INTRODUCTION

Due to the evolution of its demography as well as its consumption, Burkina Faso (West Africa) is experiencing a situation of high waste production currently estimated at 500 000 tons per year for its capital Ouagadougou. As in many developing countries, waste storage has migrated from uncontrolled dumping to landfills of several ha. The construction of a landfill requires phases of earthworks to define a main excavation which will be divided in several cells. These cells will be filled with waste and covered with a clayey cap liner when full in order to isolate waste. Before the installation of this cover, the rainwater percolates through the waste and is temporarily loaded to produce leachate. Leachate quality is the result of the waste composition, water budget, biological, chemical, and physical conditions in the landfill body (Erhig and Stegmann, 2018), its composition varies significantly among landfills depending on waste composition, waste age and landfilling technology (Christensen *et al*, 2001). Familiarly called “garbage juice” (Jambeck, 2007), leachate of household and similar waste has a potentiel impact on land, soils and groundwater (Wdowczyk and Szymańska-Pulikowska, 2021; Ullah *et al.,* 2018; Azizi *et al.,* 2016). These leachates must be drained by a granular material and a network of flexible pipelines before being pumped out for treatment. Despite the presence of this Leachate Collection and Removal System (LCRS), soil and groundwater protection must also be ensured by a geological barrier known as bottom liner which covers the slope and the bottom of the excavation. The bottom liners must limit the infiltration of pollutants and various authors such as Widomski *et al.* (2018) agree that it ensures the long-term safety of the site. Very often, adequate geological conditions are not satisfied and techniques of strengthening and soil treatment are implemented. The design of landfills is mainly based on a criteria related to hydraulic flow of leachate through the sealing barriers. The most stringent national and international regulations define a threshold value of 10^{-9} m/s for hydraulic conductivity (also called permeability) over a thickness of at least 1 m on the bottom and 0.5 m on the slopes (Wagner, 2013). In addition, mechanical properties such as shear strength, low compressibility, low shrinkage-swelling are required for the design (Abdellah *et al.,* 2020). Indeed, the geometry of the slopes is determined so as to ensure a sufficient coefficient of stability (Abramson *et al.,* 2002). Vertical deformations of the liner, called settlements, will occur during the exploitation of the landfill. Settlements are linked to compressibility, which similar to the hydraulic conductivity, is one of the most important properties of the liner material (Mishra *et al.*, 2010). The assessment of the settlements caused by the overloads represented by the weight of the waste accumulated over several meters vertical deformations must be verified (Dutta and Mishra, 2016) as well as the risk of failure of the landfill that may occur during the phases of construction, operation and closure of the landfill (Townsend *et al.*, 2015). All this requires the determination of the appropriate geotechnical parameters of the bottom liners. As stated above, hydraulic conductivity is the parameter used to judge of the sealing potential of the bottom liner. In soil mechanics, stability analyzes are based on the determination of cohesion and angle of friction (parameters relating to shear strength). Recompression and compression indexes are used to predict settlements. Hydro-mechanical tests are carried out to measure such parameters in order to judge the use of these local clayey materials as perennial impervious barriers. However some major concerns are not sufficiently addressed. For instance there is no regulatory specification about how to measure hydraulic conductivity (Ait Saadi, 2003) of a bottom liner. Yet, many authors such as Benson *et al.* (2018) have well established that this parameter often increase when soils suitable for liners experience leachate leakage. Also note that according to established normative procedures tests are often conducted with distilled water whereas some authors have noticed changes on the long term mechanical behavior due to the leachate impact (Cuisinier *et al.*, 2014). Sometimes the behavior can be quite unpredictable and leachate can improve or alter mechanical properties of the liner. Indeed Dutta and Mishra (2016) noticed a decrease in compressibility index of bentonites in presence of salt solutions. Naeini *et al.* (2016) showed that interaction of inorganic clay with bentonite increased shear strength of the liner. Otherwise Gratchev and Towhata (2016) noticed an increase of compressibility indexes of Kansai clay with acidic solutions, meaning an increase in settlements. Another concern is the fact that most impervious clays do not always have the best mechanical properties. Few works have highlighted the considerations described above through a comparison between two clayey materials solicited by the same leachate. This approach makes it easier to understand the criteria for choosing suitable clayey material to make a bottom liner. The study highlights the importance of a compromise between hydraulic and mechanical performances. It also highliths the importance of the representativeness of the type of fluid used for the determination of the geotechnical parameters. In summary, the study offers to environmental geotechnics professionals a reflection on how to judge the performance of clay barriers on the long term. In this study, the hydro-mechanical performances of two clayey materials, sampled in Burkina Faso (West Africa) and their evolution when they are in presence of household waste leachates are examined. The study was conducted in Burkina Faso between 2018 and 2020.

MATERIALS AND METHODS

The methodological approach consists first of all, in selecting two soils which have different mineralogical properties, both potentially suitable as bottom liners, and testing their hydro-mechanical properties in a defined reference condition. This reference condition, simulated by saturation with distilled water, aims to describe the behavior of a landfill when it is not yet solicited by the chemical action of the leachates. The hydro-mechanical properties are then assessed with two types of leachates in order to understand the modification of the behavior of the bottom liner during the operation of a landfill, including leachate leakage, deformation and risks of failure of the bottom liner. The discussion which follows will focus on the modification of properties according to the mineralogical nature of the liner and according to the type of leachate. It is oriented towards the selection criteria to consider in the choice of suitable clayey soils to make bottom liners. Fig. 1 presents the overall methodology of the characterization of the studied clayey soils.

