kPa)	80,7	80,7
$\boldsymbol{p^c}$(kPa)	61,7	70,3
$\boldsymbol{r}$	0,2988	0,1996
$\boldsymbol{\beta}$	0,999	0,999
$\boldsymbol{\phi'}$ (º)	32	36

6. Conclusions

The laboratorial tests performed allowed to study the hydro-mechanical behavior of a clay soil compacted with different waters contents and analyze the differences between both when subjected to loading or suction changes. Lower compressibility was found for the material compacted at the wet side of the curve but higher unsaturated yielding stress and saturated shear strength were found for the specimens compacted at the dry side. The results reflect the different structures induced by the compaction process.

Some practical considerations can be done based on the results found considering the construction of road embakements or earth dams. The first have efficient drainage infrastructures therefore the water content of the soil should remain practically unchanged. For this reason the designer may prescribe a compaction interval at the dry side in order to get better shear strength and stiffness. However, important volumetric behaviors may occur in case of wetting having bad consequences to the geotechnical structure.

For earth dams the compaction is prescribed to be at the wet side of the curve. It ensures strength and stiffness necessary, as well as ductile behavior. In this case the soil will be saturated or may be subjected to wetting-drying cycles, which also has a waterproofing function. The compaction in this interval reduces volumetric deformations on wetting because suction changes are less significant.

Finally, at the wet side the soil is also more plastic, assuring more flexibility and zoned embankments may strain without cracking.

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