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Study of the Influence of a Young Synthetic Leachate on the Hydromechanical Properties of a Swelling Clay

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Abstract: Despite the developments of sectors which aim at valorizing recyclable materials, landfills remain essential in integrated waste management. The construction of such infrastructures is an engineering challenge that must be proven over the long term. The purpose of this study is to understand the modification of the hydromechanical properties of bottom liners of landfills that may occur during their exploitation under leachate action. To do so, on the basis of its parameters of nature, a swelling clay from Burkina Faso is selected from soils of seven localities in Burkina Faso (West Africa). Laboratory tests carried out with distilled water and then with a young synthetic leachate show a degradation of the permeability of this clay from 2.42×10^{-10} m/s to 1.01×10^{-9} m/s. In addition, leachate leads to an inhibition of the swelling and a remarkable increase of its compressibility, inducing significant settlement. With the increase in permeability, the primary consolidation settlement is increasing faster. Changes in the hydromechanical behavior can be attributed to the clays mineralogy, mainly cation exchange and the development of the diffuse double layer.

Key words: Bottom liner, leachate, hydraulic conductivity, compressibility, consolidation.

Acronyms and Abbreviations

Symbols	*Meanings*
API	American Petroleum Institute
CCL	Compacted Clay Liner
DDL	Diffuse Double Layer
EG	Ethylene Glycol
GCL	Geosynthetic Clay Liner
LOMC	Laboratory of Waves and Complex Media
LNBTP	National Laboratory of Building and Public Works
MIP	Mercury Intrusion Porosimetry
SEM	Scanning Electron Microscopy
ULB	Free University of Brussels
USCS	Unified Soils Classification System
UTM	Universal Transverse Mercator
VFA	Volatile Fatty Acids
XRD	X-Rays Diffraction

Notations

Symbols	*SI Units*	*Meanings*
A	m^2	Section of filter press cell
b	m	Thickness of the cake
C	*dimensionless*	Index obtained from the void ratio-pressure curve
C_c	*dimensionless*	Compression index
C_g	*dimensionless*	Swelling index
C_r	*dimensionless*	Recompression index
c_v	*dimensionless*	Coefficient of consolidation
e	*dimensionless*	Void ratio
e_0	*dimensionless*	Initial void ratio
g	$m \cdot s^{-2}$	Acceleration due to gravity
H	m	Initial thickness of the sample
K	m^2	Intrinsic permeability
k	$m \cdot s^{-1}$	Hydraulic conductivity
PI	*dimensionless*	Plasticity Index
s	m	Settlement due to consolidation
t	s	Time
t_{90}	s	Time to complete 90% of consolidation
ΔP	Pa	Pressure drop through the filter press cell
$\Delta\sigma_v$	Pa	Change in pressure
ρ	$kg \cdot m^{-3}$	Liquid mass density
σ'_{v0}	Pa	Effective stress of the in-situ soil
σ'_p	Pa	Preconsolidation pressure
μ	$kg \cdot m^{-1} \cdot s^{-1}$	Filtered liquid viscosity
w_{OPM}	*dimensionless*	Water content corresponding to the modified Proctor test optimum
w	*dimensionless*	Water content
ω	m^3	Volume of filtrate
ω_t	m^3	Total cumulative volume of filtrate

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1. Introduction

Waste management around the world has evolved considerably over the past five decades. From uncontrolled dumping and indiscriminate burning, it has turned to complex systems that integrate energy recovery processes and waste containment to reduce environmental impacts. Containment measures are used to prevent the migration of contaminants (leachates or gases) out of landfills or polluted sites [1]. Among these, bottom liners at the base of the landfill, made of clays, inhibit the migration of leachate (liquids from percolating rainwater through the waste) to groundwater. The design of such barriers requires the knowledge of the hydromechanical behaviour (shear resistance, compressibility, shrinkage, swelling and permeability) of the clay materials which constitute them. Numerous studies have shown that the interstitial fluid according to its chemical composition often alters the hydromechanical behaviour of clays [2-4]. These studies take into account the mineralogy of clays, the concentrations of chemical species present in the solution as well as the pH of the solution. Cuisinier, O., et al. [2] have shown that compacted clays subjected to the circulation of high pH water were under a long-term change in their hydromechanical behaviour. Gratchev, I. and Towhata, I. [5] investigated the compressibility of soils containing kaolinite in an acidic environment. They found that the soil structure (depending on whether soil samples were undisturbed or not) had a significant effect on soils compressibility for low pH media.

The change in the hydromechanical behaviour of clays is attributed to the dissolution and precipitation of some mineral phases. Moreover, cations present in solution modify the development of the diffuse double layer, modify the texture of the clay, condition the "water-particle" equilibrium and consequently the hydromechanical behaviour of the material [6]. This change in hydromechanical behaviour must be understood if one wants to control and anticipate the effects that can be induced and test the material under conditions close to the conditions of use [7]. This is all the more difficult because there is a multitude of leachates of different chemical compositions depending on the nature of the waste and the conditions under which the landfill is operated. The increase in hydraulic conductivity caused by leachate is probably the most damaging phenomenon for a bottom liner; this is why regulatory requirements are based on this parameter. In addition, on the surface of the landfill's cells, the change in compressibility (related to the consolidation phenomenon: reduction of soil volume by gradual drainage of water under normal stress) from the bottom liner is likely to result in differential settlement that may induce deformation (localized collapses or bending) and slope inversions of the cover liners [8]. It is controlled by mechanical and physico-chemical factors. The volume changes of the barrier are therefore important because compressibility has an influence on the strength and deformation properties that affect stability [9-11].

