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Technical note

Hydro-mechanichal characterisation of bentonite/steel interfaces

Eleni Stavropoulou[a,*], Fabiana Sannasardo[a], Alessio Ferrari[a,b]

[a] Ecole Polytechnique Fédérale de Lausanne (EPFL), Laboratory for Soil Mechanics (LMS), EPFL-ENAC-LMS, Station 18, CH-1015 Lausanne, Switzerland
[b] Università degli Studi di Palermo, Engineering Department Viale delle Scienze, edificio 8, 90128 Palermo, Italy

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ABSTRACT

The hydromechanical response of a Wyoming-type bentonite (MX-80) and its interface with steel was studied in terms of shear resistance under different hydration levels. A series of shear tests under constant normal stress were performed in total suction controlled conditions. In the case of bentonite samples, higher shear resistance was obtained for higher levels of applied suction. The shear properties of the bentonite/steel interface were overall lower than the internal properties of the bentonite, and they were not affected in a significant way by the hydration level. All samples presented a compactive response during shearing.

1. Introduction

The multi-barrier concept of geological repositories aims to create a safe storage system for potentially harmful material, such as high level radioactive waste. In the context of nuclear waste storage, bentonite is studied as a buffer material between the host rock and the waste canisters that will be used in two forms: in form of blocks sustaining the steel canister with nuclear waste and in granular form filling the space between the canister and the host rock. The choice of bentonite is made based on its isolation properties such as low permeability, solute retention and swelling ability (Marcial et al., 2006; Hoffmann et al., 2007; Wang et al., 2012; Seiphoori et al., 2014). Bentonite will swell upon hydration and fill existing gaps that may be created during the emplacement phase or throughout the life of the system. Bentonite will be placed in its hygroscopic state in the tunnel excavated in the host rock, however, the state of the material is expected to be affected by the mechanical impact of the shear stresses caused by possible deformation of the outer rock (Alonso et al., 2005; Tang et al., 2008; Bosch Llufriu, 2021).

In the context of underground nuclear waste storage, the study of interfaces is important for evaluating the safety of the repository. Sinnathamby et al. (2014) explained the importance of the shear strength of the backfill material interfaces in limiting the swelling of the buffer. Some studies were conducted on rock/bentonite interfaces in order to examine the hydration process of the buffer (Gens et al., 2002) or to investigate the evolution of the voids between the buffer and the rock due to bentonite swelling (Grindrod et al., 1999), while a few shear tests on rock/bentonite interfaces were also reported in literature (Börgesson et al., 2003; Buzzi et al., 2008). Nevertheless, to the Authors knowledge, there is no information regarding the shear response of the bentonite with the canister steel. In the field, the bentonite's state is non-homogeneous due to possible differences in dry density resulting from both the emplacement of the barrier and the use of different bentonite forms. During resaturation of the barrier, this non-homogeneous state might activate the bentonite/canister interfaces in shear, the response of which should be taken into account throughout the repository's life-time for safe storage.

The objective of this study was to determine the shear strength of a Wyoming-type bentonite (MX-80) and its interface with steel in various hydric states. A series of suction-controlled direct shear tests under drained conditions were carried out aiming to investigate the hydro-mechanical behaviour of the interface, considering the bentonite's granulation and water content.

The shear behaviour between various types of soils and steel, was previously studied mostly in the context of pile foundation design (*e.g.* Mortara et al., 2007; Ho et al., 2011; Quinteros et al., 2017). Similarly to standard soil testing, the shear response of soil/structure interfaces can be expressed based on the Mohr-Coulomb criterion:

$$\tau_f = c + \sigma_n^{'} \cdot tan(\delta) \quad (1)$$

where τ_f is the shear stress at failure, $\sigma_n^{'}$ the effective normal stress, c the apparent cohesion of the interface, and δ the interface friction angle at failure (similarly to ϕ that denotes the internal friction angle of a soil). Some of the most important factors affecting the friction of an interface are mineralogical composition, density and the gradation of the soil, as

* Corresponding author.
E-mail address: eleni.stavropoulou@epfl.ch (E. Stavropoulou).

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Table 1
Basic properties of the tested material (Plötze and Weber, 2007; Seiphoori et al., 2014).