Choice and identification of soils

In this study, two soils were collected in Burkina Faso. The first one is natural and comes from Nouna located 284 km northwest of the capital Ouagadougou. In this zone, the geological conditions indicate a cover of aeolian sands, clays and alluvium constituting young sediments on old lands. The sampling area is located in a vast plain flooded in places and covered with weeds in the winter season. When sampled, the soil is in the form of hardened blocks. Soils from Nouna are gray and hard when dry. They are moistened when black, they are soft and they smell as organic matter in decomposition. The sampling area is X = 406,327 and Y = 1,405,498 (UTM ZONE 30P). The second one comes from Boudry located 100.5 km east of Ouagadougou (X = 749,953 and Y = 1,353,945 UTM ZONE 30P). These soils from Boudry are generally shallow and not very fertile, of the ferruginous tropical type, vulnerable to the action of erosion and runoff. The sampling area is located

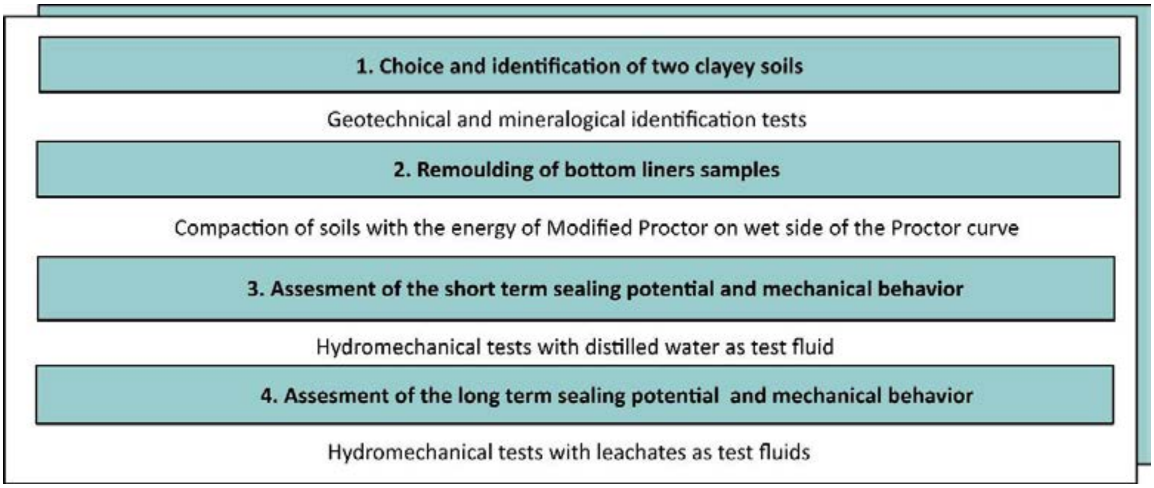

Fig. 1: Methodology of characterization of the hydro-mechanical behavior of the two clayey soils

Table 1: Geotechnical identification parameters of the studied soils

Soils	Fine fraction (≤ 80 µm) [%]	Clay fraction (≤ 2 µm) [%]	Liquidity limit w_l [%]	Plasticity limit w_p[%]	Plasticity index PI[%]	Organic matter content [%]	Optimum water content w_{OPM} [%]	Maximum dry unit weight γ_{dmax} [kN/m^3]
Nouna	95	74	44	22	22	10.8	16.30	16.53
Boudry	47.6	22.5	42	20	22	3.9	9.20	19.91

