Effect of bentonite on the saturated hydraulic conductivity of landfill liners based on dune sand

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Abstract. Sand-bentonite (SB) mixtures have been used successfully for construction of hydraulic barriers when clayey soils are not available. Compacted layers of SB mixtures have been proposed and used in a variety of geotechnical structures as engineered barriers for the enhancement of impervious landfill liners. In the practice we will try to get an economical mixture that satisfies the hydraulic and mechanical requirements.
The effects of the bentonite additions are reflected in lower water permeability, and acceptable shear strength. In order to get an adequate dune sand bentonite mixtures, an investigation relative to the hydraulic and mechanical behavior is carried out in this study for different mixtures. According to the results obtained, the adequate percentage of bentonite should be between 12% and 15 %, which result in a hydraulic conductivity less than 10^{-6} cm/s, and good shear strength.

Key words: Dune sand, bentonite, hydraulic conductivity, shear strength, insulation barriers.

1. Introduction

Rapid technological advances and population needs lead to the generation of increasingly hazardous wastes. The society should face two fundamental issues, the environment protection and the pollution risk control. One of the actual solutions, for handling these contamination problems, is by enclosing the wastes in a specific location, using insulated barriers. The efficiency of these insulated barriers depends largely on their hydraulic and mechanical behavior along with their capacities of attenuation and retention of the contaminant. Compacted sandy soils with small additions of bentonite, known also by sand-bentonite (SB) mixtures, have been proposed and used as an adequate material for these insulation layers. In order to be efficient, theses insulation barriers should fulfill some requirements (Chapuis, 1990; Parker, 1993):

- The typical thickness for these layers ranges between 15 and 30 cm;
- Permeability at saturated state varies between $10^{-6}$and 10^{-8}cm/s (Chapuis, 1990; Parker, 1993);
- Properties of exchange and adsorption should be capable to hold some preferentially pollutants (ADEME, 1999);
- Physical stability of the material in contact with water;
- A swelling potential that ensure good contact with the host rock and permit the replenishment of existing cracks or that will develop in the future;
- The sand must also possess some characteristic such grain size distribution, in order to prevent bentonite leaching from the skeleton and hence ensuring the hydraulic stability of the mixture.

In Algeria, the rapid development of urban areas and the growth of oil industry in the south regions, begin to generate enormous quantities of hazardous wastes. In order to avoid

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groundwater pollution and environment degradation, an insulation barrier using dune sand, which is an available and economical local material, enhanced by small addition of bentonite is proposed.

In searching for an adequate mixture, an investigation study is carried out on several dune sand calcium bentonite mixtures with different percentages of bentonite additions, which varies between 3% and 15%.

2. Materials used for study

The bentonite used in this study is extracted from Maghnia mine (Hammam Boughrara, 600 km west of the capital Algiers). Dune sand is a material which available in large quantities within the Algerian south, it is known as desert sand. The dune sand used is a local material from Laghouat region.

Results of chemical analysis showed that Maghnia bentonite is composed mostly of silicate with 17 % of aluminates (Table 1). For dune sand and according to the chemical analysis (Table 1), the major component is silicate SiO_2 (95%).

Table 1. Chemical composition of Maghnia bentonite and dune sand.

%	SiO_2	Al_2O_3	Na_2O	CaO	K_2O	MgO	Fe_2O_3	$CaCO_3$	SO_3
Bentonite	65.2	17.25	3	5	1.7	3.10	2.10	/	2.65
Dune sand	95.87	/	/	/	/	/	/	2.9	0.91

The grain size distribution of the bentonite is shown in Figure 1. It is very fine clay; about 60% of particles have a diameter less than 2 µm (Table 2). The value of the plasticity index indicates that the bentonite of Maghnia is highly plastic; this is confirmed by large specific surface (Sp) of 462 m^2/g. According to the classification of Skempton (1953), based on the activity, the bentonite of Maghnia presents a high percentage of calcite Montmorillonite (Ca^{+2}). The grain size distribution of dune sand is also plotted in Figure 1. Values corresponding to uniformity and curvature coefficients are Cu = 1,67 and Cc=1,1, respectively. Thus, the dune sand is classified as poorly graded fine sand according to the unified soil classification system (USCS). The physical characteristics of bentonite and dune sand are summarized in Table 2.