In this paper, filter press permeability tests as well as compressibility and consolidation œdometer tests were carried out on a clay sampled at Nouna (Burkina Faso) saturated with distilled water and then by a synthetic leachate to evaluate the modification of its hydromechanical behaviour. In landfills, bentonite is often used as GCL or CCL. However, since bentonite is commercial and expensive, authors are planning in this study the formulation of bottom liners from local natural resources. The synthetic leachate used for this purpose is a young leachate in the acidogenesis phase and therefore potentially aggressive towards the bottom liner [12].

2. Material and Methods

2.1 Choice and Identification of Soils

The soil subjected to this study comes from a selection among several soils sampled in Burkina Faso (West Africa) in seven (07) of its localities namely: Boudry (UTM X = 749,953, Y = 1,353,945), Bugi (UTM X = 874,055, Y = 1,335,410), Koupéla (UTM X

= 785,347, Y = 1,348,389), Mogtédo (UTM X = 735,767, Y = 1,357,173), Nakamtenga (UTM X = 936,038, Y = 1,397,247), Nouna (UTM X = 406,327, Y = 1,405,498) and Ziga (UTM X = 707,095, Y = 1,382,989) (Fig. 1).

The choice of sampling sites was motivated by the availability of information on their location, and in some cases on properties such as mineralogy and plasticity. The clays whose mineralogical properties indicated the presence of smectites were prioritized because of the remarkable hydrating and swelling properties of smectites, which give the clays a strong sealing potential. Samples disturbed at the sampling stage by digging of 75 cm deep holes were brought to the laboratory in plastic bags after an in-situ quartering operation. The results of soil identification (obtained by particle size analysis according to AFNOR NF P94-056 (13) and NF P94-057 (14) and by the Atterberg limits according to AFNOR NF P94-051 (15)) are presented on Table 1 and Fig. 2.

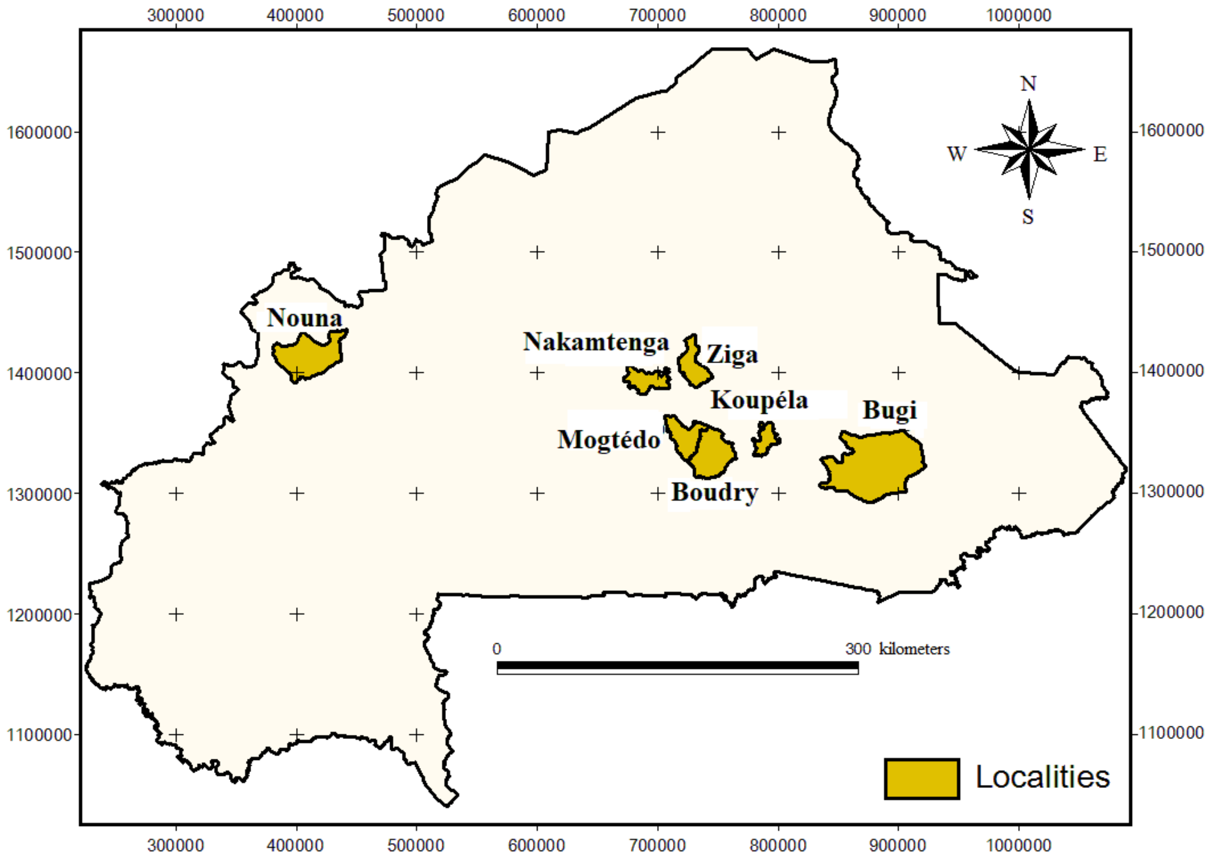

Fig. 1 Location map of sites of sampled soils.

