Degradation of compacted marls. A microstructural investigation.

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ABSTRACT
Marls are classified as hard-soil/soft rocks and exhibit a typical evolutive behaviour since their mechanical and hydraulic properties change due to alternate wetting-drying cycles as well as to other weathering processes. Crack opening and/or loss of bonding are associated with these processes, having in general negative impact on the strength and compressibility of the material.

Embankments made with marls and other soft clayey materials result in an agglomerated structure of rock fragments. However, the grading size of these materials evolves resulting in relevant modifications of the overall behaviour of the aggregate. Settlements and loss of strength are the main concerns in practice and require suitable constitutive and computational models to predict these phenomena.

This paper presents a micromechanical study where the evolution of Jurassic marls (Arruda dos Vinhos, Portugal) is simulated considering concepts of unsaturated soil mechanics. In fact, wetting and drying cycles, controlled by atmospheric changes, are probably one of the main factors of rock degradation.

The mechanisms leading to the breakage and eventually the destructuration of rock particles are investigated. Numerical simulations of the behaviour of individual rock fragments submitted to suction cycles were performed, where several contributing factors (wetting rate, initial suction and confinement) have been analysed.

The results obtained provide an interesting insight into the nature of degradation induced by wetting and drying. They give also some light about the overall mechanical behaviour of the aggregates (compacted material).

Key-words: marl, weathering, embankment, suction, degradation mechanism.

1 INTRODUCTION

Marls are classified as hard-soil/soft rocks and exhibit evolutive behaviour mainly associated to crack opening and/or loss of bonding. These processes usually have negative impact on the strength and compressibility of this type of material.

There are increasing number of studies on the evolution of the mechanical behaviour of materials such as shales and other soft sedimentary rocks (mudstones, claystones, calcarenites and weak limestones) (Leroueil and Vaughan, 1990, Gens and Nova, 1993, Vaughan, 1997, Rouania and Muir Wood, 2000, Vaunat and Gens, 2003, Pinyol et al., 2007, among others). However, very few studies are known to exist concerning the behaviour of aggregates of these materials.

This paper examines the physical phenomena controlling the evolutive behaviour hard-soils/soft rocks when compacted and used for embankment construction in particular. In fact, embankments made with marl and other soft clayey rocks result in an agglomerated structure of finite size particles (just as in a rockfill). However, these particles evolve and result in major changes of the overall behaviour of the aggregate.

Common compaction practices do not avoid the consequences of the evolutive behaviour of the aggregates, since the fragment sizes after the compactation (Figure 1) still allows the development of settlements and the loss of strength in time. These evolutive phenomena are the main concerns in practice and their prediction is not easy and requires suitable constitutive and computational models.

Wetting and drying cycles controlled by atmospheric changes which result in strong changes in suction are probably one of the main reasons for rock degradation. Therefore it was considered appropriate to introduce concepts associated with the mechanics of unsaturated soils to investigate the causes of the degradation, mainly associated to
particle breakage due to crack opening and other degradation phenomena.

This paper presents a microstructural approach of the problem since the behaviour of aggregates of marl particles (compacted material) is analysed by investigating the evolutive behaviour of individual rock fragments. The mechanisms leading to the breakage and eventually to the destructuration of single rock fragments are investigated and used to describe the behaviour of aggregates of particles (compacted material) observed in experimental tests presented in this paper.

2 HYDRO-MECHANICAL BEHAVIOUR OF ABADIA MARLS

2.1 Marl matrix

The material under investigation comes from Abadia Formation (Upper Jurassic, Arruda dos Vinhos, Portugal) (Jeremias, 2000). Mineralogy analysis showed the presence of chlorite and gypsum, besides quartz, CaCl2 and mica. Some of its most relevant properties are a porosity of 37% for in situ water content of 17% (saturation degree of 77%), liquid limit (LL) of 49%, plastic index of 25% and volumetric weight of 27.4kN/m^3.

