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Unsaturated Hydraulic Characteristics of Compacted Local Geo-Materials for use as Landfill Liners

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Abstract. The important hydraulic properties of compacted soil-bentonite liners in semi-arid areas are hydraulic conductivity (ksat < 10^{-9} m/s), soil-water characteristic curve (SWCC) and initial water content. This paper studies the valorization of local materials containing calcareous sand, tuff obtained from Laghouat region (in South Algeria), to associate with bentonite in order to improve their hydraulic characteristics for use as landfill liner material. Firstly, the 10% bentonite + 20% calcareous sand + % 70 tuff mixture was selected based on the minimum saturated hydraulic conductivity (ksat) by the oedometric test. The results show that the effect of the initial water content variation from 12.35% to 16.35% does not make a difference in the ksat values; values are between 10^{-8} m/s and 10^{-11} m/s. Next, the unsaturated hydraulic conductivity (Kw) study of the adequate mixture with different initial water content was measured with an original vapor equilibrium technique (VET) used for Sr < 30% (very high suction s > 3 MPa). The results showed that the unsaturated hydraulic conductivity increases with the degree of saturation and decreases with the suction. The results showed that the Kw varied between, 3 10^{-17} m/s and 4 10^{-15} m/s, for one period of 90 days. The effect of initial water content on the Ksat and Kw of this mixture is hardly apparent for the much less (Sr>80%, k=ksat) and very high of suction values, respectively. In conclusion, the selected 10% bentonite + 20% calcareous sand + % 70 tuff mixture satisfies the regulatory requirements and hence constitutes a good local material for engineered barriers.

Keywords. Landfill liners, Hydraulic conductivity, Bentonite, Calcareous sand, Tuff.

INTRODUCTION

Compacted bentonite-sandy soil mixtures have been preferred as suitable hydraulic barrier materials for the landfill liners. Initially, unsaturated state on placement and undergoes very high suction, especially in geographical zones having arid, semi-arid and climatological tropical conditions. The hydraulic barriers may become saturated upon the availability of

meteoric water or waste leachate (after setting up waste). Typically, hydraulic conductivity for landfill liners must be less than or equal to 10^{-9} m/s.
The Laghouat geology area in south Algeria is represented by very thick a marl- calcareous rock complex at the base and the tuff calcareous crust group at the top cover (from about 20 cm to around 2 m). Abeel et al. (1981) show that the unsaturated hydraulic conductivity (k_w) of crushed Bandelier tuff under matric potential of 195 kPa and a saturation rate 22.3%, gives a hydraulic conductivity value of about 5.13 10^{-11} m/s. It is mainly found in arid and semi-arid Algeria regions; tuff and crushed sand (crushed marl-calcareous rocks waste) present a cheap alternative to sand as an additive to bentonite, which be used as a hydraulic barrier satisfying the recommendations for landfill liners design.
Chen et al. (2011) indicated that the increasing bentonite content beyond 10% does not lead to greater improvement in the impermeability ($k_{sat}<10^{-9}$ m/s) of bentonite-sandy soil mixtures. Manca (2015) shows that the k_w increases as the degree of saturation increases and decreases as the dry density decreases for 20%bentonite–80%sand mixture. At a degree of residual saturation corresponding to a suction value of 400kPa (S_r = 0.37 for γ_d= 1.50 Mg/m^3 and S_r = 0.52 for γ_d = 1.79 Mg/m^3), the k_w is between 8 10^{-14} – 1 10^{-13} m/s.
This paper presents the experimental results of saturated hydraulic conductivity by oedometer tests. As the vapor equilibrium method has been proven to be a reliable estimate of the unsaturated hydraulic conductivity of sandy and clay soils (Sayad-Gaïdi, 2003; Gueddouda et al., 2016), the unsaturated hydraulic conductivity was determined by a desiccator. The test results were compared with each other to analyze the influence of water content on the unsaturated hydraulic conductivity. The focus of this study is the valorization of local Algerian materials for engineered barriers intended for landfill site design.