Table 1 Identification of studied soils.

Soils	Thin fraction (≤ 80 µm)	Clay fraction (≤ 2 µm)	Plasticity Index PI (%)	USCS Classification	Description
Bugi	42.5	18.2	20	SC	Clayey sand
Boudry	47.6	22.5	22	SC-CL	Clayey sand of low plasticity
Koupéla	36	15.5	21	SC	Clayey sand
Nouna	95	74	22	CL	Clay of low plasticity
Mogtédo	70.5	16.5	15	CL	Clay of low plasticity
Nakamtenga	35.5	11	12	SC	Clayey sand
Ziga	100	61	39	OH	Organic clay of high plasticity

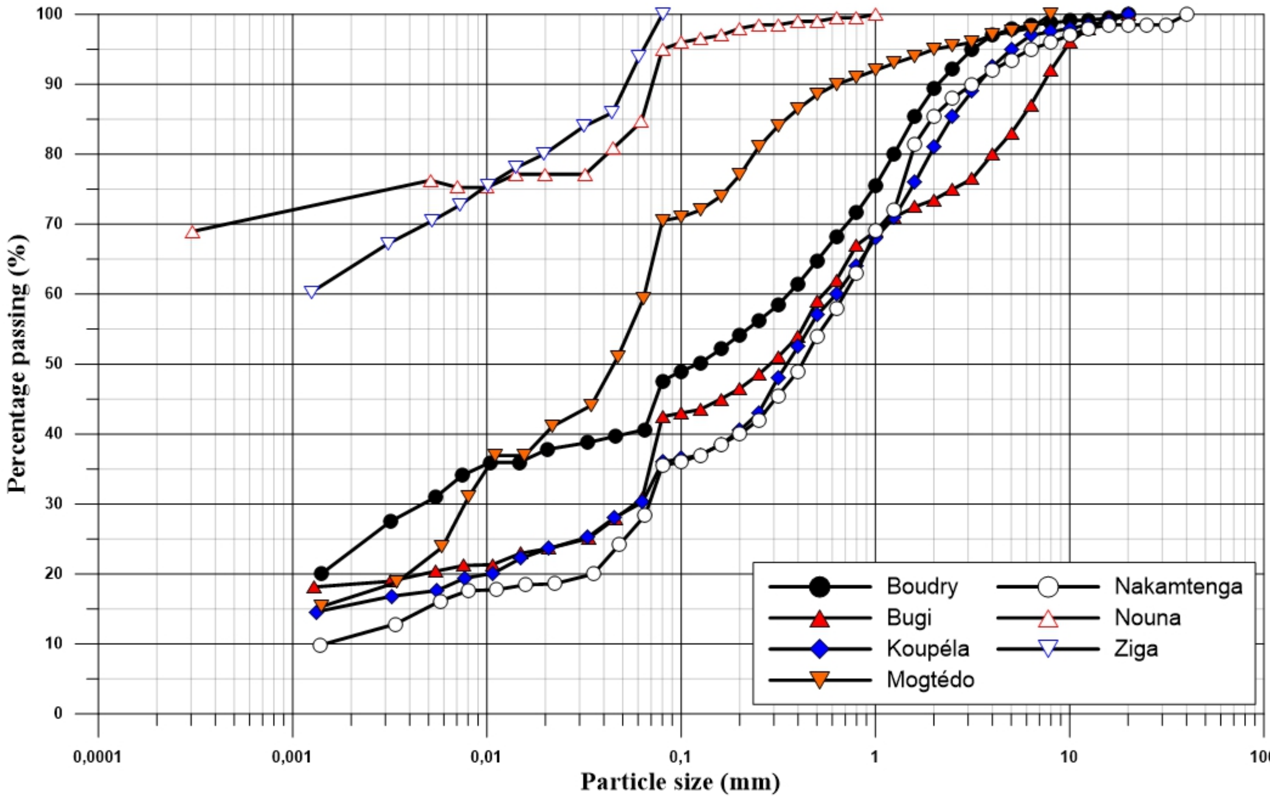

Fig. 2 Grain size analysis of studied soils.

The USCS classification, which uses grain size analysis and soil consistency limits, shows that most of the soils studied are clays and clayey sands. Among them, the soil from Nouna with 74% of clay fraction and a plasticity index PI of 22 % appears to be the most promising in terms of its sealing properties. From a mineralogical point of view, Nouna clay consists mainly of 74.11% of kaolinite identified by XRD (X-Rays Diffraction) at 7 Å (air 7 Å, EG (Ethylene Glycol) 7 Å, 500 °C not present), a little amount of muscovite at 10Å (air 10 Å, EG 10 Å, 500 °C 10 Å) and 1.71% of montmorillonite identified at 1.71%. Also present are quartz (21.46%), anatase (2.10%) and rutile (0.63%).

In addition, the CEC of this soil was determined by Metsen's method. The CEC, which is a collective term for several interacting processes such as chemical and physical adsorption, ionic exchange, precipitation and co-precipitation [16], can be very useful in quantifying the retention of pollutants if the retention process is mainly due to ion bonds. The CEC value of 42.40 meq/100 g for Nouna soil is very high.

This soil was therefore selected for the evaluation of its hydromechanical properties. The study of permeability was conducted on clay suspensions and the compressibility/consolidation study on compacted soil samples. For this purpose, after determining the compaction characteristics (Fig. 3) by conducting out Proctor tests, the soil samples were made by compaction on the wet side with the energy of the Modified Proctor (at w_{OPM} + 3%). Compaction under such conditions would thus ensure a low permeability, which is the aim in the context of waste disposal sites.

