Environmental degradation of clayey rocks

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ABSTRACT

This paper explores the mechanisms that lead to the degradation of clayey rocks when exposed to environmental effects as those caused by unloading and cyclic variations in relative humidity. The following aspects are evaluated: (i) the number of applied RH cycles, N, (ii) the amplitude of relative humidity cycles, ΔRH, (iii) the stress level (p-ua) and (iv) the effect of the fluid used to induce rock saturation (liquid water or vapour). The implementation of non-conventional experimental techniques for inducing and tracking rock degradation, at ‘macro’ and ‘micro’ scales, is described. An experimentally-based framework of behaviour is presented which may be used in practice for the evaluation of the degradation potential of clayey rocks.

Keywords: clayey rocks, rock degradation, wetting-drying cycles, relative humidity, damage law.

1 INTRODUCTION

Clayey rocks are widespread in nature and represent as much as 50% of the global sedimentary rock mass (Pettijohn, 1957). Typical examples include mudstones, claystones, siltstones, marls, shales or fissile rocks, and cemented and overconsolidated clays (e.g., Chandler, 1969, 1972; Bjerrum, 1967; Botts, 1986; Ghafouri et al., 1993; Cafaro & Cotecchia, 2001; Gens et al., 2007; Alonso et al, 2010; Pineda, 2012; Gens, 2013; Nguyen, 2019; among others). These materials are present in many civil engineering works such as dams, tunnels, excavations, shallow foundations, highway embankments as well as in underground facilities for nuclear waste disposal. A recurrent observation in clayey rocks is their transitional nature, which emerges mainly when they are excavated and exposed to weathering processes as those caused by cyclic variations in relative humidity (RH) or suction. As a result, rock degradation occurs. In practice, this is commonly associated with increase in water content. However, rock degradation also involves swelling, reduction in stiffness and strength, as well as increase in compressibility and permeability. A proper prediction of the response of clayey rocks under various mechanical and hydraulic conditions is therefore of fundamental importance for the design of civil infrastructure.

Figure 1 shows the stratigraphic profile encountered at Monreal dam site, a gravity dam located in Navarra (Spain) founded on Pamplona marls (Alonso et al., 2010). Only three layers were identified during the excavation of the dam’s foundation: an upper mixed gravel-clay layer, followed by a weathered marl layer in which weathering processes have transformed the stiff and strong rock into stiff weathered clay. Finally, the undisturbed and unfissured marls were found. A rapid cracking process was identified in the undisturbed layer which took place few hours after excavation due to the stress relief and the exposure to the local environment. Figure 1(a) shows these four layers including the layer of fissured marls at foundation plane. Crack formation immediately after excavation is shown in Figure 1(b). This behaviour raised some doubts on the strength parameters to be used in the analysis of Monreal dam stability against foundation sliding. Large scale laboratory shear tests were carried out to determine the strength parameters for the undisturbed rock and their dependency on weathering effects.

Figure 2 shows the shear stress-horizontal displacement curves obtained from two block samples subjected to direct shear tests under similar vertical stresses (32 kPa and 42 kPa). The only difference between them was the condition of shearing. The saturated sample (σv = 42kPa) was sheared at fully saturated conditions (via soaking the direct shear box prior consolidation). The second sample (σv = 32kPa) was sheared at natural water content conditions. Figure
2 indicates that the saturation process leads to significant decrease of the peak strength and brittleness of the marl. At large displacements the strength obtained in both cases are very similar and tend to the residual strength value. Photographs taken after shearing demonstrate the string water sensitivity of Pamplona marls and its effect on the failure mode. Shear strength parameters obtained at fully saturated and natural water content conditions are also included in Figure 2. It can be seen that the saturation of the rock at low stress levels caused a strong reduction in cohesion but also an important decrease in friction angle.