Smectite content (%)	Cation Exchange Capacity (CEC)	Specific surface area (m^2/g)	Specific gravity (−)	Liquid limit (%)	Plastic limit (%)
84.9	72.16	523	2.74	420	65

well as on the roughness of the in-contact surface. The strength of the interface can reach a maximum value equal to the strength of the contacting soil, resulting in '$\delta = \phi$ conditions' (Uesugi and Kishida, 1986; Dove and Jarrett, 2002; Lings and Dietz, 2005).

The behaviour of a partially saturated soil or soft rock interfaces is quite different from saturated or fully dried conditions (Hossain and Yin, 2010; Pellet et al., 2013; Hossain and Yin, 2014; Stavropoulou et al., 2020). Hossain and Yin (2010) pointed out that the dilatant response of a soil is significantly influenced by the stress state variable and in fact by the matric suction. As suction increased, a more dilatant response was observed.

In the current study, the results of a series of direct shear tests under total suction control conditions are presented and analysed. First, the shear response of the bentonite at hygroscopic state is characterised with a series of direct shear tests. These shear results are then compared to the shear response of the steel/bentonite interface.

2. Tested material

The main properties of this bentonite were previously identified by Plötze and Weber (2007) and Seiphoori et al. (2014) and are summarised in Table 1. The tested material is the same material tested by Seiphoori et al., 2014, containing >85% Na-smectite. The exact mineralogical composition of the material was reported by Plötze and Weber (2007): 84.9% smectite, 4.8% muscovite, 3.7% quartz, 5.2% feldspar and 1.3% calcite. They additionally measured a cation-exchange capacity of 74 meq/100 g including 52.4 meq/100 g Na (Sodium), 13.2 meq/100 g Mg (Magnesium) and 1.4 meq/100 g K (Potassium). In this study, a grain size distribution (GSD) similar to Seiphoori et al. (2014) was used, without considering the finest fraction. In the *as-poured* hygroscopic state the moisture content measured ≈ 5.8%, the initial void ratio $e_0 = 0.75$ and the initial bulk and dry densities of the samples $\rho \approx 1.50$ g/cm^3 and $\rho_d \approx 1.36$ g/cm^3 respectively.

Seiphoori et al. (2014) and Ferrari et al. (2022) discussed the influence of the total suction/water content on the material's response at static compaction, explaining that the compression index of granular bentonite increases with the decrease of total suction. In order to minimise the high overconsolidation state of the material and its possible influence on the shearing response, in this work, the initial state of the samples was considered at *as-poured* hygroscopic state. The influence of the hydration on the volumetric behaviour and the compaction response was then carefully assessed.

3. Methodology

3.1. Experimental setup and sample preparation

All shear tests were performed using a direct shear device (Di Donna et al., 2015) that was adjusted for total suction control throughout the test (Fig. 1). The vertical and horizontal axes can be controlled independently both in force (maximum load 5 kN) and displacement. Two LVDTs (Linear Variable Differential Transformers) were used for the measurement of the horizontal and vertical displacements with a maximum range of 25.0 mm and 12.5 mm respectively. For the creation of the bentonite-steel interface, a flat steel plate (area 105 mm × 60 mm and height 16 mm, Young's modulus = 210 GPa) was positioned in the lower part of the shear box (Fig. 1). The bentonite sample (area 30 × 30 mm and height 20 mm) was placed on top of the steel plate, in the upper part of the shear box, ensuring a constant contact area between the two materials. All tests were performed in temperature-controlled conditions (23±1°C).

The bentonite samples were initially hydrated outside the shear box in free swelling conditions. Three different hydration states were considered based on the vapour equilibrium technique (VET). This

Table 2
Saline solutions and corresponding levels of total suction and water content of bentonite.

saline solution	total suction (MPa)	water content (%)
KNO_3	15	16.3
NaCl	40	12.8
hygroscopic	130	5.8