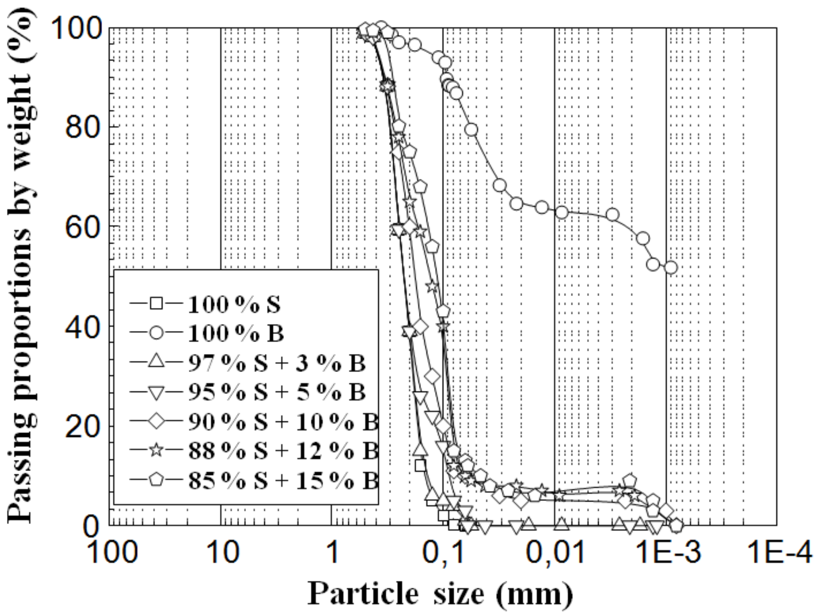

Fig 1. Grain size distribution of dune sand-bentonite mixtures (S: dune sand, B: bentonite).

Dune sand – bentonite (SB) mixtures used in this study are: 3% B + 97% S, 5% B + 95% S, 10% B + 90% S, 12% B + 88% S, 15% B + 85% S.

Table 2. Physical and mechanical properties of SB mixtures

	$\phi \leq$ 80μm	$C_2 \leq$ 2μm	Cu	γ_{dmax} (kN/m)	w_{opt} (%)	w_L	w_P	Ip	Gs	Sst (m^2/g)	G (%)	Pg (kP)
100 % S+0 % B	2%	0%	1,7	19 ,2	10	---	---	---	2,65	1,4	----	----
97 % S +3 % B	4%	0%	1,8	19,1	10,5	20	---	--	2,6395	10	0,85	17
95 % S +5 % B	5%	0%	2,5	18,8	11,5	21	---	--	2,6325	15	2,2	38
90 % S+10 % B	11%	5%	2,6	18,3	12,8	27	21	6	2,6153	43	5,90	124
88 % S +12 % B	12%	7%	2 ,6	17,8	14,0	28	18	10	2,6085	60	7,30	150
85 % S+15 % B	15 %	9%	3,8	17,0	15,2	34	22	12	2,5983	83	8,70	178
0 % S +100 % B	85%	60%	-----	12,1	32	141	48	93	2,34	462	47,5	852

Atterberg limits obtained for different mixtures are presented in Figure 2; mixtures with less than 10% are non-plastic soils, for percentage of bentonite additions between 10% and 12%, the soils become as little plastic clayey soils, while with percentage of 15% the soil appears to be a plastic. Evolution of consistence limits according to percentage of bentonite additions follows a parabolic law. The plastic index ranges from 5,9 to 12,5 for bentonite content varies between 10% and 15%.

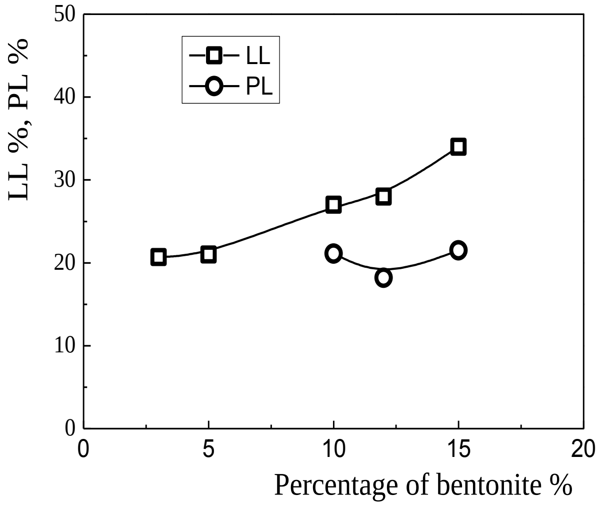

Fig 2. Relationship between Atterberg limits and bentonite content.