When a natural rock deposit is excavated and exposed to the atmosphere, unsaturated conditions are likely to prevail due to cyclic variations in relative humidity which in turn leads to changes in moisture content. Tunnels are typical examples where the excavated material is subjected to cyclic variations in relative humidity (or total suction). Although relative humidity is not a variable commonly controlled during tunneling operations it may change over a wide range following specific ventilation conditions. Figure 3 shows the variation in relative humidity and temperature inside Lilla tunnel (Spain) for a period of 8 months. Lilla tunnel was excavated through sulfate-bearing claystones, (Alonso et al., 2013). The relative humidity is shown to vary between extreme conditions: from around 96% to a dry state around 15%. Values of relative humidity can be converted into total suction via Kelvin’s law (Coussy, 1995):

\[ \psi = \frac{-R T \rho w}{M_w} \ln(RH) \]

(1)

where \( R \) is the gas constant (8.314 J/(mol K)), \( T \) is the absolute temperature, \( M_w \) is the molecular mass of water (18.016 kg/kmol) and \( \rho w \) is the density of pure water (998 kg/m³ at 293 °K).

According to Eq. 1, maximum and minimum total suctions imposed by the cyclic variations in relative humidity at Lilla tunnel varies between around 230 MPa and 6 MPa. Figure 3 also indicates that the tunnel wall along the 8 months-long record experienced significant suction cycles.
This paper discusses the main aspects that control the degradation of clayey rocks due to environmental effects. The development and implementation of non-conventional experimental techniques for inducing and tracking rock degradation, at micro and 'macro' scales, is first described. A framework of behaviour is presented which may be used in practice for the evaluation of the degradation potential of clayey rocks.

2 INDUCING AND MONITORING ROCK DEGRADATION IN THE LABORATORY

An important challenge in the study of degradation of clayey rocks is to find adequate laboratory techniques to induce and monitor in a continuous way rock alteration while maintaining stress conditions. This requires the implementation of different instrumentation and experimental techniques—such as those used in unsaturated soil mechanics to control soil water potential—in triaxial devices, oedometer and direct shear cells, which have not been specifically designed for that purpose. Although rock degradation takes place at low stress conditions, high pressure laboratory equipment is needed to evaluate yielding and other mechanical properties. To do so, the technology recently gained in the design of high-pressure equipment (see for instance, Cuccovillo & Coop 1997; Béssuelle & Desrues, 2001; Berre, 2010; among others) has to be combined with the broad expertise gained in the control of water potential and already implemented in different mechanical cells (Oldecop & Alonso, 2004; Chávez et al., 2009; Pintado et al., 2009a; Merchán et al., 2011).

Figure 4 shows three experimental set-ups used to apply long-term wetting-drying cycles to low porosity clayey rocks via vapour transfer. The vapour transfer technique (Blatz et al., 2008) is based on controlling the relative humidity applied to the sample boundaries. This is achieved by means of a closed system of constant vapour mass. When equilibrium is reached, the vapour concentration in the rock pores becomes equal to the externally imposed relative humidity. The total suction imposed to the rock by the relative humidity of the surrounding environment is estimated via Eq. (1).

The experimental set-up employed in unstressed tests is shown in Figure 4(a). Specimens are placed inside Pyrex dessicators on a porous disc above a solution that generates a target vapour pressure environment. Vapour transfer is controlled by pure diffusion. Digital hygrometers are used to monitor relative humidity and temperature inside the dessicator. Volume change and water content variation are estimated from periodic weight and volume measurements.
Figure 4(b) shows the experimental set-up developed by Pineda et al. (2014a) to induce and track rock degradation under confined conditions. Two independent forced convection systems are included to control the relative humidity of the air in contact with the material. The use of forced convection systems speeds up the vapor transfer from the reference vessels to the low porosity rock. It can be seen that two independent circuits are used –for top and bottom caps–, each with an air pump, a vessel containing the reference saline solution to control relative humidity, and a hygrometer. The vessels are placed on electronic balances to register water mass transfer from or to the material, during drying or wetting, respectively. Volume change is estimated using local measurements of axial and radial displacements obtained from submersible LVDTs and a radial extensometer, respectively.