The photographs of marl fragments before and after wetting presented in Figure 2 show the degradation phenomena of an unconfined set of particles with uniform size (dimensions between 9mm and 4.75mm (ASTM sieves #3/4 and #4)) subjected to one wetting-drying cycle at laboratory environment (T=20ºC±5ºC and HR=45%±10%). The water content before wetting was 9% (approx. 10MPa, according to the water retention curve of the material). Similar behaviour was observed for materials with different initial water content. The observed degradation was higher for drier fragments.

As observed in Figure 2, wetting causes particle breakage and the destructuration of the smallest particles. Figure 3 shows the grade size evolution along eight wetting-drying cycles of the uniform size material presented in Figure 2. It can be observed that a strong size reduction occurs just after the first wetting. It can also be observed that the biggest sizes are the most affected by wetting.

Special attention was given to the characterization of the hydro-mechanical behaviour of the marl, namely to the influence of suction changes in its volumetric behaviour. In fact, volume (or void ratio) and water content are strongly related, as presented in Figure 4.

Swelling tests in oedometric conditions of rock samples under different vertical stresses and with different initial suctions were performed. The results of the tests are presented in Figure 5, as well as the

Fig. 1 – Abadia marls used for embankment construction.

Fig. 2 – Particle breakage and destructuration observed on uniform-size particles (9mm≥D>4.75mm) along a wetting-drying cycle.

Fig. 3 – Size evolution along 8 wetting-drying cycles of a set of particles with uniform size (9mm≥D>4.75mm).

Fig. 4 - Void ratio dependence on water content.

Swelling tests in oedometric conditions of rock samples under different vertical stresses and with different initial suctions were performed. The results of the tests are presented in Figure 5, as well as the
vertical stresses applied and suction paths. As expected, independently of the vertical stress applied, the tests performed showed higher volumetric deformations for the driest samples. The smaller swelling strains were observed for the higher vertical stresses.

![Graph showing swelling strain vs. vertical stress](image)

Fig. 5 – Results of swelling tests on laterally confined rock samples (rock disks with 5mm high and 30mm diameter) under different vertical stresses and with different initial suction.

The water retention curve (WRC) is presented in Figure 6. It was fitted by Equation (1) (Van Genuchten, 1980), where $S_e$ is the saturation degree at the current liquid pressure, $P_h$, $P_g$ is the gas pressure (assumed to be the atmospheric pressure, 0.1MPa), $P$ is the pressure corresponding to the air entry value and $\lambda$ is a fitting parameter. It was obtained $P=0.3$MPa and $\lambda=0.20$, for the drying branch, and $P=0.9$MPa and $\lambda=0.20$ for the wetting branch.

$$S_e = \left[1 + \left(\frac{P_g - P}{P_h}\right)^{\lambda}\right]^{-\lambda} $$

(1)

![Graph showing water retention curves](image)

Fig. 6 – Water retention curves of marl from Abadia Formation.

With the data presented in Figure 4 and the WRC presented in Figure 6, the value of 0.020 was obtained for $\kappa_s$, the elastic stiffness parameter for changes in suction. The intrinsic permeability coefficient of the marl is $8\times10^{-21}$ m². Brazilian splitting tests and unconfined compression tests were performed in marl samples under different suctions. The experimental data allowed calibrating the numerical model, as will be mentioned later in this paper.

### 2.2 Compacted samples

Suction controlled tests on compacted aggregates of marl were performed in oedometer cells. All the samples tested were compacted in similar conditions ($e=1.078\pm0.005$, $w=15\%\pm2\%$), adopting uniform size of particles in order to speed up the suction imposition by vapour equilibrium. The protocol followed for these tests included drying under a small vertical load ($\sigma_v=50$kPa) for suction applied by standard salt solutions (OIML R 121, 1996), loading and finally saturation at $\sigma_v=600$kPa. According to the WRC of the rock matrix (Figure 8), the initial suction was approximately 3MPa. Test results are presented in Figure 7 and Table I.

![Graph showing suction controlled oedometric tests](image)

Fig. 7 - Suction controlled oedometric tests of marl aggregates for different initial suctions.

Table I – Results of suction controlled oedometric tests of marl aggregates ($e=1.078\pm0.005$, $w=15\%\pm2\%$).

