TECHNICAL NOTE

Shear strength degradation in claystones due to environmental effects

J. A. PINEDA*, E. ROMERO†, M. DE GRACIA‡ and D. SHENG§

This note explores the influence of environmental effects, as those induced by cyclic changes in relative humidity, on the degradation of the shear strength parameters in Lilla claystone, a low-porosity clayey rock from northern Spain. The results of a comprehensive experimental programme, combining long-term relative humidity cycling tests with saturated direct shear tests, are described. A continuous monitoring of the evolution of volumetric strain during the previous relative humidity cycling is used to evaluate the swelling behaviour of the rock. Both undisturbed and degraded specimens are subjected to shearing at saturated conditions to determine the peak and post-rupture shear strength envelopes. The effects on rock brittleness and dilation angle are also analysed. Shear strength shows a strong dependence on the history of relative humidity cycling. In particular, the evolution of the peak shear strength parameters (c' and ϕ') seem to be related to the accumulated irreversible strains developed during each cycle. A damage law, recently proposed by the authors, is used to represent the progressive degradation of the shear strength parameters as a function of the accumulated irreversible strains.

KEYWORDS: laboratory tests; landslides; shear strength; soft rocks; suction; tunnels

INTRODUCTION

Physical weathering processes such as stress relief and environmental effects have been recognised to play a key role in the behaviour of clayey rocks, leading to stability problems or unexpected deformations of geotechnical structures (Alonso *et al.*, 2010). Despite their practical relevance, few studies have evaluated the influence of environmental effects like relative humidity (RH) cycles on the shear strength parameters of clayey rocks (e.g. Tovar & Colmenares, 2011; Pineda & Romero, 2013). This note explores the evolution of the peak and post-rupture shear strength parameters in Lilla claystone when subjected to wetting–drying cycles. The study adds new experimental evidence to the environmental degradation of claystones described by Pineda *et al.* (2014), with particular emphasis on the sensitivity to liquid water at low stress levels as observed in slopes, tunnels and shallow foundations. A clear dependence between the irreversible volume change caused by the application of long-term wetting–drying cycles and the evolution of the shear strength parameters is described. This behaviour is in agreement with the reduction in volumetric and shear moduli, as well as tensile strength, with the increase in the irreversible volume change reported by Pineda *et al.* (2014). The degradation of the shear strength parameters caused by environmental effects is separated from the degradation induced by large horizontal displacements, mainly account-

ing for friction, by considering the post-rupture shear strength, as well as the maximum dilation remaining in the degraded specimens.

MATERIAL, EQUIPMENT AND EXPERIMENTAL PROGRAMME

Material

Lilla claystone is a Tertiary sulfate-bearing rock in north-eastern Spain, mainly composed of: (a) host low-plasticity argillaceous matrix (illite, palygorskite, dolomite and quartz) and (b) sulfated crystalline fraction (anhydrite and gypsum) (Pineda *et al.*, 2014). Tested specimens were obtained from vertically oriented cores retrieved at Lilla tunnel (Alonso *et al.*, 2013). Dry coring was used to minimise alteration induced by liquid water due to their high slaking potential (slake-durability index after the second cycle, $I_{d2} \approx 5\%$). Average water content in specimens is 4.1% associated with an initial total suction of 65 MPa. Initial void ratio is around 0.13 with a density of solids 2.80 Mg/m³ (initial degree of saturation $S_{r0} \approx 0.88$).

Equipment and experimental programme

A conventional direct shear device was modified in this study to apply hydraulic cycles by controlling the RH using the vapour transfer technique (Merchán *et al.*, 2011). The shear box was covered with a neoprene membrane to create a closed environment (Fig. 1(a)). RH cycles were applied using a forced convection system, including an air pump to circulate the vapour from a glass container, with reference solution, towards the shear box. Readings of RH and temperature from both shear box and reference solution were obtained using two digital hygrometers. Axial displacements were continuously registered using a linear variable differential transducer (LVDT).

The experimental programme combined long-term RH cycling tests with saturated direct shear (DS) tests. The long-term RH cycling tests are used to induce different

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* ARC Centre of Excellence for Geotechnical Science and Engineering, the University of Newcastle, NSW, Australia; formerly Universitat Politècnica de Catalunya, Barcelona, Spain.

† Department of Geotechnical Engineering and Geosciences, Universitat Politècnica de Catalunya, Barcelona, Spain.

‡ Fugro Panamá S.A., Ciudad del Saber, Clayton, Panama; formerly Universitat Politècnica de Catalunya, Barcelona, Spain.