In the experimental configurations shown in Figures 4(a) and 4(b), bender elements transducers are included to determine the shear wave velocity -as a non-destructive way to evaluate the material stiffness- and to track its degradation state. Their implementation for testing clayey rocks under unstressed conditions was described in detail by Arroyo et al. (2010). Its extension to monitor the stiffness evolution of clayey rocks under hydraulic and mechanical paths is described in Pineda et al. (2014a,c) and Nguyen (2019).

Figure 4(c) shows a simple yet versatile experimental set-up used to apply wetting-drying cycles via vapour transfer in a modified direct shear apparatus (Pineda et al., 2014b). Hydraulic cycles are applied using a forced convection system, prior shearing under either saturated or unsaturated conditions. Two hygrometers are used to compare the relative humidity of the saline solution (target) against the value measured inside the shear box (applied).

3 MATERIAL AND EXPERIMENTAL PROGRAM

Experimental results obtained on Lilla claystone are presented in this paper to highlight the influence of environmental actions on rock degradation. Lilla claystone is a low porosity sulfate-bearing rock of Tertiary age from the Lower Ebro basin in Tarragona Province, Catalunya (Spain). Core specimens (ϕ = 110mm) were obtained from vertical boreholes drilled from Lilla tunnel floor (Alonso et al., 2013), between 5.7 - 6.2 m depth, using dry coring and a single tube barreling to avoid alteration caused by liquid water. The clayey fraction has low plasticity and a low activity (LL ≈ 23 %, PI ≈ 5 %, A ≈ 0.20) which is consistent with the absence of expansive minerals. Natural water content of undisturbed specimens ranges between 3.2 % and 4.1 % which corresponds to total suction measurements (□) of 120 and 70MPa, respectively. Dry density varies between 2.49 to 2.52 Mg/m³ whereas density of the solid particles (□) ranges from 2.78 to 2.82 Mg/m³. Average initial void ratio is close to 0.11. X-Ray analysis showed an average clayey fraction around 52.4% (mainly composed by illite) whereas dolomite and calcite contents were 19.6% and 13.3%, respectively. Anhydrite and gypsum contents were rather low (0.7% and 3.9%, respectively) in the specimens tested.

A typical feature of low porosity soft rocks is their sensitivity to liquid water. Figure 5 shows a simple soaking test performed on undisturbed Lilla claystone. Immersion in distilled water at unstressed conditions produced a very rapid degradation of the rock. Less than 2 min were required to observe evidence of flaking. A crack came into view at the centre of the sample after 5 min whereas the cracking pattern extended over the whole specimen after only 22 min. Full disintegration of the specimen was observed after 46 h of soaking. This qualitative result is consistent with the very low slaking-durability index, Id2 = 4 %, obtained according to ASTM D4644.

![Fig. 5. Soaking test on undisturbed Lilla claystone](image)

The influence of environmental effects on rock volumetric behaviour, rock stiffness, rock tensile strength and rock shear strength was evaluated through the following Test Series (see also Table 1):

- **Test Series 1** (p-ua = 0 kPa; 50% < RH < 99%): specimens were exposed up to four wetting-drying cycles under unstressed conditions using the experimental set-up described in Figure 4(a). The amplitude of the relative humidity applied was ΔRH = 50 %. P-wave velocity measurements were also obtained in this Test Series in addition to shear wave velocity readings to evaluate the evolution of the compressional wave velocity, Vp, at the end of each hydraulic path.

- **Test Series 2** (p-ua = 50 kPa; 20% < RH < 99%): a triaxial specimen was subjected to 2
long-term wetting-drying cycles under a mean 
net stress of 50 kPa using the triaxial setup 
shown in Figure 4(b). In this case, \( \Delta RH \approx 80\% \).

- **Test Series 3** \( (p-u_a = 200 \text{ kPa}; 20\% < RH < 99\%) \): a triaxial specimen was subjected to 2 long-term wetting-drying cycles under a mean net stress of 200 kPa using the triaxial setup shown in Figure 4(b). In this case, \( \Delta RH \approx 80\% \).