MATERIALS AND METHODS
Three basic materials have been used in this work. The first material is the Maghnia bentonite that is extracted from the Hammam Boughrara deposit (Maghnia–Tlemcen). Its main mineral constituents are silica (55–65%) and the alumina (12–19%) (Demdoum et al., 2017). The liquid limit is 141%, the plastic limit is 48%, the specific gravity 2.75, and 60% of particles are smaller than 2 μm (**Error! Reference source not found.**1). The value obtained for the total specific surface area using the blue methylene technique is 462 m^2/g (Demdoum et al., 2018).
Tuff is the second material.It is available within Laghouat region in the south of Algeria. It is often used in road construction of low traffic (Demdoum et al., 2016). The third material is the calcareous sand, which is a residue of the crushing stations of calcareous rocks located in the north of Laghouat City. Tuff particles present a maximum diameter (D_{max}) of 3 mm with sand fraction (< 2 mm) of about 85%, and more than 5% of particles have a diameter smaller than 0/2 μm. Concerning the calcareous sand , this one presents a fine particle content (< 2 μm) of about 3% (**Error! Reference source not found.**).
The materials used are symbolized as follows: Bentonite by B, Calcareous Sand by CS and Tuff by T. Five mixtures were selected for the investigation. For each mixture, the percentage of bentonite is fixed at 10%. The mixtures are named $B_{10}CS_XT_Y$, where X and Y are the percentages of calcareous sand and tuff used complementary to 90%. By steps of 10, and for each formula. Mixtures that have been used:

- Mixture 1 : 10% B + 10% CS + 80% T, named $B_{10}CS_{10}T_{80}$;
- Mixture 2 : 10% B + 20% CS + 70% T, named $B_{10}CS_{20}T_{70}$;
- Mixture 3 : 10% B + 30% CS + 60% T, named $B_{10}CS_{30}T_{60}$;
- Mixture 4 : 10% B + 45% CS - 45% T, named $B_{10}CS_{45}T_{45}$;
- Mixture 5 : 10% B + 60% CS + 30% T, named $B_{10}CS_{60}T_{30}$.

According to USCS classification, the Mixtures can be classified as silty sands (Fig.1). Figure

2 shows that the incorporation of calcareous sand improved the material by increasing its maximum dry density (γ_{dmax}) of 16.62 kN/m^3 to 17.82 kN/m^3 and reducing its optimal content (w_{opt}) from 14.4% to 9%.

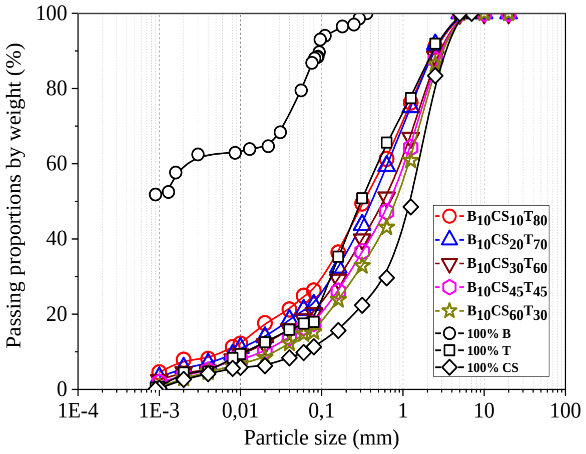

Fig. 1. Grain size distribution curves of all mixtures, bentonite (B), tuff (T) and calcareous sand (CS).

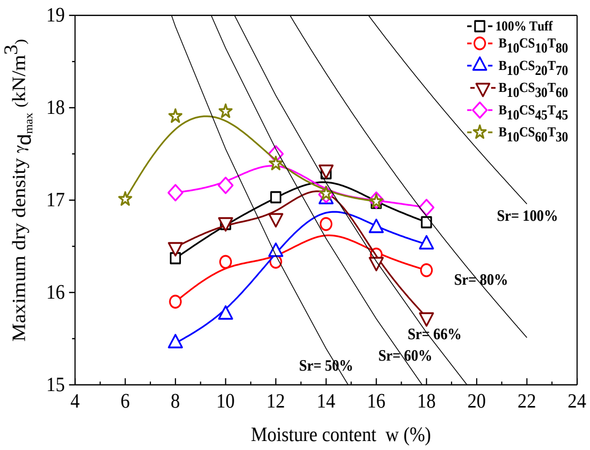

Fig. 2. Compaction curves of all the mixtures.