2.2 Formulation of the Synthetic Leachate

The synthetic leachate used was formulated in such a way to be as close as possible to the characteristics of a young leachate from a waste disposal site in an acidogenesis phase. This implies that it has a relatively high biodegradable organic load consisting mainly of VFAs and it is also loaded with heavy metals due to

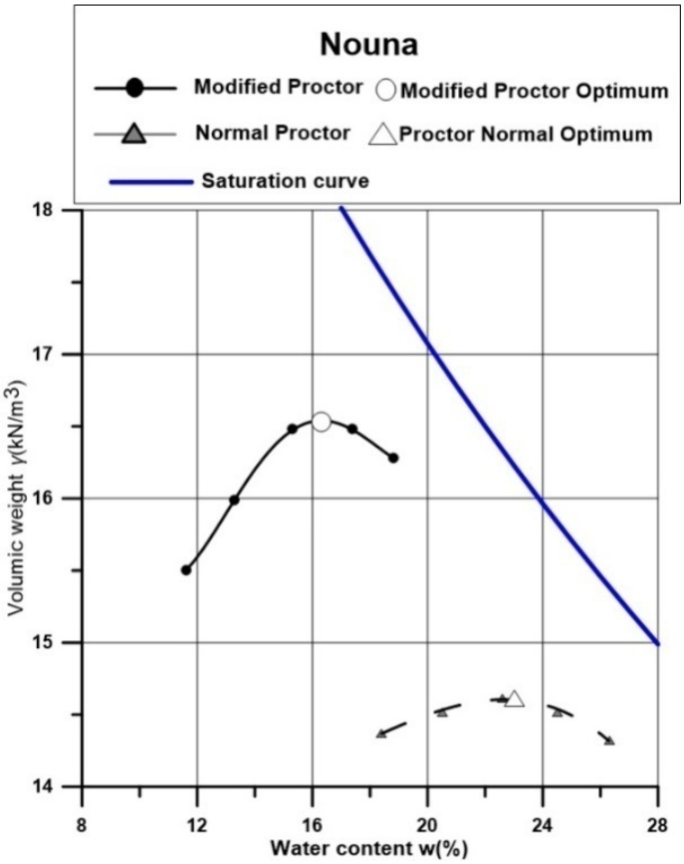

Fig. 3 Proctor curves of Nouna clay.

its relatively low pH. In addition to VFA and heavy metals, landfills contain inorganic macro-components and xenobiotic compounds originating from household and industrial chemicals present in relatively small quantities (lower than 1 mg/L) [17-19]. The synthetic leachate was obtained by dissolving several salts (ammonium chloride, magnesium sulfate, copper sulfate, potassium sulfate and sodium chloride) in distilled water and diluting a solution of acetic acid (representative of VFA) at a concentration of 0.34 mg/L, giving it a pH of 5. Heavy metals are represented by Cu^{2+} cations while xenobiotic compounds are neglected. Concentrations of chemical species (Table 2) are selected to remain within the usual ranges found in landfills and described by Christensen, T. H., et al. [18].

2.3 Assessment of Hydraulic Conductivity

The hydraulic conductivity was measured from clay suspensions using an API filter press. To do so, 40 g of Nouna soil were dissolved in 400 mL of solvent (distilled water on the one hand and leachate on the other hand). The suspension was homogenized and stored for at least 24 hours. API filter press cell having 90 mm diameter and 90 mm height was then filled with 300 mL of the suspension. The cell was then assembled against its frame. The installation of a compressed air inlet pipe at the cell head and a recipient under the drainage tube completes the assembling of the equipment for its use (Fig. 4). The filtration test begins as soon as the pressure is adjusted to the desired value: a pressure of 100 psi (690 kPa). This applied pressure forces the liquid to flow through the filter paper while it retains the solid particles of the mixture. The experiment is left to run while taking care to regularly note the cumulative volume and the time required to filter this volume. The experiment is stopped after one hour. The cell is removed from the frame, then a

Table 2 Chemical composition (major ions) of the synthetic leachate.

Ionic species	Concentrations in mol/L	Concentrations in mg/L
Ca^{2+}	0.014	570.2
Cl^{-}	0.070	2,475.8
Cu^{2+}	0.000	5.0
K^{+}	0.017	673.5
Mg^{2+}	0.002	50.0
Na^{+}	0.035	793.2
NH^{4+}	0.003	50.0
SO_4^{2-}	0.009	834.9

Fig. 4 API filter press.

solid so-called cake placed on the filter is collected. This cake results from the agglutination of solid particles that were present in the mixture.

The cake intrinsic permeability K (m^2) is determined using Darcy's law and assuming that the permeability and the specific volume are constant during filtration [12, 20-22]. These authors noted that Darcy's law could be expressed into a linear relationship between the filtered volume ω and the square root of time t and be written as Eq. (1):

$$\omega = \left[\frac{2\Delta P A^2 K}{\mu b}\right]^{0.5} t^{0.5} \quad (1)$$

With ΔP the pressure drop (Pa), A the cross sectional area (m^2), μ the filtered liquid viscosity $(kg.m^{-1}.s^{-1})$, t the time (s), and b the specific volume (dimensionless) defined as Eq. (2):

$$b = \frac{cA}{\omega_t} \quad (2)$$

With ω_t the total cumulative filtrate volume (m^3) and c the thickness of the cake (m). Having interrupted the filtration after one hour, c is measured after having removed the supernatant liquid from the filter press cell.