- **Test Series 4** \( (\sigma_v = 5 \text{ kPa}; 15\% < RH < 100\%) \): up to 3 wetting-drying cycles were applied to direct shear specimens, under a vertical total stress of 5 kPa, prior shearing at saturated conditions. The experimental set up shown in Figure 4(c) was used for this purpose. It can be noted that liquid water (soaking) rather than vapour transfer was used in wetting paths. The \( \Delta RH \approx 85\% \).

| Table 1. Stress paths applied to induce rock degradation |
|---------------------------------|
| **Test type** | **Stress level** | **Relative humidity (\%)** | **# cycles** | **Test time (days)** |
|----------------|-----------------|---------------------|--------------|-------------------|
| Test Series 1  | 0               | 50 – 99             | 4            | 390               |
| Test Series 2  | 50              | 20 – 99             | 2            | 300               |
| Test Series 3  | 200             | 20 – 99             | 2            | 300               |
| Test Series 4  | 5               | 15 - 100            | 3            | 270               |

### 4 WATER RETENTION BEHAVIOUR

Figure 6 shows the water retention curve (WRC), defined in terms of total suction \( \psi \) versus gravimetric water content \( w \), obtained using a dew-point chilled mirror psychrometer (WP4). Three wetting-drying cycles were applied to six undisturbed specimens via vapour transfer. The relative humidity varies from 10\% to 99\%. It can be seen that the hydraulic behaviour of the undisturbed rock remained inside the main wetting and drying branches obtained during the first cycle. In other words, the water retention properties of the rock are not highly affected by cyclic variations in moisture content using vapour transfer. This behaviour is consistent with the negligible variation of the diffusivity coefficient \( D_v \), estimated according to Gardner (1956), with the application of wetting-drying cycles. \( D_v \) ranged from \( 2.2 \times 10^{-10} \text{ m}^2/\text{s} \) (wetting paths) and \( 1.5 \times 10^{-9} \text{ m}^2/\text{s} \) (drying paths) (Pineda et al., 2014a).

In an increase in the maximum water retention capacity of the rock is observed in Figure 6 for specimens that were previously exposed to liquid water during a slaking test (three cycles: liquid water + oven drying at 105\° C). Clear differences in the WRCs between undisturbed and slaked material are observed in the low suction range \( (\psi < 8 \text{ MPa}) \). At high suctions, where the water retention capacity is mainly controlled by the specific surface of the clayey fraction, both undisturbed and slaked materials showed a similar response. This behaviour underlines the importance of liquid water in the degradation process. Similar results have been recently reported by Cardoso et al (2010) for Abadia marls (Portugal) and more recently by Nguyen (2019) for Ashfield shale (Australia).

![Fig. 6. Water retention curve for undisturbed and degraded Lilla claystone](image)

### 5 VOLUMETRIC BEHAVIOUR

Figure 7 presents the temporal evolution of water content and volumetric strain for specimens subjected to **Test Series 1** \( (p-u_a = 0 \text{ kPa}, 50\% < RH < 99\%) \). Readings of relative humidity and temperature inside the Pyrex desiccators are included. Up to four wetting-drying cycles were applied in **Test Series 1**, which required around 390 days for completion. The application of wetting-drying cycles caused a progressive volumetric expansion of the rock. This behaviour was accompanied by negligible variations in the maximum water retention capacity of the rock, in agreement with the results presented in Figure 6. It may be noted that drying was more efficient (in time) than wetting to reach the equilibrium. It means that the rate of water absorption was always lower than water desorption. This behaviour is explained by the higher diffusivity coefficient obtained for drying paths as discussed above.

A similar volumetric response was observed in all specimens subjected to **Test Series 1**. Wetting induced swelling while some shrinkage was measured during drying. Shrinkage was always lower than the previous swelling, leading to a progressive and cumulative swelling as indicated in Figure 8. The volumetric
behaviour of Lilla claystone specimens showed strain anisotropy. The strain ratio ($\varepsilon_{\text{axial}}/\varepsilon_{\text{radial}}$) increased during drying as a consequence of minor axial shrinkage compared with radial deformation. This leads to fissuring of sub-horizontal orientation which progressively came into view as observed in Figure 8(b). This fissuring pattern is consistent with the orientation of samples which had the vertical axis perpendicular to bedding.