§ ARC Centre of Excellence for Geotechnical Science and Engineering, the University of Newcastle, NSW, Australia.

Fig. 1. Experimental set-up: (a) modified direct shear apparatus; (b) stress paths followed

degradation states in the studied specimens. The saturation stage, using a conventional short-term laboratory protocol, is intended to bring the material to a common reference state to perform the DS tests. Each test included three stages: (a) RH cycling at $\sigma_v = 5 \text{ kPa}$, (b) consolidation to the target vertical effective stress and (c) shearing under saturated conditions. Twelve samples ($50 \times 20 \text{ mm}$), three for each degradation state, were used to obtain the shear strength envelopes (Fig. 1(b) and Table 1). Wetting was applied by soaking the shear box using distilled water ($\text{RH} = 100\%$). A lithium chloride solution ($\text{RH} \approx 15\%$) was employed during drying paths using the forced convection system. The amplitude of RH applied was chosen to be similar to the maximum variation recorded at Lilla tunnel (see Alonso *et al.*, 2013). Each long-term stage was maintained for 7–8 days to keep constant the influence of time on the degradation of Lilla claystone. To separate the swelling induced by the first saturation process from the volume change caused by RH cycling, the undisturbed specimens were soaked following a conventional short-term laboratory protocol before consolidation. Shear strength envelopes were determined at three vertical effective stresses (100, 200 and 300 kPa). Two additional DS tests (constant water content, loaded at $\sigma_v = 100$ and 200 kPa) were performed to evaluate the influence of the partial saturation. A horizontal displacement rate equal to $5 \mu\text{m}/\text{min}$ was used during shearing.

TEST RESULTS

Volumetric behaviour

The evaluation of the equilibrium conditions at the end of each long-term wetting and drying stage was based on the evolution of the volumetric strain, ε_v , and RH. Fig. 2 shows the results obtained during the first wetting and drying stages in three representative specimens. The faster increase in ε_v took place during the first day, whereas a strong reduction in the rate of volumetric swelling was observed after around 2 days of soaking (Fig. 2(a)). This behaviour indicates the advance and equalisation of the saturation front inside the specimens. The process of volume change during drying is, on the other hand, more complex (Fig. 2(b)). Volumetric swelling was recorded during the first 3 days of drying, and this may be attributable to the aperture of new fissures induced by non-homogeneous volumetric shrinkage, as ob-

Table 1. Main properties of samples tested in the direct shear device

Sample	Dry density, ρ_d : kN/m^3	Void ratio, e	No. of RH cycles applied (path) ($\sigma_v = 5 \text{ kPa}$)	Vertical effective stress, σ'_v : kPa	Testing time, per sample: days
S1_0_100	25.0	0.125	Undisturbed 0 (Fig. 3(a))	100	2
S2_0_200	25.0	0.123		200	
S3_0_300	24.8	0.131		300	
S4_1_100	25.0	0.123	1 (A-C) (Fig. 3(b))	100	23
S5_1_200	24.6	0.142		200	
S6_1_300	24.8	0.134	2 (A-E) (Fig. 3(c))	300	37
S7_2_100	24.7	0.138		100	
S8_2_200	24.9	0.127		200	
S9_2_300	25.0	0.125	3 (A-G) (Fig. 3(d))	300	51
S10_3_100	24.9	0.131		100	
S11_3_200	24.8	0.132		200	
S12_3_300	24.9	0.130		300	
S13_Dry_100	24.8	0.132	—	100	1
S14_Dry_200*	24.9	0.129	—	200	5

* Unfinished test under partially saturated state. Then, saturated and subjected to shearing twice.

Fig. 2. Evolution of volumetric strain: (a) during wetting and (b) during drying

served by Pineda *et al.* (2014). Afterwards, volumetric shrinkage took place without full equalisation in ε_v after 7 days. The equilibrium of the RH during drying was evaluated by computing the theoretical time required to reach 95% of water outflow, $t_{95} = 1.129 \times L^2/D_w$ (Delage *et al.*, 2008), where L is the drainage length and D_w is the moisture diffusivity coefficient ($D_w = 1.9 \times 10^{-9} \text{ m}^2/\text{s}$; Pineda *et al.*, 2014). Assuming single drainage (extreme case) the value of t_{95} was around 3 days. This suggests a quasi-complete equilibrium state of RH at the end of each drying stage, despite the non-equalisation of ε_v (probably affected by the propagation of micro-fissures).