<table>
<thead>
<tr>
<th>Suction of the test (MPa)</th>
<th>Compres. index, Cc</th>
<th>Volume decrease due to drying (%) (1)</th>
<th>Collapse due to full wetting (%) (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>230</td>
<td>0.095</td>
<td>3.9</td>
<td>20.4</td>
</tr>
<tr>
<td>38</td>
<td>0.379</td>
<td>3.4</td>
<td>15.7</td>
</tr>
<tr>
<td>12</td>
<td>0.394</td>
<td>1.3</td>
<td>13.9</td>
</tr>
<tr>
<td>3</td>
<td>0.536</td>
<td>--</td>
<td>9.7</td>
</tr>
</tbody>
</table>

(1) initial suction $s=3$MPa, vertical stress, $\sigma_v=50$kPa

(2) after saturation (final $s=0$MPa), $\sigma_v=600$kPa

Tests results show that the compressibility of the compacted samples of marl decreases with increasing suction. A similar behaviour is exhibited by rockfills and can explained as a crack propagation phenomenon with cracking speed increasing with water content, as if water would act as a corrosive agent (Oldecop and Alonso, 2003). Test results also show that marl aggregates and
rockfills have similar behaviour on the high suction range (deformation is mainly explained by particle breakage). However, as the suction decreases, the observed response becomes similar to a clay soil. In fact, as presented in Figure 8 the compressibility of the saturated marl aggregates (Cc=0.141) is similar to the one of the reconstituted sample prepared with water content w=1.35LL (Burland, 1990) This result indicates that wetting leads not only to particle breakage but also to strong destructuration and is consistent with the observed along the wetting-drying cycle of marl fragments previously presented in Figure 2.

2.3 Microstructural behaviour of compacted samples

The experimental results on compacted samples (Figure 7 and in Table I) can be analysed under the light of microstructural behaviour of the single fragments of marl:

- volume decrease caused by drying are higher for higher suctions applied to the compacted material. This is due to volume decrease of each particle when dried, as can be seen in Figure 4;
- collapse is associated with saturation. Particle breakage and rearrangement of the broken fragments explain the global volume decrease observed (see Figures 2 and 3);
- the compressibility of the saturated compacted material and reconstituted material are similar (Cc=0.141). This is due to the degradation suffered by the smallest fragments. The causes of this degradation are probably the decrease in suction and also the high tensions applied to the compacted samples before saturation.

Finally, the drier samples exhibit higher collapse when saturated due to cracking mechanisms, as will be explained in the next section.

3 DEGRADATION MECHANISMS

A possible explanation of the degradation mechanisms of marl fragments is schematically presented in Figure 9. When wetting occurs the exterior perimeter is wetted first than the interior of the fragment, consequently, a differential of suction is created, defined as the difference between the zero suction (saturation) in the exterior border and the initial suction in the interior of the fragment, sinitial. This suction differential reduces in time until reaching zero when the fragment becomes saturated. Suction differential inside the fragment gives origin to differential swelling deformations, leading to stress tension and shear stresses, therefore to cracking and destructuration.

![Degradation mechanism due to differential suction inside a rock fragment.](image)

Probably relevant damage would not occur if the swelling deformations occurred simultaneously. The behaviour observed along saturation of marl fragments with different initial suctions (Figure 5) agrees with this mechanism because the driest fragments had shown more pronounced reactions (higher swelling if in single fragments and higher collapse if in aggregates of fragments). This experimental evidence indicates that numerical simulations of the behaviour of individual rock fragments submitted to suction cycles can help to understand the mechanisms leading to the breakage and eventually the destructuration of one single rock particle. They can also be useful to make known the mechanical behaviour of aggregates of particles.

4 NUMERICAL MODEL

It was intended to investigate the degradation mechanism of the marl fragments when saturated. Numerical simulations of individual fragments of rock submitted to suction cycles were performed, where wetting was imposed from the entire exterior perimeter. For simplification it was adopted a
circular geometry (9mm diameter) as well as a plane deformation condition. Figure 10 presents the finite element mesh used.