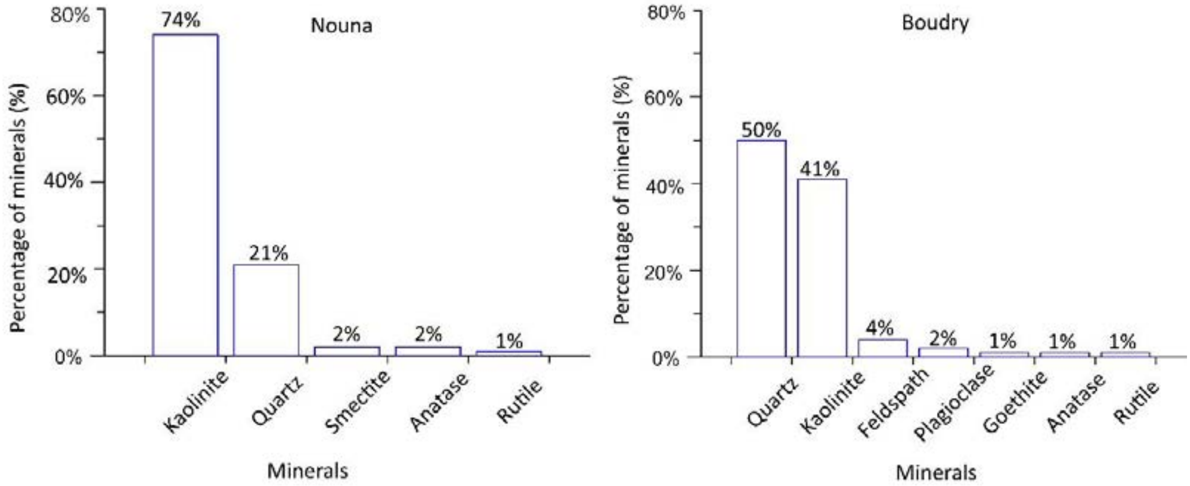

Fig. 2: Mineralogical composition of the fine fraction of the studied soils

on a large, sparsely treed plain. The reddish surface of the soil is sandy-silty. When sampled, the soil is in the form of hardened blocks. The walls remain vertical. The soil is completely dry, light brown to yellow with gravel or nodules. Soils were collected by hand digging of 75 cm deep hole. These samples were brought to the laboratory after a first on-site quartering operation. These samples of about 100 kg of soil were air-dried in the laboratory and broken up by hand. By a second quartering operation, several homogeneous batches were made, which will serve as test samples as well as for the production of test specimens. Identification tests (mineralogy by X-Ray diffraction over the infra 80 µm, particle size analysis using sieve analysis and sedimentometry, Atterberg limits, and determination of organic matter by calcination according to NF standards (AFNOR, 1992; 1996; 1998; 2002) and modified Proctor tests were carried out on these soils in order to determine their nature parameters of and compaction characteristics. The results of the geotechnical identification are shown in Table 1. The semi-quantitative mineralogical composition of the powders, which can be obtained by XRD analysis, is shown in Fig. 2. This mineralogical analysis were carried out on air-dried and glycol saturated preparations from the fine fraction of the soils. The diffractograms analysis was carried out according to Rietveld method.

The geotechnical identification tests essentially indicate clayey materials; the results of the mineralogy confirm that the fine fraction is mainly clayey respectively 76% for soils from Nouna and 41% for soils from Boudry. XRD results from oriented preparations and glycol-saturated oriented preparations reveals that the predominant mineral is kaolinite (74% of kaolinite and 2% of smectites for soils from Nouna, 41% of kaolinite for soils from Boudry). The results also report a significant amount of organic matter. In the Casagrande diagram, these materials are described as medium inorganic clays (CL), however the soil from Boudry are rather clayey sand (SC-CL). Their PI values are relatively high and thus make them promising from the point of view of their sealing potential.

Table 2: Composition by category of waste for Ouagadougou landfill (Haro *et al.*, 2018)

Category of waste	Percentage composition of waste fraction	
	Rainy season	Dry season
Fermentable waste	23.86	19.94
Paper	1.65	2.37
Cardboard	4.49	5.19
Composites	1.53	2.28
Textiles	5.41	4.32
Sanitary textiles	1.69	1.94
Plastics	11.13	12.1
Non-classified combustibles	3.46	2.81
Glass	1.14	3
Metals	2.89	1.71
Non-classified incombustibles	4.27	5.12
Special wastes	0.22	1.14
Fine materials	38.27	38.08

Table 3: Chemical composition (major ions) of the synthetic leachate

Ionic species	Ca^{2+}	Cl^{-}	Cu^{2+}	K^{+}	Mg^{2+}	Na^{+}	NH_4^{+}	SO_4^{2-}
Concentrations (mol/L)	0,014	0,07	7.10^{-4}	0,017	0,002	0,035	0,003	0,009
Concentrations (mg/L)	570,2	2475,8	5	673,5	50	793,2	50	834,9

Choice of leachates

Two types of leachates have been used in this study. The first one is natural and has been collected from the leachate storage and treatment ponds from the drainage system of Ouagadougou landfill. The values of BOD_5/COD highlight a large amount of organic matter. The pH value of the leachate is representative of a basic leachate with a pH of 7.68. The low electrical conductivity value of 1182 µs/cm shows that the salinity and at the same time the ionic strength of this leachate are not important. More details about its composition figured in Vianney *et al.* (2017). The composition by category of waste of Ouagadougou landfills are given in Table 2.

The second leachate is synthetic and has been formulated to be as close as possible of a young leachate from a household landfill in an acidogenesis phase. The formulation of this leachate has been described by Yonli *et al.* (2017). It has a relatively high biodegradable organic load consisting mainly of VFAs (Volatile Fatty Acids) and it is also loaded with heavy metals. Concentrations of chemical species (Table 3) are selected to stay within the usual ranges found in landfills and described by Christensen *et al.* (2001). The pH of the synthetic leachate is acidic with the value of 5.07 and an electrical conductivity of 12,560 µs/cm highlighting a high value of ionic strength.

Thus, there are two leachates, the synthetic one is potentially more aggressive. The formulation of synthetic leachates is a practice used in several studies. It has the advantage of guaranteeing control of the chemical composition and of discussing the modifications induced by the chemical species present by varying their concentration or by considering their actions in isolation.