The intrinsic permeability K is thus assessed by drawing the $\omega = f(\sqrt{t})$ curve and then drawing the linear fitting of this straight line. The slope of this straight line allows the determination of the hydraulic conductivity k by Eq. (3):

$$k = \frac{\rho g}{\mu} K \quad (3)$$

Assuming that the viscosity of the filtrate was equal to the viscosity of water.

2.4 Assessments of Compressibility and Consolidation

Cyclic compressibility œdometer tests were conducted on samples of Nouna clay to estimate its deformability properties. The samples are placed in œdometric cells supplied with rings having 51 mm diameter and 20 mm preventing any lateral deformation and allowing the measurement of the vertical deformation (Fig. 5). Placed between two draining porous stones, they are brought and maintained in a saturated state by two types of fluids: the first consists of distilled water and the second of the solution described above, representative of a young and therefore potentially "aggressive" leachate [12].

The soil sample is allowed to swell almost freely (under the piston weight corresponding to a stress of 0.03 bar). Later on, the loading program is chosen so as to define loading/unloading cycles with stresses ranging from 0.03 to 4.83 bars, taking into account the order of magnitude of the stresses generated by the weight of wastes in landfills in Burkina Faso. This method allows to assess the swelling potential of a material through the apparition of hysteresis loops. For each loading increment, the thickness variation of the sample was measured using a 0.01 mm dial gauge.

At each stress increment, the corresponding void ratio variation is calculated as Eq. (4):

Fig. 5 Compressibility œdometer test conducted with Nouna clay.

$$\Delta e = \frac{\Delta H}{H} \times (1 + e_0) \quad (4)$$

With ΔH the change in the thickness of sample due to an increase in pressure; H is the initial thickness of the sample; e_0 is the initial void ratio.

The œdometric compressibility curve representing the void ratio e versus the vertical effective stress σ with a semi-logarithmic scale is represented. Compression index C_c was calculated as the slope of the straight lineportion of the virgin void ratio curve $e - logP$, recompression index C_r as the slope of the part of the curve following the slope of the sample under 0.03 bar after an unloading stage. At the different parts of the curve, a given index C is calculated by Eq. (5):

$$C = \frac{\Delta e}{\Delta log\sigma} \quad (5)$$

The use of compression and recompression indexes is important in assessing the settlement of a soil deposit as it can be seen in Eq. (6) for a normally consolidated soil:

$$s = \frac{C_c}{1 + e_0} Hlog\left(\frac{\sigma'_{v_0} + \Delta\sigma_v}{\sigma'_{v_0}}\right) \quad (6)$$

Or for an overconsolidated soil with a final effective stress less than the pre-consolidation pressure:

$$s = \frac{C_r}{1 + e_0} Hlog\left(\frac{\sigma'_{v_0} + \Delta\sigma_v}{\sigma'_{v_0}}\right) \quad (7)$$

With e_0 the initial void ratio, σ'_{v_0} the effective stress of the in-situ soil, $\Delta\sigma_v$ the increase in effective vertical stress.

In saturated clays, the consolidation phenomenon can take many years because of the low permeability of these soils. It must be apprehended taking into account leachate. The study of consolidation is done using Taylor's method. The time corresponding to 90% of the primary consolidation t_{90} and the consolidation factor c_v are calculated for different stress values. The variation of these different parameters is discussed according to the nature of the saturated fluid.

3. Results-Discussion

3.1 Hydraulic Conductivity

The main criterion of a bottom liner is its permeability. Its increase could have a very negative environmental impact on the long-term behavior of the landfill liner. Filtration tests carried out on Nouna clay allowed to plot the evolution of the cumulative filtrate volume for each suspension. The curves (Fig. 6) show a high slope at the beginning of the test and gradually shift to a straight line, which reveals the gradual formation of the cake in the bottom of the pressure cell.

Filtration with leachate is found to be faster than filtration with distilled water. The filtration volumes were 265 mL and 105 mL respectively. This means that leachate strongly alters the permeability of this clay which goes from 2.42×10^{-10} m/s to 1.01×10^{-9} m/s, i.e. a ratio of about 10 in terms of order of magnitude. According to Bonte, B. [23], this modification could be due to the dissolution of clay by the acidity of the leachate and to the fact that acids lead to flocculation