Saturated Hydraulic Conductivity Using Odometer Test

One-dimensional consolidation tests were used as an indirect method to estimate hydraulic conductivity. The test was carried out according to AFNOR XP P94-090-1 standard. Firstly, an ad for each mixture, samples were prepared by a static compaction at the optimum normal proctor (OPN) water content. The hydraulic conductivity (k_{sat}) is obtained from both the coefficient of consolidation C_V (m^2/s) evaluated by Taylor's approach and the coefficient of volume compressibility m_v (kN /m^2) (Eq. 1). Based on optimal mixture of minimal saturated hydraulic conductivity, different initial states of the mixture were prepared from OPN, OPN-%2 and OPN+2%. In this study, the hydraulic conductivity k_{sat} is written as (Eq.1):

$$k_{sat} = C_v \times m_v \times \gamma_w \qquad (1)$$

Unsaturated Hydraulic Conductivity Using Vapor Equilibrium Method

In most compacted liners of soil-bentonite, mixtures reach their optimum dry density at a saturation level (between 70% and 90% (Chapuis, 2002). A change in matric suction can produce a larger change in the degree of saturation, which may produce a variation in hydraulic conductivity and effective stress (Ye et al., 2014). The principle consists in suspending a soil sample in the desiccator and measuring the water exchange by evaporation between the sample and the desiccator ambient environment according to time (Sayad-Gaidi, 2003). In order to optimize-duration tests, the compacted samples were cut into slabs 10 mm of thick and 38 mm in diameter. To ensure a one-dimensional (axial) transfer, the sample is waxed on its contour and connected to a balance with the accuracy of 10^{-3} g, which allows following the variation of its weight over time.

The samples are subjected in successive stages, to different values of sucking using several saturated saline solutions based on the Kelvin's equation (the suction value between 2.7 MPa - 348 MPa). The volume water exchanged at each suction level is then represented by a linear evolution in the plane [t, Ln (V_{wT} - $V_{w(t)}$)] and the corresponding slope M is related to the diffusivity coefficient D by the relation (Eq.2) (Sayad-Gaidi, 2003).

$$D=\frac{l^2 M}{\pi^2} \qquad (2)$$

Unsaturated hydraulic conductivity k_w is given by the following relationship (Sayad-Gaidi, 2003) (Eq.3):

$$k_w(\theta)=\frac{D(\theta)}{\frac{\partial \Psi_w}{\partial \theta}}=\frac{D(\theta)}{\Delta \Psi_w}\times\frac{V_{wT}}{V_T} \qquad (3)$$

Where V_{wt}, the change in water volume at time t, V_{wT}, the total change in water volume (mm^3), V_T: total volume of sample (mm^3), M is the slope of the straight line in t, Ln (V_{wT} - $V_{w(t)}$) space, and ψ_w is the capillary potential given by the relationship $\psi_w=s/\gamma_w$.

A petroleum product named kerdane was employed to determine the volume of voids, and hence, the variation of degree of saturation. Total volume of the samples was then determined to use Archimedes' principle.

RESULTS AND DISCUSSION

Saturated Hydraulic conductivity (K_{sat})

The results of the indirect saturated hydraulic conductivity (K_{sat}) of the $B_{10}CS_XT_Y$ mixtures based on the vertical applied stresses are presented graphically in figure 3.

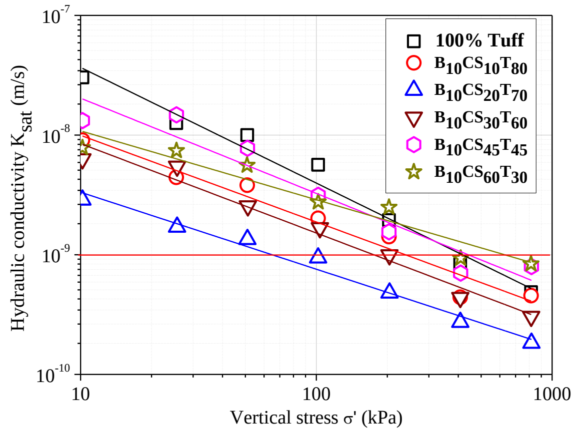

Fig. 3. Saturated hydraulic conductivity (K_{sat}) as a function of vertical stress applied for the $B_{10}CS_xT_y$ mixtures.

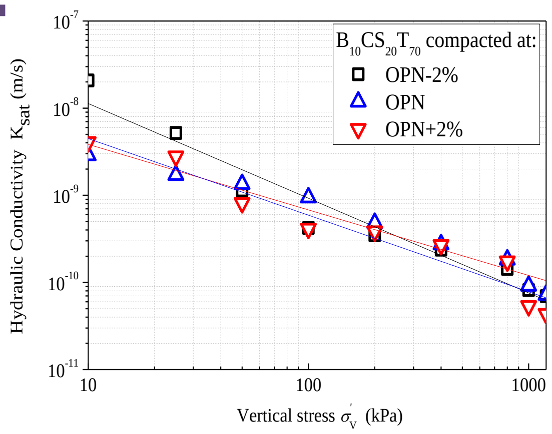

Fig. 4. Saturated hydraulic conductivity (K_{sat}) of $B_{10}CS_{20}T_{70}$ mixture as a function of the stress applied for different initial states.