A coupled hydro-mechanical computational model (CODE_BRIGHT, Olivella et al. 1996) was used adopting the Barcelona Basic Model, BBM (Alonso et al., 1990), as constitutive mechanical model. The hydraulic constitutive equations considered the balance of water in the liquid and gas phases, adopting Darcy’s law in the calculation of the conductive flux and Fick’s law in the calculation of the diffusive and dispersive fluxes. The intrinsic permeability was calculated by Kozeny’s model and for the definition of the WRC Eq. (1) was used. The model was calibrated with the results of tests on marl matrix samples previously presented. Table II presents the parameters adopted for its calibration.

Figure 11 presents the confinement cases considered in the study. They intend to represent realistic confinement cases of single rock fragments when aggregated in compacted samples.

Several contributing factors were investigated in this study, namely the influence of wetting rate and the effects of the initial suction and of the confinement. The consequences of wetting-drying cycles for particle degradation were also investigated.

Since fracture is not incorporated in the numerical model adopted, crack development will be identified by the pattern of tension developed in the fragment (according to the sign convention of Code Bright, positive stress corresponds to tension) and by the pattern of plastic deviatoric deformation, \( \delta \varepsilon^p \), and of plastic volumetric deformation, \( \delta \varepsilon^v \). The net mean stress computed corresponds to total stress assuming unsaturated material.

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Table II – Parameters for model calibration.

<table>
<thead>
<tr>
<th>Constitutive model</th>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BBM</td>
<td>( \lambda(0) )</td>
<td>Stiffness parameter for changes in net mean stress for virgin states in saturated conditions</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>( \lambda(s) )</td>
<td>Stiffness parameter for changes in net mean stress for virgin states</td>
<td>( \lambda(s) = \lambda(0) [1 - r] e^{-\beta \lambda} + r )</td>
</tr>
<tr>
<td></td>
<td>( r )</td>
<td>Parameter defining maximum stiffness</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>( \beta )</td>
<td>Parameter controlling the rate of stiffness increase with suction</td>
<td>0.05MPa(^{-1})</td>
</tr>
<tr>
<td></td>
<td>( \kappa )</td>
<td>Elastic stiffness parameter for changes in net mean stress</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td>( \kappa_s )</td>
<td>Elastic stiffness parameter for changes in suction</td>
<td>0.020</td>
</tr>
<tr>
<td></td>
<td>( p_0^* )</td>
<td>Pre-consolidation stress for saturated conditions</td>
<td>0.05MPa</td>
</tr>
<tr>
<td></td>
<td>( p' )</td>
<td>Reference stress</td>
<td>0.01MPa</td>
</tr>
<tr>
<td></td>
<td>( M )</td>
<td>Slope of the critical state lines</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>( K )</td>
<td>Parameter describing the increase in cohesion (apparent) with suction</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>( c_0 )</td>
<td>Tension resistance for saturated conditions</td>
<td>0.005MPa</td>
</tr>
<tr>
<td></td>
<td>( \nu )</td>
<td>Poisson coefficient, used in the calculation of shear modulus, ( G )</td>
<td>0.25</td>
</tr>
<tr>
<td>WRC</td>
<td>( P_g )</td>
<td>gas pressure (assumed to be equal to the atmospheric pressure,)</td>
<td>0.1MPa</td>
</tr>
<tr>
<td></td>
<td>( P )</td>
<td>pressure corresponding to the air entry value</td>
<td>0.3MPa (drying branch) 0.9MPa (wetting branch)</td>
</tr>
<tr>
<td></td>
<td>( \lambda )</td>
<td>fitting parameter</td>
<td>0.20 (independently from the branch)</td>
</tr>
<tr>
<td>Permeability</td>
<td>( k )</td>
<td>Intrinsic permeability</td>
<td>( 8 \times 10^{-21} \text{ m}^2 )</td>
</tr>
</tbody>
</table>
5 RESULTS

5.1 Influence of the suction change rate

The suction change rate can be assumed to be the relation between a suction variation and the time necessary for it to occur. It was modelled by imposing a fixed time for the occurrence of a suction variation on the exterior perimeter.

For the saturation of the fragment (suction $s=0$ MPa), assuming constant initial suction on the material, the suction change rate will depend, inversely, on the wetting time adopted. The wetting time must assure the saturation of the fragment. For Case 1 (Figure 11), assuming an initial suction of 10 MPa, three different rates were analysed adopting 15, 30 and 60 minutes for wetting time. The saturation of the fragment was achieved in all cases.