![Figure 7](image1.png)

**Figure 7.** Evolution of water content and volumetric strain during Test Series 1

Figure 9 compares the volumetric strain measured during Test Series 1 with values obtained from specimens exposed to Test Series 2 ($p_{\text{ua}} = 50$ kPa, $20\% < \text{RH} < 99\%$) and Test Series 3 ($p_{\text{ua}} = 200$ kPa, $20 > \text{RH} < 99\%$). The comparison between Test Series 1 (only the first two cycles) and Test Series 2 may be used to evaluate the influence of the amplitude in relative humidity ($\Delta \text{RH}$) on rock degradation. The increase in $\Delta \text{RH}$ during Test Series 2 induced a larger volumetric swelling, despite the higher confining stress applied in this test. On the other hand, the influence of the confining level on rock degradation is clear when comparing the results from Test Series 2 and Test Series 3. As observed in Figure 9, increasing the confining level substantially reduces the accumulated swelling of the rock.

![Figure 8](image2.png)

**Fig. 8.** (a) Variation of the volumetric strain with the relative humidity. (b) Sub-horizontal fissuring pattern observed after first drying.

### 6 ROCK STIFFNESS

The evolution of the normalized Young modulus $E/E_0$, estimated from compressional wave velocity...
measurements, for specimens exposed to Test Series 1 is shown in Figure 10. The normalized Young modulus $E/E_0$ decreased during wetting phases but also along drying paths. The larger reduction in Young modulus took place during the first cycle where it decreased to around $0.4E_0$. Then, the degradation of Young modulus exhibited a smaller rate.

Figure 10(b) also includes the evolution of the normalized shear modulus $(G/G_0)$ with the number of wetting-drying cycles for specimens subjected to Test Series 2 and Test Series 3. The comparison between Test Series 1 and Test Series 2 indicates that, despite a similar reduction in moduli observed at the end of the first wetting in both tests, a strong decrease in shear modulus was produced in Test Series 2 due to the increase in the amplitude of relative humidity $\Delta$RH. At the end of the second wetting-drying cycles the shear modulus for the specimen used in Test Series 2 reduced to $0.15G_0$. The effect of the stress level on the degradation of shear modulus is evaluated by comparing results from Test Series 2 and Test Series 3. Confining stress helped to reduce the degradation in Test Series 3. Direct observation of the sample at the end of the test also suggests that micro-fissuring is the main degradation mechanism. A practical upshot of the previous results shows the importance of maintaining some confinement on open-faces in slopes and excavations in order to minimize the degradation of the rock.

7 TENSILE STRENGTH

Figure 11 shows the time evolution of both gravimetric water content and volumetric strain for cylindrical specimens (50 mm in diameter and 20 mm in height) subjected to Test Series 1 ($p-u_0 = 0$ kPa, $50\% < \text{RH} < 99\%$) prior the estimation of the tensile strength via Brazilian (splitting) tests. The application of hydraulic cycles did not change in an appreciable way the maximum and minimum values of gravimetric water content. As previously observed in Figure 7 the equalization of gravimetric water content was more efficient (in time) during drying than wetting. The application of wetting-drying cycles induced progressive and irreversible volumetric swelling of Lilla claystone as shrinkage caused by drying was always lower than the previous swelling due to wetting.
Brazilian (splitting) test results shown in Figure 12 indicates that the first wetting reduced the tensile strength to around $0.40 \sigma_0$ with a subsequent smaller increase during first drying. After that, the application of the second relative humidity cycle reduced again the tensile strength to $0.20 \sigma_0$. At the end of the fourth cycle the tensile strength reduced to $0.10 \sigma_0$.

Fig. 12. Variation of the normalized tensile strength with the number of wetting-drying cycles.