The result of indirect hydraulic conductivity above shows that:

1. For all the mixtures, saturated hydraulic conductivity (K_{sat}) decreases with applied vertical stress increase;
2. The effect of loading pressures applied on hydraulic conductivity is less significant, once the vertical pressure is more than 100 kPa. Other researchers found these limiting values were around 100 kPa and 200 kPa (Alston et al., 1997);
3. The $B_{10}CS_{20}T_{70}$ mixture presents the minimum indirect hydraulic conductivity value is between 7 10^{-9} to 1.83 10^{-10} m/s, for the vertical stresses from 10kPa to 800kPa;
4. The increase in the calcareous sand proportion higher than 30% in the $B_{10}CS_xT_y$ mixture negatively affects the hydraulic conductivity;
5. Finally, the optimal $B_{10}CS_xT_y$ mixture used for the following studies is the $B_{10}CS_{20}T_{70}$ mixture.

Figure 4 shows the variation in hydraulic conductivity as a function of vertical effective stress for these different states. Compacted mixture with OPN, OPN-2% and OPN+2% have very close saturated hydraulic conductivity values. As stress increases, hydraulic conductivity decreases with increasing slope curvature with stress. The difference in k_{sat} values observed in the OPN, OPN -2% and OPN +2% for low stresses decrease for high stresses to reach a factor of 100 for a vertical stress of about 1.2 MPa. Finally, the effect of water content on the saturated hydraulic conductivity of $B_{10}CS_{20}T_{70}$ mixture is small compared to vertical stress impact in the oedometer test. A similar trend was made by Haug et Wang (1991) for a 8% bentonite - 92% sand mixture; they showed that water content did not affect the saturated hydraulic conductivity.

Unsaturated Hydraulic Conductivity (k_w)

During the long-term sample storage operation, the regular weighing of the sample makes it possible to follow the water quantity exchanged over time. These weighing operations are continued until the balance has been established. At this point, the sample mass no longer varies (the test duration is about 90 days). The suction values are imposed by VET method, and the corresponding saturation values are obtained using a Kerdane oil to determine the external total volume of the samples. The mixture that was compacted with OPN-2% presented a minimum value of the volume water exchanged (0-3 cm^3) compared to the OPN+2% (0-4.5 cm^3) and OPN (0-3.5 cm^3) mixtures.

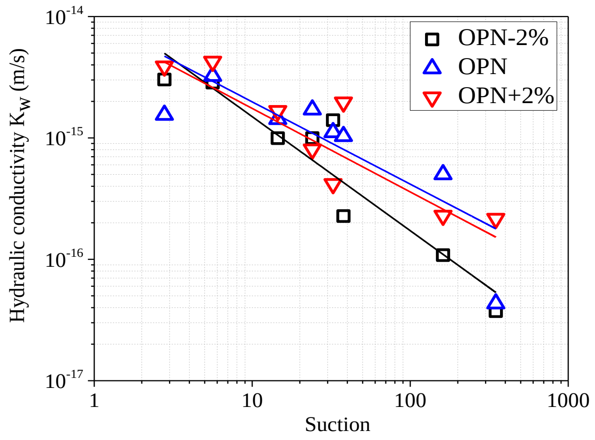

Fig.5. Evolution of hydraulic conductivity k_w with imposed suction.

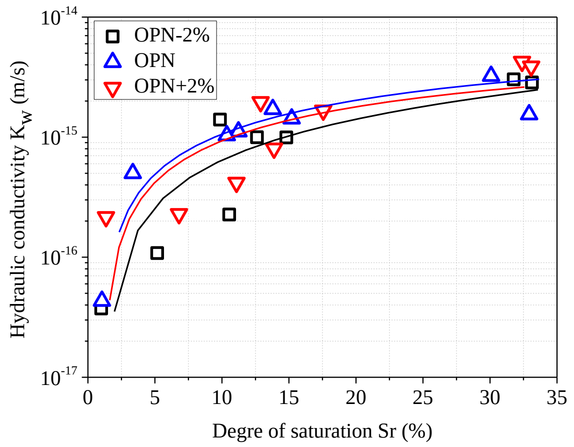

Fig. 6 Evolution of hydraulic conductivity k_w with degree of saturation.