Swelling tests are carried out using a classical œdomètre. Dimensions of samples are 50 mm in diameter and 20 mm in height. The test is realized according to the free swelling method. The dune sand – bentonite mixture samples are prepared by a static compaction (velocity of 1 mm/min) for water contents and dry densities corresponding to the optimum Proctor conditions. The total free swelling (G %) is computed using the following relationship:

$$G(\%) = \frac{\Delta H}{H} x100 \tag{1}$$

Results of free swelling are grouped in Table 2. Swelling evolution of SB mixtures over time is shown in Figure 3. The free swell of the bentonite is approximately 47,5%, while for SB mixtures varying between 0,85% and 8,70% for bentonite content of 3 to 15%. As expected, the free swell is proportional with bentonite additions. For swelling pressure test (Pg), we used the constant volume method (Serratrice and Soyez, 1996). Results of swell pressure of SB mixtures are indicated in Table 2. The swelling pressures of SB mixtures increases from 17 to 178 kPa for bentonite content 3 to 15% respectively. When bentonite content addition is more than 10%, swelling pressure is over 100kPa. Results of physical and mechanical properties of SB mixtures are presented in Table 2.

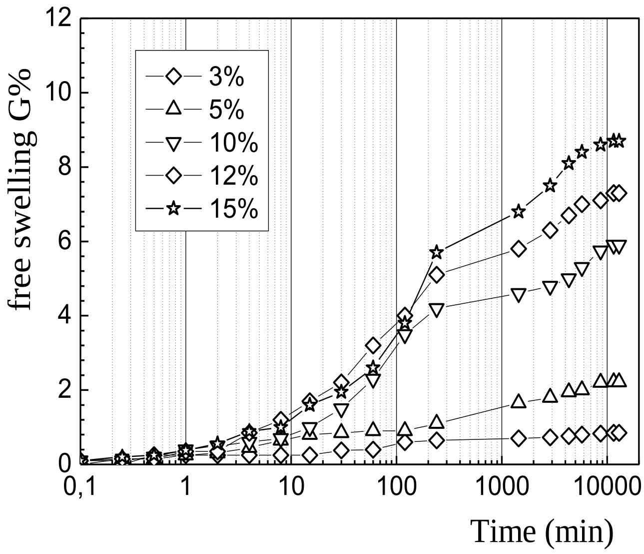

Fig 3. Swelling evolution of SB mixtures versus time.

3. Measure of the hydraulic conductivity

3.1. Measure of the hydraulic conductivity using oedometer

An indirect method for evaluation of saturated hydraulic conductivity k is based on results of oedometer test (Olson and Daniel, 1981). In this method the coefficients of volume change m_v [m^2/kN] and consolidation C_v [m^2/s] deduced from compressibility and consolidation curves respectively, are used to obtain the conductivity coefficient. A specimen of 50 mm in diameter and 20 mm height is placed in metal ring and saturated during 24 hours. The loading pressure was selected according to a geometric progression σ_{i+1}/σ_i =2. The conductivity coefficient k [cm/s] is obtained using equation (2). In the present study, the C_v coefficient is evaluated by Taylor's approach (Figure 4). Evolution of saturated hydraulic conductivity of SB mixtures as function of loading pressures is shown in Figure 5.

$$k = C_v \, m_v \, . \gamma_w \tag{2}$$

γ_w: unit weight of water [9.8 kN/m^3].

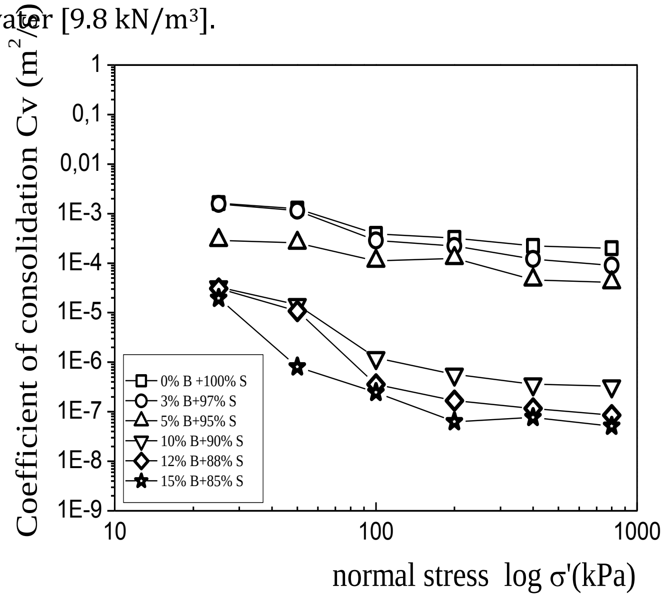

Fig 4. Coefficients of consolidation Cv evolution of SB mixtures vs normal stress.