8 SATURATED SHEAR STRENGTH

The dependency of long-term wetting-drying cycles on the shear strength parameters ($c'$, $\phi'$) of Lilla claystone was evaluated by Pineda et al. (2014b). A conventional direct shear device was modified to apply hydraulic cycles via vapour transfer under constant vertical stress conditions (see Figure 4(c)). Up to three wetting-drying cycles ($\sigma_v = 5$ kPa, $15\% < \text{RH} < 100\%$) were applied to direct shear specimens prior shearing at fully saturated conditions. The amplitude of RH applied was chosen to be similar to the maximum variation recorded at Lilla tunnel (see Alonso et al., 2013).

The evolution of the volumetric strain with the application of wetting-drying cycles is shown in Figure 13. Strong swelling took place during the first wetting which will be used in following sections as reference to evaluate rock degradation. Swelling took place on wetting (soaking), while some shrinkage was induced during drying. Shrinkage was always lower than the previous swelling, leading to a progressive and cumulative swelling. Larger swelling is observed when compared against Figure 7 and Figure 11 due to the use of liquid water during wetting paths.

Figure 14 shows the peak shear strength envelopes for undisturbed and specimens exposed to wetting-drying cycles. The residual envelope (remoulded soil) estimated from ring shear tests is also included for comparison. Peak shear envelopes were estimated by adopting the Mohr-Coulomb failure criterion in all cases. Shear strength parameters ($c'$ and $\phi'$) shows a progressive reduction as a consequence of the previous application of wetting-drying cycles. For undisturbed specimens: $c' = 108$ kPa and $\phi' = 46^\circ$. The application of 1 RH cycle significantly
reduced $c'$ to 71 kPa whereas $\phi'$ reduced only 2° ($\phi' = 44°$). After 2 RH cycles: $c' = 37$ kPa and $\phi' = 41°$. Finally, after 3 RH cycles $c' = 17$ kPa and $\phi' = 36°$.

The variation of the normalized effective cohesion ($c'/c'_{0}$) and friction angle ($\tan\phi'_{0}$-$\tan\phi_{res}^{'}/(\tan\phi'_{0}$-$\tan\phi_{res}^{'}$) with the number of wetting-drying cycles is presented in Figure 16. In this figure, the effective cohesion for undisturbed material $c'_{0}$ and the residual friction angle $\tan\phi_{res}^{'}$ are used to normalize the shear strength parameters. A strong reduction in cohesion is observed compared with friction. The degradation of $c'$ seems consistent with the reduction in E, G and $\sigma_t$ described above. According to the limiting friction behaviour with dominant $c'$ reduction observed in brittle clayey geomaterials. The assumption of a fully degradation of $c'$ with the application of wetting-drying cycles seems consistent with the trend of experimental data. This behaviour is represented in Figure 15. There, the separation between weathering from the displacement mechanism is given by an average limiting value $\phi'_{\text{lim}}=31°$. This value has been determined as the average between an upper limit defined by the post-rupture friction angle for degraded material and a lower limit defined as the residual friction angle for remoulded material plus the contribution of the maximum dilation angle obtained for the degraded specimens ($\phi'_{\text{res}} + \phi'_{\max(\text{degraded})}$). Further details are given in Pineda et al. (2014b). The limiting value, $\phi'_{\text{lim}}$, has a practical relevance as it defines the maximum degradation in friction to be expected from weathering processes. Thus, the remaining degradation in friction, from $\phi'_{\text{lim}}$ to $\phi'_{\text{res}}$, will take place only by displacement accumulation, as in the case of progressive failure phenomenon in hard soils-soft rocks once the post-rupture strength is achieved (e.g., Gens, 2013).
angle defined above, the maximum reduction in friction induced by wetting-drying cycles would be around
\[
\tan \psi'_{\text{limit}} = \frac{(\tan \psi'_0 - \tan \psi'_{\text{res}})}{(\tan \psi'_0 - \tan \psi'_{\text{res}})} = 0.40
\]  
(solid line in Figure 16).

Fig. 16. Variation of normalized cohesion and friction with the number of wetting-drying cycles.