The evolution of ε_v during RH cycling is shown in Fig. 3 for undisturbed and increasing RH cycles (refer to Table 1). Strong swelling took place during the first wetting (towards point A), which will be used as reference to evaluate rock degradation, since most of the DS tests are carried out under saturated conditions. As observed in Fig. 3, expansion took place on wetting, while some shrinkage was induced during drying. Shrinkage was always lower than the previous swelling, leading to a progressive and cumulative swelling that induces degradation (loss of bonding). This behaviour is clearly observed in Fig. 4 where ε_v is plotted against the number of RH cycles applied.

Fig. 3. Evolution of volumetric strain during RH cycling: (a) undisturbed state and (b)–(d) after increasing RH cycles

Fig. 4. Evolution of volumetric strain with the number of relative humidity cycles

Shearing

The stress–displacement curves of specimens tested under undisturbed conditions, after one cycle, after two cycles and after three cycles are shown in Figs 5(a), 5(b), 5(c) and 5(d), respectively. The evolution of vertical displacements during shearing is also included. The complete stress–displacement curve of sample S10_3_100 (after three cycles) could not be obtained due to electronic problems with the acquisition unit just before failure. The following aspects deserve to be highlighted.

- The peak shear stress (τ_{peak}) was reached at small horizontal displacements ($x < 1.5$ mm) irrespective of the degradation state.
- τ_{peak} for a given σ'_v decreased with the number of RH cycles applied.
- Dilation decreased with the number of RH cycles and with σ'_v .

Figure 6 shows the evolution of the brittleness index with the number of RH cycles. The brittleness index (Bishop, 1971) is defined as

$$I_B(\%) = \frac{(\tau_{\text{peak}} - \tau_{\text{post-rupture}})}{\tau_{\text{peak}}} \times 100 \quad (1)$$

where $\tau_{\text{post-rupture}}$ is the shear stress obtained at the maximum horizontal displacement achieved. Despite some scatter, I_B decreased with the number of RH cycles and with increasing σ'_v .

Figure 7 shows the stress–displacement curves of unsaturated samples S13_Dry_100 and S14_Dry_200 at the initial state (total suction of 65 MPa). In the first case, τ_{peak} was around 600 kPa, three times higher in relation to the undisturbed saturated reference state (point A in Fig. 1(a)). A fragile post-rupture response was observed in this case ($I_B = 77\%$, twice the saturated value). The overall stress–displacement curve for sample S14_Dry_200 (continuous line) could not be obtained because the maximum capacity of the load cell was reached before achieving failure. This specimen was then unloaded and saturated before shearing. Shearing was applied twice (filled squares). First shearing stage was applied until $x = 2.5$ mm (enough to reach τ_{peak}). Then, the shear box was relocated at the initial position by reversal loading before the second shearing. τ_{peak} decreased

from 312 kPa to 200 kPa during the second shearing. τ_{peak} at the end of the first shearing was similar to the undisturbed reference value (see Fig. 5(a)).

The peak shear strength envelopes are shown in Fig. 8 including the residual envelope–remoulded soil, determined from ring shear tests. A Mohr–Coulomb failure criterion was adopted in all cases. Shear strength parameters (c' and ϕ') were clearly affected by the previous RH cycling that induces degradation. For undisturbed specimens: $c' = 108$ kPa and $\phi' = 46^\circ$. The application of one RH cycle significantly reduced c' to 71 kPa, whereas ϕ' reduced only 2° ($\phi' = 44^\circ$). After two RH cycles: $c' = 37$ kPa and $\phi' = 41^\circ$. Finally, after three RH cycles $c' = 17$ kPa and $\phi' = 36^\circ$. Important differences in τ_{peak} were observed between saturated and unsaturated samples ($\sigma'_v = 100$ kPa in Fig. 7). After the second shearing ($\sigma'_v = 200$ kPa), τ_{peak} fell on the shear strength envelope for specimens subjected to two RH cycles. This fact evidences certain analogy between the degradation induced by irreversible volumetric strain accumulation and the post-rupture behaviour at increasing horizontal displacements. Table 2 summarises the results obtained at each degradation state.

Figure 9 shows the variation of dilation angle, ϕ , with σ'_v . ϕ was computed using Taylor's expression: $\phi = \tan^{-1}(\delta y / \delta x)$. ϕ decreased with the application of RH cycles and with the increase in σ'_v . Undisturbed specimens showed values around $14\text{--}5^\circ$ (at $\sigma'_v = 100$ and $\sigma'_v = 300$ kPa, respectively). ϕ decreased to around 4° in specimens subjected to one RH cycle. A small reduction was obtained with the application of the second and third cycles. A value equal to $\phi = 33.5^\circ$ (2.5 times higher the saturated value) was obtained for the unsaturated specimen. The decrease in I_B and ϕ with the degradation state suggests the evolution from a 'rock-type' to a 'soil-like' state.