Through experience, it can be seen that most of the water exchanged between sample and desiccator atmosphere takes place during the first days of the test (between 10 and 15 days). Taibi et al. (2009) mentioned that the equilibrium time depends on the soil properties, the soil specimen sizes and the suction differences. This explains the low water exchanged in the OPN-2% mixture, due to the high suction force compared to other mixtures. These results are consistent with those of Gueddouda et al. (2016).

The evolution of the unsaturated hydraulic conductivity (k_w) calculated with different imposed suctions is presented in **Error! Reference source not found.**ure 5. It can be seen that the compact mixtures have k_W values, which are similar. Figure 6 shows that the minimum hydraulic conductivity k_W values for the degree of saturation levels below 15% in the compact mixture at OPN-2% and in the degrees of saturation above 15% for the compact mixture at OPN. When the suction was increased from 2.7 MPa to 348 MPa, the unsaturated hydraulic conductivity (k_w) decreased from 4 10^{-14} m/s to the order of 3 10^{-17} m/s, becoming relatively impermeable to water. These results contradict some of literature for a bentonite-sand mixture by the instantaneous profile method such as Cui et al. (2008) which indicate that the unsaturated hydraulic conductivity decreases as suction decreases with suction decreases to a certain value and then turns to increase. It is clear that a significant unsaturated hydraulic conductivity decreased while degree of saturation is decreased (Fig. 6).

In low suction, some authors have shown the equivalence between the action of mechanical stress and that of capillary pressure (matric suction), which makes it possible to generalize the notion of Terzaghi's effective stress to the case of saturated soils at capillary pressure (Biarez et al., 1989). In this sense, starting from a saturated state (S_r>80%, k= k_{sat}) (point A), the hydraulic conductivity remains almost constant on the path AB, which represents the saturated domain assuming that suction does not induce a change in the volume of the sample (Fig. 7). Once the desaturation suction has been reached (s_d) (point B), the degree of saturation drops slightly in the almost saturated range and, then, decreases rapidly from the capillary pressure of the shrinkage limit (s_{SL}). This drop causes a decrease in hydraulic conductivity. This is consistent with the results presented by Van Genuchten (1978).

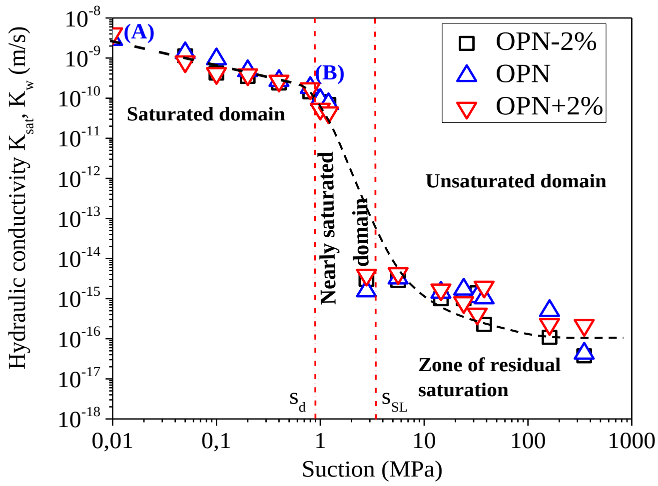

Fig. 7. Comparison between saturated hydraulic conductivity values k_{sat} and those measured using the VET method

CONCLUSIONS

Several conclusions can be made as a result of this study:

1. In saturation state, the $B_{10}CS_{20}T_{70}$ mixture is the recommended optimal mixture which satisfies the saturated hydraulic conductivity (k_{sat} = 1.83 10^{-10} m/s). In addition, the more than 30% increase in the calcareous sand proportion in the mixture has a negative effect on hydraulic conductivity. However, the effect of initial water content on the saturated hydraulic conductivity is low, and the best water content that gave a minimum conductivity is OPN+2%;

2. The estimated unsaturated hydraulic conductivity (k_W) does not change significantly, with initial water content changing from 12.35% - 16.35%. Data shows that the unsaturated hydraulic conductivity value decreases when water content decreases. The unsaturated hydraulic conductivity of the $B_{10}CS_{20}T_{70}$ mixture in this research is below 4 10^{-15} m/s.

Finally, the effect of initial water content on the saturated and unsaturated hydraulic conductivity of this mixture is hardly apparent for the much less (S_r>80%, k=k_{sat}) and very high of suction values, respectively. Generally, it can be noted that compaction of the $B_{10}CS_{20}T_{70}$ mixture at 2% wet side of the optimum can improve their hydraulic properties for use as a soil liner at the waste disposal site.

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