9 ROCK MICROSTRUCTURE

Tracking rock degradation at microstructural level is not an easy task. Despite of some limitations, Scanning Electron Microscopy (SEM) as well as Mercury Intrusion Porosimetry (MIP) analysis are nowadays widely used to assess the microstructure of geomaterials. Pineda et al. (2019) presented a simple yet versatile methodology to assess the sensitivity of clayey rocks to liquid water via SEM analysis. This approach is aimed at exposing the rock to a fast wetting-drying cycle using liquid water as degradation precursor. Rock degradation is evaluated by comparing microphotographs taken at pre-defined locations before and after the application of the hydraulic cycle. The experimental procedure is schematically indicated in Figure 17.

![Diagram](image)

Fig. 17. Proposed methodology for assessing structural modifications caused by moisture content changes.

Figure 18 compares microphotographs taken at initial (undisturbed) and final (degraded) states on a 1 mm-thick Lilla claystone specimen. Figure 18(b) shows an increase in the thickness of pre-existing fissures due to the application of the fast wetting-drying cycle. Pre-existing fissure 2 grows up to 30μm after wetting and drying. An important aspect to remark here is the fissuring detected at the highest magnification in the interface between the clayey matrix and large-size minerals. The creation of new volume of ‘pores’ due to fissuring explains the progressive expansion of the rock without increasing the maximum water retention potential.

![SEM microphotographs](image)

Fig. 18. SEM microphotographs at initial and degraded states.

Figure 19 shows the pore size distributions obtained from Mercury Intrusion Porosimetry (MIP) and nitrogen adsorption (BJH method) analyses on both undisturbed (dashed line) and degraded (solid line) samples. The degraded state was obtained after the application of three wetting and drying cycles in the direct shear apparatus as described above. The intact curve displays a distribution with dominant modes below 13nm (the dominant peak at 4 nm was estimated from BJH results and the one at 13nm by MIP interpretation). Both modes correspond to the dominant intra-matrix pore sizes of the dense clayey matrix. The application of wetting-drying cycles creates a new mode at large entrance pore diameters (36μm), which coexists with the lower modes associated with the dense clayey matrix. This large dominant mode is similar in magnitude to the thickness of fissures detected by SEM analysis (see Figure 18). It confirms that the main degradation mechanism –due to hydraulic cycling- is caused by non-homogeneous volume change at micro level, which induces micro-fissuring.
DEGRADATION LAW FOR CLAYSTONES

Macroscopic (element) tests described above have demonstrated that the reduction in E, G, \( \sigma \), as well as in \( c' \) and \( \phi' \), seems to be related to the volumetric strain developed during the application of wetting-drying cycles. The derivation of a unified damage law should include this dependency. Pineda et al. (2014a) proposed a degradation law for Lilla claystone, defined in terms of the damage (irreversible) volumetric strain \( \varepsilon^\text{damage} \), which is equal to the difference between the dominant volumetric expansion (wetting) and the volumetric shrinkage (drying) strain undergone during each cycle:

\[
\varepsilon^\text{damage} = |\varepsilon^\text{wetting}| - |\varepsilon^\text{drying}|
\]

The reduction in rock mechanical properties induced by hydraulic cycling can be described by a damage parameter \( D \). This way, the degradation law could be expressed in a general way as:

\[
S = S_0, L = S_0, (1 - D)
\]

where \( S \) and \( S_0 \) are the current and initial values of a given property and \( D \) is a damage parameter ranging between 0 (undisturbed state) and 1 (fully disturbed state). It is assumed that the normalized decrease in \( S/(S_0) \) with the increase of the accumulated damage volumetric strain \( \varepsilon^\text{damage} \) is proportional to \((1-D)\). This can be mathematically expressed as:

\[
-\frac{d(1-D)}{d\varepsilon^\text{damage}} \propto (1-D)
\]

The following equation was proposed by Pineda et al. (2014a) to describe the degradation of mechanical properties in Lilla claystone:

\[
(1 - D) = [(1 - D_0) - r]\exp^{-\chi \varepsilon^\text{damage}} + r
\]

where \( D_0 \) is the value of the damage parameter at \( \varepsilon^\text{damage} = 0 \), \( \chi \) controls the rate of degradation and \( r \) represents a residual value for the rock property under consideration.