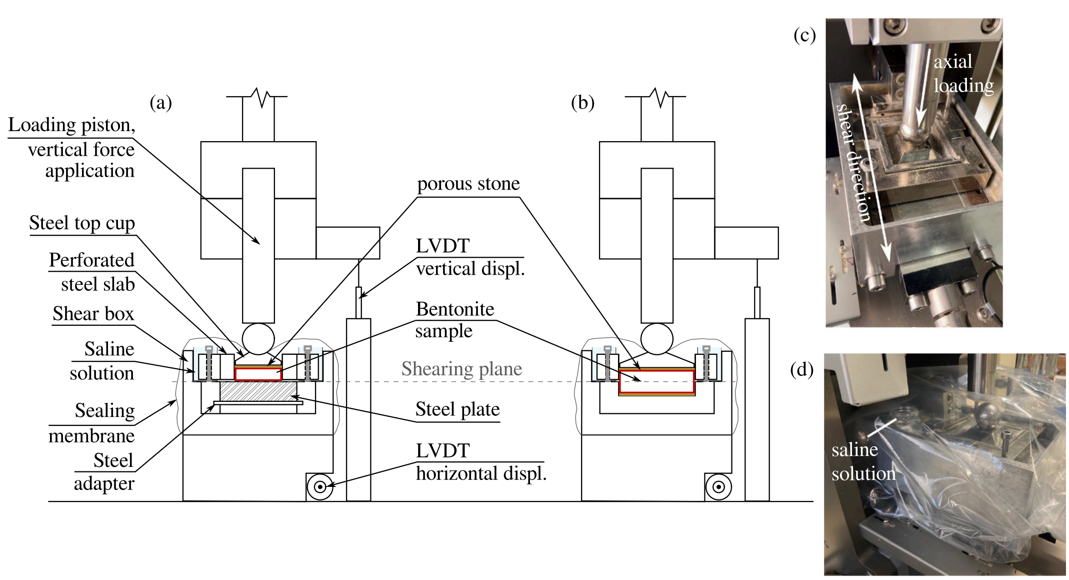

Fig. 1. Experimental set-up for direct shearing under suction-controlled conditions, (a) bentonite/steel interface setup, (b) bentonite setup, (c) top view of the shear box, (d) side view of the setup with the insulating membrane and the saline solution jars.