DISCUSSION

Experimental results showed that the degradation of the shear strength parameters takes place at different rates. Cohesion c' is almost completely degraded during RH cycling. Gens (2013) reported shearing results in which a significant drop in cohesion c' – compared to the small reduction in friction angle ϕ' – was observed in the post-rupture stage. The reduction in friction angle ϕ' , on the other hand, is consistent with the fact that friction reduces mainly as displacements are accumulated and particles are gradually realigned. There, ϕ'_{res} defines the lower bound which does not seem to be reached in typical geotechnical structures affected by natural weathering processes.

Thus, the degradation of the shear strength parameters can be divided into two main mechanisms: (a) weathering–RH cycling and (b) displacement accumulation towards residual sliding shear–particle realignment. The first mechanism is similar to the drop in shear strength associated with the post-rupture behaviour with dominant c' reduction. The assumption of a full degradation of c' during RH cycling seems consistent with the trend of the experimental data (Table 2). As a first approximation, the approach adopted here to separate the effects of weathering from the displacement mechanism considers the contributions coming from brittleness ($\phi'_{\text{post-rupture (degraded)}}$: post-rupture shear strength at the most degraded state after three cycles) and dilation ($\phi'_{\text{res}} + \phi'_{\text{max (degraded)}}$: residual friction plus the maximum dilation at the most degraded state). As observed in Fig. 10, the separation between weathering from the displacement mechanism is given by an average limiting value $\phi'_{\text{limit}} = 31^\circ$. This has been determined as the average between $\phi'_{\text{post-rupture (degraded)}} = 36^\circ$ (with $c' = 0$) obtained after 3 RH cycles (grey squares) and a lower limit $\phi'_{\text{res}} +$

Fig. 5. Stress-displacement curves obtained during shearing: (a) undisturbed state and (b)–(d) after increasing RH cycles

Fig. 6. Variation of I_B with the number of RH cycles applied

Fig. 8. Peak shear strength envelopes for different degradation states. Shear strength envelope for residual conditions

Fig. 7. Stress-displacement curves for unsaturated samples. Sample at $\sigma_v = 200$ kPa subjected to shearing twice under saturated conditions

$\phi'_{\max}(\text{degraded}) = 26^\circ$, that considers a maximum dilation remaining in degraded specimens of $\phi'_{\max} = 9^\circ$ (see Fig. 9 for $\sigma'_v = 100$ kPa). This limiting value, ϕ'_{limit} , has a practical relevance since it defines the maximum degradation in friction to be expected from weathering processes. The remaining degradation in friction, from ϕ'_{limit} to ϕ'_{res} , will take place only by displacement accumulation, as described to occur during progressive failure phenomenon in hard soils-soft rocks once the post-rupture strength is achieved (e.g. Gens, 2013).

Figure 11(a) shows the evolution of the normalised cohesion (c'/c'_0) and friction angle ($\tan \phi' - \tan \phi'_{\text{res}} / (\tan \phi'_0 - \tan \phi'_{\text{res}})$) with RH cycles. Initial cohesion (undisturbed) is employed to normalise c' , whereas friction is normalised using $\tan \phi'_{\text{res}}$. A strong reduction in cohesion is observed compared with friction. According to the limiting friction angle defined above, the maximum reduction in the normalised friction induced by RH cycling is around $r_{\phi'} = (\tan \phi'_{\text{limit}} - \tan \phi'_{\text{res}}) / (\tan \phi'_0 - \tan \phi'_{\text{res}}) = 0.40$ (solid line in Fig. 11(a) and levelling off in Fig. 11(b)). As pointed out by Pineda *et al.* (2014) the environmental degradation of claystones is mainly associated with the accumulated damage strains (cumulative irreversible volumetric strains), defined here as

$$\varepsilon_v^{\text{damage}} = |\varepsilon_v^{\text{wetting}} - \varepsilon_v^{\text{reference}}| \quad (2)$$

with $\varepsilon_v^{\text{reference}}$ being the volumetric strain at point A (see Fig. 2). Table 2 summarises the average damage strains obtained in each case. Fig. 11(b) shows the variation of normalised cohesion and friction with average $\varepsilon_v^{\text{damage}}$ (in log scale). Cohesion degraded almost completely for $\varepsilon_v^{\text{damage}} = 2\%$, whereas normalised friction reduced to 0.58 (see Table 2). Fig. 11(b) also includes the degradation law recently proposed by Pineda *et al.* (2014), rewritten as follows