Figure 20 shows the evolution of the normalized Young modulus, shear modulus and tensile strength as a function of the cumulated volumetric damage strain. A solid line is used in this figure to represent the proposed degradation law by adopting \( D_0 = 0, \chi = 130 \) and \( r = 0.06 \). It is important to remark here that a unique law seems to describe the damage of volumetric and shear stiffness as well as tensile strength, irrespective of the stress level, number of wetting-drying cycles and the amplitude of relative humidity. This result simplifies the derivation of a general degradation law if only results for a given property, say rock stiffness, are available.
\( \chi_\phi = 27.5 \) in the case of the friction angle. Values of residual cohesion and friction were equal to \( r_c = 0 \) and \( r_\phi = 0.40 \), respectively.

Fig. 21. Variation of normalized cohesion and friction with the cumulated damage volumetric strain.

4 ENVIRONMENTAL EFFECTS IN ANISOTROPIC ROCK

The framework of behaviour described in previous sections has been recently adopted by Nguyen (2019) to study the environmental degradation of Ashfield shale, a low porosity anisotropic clayey rock from the Sydney basin (NSW, Australia). As indicated in Figure 22, Ashfield shale specimens show sub-horizontal stratification as well as joints (cracks) with low dip angles (\( \sim 20^\circ \)). This shale is mainly composed by kaolinite (31.4 %), quartz (27.7 %), illite (21 %), muscovite (15 %) and siderite (4.8 %). The fine fraction (<425 \( \mu \)m) has a liquid limit of 26.8 % and a plasticity index of 9.4 %.

Fig. 22. Ashfield shale cores tested by Nguyen (2019).

Nguyen (2019) carried out laboratory tests aimed at evaluating the influence of hydraulic cycling on the mechanical properties of Ashfield shale. Figure 23 shows the variation of the normalized shear modulus, \( G/G_0 \), with the cumulated damage volumetric strain. The degradation of the shear modulus in Ashfield shale is similar to the response observed in Lilla claystone. Good agreement with the experimental data is achieved for \( D_0 = 0 \), \( \chi = 4.63 \) and \( r = 0.341 \). Overall, the results presented in this paper demonstrate the applicability of the proposed degradation law for representing the degradation of clayey rocks.

Fig. 23. Variation of the normalized shear modulus with the cumulated volumetric strain in Ashfield shale.

4 CONCLUDING REMARKS

The degradation of clayey rocks caused by environmental effects has been examined in this paper. The influence of wetting-drying cycles on the mechanical properties of Lilla claystone were evaluated via laboratory testing. Factors like the number of wetting-drying cycles applied (\( N \)), the amplitude of the relative humidity change (\( \Delta \)RH), the stress level (\( p-u_0 \)) as well as the sensitivity of the rock to liquid water, were all evaluated in this paper. The application of wetting-drying cycles caused a progressive volumetric expansion of the rock. This was accompanied by a reduction in rock stiffness (Young and shear moduli) as well as in tensile strength. This behaviour was enhanced by increasing the amplitude of the relative humidity change applied during the hydraulic cycle. On the contrary, a the increase in the stress level during the application of hydraulic cycles reduced the volumetric expansion and the rate of stiffness degradation of the rock.

The application of wetting-drying cycles also caused a progressive reduction in the saturated shear strength parameters (\( c' \) and \( \phi' \)). Cohesion was almost completely erased with the application of 3 hydraulic cycles prior shearing. Friction also reduced but at
slowest rate. SEM and MIP analyses provided evidence on the progressive microfissuring induced with the application of wetting-drying cycles.

Macroscopic (element) and microstructural results were used to derive a unique degradation law, expressed in terms of the cumulated volumetric damage strain, able to represent the degradation in rock stiffness, tensile strength and shear strength parameters. which could be of benefit for the development of new constitutive models for soft rocks.

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