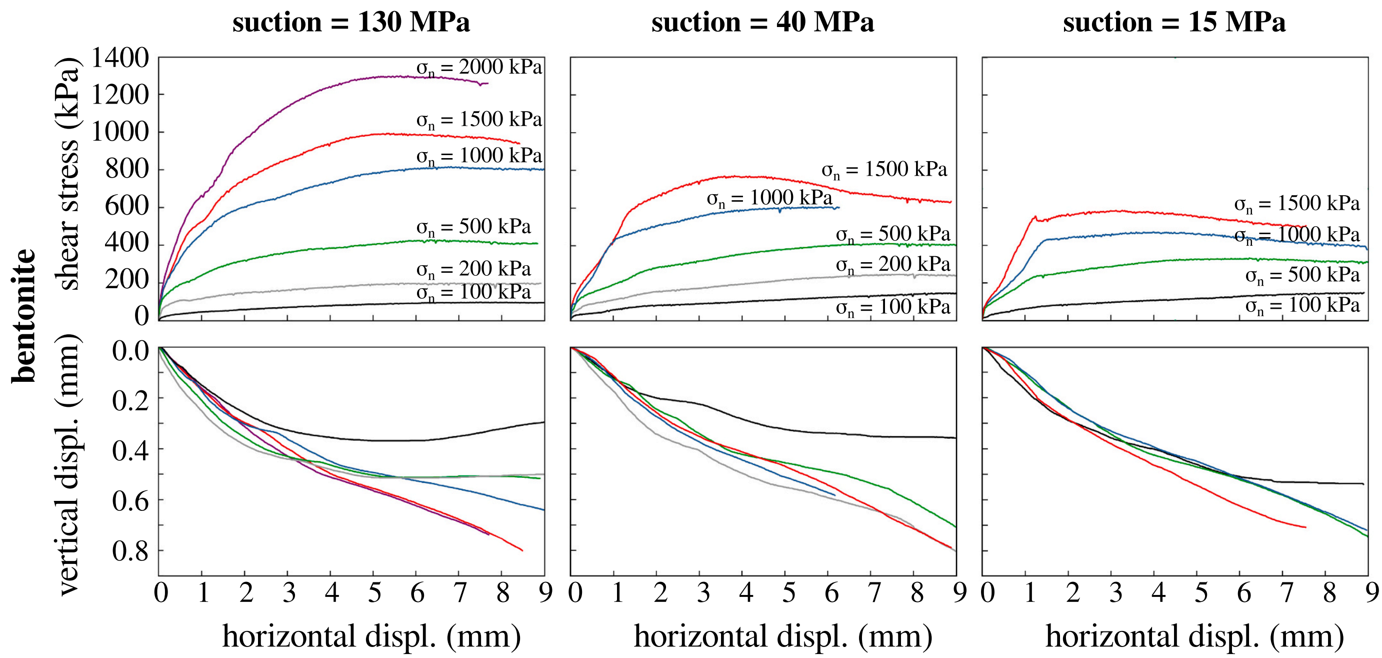

Fig. 2. Shear results of the bentonite samples for each level of applied normal stress and total suction.

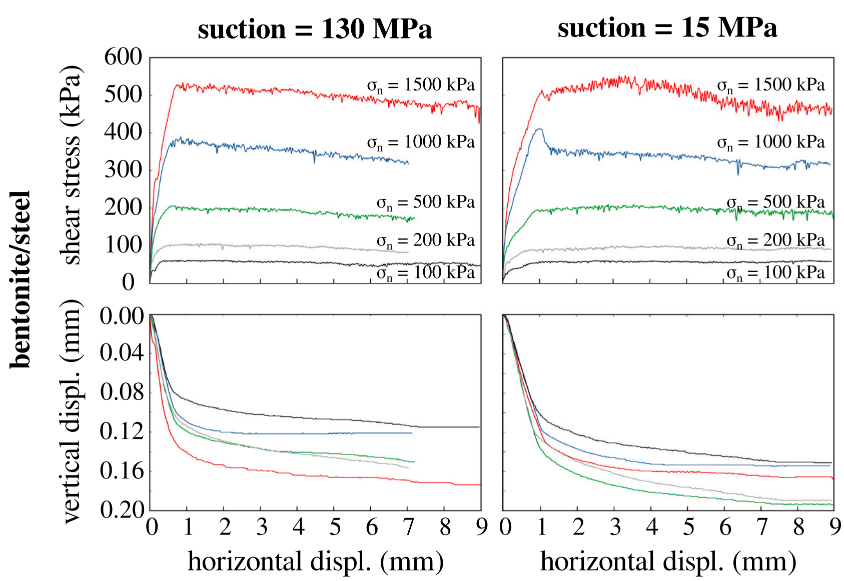

Fig. 3. Shear results of the bentonite/steel interface for each level of applied normal stress and total suction.

technique incorporates control of the relative humidity using saline solutions at a given temperature and was applied on various geomaterials (Romero, 2001; Delage et al., 2008; Minardi et al., 2018). Relative humidity (RH) can be converted to total suction (Ψ) according to the psychrometric law (Fredlund and Rahardjo, 1993). In this study, the level of total suction in the sample was measured using a dew-point psychrometer WP4C (Leong et al., 2003; Cardoso et al., 2007).

The hydration of the samples was achieved inside desiccators using two different types of saturated saline solutions targeting two levels of total suction: KNO_3 solution for ≈ 15 MPa total suction and NaCl solution for ≈ 40 MPa total suction. The concentration of each used solution was 36% and 46% respectively, as per Romero, 2001. The evolution of hydration was monitored by means of total suction and mass evolution of the samples, taking them out of the desiccators periodically. For the achievement of the desired value of total suction, a period of 40 days was required (see Figure SM1-a, in Supplementary Material available online). A third hydration state that corresponds to the bentonite's hygroscopic state was considered, with a measured total suction of around 130 MPa. The corresponding gravimetric water content of the material for each target level of total suction was determined after drying the samples in 105°C and is reported in Table 2.