Assessment of hydraulic conductivity by means of filtration tests on the two materials

The hydraulic behavior of the soils was assessed by means of API (American Petroleum Institute) type filtration tests. The method is well documented and consists of subjecting a suspension of soil and solvent to a pressure of 690 kPa (Sherwood, 1997; Benna-Zayani *et al.*, 2001; Pantet and Monnet, 2007 ; Rosin-Paumier *et al.*, 2011). The applied pressure forces the liquid to flow while the solid part called cake is retained on a filter paper. The kinetics of filtration are related to the hydraulic properties of the cake as well as the chemical composition of the filtered liquid. Although Darcy's law was developed for grainy soils (sands and gravels), to this day, it is still used, for cohesive soils (clays and silts). Application to fine soils assumes a sufficiently high hydraulic gradient so as not to observe deviations from Darcy's law. This condition is fulfilled within the framework of this study, given the high pressure value applied to the clay suspensions. From Darcy's law, it is established that the cumulative volume of filtrate $V(m^3)$ is expressed as a linear relation as a function of the square root of time t(s) using Eq. 1.

$$V^2=2.K.S^2.P.t/(\mu.b) \quad (1)$$

Where, K is the desired intrinsic permeability (m^2) of the material, S the surface of the sample (m^2), P the pressure (Pa), μ the viscosity of the water ($Pa.s^{-1}$) and $b = cS/V_f$ the specific volume of the cake deposited per unit volume, c the cake thickness (m), V_f is the final volume at the end of filtration (m^3). The coefficient of permeability or hydraulic conductivity k(m/s) is thereafter obtained by Eq. 2.

$$k = \rho.g.K/\mu \quad (2)$$

Where, ρ is the bulk density of water (kg/m), g is the acceleration due to gravity (m^2/s)

The suspensions dosed at 100 g/L are prepared with distilled water (which serves as a reference situation) then in the presence of the leachates (natural leachate and synthetic leachate) at the same dosage. The void ratio of the cake is calculated after determining its dry density ρ_d using Eq. 3.

$$e = \rho_s/\rho_d-1 \quad (3)$$

Where, ρ_s is the density of the solid particles assumed equal to 2.65 g/cm^3.

The advantage of the filtration tests method lies in its rapidity since it makes it possible to avoid the saturation period required before permeability falling head tests. Although the void index is not the same in both tests, filtration tests and permeability falling head tests lead to the same orders of magnitude of the hydraulic conductivity.

Assessment of mechanical behavior of soils from Nouna

The various mechanical parameters were determined by conducting tests on compacted samples of soils from Nouna and Boudry under drained conditions with water as saturating fluid and then with leachates. Conditions of compaction and conditions of drainage are identical in both cases. To ensure a low permeability, the samples have been remoulded by compaction with the energy of Modified Proctor on wet side of the Proctor curve (at w_{OPM}+3%).

Assessment of compressibility

The deformation properties of the soils were assessed by means of oedometric tests, applying a loading stage every 24 hours. In this approach, the consolidation phenomenon involded, implies a strong coupling between the mechanical compressibility of the soil skeleton and the drainage of the interstitial fluid and supposes a saturation of the soil. The samples of soils tested in this study were allowed to swell almost freely during a saturation phase, the sample is only subjected to a vertical stress corresponding to the weight of the piston (3 kPa). Then, the loads applied to the sample were increased, step by step, up to 483 kPa, with three loading/unloading cycles. The value of 483 kPa corresponds to the order of magnitude of the stresses caused by the weight of the waste in the landfills in Burkina Faso. The deformation parameters were calculated from the compressibility curve e-logσ'_v where e is the soil void ratio and σ'_v is the corresponding applied effective vertical stress. The compression and recompression indexes C_c and C_r are important because they allow to calculate the settlement (vertical deformation of the bottom liner). In the case of excessive settlements and especially differential settlements, the clayey bottom liner may be damaged.

Assessment of shear strength

The shear strength is measured by means of direct shear test, using a shear test appartus equipped with an automated acquisition device. It is assumed that, in landfills, the application of loads related to the weight of waste leads to the consolidation of the soil through the dissipation of interstitial pressures. This is why, tests conducted with different loads were carried out under saturated conditions with a sufficiently slow speed (of 0.02 mm/mn), in order to measure the effective characteristics. The shear stress at the rupture obeys Coulomb's law, using Eq. 4.

$$\tau = C' + \sigma'_v.tan\phi' \quad (4)$$

Where, C' is the effective cohesion and ϕ' the effective angle of internal friction.

Table 4: Hydraulic conductivities of studied soils obtained with distilled water

Soils	Nouna	Boudry
Hydraulic conductivity k(m/s)	1.71×10^{-10}	1.01×10^{-9}
Void ratio e	1.11	0.90

Table 5: Influence of the leachate on hydraulic conductivities of studied soils

Test fluids	Hydraulic conductivities k(m/s)	
	Nouna	Boudry
Distilled water	1.71×10^{-10}	1.01×10^{-9}
Natural leachate	3.51×10^{-10}	2.70×10^{-9}
Synthetic leachate	1.18×10^{-9}	7.72×10^{-9}

RESULTS AND DISCUSSION

Filtration tests with water and leachate

The results of filtration tests carried out on suspensions dosed at 100 g/L with soils from Nouna and Boudry are presented below. Table 4 also presents the characteristic values of the cake obtained.