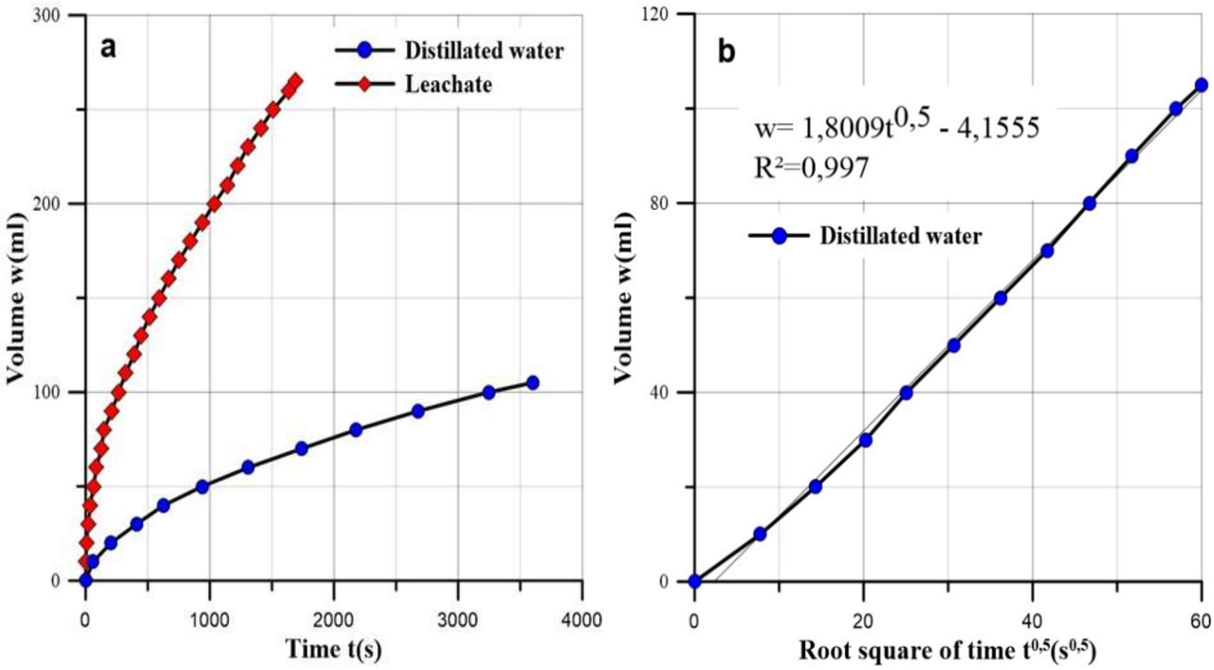

Fig. 6 a-Cumulative filtrate volume as a function of time; b-Linear fit of the cumulated filtrate volume as a function of the square root of time.

and attack the crystalline structure of clays, in particular the octahedral layer. The leachate leads to a reduction of the DDL and consequently a rapprochement of the particles, favoring an increase in the size of the poral network and preferential flow paths which increase the permeability of the clay.

3.2 Compressibility from Œdometer Tests

The œdometric compression curves $e-log\sigma$ obtained after saturation with distilled water and leachate are shown on Fig. 7(a) and (b) respectively. Table 3 shows the values of the recompression, compression and swelling indexes as well as the preconsolidation pressure calculated from the two curves.

On curve (a), the studied clay shows the characteristics of a swelling clay, the void ratio increasing from 0.65 to 0.85. This corresponds to a swelling of 2.41 mm representing 12.05% of the initial height. In addition, with the loading-unloading cycles, it is noticed that the soil does own an elastic behavior and the curve shows hysteresis loops. It can also be seen that the swelling indexes after unloading at 1.03 bars, 2.43 bars and 4.83 bars respectively of 0.012, 0.017 and 0.022 are quite high. The release of the mechanical stress during unloading phase causes the soil to swell as a result of the unbalanced forces of repulsion. In addition, although Nouna clay is compact, it exhibits significant settlements apparent on the virgin compression curve, as highlighted by the compression index of 0.164.

Curve (b) clearly shows that the leachate has almost inhibited the swelling. The void ratio increases from 0.65 to 0.75, meaning that the soil has only swollen by 1.15 mm or 5.75% of its initial height, a phenomenon that has been observed by various researchers [4, 24, 25] and that is attributed to the reduction in the thickness of the diffuse double layer of clay due to the use of leachate for saturation. Indeed, the cations contained in the solution diffuse through the interlayer space of the clay resulting in a reduction of repulsive forces between the clay particles. The result is a decrease in porosity and therefore a moderate increase in the void index. The noticeable difference between the two tests can be seen on the virgin compression curve, where leachate has a considerable influence on