Table 2. Peak (undisturbed and after RH cycling) and residual shear strength parameters. Normalised cohesion and friction

State	c' : kPa	ϕ' : degrees	Normalised cohesion c'/c'_0	Normalised friction*	Average $\varepsilon_v^{\text{damage}}$: %
Undisturbed	108	46	1	1	0
After one cycle	71	44	0.66	0.90	0.65
After two cycles	37	41	0.34	0.77	1.65
After three cycles	17	36	0.16	0.58	1.98
Remoulded (residual)	0	17	—	—	—

* $(\tan \phi' - \tan \phi'_{\text{res}})/(\tan \phi'_0 - \tan \phi'_{\text{res}})$.

Fig. 9. Variation of dilation angle with the stress level and degradation state

$$\frac{c'}{c'_0} = (1 - D) = [(1 - D_0) - r_{c'}] \exp^{-\chi_{c'} \varepsilon_v^{\text{damage}}} + r_{c'}$$

$$\frac{(\tan \phi' - \tan \phi'_{\text{res}})}{(\tan \phi'_0 - \tan \phi'_{\text{res}})} = (1 - D)$$

$$= [(1 - D_0) - r_{\phi'}] \exp^{-\chi_{\phi'} \varepsilon_v^{\text{damage}}} + r_{\phi'} \quad (3)$$

where D_0 is the initial damage and r is the residual value of the evaluated property, whereas $\chi_{c'}$ and $\chi_{\phi'}$ are, respectively, the degradation rates for cohesion and friction. $D_0 = 0$, $r_{c'} = 0$ and $r_{\phi'} = 0.40$ were adopted in this case. Degradation rates of $\chi_{c'} = 80$ for cohesion and $\chi_{\phi'} = 40$ for friction describes well the experimental behaviour of the rock. The damage strain required to reduce friction to the limiting value $\phi'_{\text{limit}} = 31^\circ$ is around 8% according to the adopted law, whereas reaching residual strength requires the accumulation of displacements along a preferential direction.

CONCLUDING REMARKS

The dependence of the shear strength parameters of Lilla claystone on long-term RH cycling was described. Experi-

Fig. 10. Maximum degradation of the shear strength parameters induced by RH cycling and by displacement accumulation

Fig. 11. Variation of normalised cohesion and friction: (a) with the RH cycles; (b) with the accumulated damage volumetric strains

mental results showed important reduction in both cohesion and friction, but at different rates, with the application of RH cycles. Brittleness and dilation angle also reduced with the application of RH cycles and vertical stress σ'_v . A limiting value for the maximum degradation in friction was defined by considering the post-rupture shear strength at the maximum degraded state (after three RH cycles) and the maximum dilation of degraded specimens (that was added to the residual shear strength). Degradation was related to the accumulated damage strains induced during RH cycling. Degradation was successfully represented by the damage law proposed by Pineda *et al.* (2014).

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NOTATION

c'	effective cohesion
c'_0	undisturbed effective cohesion
D	damage parameter
D_w	moisture diffusivity coefficient
D_0	initial damage
e	void ratio
I_{d2}	slake-durability index
I_B	brittleness index
L	drainage length
$r_{c'}$	residual cohesion
$r_{\phi'}$	residual friction
S_{r0}	initial degree of saturation
t_{95}	theoretical time required to reach 95% of water outflow
ε_v	volumetric strain
ε_v^{damage}	damage (irreversible) volumetric strain
$\varepsilon_v^{reference}$	reference volumetric strain
$\varepsilon_v^{wetting}$	volumetric strain at the end of wetting
ρ_d	dry density
σ_v	total vertical stress
σ'_v	effective vertical stress
τ_{peak}	peak shear stress
$\tau_{post-rupture}$	post-rupture shear stress
ϕ'	effective friction angle
ϕ'_{limit}	limiting friction angle
$\phi'_{post-rupture (degraded)}$	post-rupture friction angle at degraded state
ϕ'_{res}	residual friction angle
ϕ	dilation angle
$\phi_{max (degraded)}$	maximum dilation angle at degraded state
$\chi_{c'}$	degradation rate for cohesion
$\chi_{\phi'}$	degradation rate for friction

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