The water retention properties of the material during wetting are presented in Figure SM1-b in terms of total suction and corresponding water content. Once the desired water content level was achieved, the bentonite was poured in the upper part of the shear box (*as-poured* state). Given the volume of the shear box, the necessary soil mass was weighed and used for a constant initial sample density. A sealing membrane was introduced around the shear box. Two open glass recipients containing the saline solution corresponding to the target total suction level were placed inside the membrane to ensure constant relative humidity (RH) conditions. The level of total suction before and after each shear test was measured with the dew-point psychrometer to confirm successful

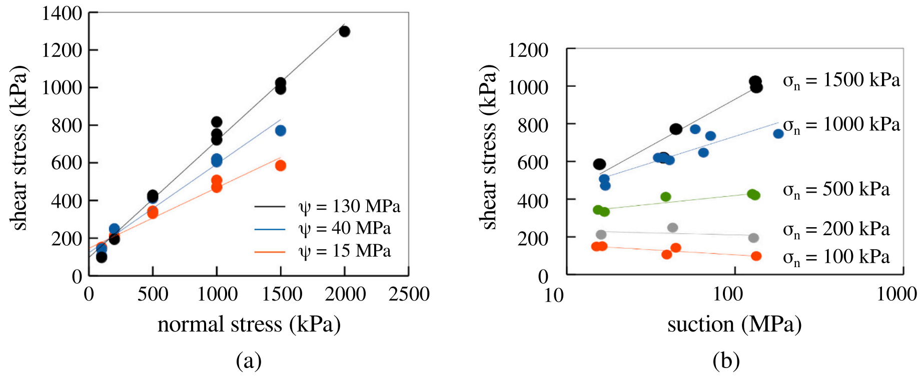

Fig. 4. (a) Peak failure envelopes for bentonite for all the suction levels, (b) Shear stress evolution with suction for different levels of normal stress for bentonite samples.

Table 3
Internal shear strength parameters and preconsolidation pressure for the three suction datasets of bentonite.

suction (MPa)	ϕ_{peak} (°)	c_{peak} (kPa)	ϕ_{ult} (°)	c_{ult} (kPa)	σ_c (kPa)
130	31.8	96.8	30.0	106.0	352.1
40	25.5	121.9	21.8	138.0	141.9
16	17.8	146.1	14.5	148.9	118.1

Table 4
Shear strength parameters and preconsolidation pressure for the two suction datasets of the bentonite/steel interface.

suction (MPa)	δ_{peak} (°)	c_{peak} (kPa)	δ_{ult} (°)	c_{ult} (kPa)	σ_c (kPa)
130	18.9	42.5	19.3	30.0	216.6
16	17.4	37.2	16.1	33.3	155.2

maintenance of the targeted level of total suction.

3.2. *Testing methodology*

Two main series of shear tests were performed, aiming to evaluate the impact of the material's moisture content by means of applied total suction on (i) its internal friction properties, as well as (ii) those of the steel/bentonite interface.

In the case of the bentonite/bentonite interface (internal), a total sample thickness of 20 mm ± 1 mm was adopted, while for the bentonite/steel interface the bentonite thickness was reduced to 10 mm ± 1 mm. A constant normal load was applied to each interface sample and once consolidation was completed shear displacement was applied. An average duration of 2 h after application of the normal load was required to observe the stabilisation of the settlement. The shear response of bentonite was tested under a series of constant normal stress $\sigma_n = 100$, 200, 500, 1000, 1500 and 2000 kPa, and of the bentonite/steel interface under $\sigma_n = 100$, 200, 500, 1000 and 1500 kPa.

Shearing was applied under the same constant normal load (CNL conditions) with a shear rate of 0.05 mm/min until failure, based on the Mohr-Coulomb failure criterion (average shear duration 3.5 h). At the end of the shear phase, the total suction and water content of the bentonite sample were measured. The total suction was overall successfully maintained during shearing (within the accuracy of the measurement), as highlighted in the Supplementary files.

4. Results

The response of the bentonite/bentonite samples in compression-only is presented in Figure SM1-c and compared to previous results by Seiphoori et al. (2014) for validation. A similar trend was obtained for both campaigns, proving the coherence of the obtained results. The differences were mainly related to the difference of the total applied suction. Overall, a more compressible response – more pronounced decrease of void ratio – was observed for lower applied total suction, *i.e.* higher water content, which can be explained by a higher initial swelling of the bentonite upon hydration.