These results show that the soil from Nouna has a hydraulic conductivity at saturation less than 10^{-9} m/s, confirming the possibility of being used as a bottom liner. The soil from Boudry however has a value of hydraulic conductivity of 1.01×10^{-9} m/s. This value of hydraulic conductivity is at the limit of the acceptable threshold. It appears otherwise that even with trace amounts, smectites are very necessary to obtain an optimal sealing. Indeed, the permeability of clay materials is highly dependent on the mineralogical composition of the clay compounds, the texture, its water content and its state of consolidation (Marcoën *et al.*, 2000). The results of the filtration tests with the synthetic leachate (Table 5) showed an important increase in the hydraulic conductivity k of the soils from of Nouna, which varies from 1.71×10^{-10} m/s to 1.18×10^{-9} m/s, i.e. k almost multiplied by 10; it results in the decrease in their sealing potential. Concerning the soils from Boudry, the increase with this leachate is slightly less significant. The less impervious material appears to undergo the deeper alteration. The degradation of the sealing potential with leachates is a phenomenon highlighted by many authors. For example Badv and Omidi (2007) who studied the effect of a synthetic leachate rich in calcium (4000 mg/l concentration) on the hydraulic conductivity of a clayey sand found an increase in the hydraulic conductivity of 20%. Wang *et al.* (2019) used a natural leachate (stabilized inorganic hazardous waste leachate) to conduct hydraulic conductivity tests on bentonites and also noticed an increase in the hydraulic conductivity. The phenomenon of degradation of the sealing potential deserves further investigation, because many parameters are involved such as the composition of the leachate and its concentration. The natural leachate has a very slight impact on the permeability of the materials. This result is in agreement with the nature of the leachate: the synthetic leachate formulated has a very high ionic strength compared to that of the natural leachate. This indicates that the mineral pollutant load of the landfill leachate is not so high. Setz *et al.* (2017) noticed that solutions having high ionic strength or predominantly divalent cations lead to larger pores and higher hydraulic conductivity.

Influence of leachates on compressibility

Compressibility of soils from Nouna

The results of œdometric tests conducted on soils from Nouna are given in Table 6. They show that although compacted (with an initial void ratio e of 0.65 and an initial density (saturated density) g_{sat} of 18.92 kN/m^3 compared to the value e of 1.11 and g_{sat} of 13.42 kN/m^3 obtained by filtration), the soils from Nouna have values of compression and recompression indexes which characterize compressible soils. Despite the low percentage of smectites of 2%, the swelling of the soils from Nouna (part "AB" of the curve) appears to be very important. Indeed, according to Tabani (1999) and Xu *et al.* (2003), the amount of swelling clay is one of the first factors which condition the swelling of clayey soils. Tabini (1999) found a swelling rate of 6.3% for a soil having a percentage of bentonite of 10% under a pressure of 5 kPa. Nouna clay, for its part, has a swelling rate of 12.05% under a pressure of 3 kPa. Nevertheless, many

Table 6: Influence of leachate on the parameters of the mechanical behavior of the soil from Nouna

Test fluids	Initial specific weight γ_{sat} (kN/m^3)	Deformabilty properties		Preconsolidation pressure $\sigma'_p(kPa)$
		Recompression index C_r	Compression index C_c	
Distilled water	18.92	0.049	0.164	55
Natural leachate	18.83	0.054	0.148	55
Synthetic leachate	19.37	0.095	0.225	50

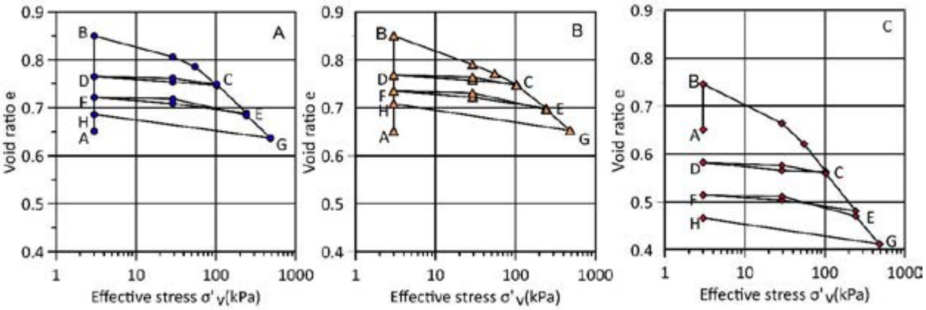

Fig. 3: Compressibility curves obtained for soils from Nouna (A. Distilled water; B. Natural leachate; C. Synthetic leachate)

authors agree that the initial state of the soil (water content and dry density) and other structural effects, seasonal influence and even test conditions may have an influence on the swelling rate (Chrétien, 2010). All else being equal, the mechanical behavior of Nouna clay is also modified under the influence of leachates. Results are summarized in Table 6 and on Fig. 3. The compressibility curves e-logσ'_v seem quite similar for distilled water (Fig. 3A) and natural leachate (Fig. 3B). Thus, it appears that the natural leachate having a weak ionic strength has few interactions with the soil. On the other hand, the impact of the synthetic leachate is very noticeable (Fig. 3C). This raises the question of the representability of leachate as a test fluid. Let's remember that the synthetic leachate is formulated to be as close as possible to a leachate of household landfill in its early stages of maturation. The swelling of Nouna is partially inhibited. Indeed, the cations contained in this solution diffuse through the layer space of the clay resulting in a reduction of repulsive forces between the clay particles (Yonli *et al.*, 2017). The compression index undergoes a significant increase from 0.164 to 0.225 and it is necessary to consider in the design of the bottom liner as it will lead to higher settlements. Gratchev and Towhata (2009) made this same observation. The authors noted that the compressibility of Ariake clay leached with acidic fluids increased because of the dissolution of ferric oxide between the clay aggregates.