Figure 12 presents the results obtained for point A (identified in Figure 6). It can be observed that the highest tensions occur when the wetting time is 15 minutes. Analogous results were found for the plastic shear deformations developed at this point. A similar pattern was obtained on the other points besides point A.

![Diagram](image)

Fig. 12 – Effect of wetting time in crack development (Point A identified in Figure 11 for Case 1). Tension identified by positive values of principal stress, $\sigma_I$.

The results presented confirm that damage depends on the value of the differential of suction in the fragment.

In further analysis the wetting time adopted was 15 minutes and the initial suction was 10 MPa. Those values are assumed to be realistic if the marl permeability has the value presented in Table II.

5.2 Influence of the initial suction

Wetting under different initial suctions was analysed to verify the influence of the initial suction on the degradation. The initial suctions considered were 20 MPa, 10 MPa and 5 MPa and wetting was simulated with the same velocity. Tension cracking (positive stress, $\sigma_I$) and plastic shear deformations were compared for all cases and are presented in Figure 13 for point C in Case 1. Similar results were obtained for the other points.

![Diagram](image)

Fig. 13 – Effect of initial suction on the conditions for cracking development (Point C - Case 1).

The results confirm that dryer samples exhibit more severe damage because in the driest fragments tensions and plastic deformations are higher (Figure 13). These results are in accordance with experimental data obtained on the tests on compacted samples since the driest material exhibited the highest collapse.

5.3 Identification of cracking threshold

The cracking threshold of the fragment was analysed considering tension and plastic deviatoric deformations developed along wetting time. Confinement Case 1 was chosen since it does not affect swelling displacements, allowing a better understanding of the cracking mechanism. Stresses $\sigma_I$ developed along wetting are presented in Figure 14. Inside the fragment (points B, C and D) it can be seen tension (positive value) development during wetting time, followed by compression (negative value) as soon as full saturation is reached. In the perimeter (points A and D) only tension is observed but only after saturation.

Cracking will occur if stresses installed are higher than the tension strength. This strength is minimum when the fragment is saturated and it is in this same situation that the tension reaches the maximum values. This indicates a strong cracking potential
when the fragment is saturated. The vectors corresponding to the maximum principal stresses allow the identification of the cracking pattern. The plastic shear deformations show higher values in the perimeter, indicating shear damage concentration mainly in the exterior perimeter.

![Graph showing time evolution of maximum principal stress](image)

**Fig. 14** – Time evolution of the maximum principal stress, \(\sigma_1\), inside the particle for the identification of the cracking mechanism (Case 1) - points A, B, C, D and E, identified in Figure 6.

![Diagram showing damage pattern](image)

**Fig. 15** – Damage pattern identification (Case 1).

The analysis performed shows swelling starting from the perimeter into the interior. Tensions appear in the inner part of the fragment while the volume is increasing in the outer zones, as if the exterior layers were pulling the interior material. This mechanism leads to stress conditions that allow peripheral detachment as can be seen at 15 minutes after wetting (Figure 15 a). When the water reaches the interior zone it starts swelling, pushing the exterior layers. This mechanism corresponds to radial cracking (Figure 15 b) for instant 5 hours after wetting. The plastic shear deformations are observed in the exterior perimeter, indicating shear cracking in the entire periphery of the fragment.

These results are in accordance with the expected degradation mechanism previously presented in Figure 9 and with experimental evidence of fragments degradation presented in Figure 2.

### 5.4 Influence of confinement

The confinement cases analysed were previously presented in Figure 11. For all cases, the initial suction was assumed to be 10MPa. The degrees of freedom of the displacements diminishes from Case 1 (almost inexistent) to Case 3 (symmetric in both directions in plane (x,y)).

The displacements obtained are presented in Figure 16. As expected, the increasing confinement reduces the amplitude of the maximum displacements and the degree of symmetry affects their global direction.

**Fig. 16** – Displacements (scale factor=5) and maximum value \((t=10h)\) for each confinement case (location identified with a circle).