4.1. *Shear response of bentonite*

The shear response of the internal bentonite interface under the three different applied levels of total suction is presented in Fig. 2: 130 MPa (hygroscopic), 40 MPa and 15 MPa. For all samples and levels of hydration the volumetric response during shearing was overall compactive

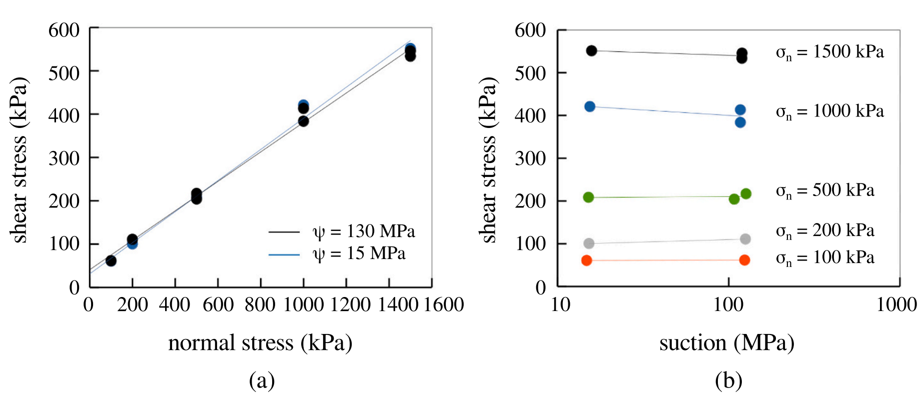

Fig. 5. (a) Peak failure envelopes of the bentonite/steel interface at two total suction levels, (b) Shear stress evolution with suction for different levels of normal stress.

regardless of the level of applied normal stress (Fig. 2 bottom). A higher compaction level was obtained for higher normal load at hygroscopic conditions. However, at lower suction levels, the correlation between vertical displacement and normal stress was less obvious. In the case of the lowest suction level (15 MPa), the volumetric response was very similar regardless the level of the applied normal load. The peak failure shear envelope is plotted after fitting the Mohr-Coulomb criterion in Fig. 4-a. To confirm repeatability of the response, multiple tests were performed under the same normal load, as shown in the same figure. The friction angle and cohesion for each level of total suction were calculated and are reported in Table 3. In the same table, the values of preconsolidation pressure (σ_c) calculated during the compression-only stage was reported

At low normal stress levels (< 500 kPa) there was no clear impact of suction on the shear resistance of the material. The peak friction angles decreased from 31.8° to 17.8° between total suction 130 MPa (hygroscopic) and 15 MPa, and they varied in a similar range at the ultimate stage (30.0° to 14.5°) – see Table 3. On the contrary, the initial apparent cohesion of ≈ 100 kPa at hygroscopic conditions (both peak and ultimate) increased up to 146 kPa with a decrease of suction to 15 MPa. For normal loads over 500 kPa, the shear resistance of the studied bentonite decreased with the decrease of total suction, *i.e.* with the decrease of water content, as revealed from Fig. 4-b. The increase of the level of hydration in the bentonite resulted in a paste-like material with increased adhesion between the grains that once broken presented low frictional properties. A drier bentonite involves additional failure mechanisms similar to 'non-cohesive' materials such as grain breakage that may result in a locally increased roughness of the failure surface.

4.2. Shear response of the bentonite/steel interface

Following the characterisation of the internal shear properties of bentonite, in this section, the shear response of the bentonite/steel interface was studied at two different levels of total suction: 130 MPa (hygroscopic conditions) and 15 MPa (Fig. 3).

For both suction levels a compactive response was obtained throughout shearing however in a less pronounced way compared to the internal bentonite response. In terms of friction properties the response was very similar; a peak friction angle of around 19° (for both 130 MPa and 15 MPa total suction) that decreased only slightly at the ultimate stage to 17.4° and 16.1° at 130 MPa and 15 MPa total suction respectively. In terms of apparent cohesion, the peak and ultimate values were very similar for each level of total suction (see Table 4). The failure envelopes (peak and ultimate) of the two levels of suction for the bentonite/steel interface were presented in Fig. 5-a. The peak shear strength of the interface was practically the same and only at the ultimate stage the shear response at lower suction was somewhat less significant than that at hygroscopic conditions. The shear results together with the calculated preconsolidation stress (compression-only stage) are summarised in Table 4.