In order to know the contribution of each group of chemical species contained in the synthetic leachate (VFA, major mineral ions, heavy metals) in the increase of the compressibility, œdometric tests were also performed with each one of them. The results shown in Fig. 4 reveal that while major mineral ions and heavy metals cause a decrease in compressibility (decrease in Cc), for acetic acid, the opposite occurs. It is therefore the reaction of VFA with some compounds of the soils from Nouna which contributes to such an increase in the settlements.

Compressibility of soils from Boudry

The results obtained for the soils from Boudry (Table 7 and Fig. 5) well illustrate the role of mineralogy on the modification of the mechanical properties of soils. Swelling is not affected by both leachates. Unlike soils from Nouna, the compressibility of soils from Boudry decreases because the settlements become less important. Thus, if permeability is altered by leachates regardless of the type of clay, it is not the same way for compressibility. This observation leads us to reflect on the criteria for choosing suitable clayey soils to make bottom liners. Shouldn't it be the result of a compromise between hydraulic and mechanical

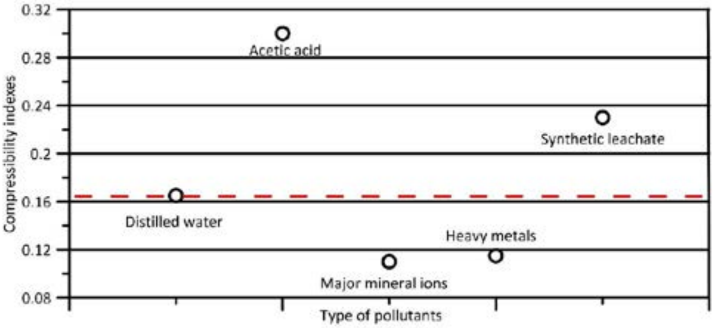

Fig. 4: Influence of the type of pollutants contained in the synthetic leachate on the compressibility of Nouna clay, comparison with distilled water

Table 7: Influence of leachate on the parameters of the mechanical behavior of the soils from Boudry

Test fluids	Initial specific weight γ_{sat} (kN/m^3)	Deformabilty properties		Preconsolidation pressure $\sigma'_p(kPa)$
		Recompression index C_r	Compression index C_c	
Distilled water	20.21	0.007	0.109	50
Synthetic leachate	20.10	0.007	0.075	50
Real leachate	20.25	0.001	0.067	50

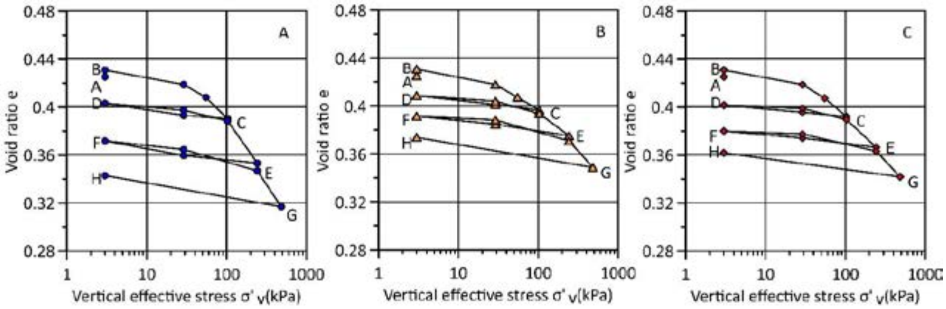

Fig. 5: Compressibility curves obtained for soils from Boudry (A. Distilled water; B. Real leachate; C. Synthetic leachate)

performance which takes into account the composition of the leachate? The answer to this question would obviously involves the choice of the representability of the test fluid as leachate. According to some authors such as Dutta and Mishra (2016), the decrease of compression index may be the result of the orientation of clay particles becoming more flocculated and resisting to settlements. Litterature also suggests that the effect of diffuse double layer on the compressibility of soils is less pronounced for kaolinitic soils compared to soils containing smectites (Mitchell and Soga, 2005). This statement is in agreement with the results of this study.

Influence of leachates on shear strength

Shear strength of soils from Nouna

The effective cohesion C' and the effective angle of internal friction Φ' (measured at a state of compacity identical to the case of the oedometric tests) and determined from the Mohr relation, are respectively 3 kPa and 28° for tests with distilled water. The low value of cohesion and the relatively high value of the angle of friction are consistent with the state of saturation of the clay. Since the real leachate did not significantly alter the compressibility of Nouna, only synthetic leachate (compared with distilled water) was used to conduct shear tests. The results of shear tests with the synthetic leachate as a saturating fluid reveal that the soil experiences an increase in shear strength (Fig. 6). The shear strength is modified with only an increase in the soil cohesion at 21 kPa. The value of the angle of internal friction is not affected. The observation of this phenomenon could find an explanation in the theory of the diffuse double layer. Leachate highly concentrated in electrolytes would cause a change in the organization of particles. From a morphological point of view, the leachate favors an increase in the number of sheets per aggregate and consequently a decrease in the number of aggregates with equal dry matter quantity. All this shows that the soil migrates towards a more cohesive state. Some authors have pointed out that it is precisely aggregates which generate the shear resistance (Derriche *et al.*, 1997).