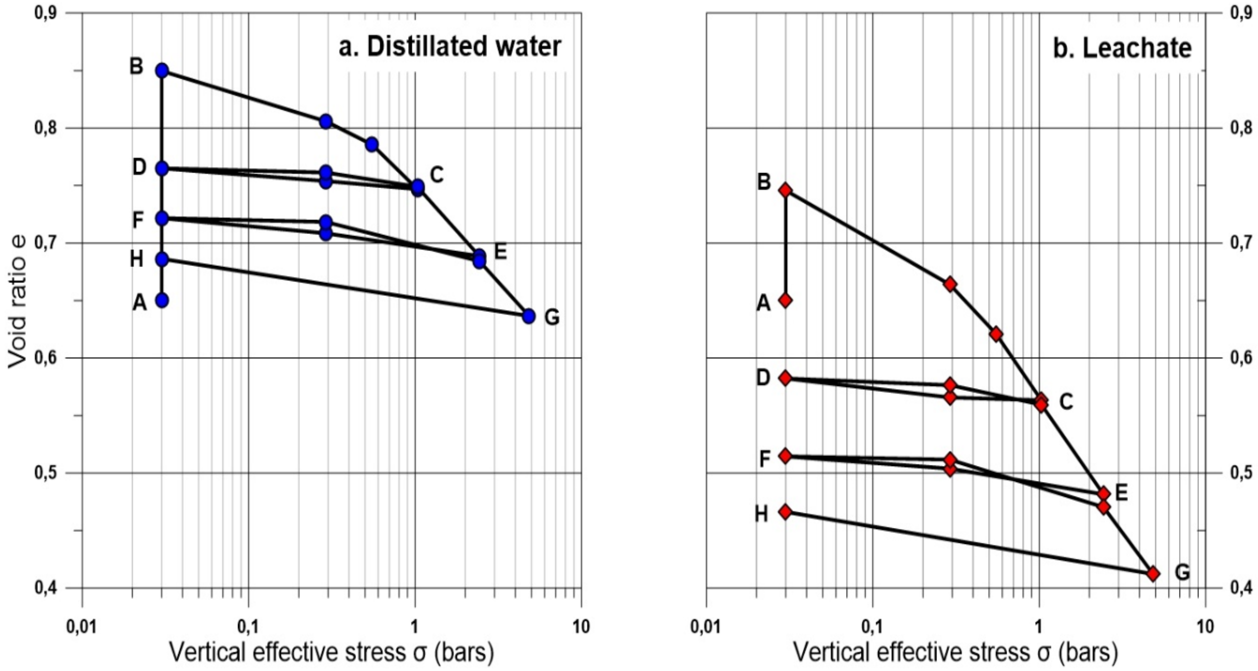

Fig. 7 Consolidation curves obtained with Nouna clay: a-Distilled water; b-Synthetic leachate.

Table 3 Values of recompression, compression and swelling indexes and values of preconsolidation pressures according to the type of fluid used.

Type of fluid used	Recompression index	Compression index	Swelling index			Preconsolidation pressure (bars)
	C_r	C_c	$C_{g_{CD}}$	$C_{g_{EF}}$	$C_{g_{GH}}$	σ'_p
Distillatedwater	0.021	0.164	0.012	0.017	0.022	0.55
Leachate	0.043	0.225	0.013	0.015	0.024	0.50

settlement. The compression index shows a significant increase from 0.167 to 0.225. There is therefore an increase in compressibility, which can be detrimental to the stability of the bottom liner and the whole landfill, which must necessarily be taken into account. From the results of previous studies, it was stated that there is sometimes an increase or decrease in the compressibility of clays depending on the nature of the solution used and the composition of the clays. Gajo, A. and Maines, M. [26] who conducted leaching of bentonite with acidic fluids reported that soil compressibility declines significantly due to the collapse of the diffuse double layer. On the other hand, Gratchev, I. B. and Towhata, I. [27] who studied the compressibility of Ariake clay containing kaolinite, leached with acidic fluids, noted that the soil compressibility increased because of the dissolution of ferric acid between clay aggregates. These latter results are consistent with those of our study. Further investigations should be carried out to provide an explanation: they could include the use of SEM, XRD, MIP before and after the leaching of Nouna clay. The combined use of these different tools would allow a better description of the processes of dissolution and formation of mineral phases. Nevertheless, it is recognized that acids can dissolve cementation agents such as calcium carbonates and ferric oxides, thus altering the structure of natural clays. Our results have the advantage to show that the tests conducted to characterize a bottom liner must be as close as possible to the real conditions of implementation and exploitation of the soil as highlighted by Marcoën, J., et al. [7] and take into account the specificity of the clays used.

As for test (a) conducted with distilled water, the hysteresis loops are always present and have the same shapes. The swelling indexes after unloading appear to be slightly affected by the leachate. The preconsolidation pressure is substantially the same regardless of the type of saturated fluid used. This is consistent with the definition that it is the greatest stress on the soil in its geological history. It should be noted that, in the context of the study, such a definition needs to be nuanced in view of the fact that it is a sample which was strongly disturbed and reconstituted by compaction.

3.3 Consolidation from Œdometer Tests

The settlement curves obtained for each of the two fluids for a normal stress of 1 bar are shown on Fig. 8. They show that, for both types of fluid, consolidation settlement progresses fast at the beginning, linearly thereafter, then slowly and slowly to reach a zero rate for long periods of time.

It can be seen that at the beginning of the test, the slope of the linear part of the consolidation curve is greater when the test is conducted with the leachate compared to the situation where the test is conducted with distilled water. At the end of the test, on the other hand, the slopes become almost identical, the curves being parallel.

The last linear part of the curve corresponds to the secondary consolidation settlement, which does not appear to be affected by the leachate. Indeed, this can be explained because in this phase the efforts are essentially transferred to the solid skeleton of the soil.

Only the primary consolidation settlement in which the grains are rearranged further to an expulsion of the interstitial fluid is affected. The primary consolidation settlement therefore occurs more quickly for a soil draining a leachate. It is well known that in saturated conditions, the rate of consolidation is proportional to hydraulic conductivity and therefore higher for the leachate. The calculation of the times to complete 90 % of consolidation confirms this statement: the parameter t_{90} is 17.64 mns for the leachate compared to 30 mns for distilled water under the stress of 1 bar, matching to an increase in the coefficient of consolidation from 0.033 to 0.0464.