5. Discussion

The internal shear strength of the bentonite was considerably higher than that of the bentonite/steel interface for both levels of applied total suction. In the case of the bentonite/steel interface, the level of applied suction did not impact the shear response, neither in terms of friction angle nor adhesion; no bentonite grains were found attached on the steel after shearing. This was mainly related to the fact that here the failure surface was pre-imposed at the interface between the two materials and therefore effects related to increased local roughness and grain breakage were eliminated.

The evolution of the failure envelopes of bentonite showed that the level of applied suction affected the frictional response of the material; increasing friction angle with increasing suction. This may be related to stiffness decrease of the grains after hydration. The failure surface was pre-imposed and horizontal between the upper and lower parts of the shear box which resulted in grain breakage during shearing and therefore increased frictional mobilisation. In the case of softer hydrated grains (lower suction), grain breakage during shearing would result in lower levels of friction angle.

6. Conclusions

In this work, the hydromechanical response of Wyoming-type bentonite and its interface with steel was characterised in terms of shear resistance through a series of total suction control direct shear tests. More precisely, the shear response of bentonite and bentonite/steel samples was evaluated under different levels of total suction and different levels of constant normal load.

The following conclusions can be drawn overall. The internal shear properties of bentonite were dependent on the level of hydration, here applied in terms of total suction. A higher shear resistance was obtained for higher levels of total suction, *i.e.* drier samples, for a given normal stress. Drier samples presented an increased frictional resistance (higher friction angle δ), while the trend was inverse for the apparent cohesion that increased with the decrease of total suction, *i.e.* wetter samples. The shear properties of the bentonite/shear interface were lower than the internal shear properties of the bentonite regardless the suction level. All tested samples, regardless water content, presented a compactive response upon shearing. Finally, no clear impact of the applied total suction was observed on the shear response of the flat steel/bentonite interface.

Credit author statement

Eleni Stavropoulou: supervision, conceptualization, methodology, data curation, writing original draft preparation

Fabiana Sannasardo: investigation, data curation.

Alessio Ferrari: supervision, conceptualization, methodology, reviewing and editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clay.2023.107046.

References

Alonso, E.E., Romero, E., Hoffmann, C., García-Escudero, E., 2005. Expansive bentonite–sand mixtures in cyclic controlled-suction drying and wetting. Eng. Geol. 81 (3), 213–226.
Börgesson, L., Johannesson, L.E., Gunnarsson, D., 2003. Influence of soil structure heterogeneities on the behaviour of backfill materials based on mixtures of bentonite and crushed rock. Appl. Clay Sci. 23 (1–4), 121–131.
Bosch Llufriu, J.A., 2021. Studies on the Mechanical Evolution of Compacted Bentonite Subjected to Environmental Actions (No. 9111). EPFL.
Buzzi, O., Boulon, M., Deleruyelle, F., Besnus, F., 2008. Hydromechanical behaviour of rock-Bentonite interfaces under compression. Rock Mech. Rock. Eng. 41 (2), 343–371.
Cardoso, R., Romero, E., Lima, A., Ferrari, A., 2007. A comparative study of soil suction measurement using two different high-range psychrometers. In: Schanz, T. (Ed.), Experimental Unsaturated Soil Mechanics, Springer Proceedings in Physics. Springer, Berlin Heidelberg, pp. 79–93.
Delage, P., Romero, E., Tarantino, A., 2008. Recent Developments in the Techniques of Controlling and Measuring Suction in Unsaturated Soils.