Shear strength of soils from Boudry

The intrinsic curves of soils from Boudry, on the other hand, show that the increase in shear strength induced by the synthetic leachate is due both to the cohesion of the soil as well as to its internal friction angle (Fig. 7). However, the increase in cohesion is less significant than that of the soils from Nouna: it goes from 19 kPa to 23 kPa, i.e. an increase of 21%. This finding is in agreement with œdometric tests which have shown that the influence of the leachate on the swelling and therefore on the diffuse double layer is negligible because of the mineralogy of the soils from Boudry, whose clay fraction mainly contains kaolinite. The slight increase in the internal friction angle, which goes from 34 ° to 37 °, may be due to the action of the synthetic leachate on the geometry of the grains of sand contained in soils from Boudry.

Some authors have also found similar results, they notice an increase in shear strength of clayey soils in contact with leachate. Indeed Naieni *et al.* (2017) studied the effect of leachate's components on undrained shear strength of clay-bentonite liners. They noticed that by addition of soluble salts of single-valence cations and leachate provided from them up to 2%, the undrained shear strength of clay-bentonite liners increased. However, they also

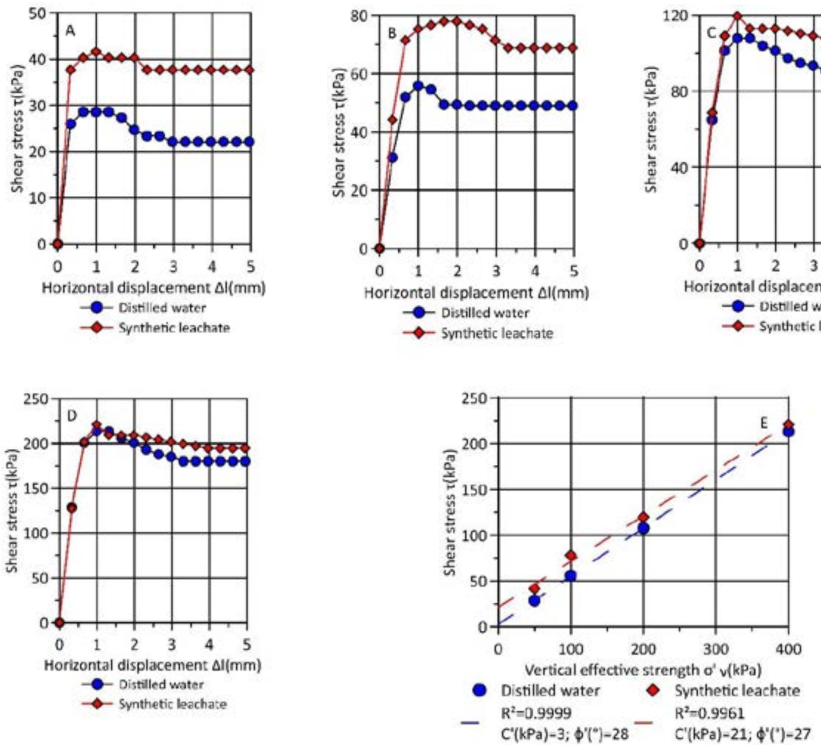

Fig. 6: Influence of synthetic leachate on the shear strength of soils from Nouna (A. Stress strain curve σ'$_v$ = 50 kPa ; B. Stress strain curve σ'$_v$ = 100 kPa ; C. Stress strain curve σ'$_v$ = 200 kPa ; D. Stress strain curve σ'$_v$ = 400 kPa E. Failure envelope)

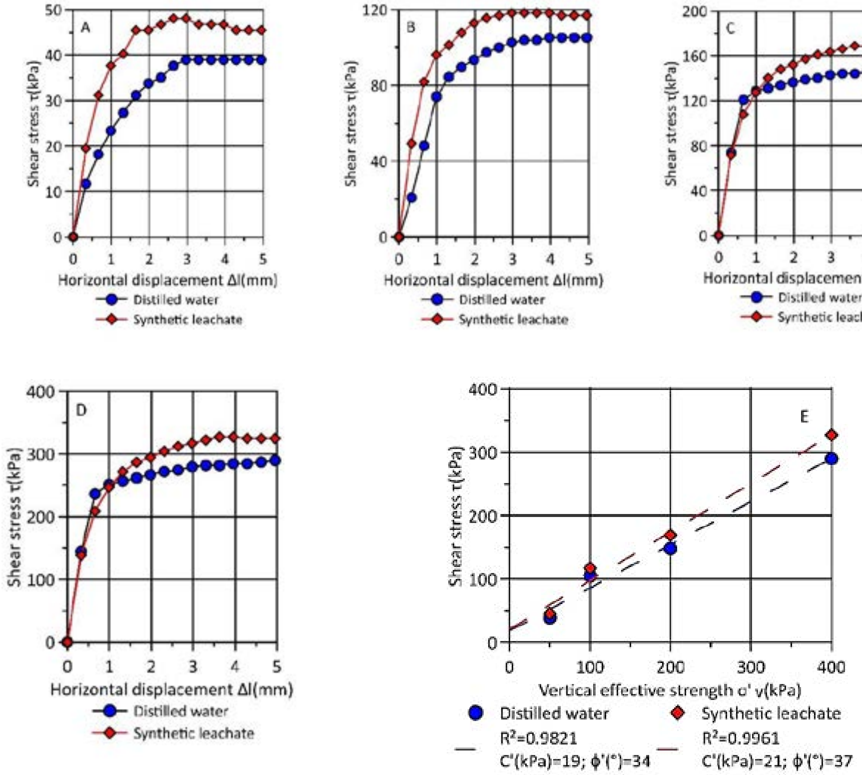

Fig. 7: Influence of synthetic leachate on the shear strength of soils from Boudr (A. Stress strain curve $\sigma'_v = 50$ kPa ; B. Stress strain curve $\sigma'_v = 100$ kPa ; C. Stress strain curve $\sigma'_{v*} = 200$ kPa ; D. Stress strain curve $\sigma'_v = 400$ kPa E. Failure envelope)