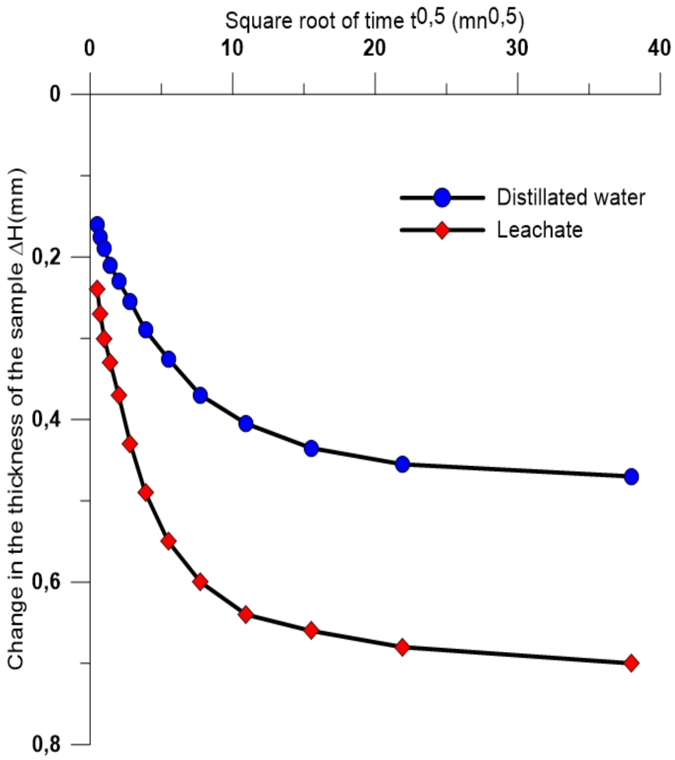

Fig. 8 Settlement curves obtained with Nouna clay for a normal stress of 1 bar.

Table 4 Parameters of consolidation according to the type of fluid used.

Type of fluid used	Time to complete 90% of consolidation t_{90} (mn)	Coefficient of consolidation c_v (cm^2/s)
Distilled water	30	0.033
Leachate	17.64	0.0464

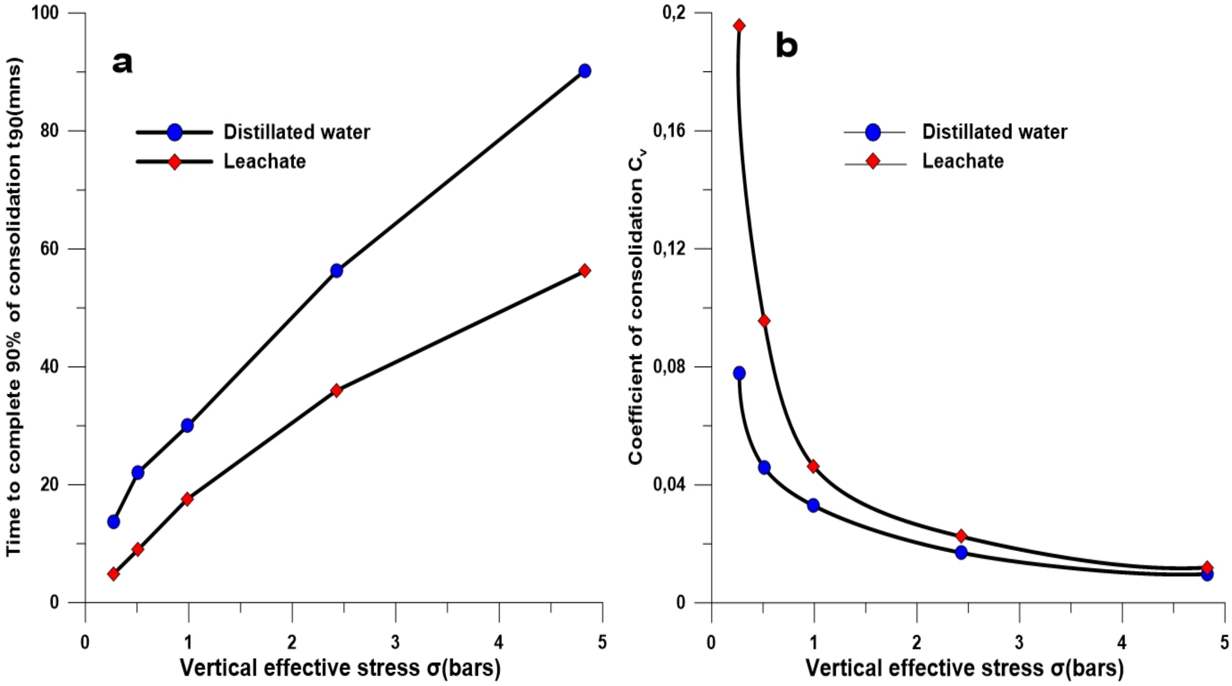

Fig. 9 a-Times to complete 90% of consolidation; b-Coefficients of consolidation as a function of the normal stress applied.

These results can be generalized to other normal stresses values used during the test (Fig. 9). Under any vertical stress in the bottom liner, times of consolidation are lower when it contains leachate. The end of primary consolidation therefore occurs faster in this case, especially when the value of the stress is high. In addition, the time of consolidation increases with the vertical stress applied to the clay, while the coefficient of consolidation decreases.

4. Conclusion

A study was conducted to understand the effect of a young synthetic leachate in the acidogenesis phase on the hydromechanical properties of a clay from Burkina Faso. The properties concerned are hydraulic conductivity, swelling, compressibility and consolidation of the clay. The results show that the sealing potential of this clay is indeed altered, with the hydraulic conductivity of the clay with leachate increasing by a factor of 10 compared to its hydraulic conductivity with distillated water. The swelling potential of the clay is also considerably reduced because the chemical species present in the leachate certainly reduce the diffuse double layer of the clay.

In the presence of leachate, the compressibility of Nouna clay increases, inducing significant settlement, and the primary consolidation settlement increases faster because of an increase in hydraulic conductivity. The present study has the interest of showing that it should nevertheless be taken into account in the dimensioning of the bottom liner without however generalizing the results to all bottom liners, since they are conditioned by the mineralogy of the clays and the chemical composition of the leachate.

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