Di Donna, A., Ferrari, A., Laloui, L., 2015. Experimental investigations of the soil-concrete interface: physical mechanisms, cyclic mobilization, and behaviour at different temperatures. Can. Geotech. J. 53, 659–672. https://doi.org/10.1139/cgj-2015-0294.
Dove, J.E., Jarrett, J.B., 2002. Behavior of dilative sand interfaces in a geotribology framework. J. Geotech. Geoenviron. 128 (1), 25–37.
Ferrari, A., Bosch, J.A., Baryla, P., Rosone, M., 2022. Volume change response and fabric evolution of granular MX80 bentonite along different hydro-mechanical stress paths. Acta Geotech. 1–12.
Fredlund, D.G., Rahardjo, H., 1993. Soil Mechanics for Unsaturated Soils. John Wiley & Sons.
Gens, A., Guimaraes, L.D.N., Garcia-Molina, A., Alonso, E.E., 2002. Factors controlling rock–clay buffer interaction in a radioactive waste repository. Eng. Geol. 64 (2–3), 297–308.
Grindrod, P., Peletier, M., Takase, H., 1999. Mechanical interaction between swelling compacted clay and fractured rock, and the leaching of clay colloids. Eng. Geol. 54 (1–2), 159–165.
Ho, T.Y.K., Jardine, R.J., Anh-Minh, N., 2011. Large-displacement interface shear between steel and granular media. Géotechnique 61 (3), 221–234.
Hoffmann, C., Alonso, E.E., Romero, E., 2007. Hydro-mechanical behaviour of bentonite pellet mixtures. Phys. Chem. Earth, Parts A/B/C 32 (8–14), 832–849.
Hossain, M.A., Yin, J.H., 2010. Behavior of a compacted completely decomposed granite soil from suction controlled direct shear tests. J. Geotech. Geoenviron. 136 (1), 189–198.
Hossain, M.A., Yin, J.H., 2014. Behavior of a pressure-grouted soil-cement interface in direct shear tests. Int. J. Geomech. 14 (1), 101–109.
Leong, E., Tripathy, S., Rahardjo, H., 2003. Total suction measurement of unsaturated soils with a device using the chilled-mirror dew-point technique. Géotechnique 2, 137–182.
Lings, M.L., Dietz, M.S., 2005. The peak strength of sand-steel interfaces and the role of dilation. Soils Found. 45 (6), 1–14.
Marcial, D., Delage, P., Cui, Y.J., 2006. A laboratory study of the self sealing behaviour of a compacted sand-bentonite mixture. Geomech. Geoeng. Int. J. 1 (1), 73–85.
Minardi, A., Ferrari, A., Ewy, R., Laloui, L., 2018. Nonlinear Elastic Response of Partially Saturated Gas Shales in Uniaxial Compression. Rock Mech. Rock. Eng. 51, 1967–1978. https://doi.org/10.1007/s00603-018-1453-x.
Mortara, G., Mangiola, A., Ghionna, V.N., 2007. Cyclic shear stress degradation and post-cyclic behaviour from sand–steel interface direct shear tests. Can. Geotech. J. 44 (7), 739–752.
Pellet, F.L., Keshavarz, M., Boulon, M., 2013. Influence of humidity conditions on shear strength of clay rock discontinuities. Eng. Geol. 157, 33–38.
Plötze, M., Weber, H.P., 2007. ESDRED: Emplacement tests with granular bentonite MX-80 (No. NAB 07–24), Laboratory Results from ETH Zürich. Wettingen, Nagra.
Quinteros, V.S., Dyvik, R., Mortensen, N., 2017. Interface friction angle soil-on-steel from ring shear tests on offshore north sea sands. Geotech. Front. 2017, 358–367.
Romero, E., 2001. Controlled-suction techniques. In: Proc. 4th Simposium Brasileiro de Solos Não Saturados, Porto Alegre, Brasil.
Seiphoori, A., Ferrari, A., Laloui, L., 2014. Water retention behaviour and microstructural evolution of MX-80 bentonite during wetting and drying cycles. Géotechnique 64 (9), 721–734.
Sinnathamby, G., Korkiala-Tanttu, L., Gallardo Forés, J., 2014. Interface shear behaviour of tunnel backfill materials in a deep-rock nuclear waste repository in Finland. Soils Found. 54, 777–788. https://doi.org/10.1016/j.sandf.2014.06.027.
Stavropoulou, E., Briffaut, M., Dufour, F., Camps, G., 2020. Time-dependent behaviour of the Callovo-Oxfordian claystone-concrete interface. J. Rock Mech. Geotech. Eng. 12 (1), 89–101.
Tang, A.M., Cui, Y.J., Barnel, N., 2008. Thermo-mechanical behaviour of a compacted swelling clay. Géotechnique 58 (1), 45–54.
Uesugi, M., Kishida, H., 1986. Frictional resistance at yield between dry sand and mild steel. Soils Found. 26 (4), 139–149.
Wang, Q., Tang, A.M., Cui, Y.J., Delage, P., Gatmiri, B., 2012. Experimental study on the swelling behaviour of bentonite/claystone mixture. Eng. Geol. 124, 59–66.