As mentioned before, as soon as wetting starts \((t<0.25h)\) and when the borders are not confined, the displacements can develop from inside to outside (swelling). In this case the exterior zone pulls the interior of the fragment. When it becomes saturated \((t\geq0.25h)\) it starts swelling pushing the outer zone. Porosity increases in all points, plastic volumetric deformations correspond to volume increase and net
mean stress decreases because swelling displacements are free. This behaviour, illustrated in Figures 17 and 18, was observed in Case 1 and in the points placed in the vertical alignment G-C (Figure 11) for Case 2 (the displacements are free in this direction).

However, if constraints exist, the displacements can only develop from outside to inside, pushing the interior zone. Porosity decreases in all points, plastic volumetric deformations correspond to volume decrease and net mean stress increases. This effect is more evident near the confined borders. But when water reaches the interior of the fragment (t ≥ 0.25h) it starts swelling, pushing the outer zone. As presented in Figure 17, porosity increases in the interior and keeps decreasing in the exterior. The plastic volumetric deformations obtained presented in Figure 18 are in accordance with porosity changes. Net mean stress decreases in the interior and increases in the exterior. However, the porosity increment in the centre is limited due to the confinement introduced by the outer zone.

Figure 19 presents, for all cases, the pattern of plastic volumetric deformations. This figure also presents the pattern of plastic shear deformations. It can be observed that plastic deformations are higher near the restrained borders.

The existence of plastic deformations indicates yielding. The stress path in space (p, q, s) presented in Figure 20 for points C in Case 1 shows that the yielding point corresponds to maximum shear stress and occurs when the material is saturated (t = 0.25h). It is a complex stress path with variable shear and net mean stress.

Figure 21 shows the stress paths in plane (p, q) obtained for point C for all cases analysed. It can be observed that the highest values of the deviatoric stress are reached for Case 3 (high degree of restrain). Hardening can also be observed in point C for Case 3 and can be explained by the compression
introduced by the volume decrease due to the restrictions.

According to Figure 23, the plastic volumetric deformations increase with the number of wettings. However the most severe changes occur after the first wetting. This result was expected and is a consequence of using BBM as a mechanical constitutive model.

6 CONCLUSIONS

The analyses performed had shown the development of definite patterns of tension and plastic deformation during wetting and drying processes. These patterns allowed the identification of the degradation mechanism of fragments of marl. Those mechanisms are mainly due to the differential suction inside the fragment developed along wetting and allows the development of differential swelling deformations, leading to tension development and consequently to cracking.

Experimental results on compacted samples were analysed under the light of the microstructural behaviour of the single fragments of marl. The main conclusions concerning the analysis performed for the single fragments and for the compacted samples were presented in the following paragraphs.

Numerical simulations of individual fragments of rock submitted to suction cycles were performed. Several contributing factors were investigated with the following main conclusions: (i) the suction differential inside the fragment is proportional to the suction change rate. Experimental evidence shows that damage due to wetting occurs just after saturation corresponding to high rates of suction change; (ii) dryer samples exhibit more severe damage due to larger values of suction differential; (iii) increasing confinement decreases swelling displacements but increases tension and plastic shear deformation. Hardening occurs when compression due to the restrain of swelling displacements occur; (iv) the first wetting causes most severe degradation. Drying is not so penalizing as wetting.

The numerical results from individual rock fragments provided a mechanical explanation, at the level of rock fragments, for the overall behaviour of aggregates (compacted material) observed in experimental tests. Cracking development due to saturation leads to fragment size reduction and the collapse observed results from the rearrangement of the broken fragments. Large collapse deformations are due to high suctions before wetting. This can be explained because the material degradation is proportional to the value of the suction differential.
7 FUTURE WORK

A micromechanical approach was adopted to analyse the behaviour of compacted marls and a possible explanation of the cracking mechanism was found, based on the mechanics of unsaturated soils. The cracking mechanism explains the changes in the amplitude of the collapse observed, however it does not explain completely the transition from rockfill behaviour (dry samples) to the one of a clayey soil (fully saturated samples). There is a need of a suitable constitutive model able to simulate this transition.

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