pointed out, shear strength decrease with further increase in contaminants. Sunil *et al.* (2009) noticed that even in lateritic soils used as landfill foundation, the contamination by municipal solid waste leachate lead to changes in the shear strength characteristics. The effective cohesion increases while the effective friction angle decreases.

The results of all the hydro-mechanical tests in this study show that while leachates are always detrimental to the sealing of a bottom liner, it is not necessarily the case for its mechanical behavior. This should draw attention to the fact that designing a bottom liner is a complex process that requires extensive investigations.

CONCLUSION

This study consisted to assess the modification of the long-term hydro-mechanical behavior of two clayey soils in presence of household waste leachate. It allowed to reconsider the criteria of choice of suitable clayey soils for a use as bottom liners. Contamination by leachate always alters the hydraulic properties of soils. However, between the two soils studied, the most clayey and the most impermeable (soils from Nouna) undergo the deeper alteration. Furthermore, whatever the soils considered, the leachate with the greatest ionic strength is also the most aggressive in terms of degradation of the sealing properties. The study emphasizes that the choice of the clayey soils as bottom liners should results from a compromise between long term hydraulic and mechanical performance. Indeed, soils from Boudry (mainly containing quartz and kaolinite), which are the less impermeable of both materials, experience an improvement of their deformation properties meaning that settlements decrease. On the contrary a bottom liner made from soils from Nouna, would experience very significant settlements over the long term because of the influence of volatile fatty acids contained in the synthetic leachate. The influence of the synthetic leachate on the shear strength characteristics shows that it always improves the stability of the bottom liner. In this case, a short-term design of the liner, is better from a safety point of view. This result requires further investigation by carrying out the same tests with other clayey soils and other leachates as research perspectives. The question of the representativeness of the leachate for carrying out a long-term characterization is also raised. The natural leachate of lower ionic strength has less impact on the hydro-mechanical behavior of the studied soils as evidenced by the values of hydraulic conductivities and those of the compression and recompression indexes. The conclusions of this comparative study of the hydro-mechanical properties of two clayey soils are of practical use to professionals in the field of environmental geotechnics. The importance of the surface properties with respect to leachate is well demonstrated. On the long term, leachate production, linked to the decomposition of waste, can lead to a loss of hydraulic performance and a modification of the mechanical characteristics of the bottom liners.

AUTHOR CONTRIBUTIONS

H.F. Yonli performed the literature review, compiled and interpreted the data, prepared and edited the manuscript. B. François interpreted the data and prepared the manuscript. D.Y.K. Toguyeni and A. Pantet performed the elaboration of the research problem.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

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PUBLISHER'S NOTE

ABBREVIATIONS

API	American Petroleum Institute
b	Specific volume of the cake
BOD_5	Biologic Oxygen Demand
c	Cake thickness
C'	Effective cohesion
C_c	Compression index
Ca^{2+}	Calcium ion
CL	Inorganic clay of low to medium plasticity
Cl^-	Chloride ion
COD	Chemical Oxygen Demand
Cu^{2+}	Copper ion
C_r	Recompression index
cm	Centimeter
cm^3	Cubic centimeter
e	Void ratio
g	Gram
i.e.	That is to say
k	Hydraulic conductivity
K	Intrinsic permeability
K^+	Potassium ion
kg	Kilogram
km	Kilometer
kN	Kilonewton
kPa	Kilopascal

g	Acceleration due to gravity
L	Liter
$LCRS$	Leachate Collection and Removal System
m	Meter
m^2	Square meter
m^3	Cubic meter
mg	Milligram
Mg^{2+}	Magnesium ion
mn	Minute
mol	Mole
P	Pressure
Pa	Pascal
Na^+	Sodium ion
NH_4^+	Ammonium ion
PI	Plasticity index
pH	Potential hydrogen
s	Second
S	Surface of the sample
$SC\text{-}CL$	Clayey sand of low to medium plasticity
SO_4^{2-}	Sulfate ion
t	Time
UTM	Universal Mercator Transverse
V	Cumulative volume of filtrate
V_f	Final volume at the end of filtration
VFA	Volatile Fatty Acids
X	X coordinate
XRD	X Rays Diffraction
Y	Y coordinate
wl	Liquidity limit
w_{OPM}	Optimum water content
w_p	Plasticity limit
ρ	Bulk density of water
ρ_d	Dry density
ρ_s	Density of the solid particles
Φ'	Effective angle of internal friction
μ	Viscosity of water
μm	Micrometer
μS	Microsiemens
γ_{dmax}	Maximum dry unit weight
γsat	Saturated density
σ'_v	Effective vertical stress
σ'_p	Preconsolidation pressure
%	Per cent
°	Degree

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