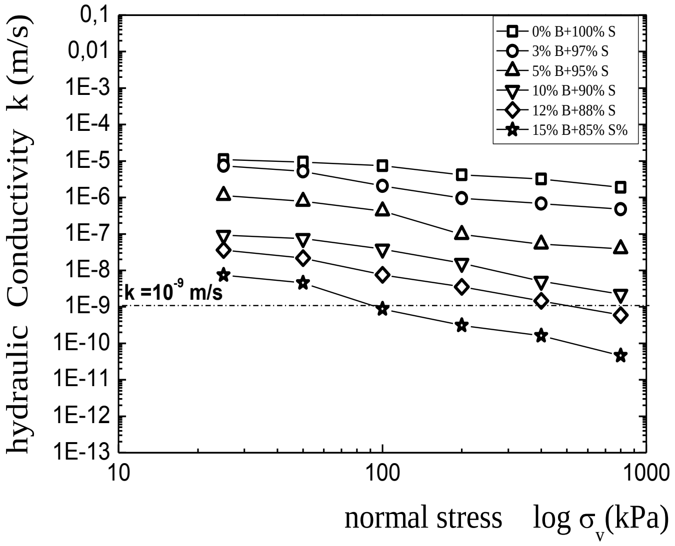

Fig 5. Saturated hydraulic conductivity of SB mixtures vs normal stress.

For all soils, the hydraulic conductivity varies inversely with the loading pressures (Figure5); For examples, the saturated hydraulic conductivity for dune sand with 0% addition of bentonite varies between 1,1 10^{-3} to 1, 9 10^{-5} cm/s; whereas for mixtures of 15 % addition the values range from to 7,41 10^{-7} to 4, 58 10^{-10} cm/s.

The effect of applied loading pressures on hydraulic conductivity is less significant, once become more than 400 kPa. Other authors found these limiting values around 100 kPa (Wu and Khera, 1990) and 200 kPa (Alston, 1997). Olson (1986) has shown that the estimated permeability values are always less than the measured one.

Hydraulic conductivity of the dune sand bentonite mixtures decreases with increasing bentonite content. The hydraulic conductivity for pressure equal to 25 kPa decreases approximately three orders of magnitude when 12% bentonite content or more is used. For high bentonite content 12%, the saturated hydraulic conductivity is less than 10^{-6} cm/s.

The target values relative to saturated hydraulic conductivity for containment liners, which should be between 10^{-6} and 10^{-8} cm/s, can be achieved for percentages of bentonite content greater than 10%, with an applied normal pressure over 200 kPa. For percentage of bentonite addition more than 12%, the hydraulic conductivity is less than 10^{-6} cm/s under a low vertical pressure (100 kPa).

3.2. Measure of the hydraulic conductivity using triaxial cell

This section presents the effect of confining stresses and hydraulic gradients on the hydraulic conductivity of compacted mixture (85%S+15%B). The measurement of the saturated hydraulic conductivity is carried on the permanent mode.

The saturated hydraulic conductivity is measured using a permeameter with flexible walls. The experimental set up is composed of a triaxial cell (Bishop-Wesley revolution) equipped with three pressure volume controllers. The set up allows testing specimens of 35 or 50 mm in diameter and variable height to diameter ratio (H/D). The triaxial cell permits to apply an isotropic confining stress (up to 1700 kPa). The flow is directed vertically from the bottom towards the top. Specimens are prepared by static compaction with double piston at Optimum Normal Proctor conditions (wopt=15,2%, γd max=17 kN/m^3). Specimen dimensions are D=35 mm and H=70 mm (Figure 6). The displacement speed of the press is about 1,14 mm/s. The static compaction was retained because it permits to obtain more homogeneous specimen.

Fig 6. Specimen dimensions.

Once the specimen is placed inside the triaxial cell, a confining stress of 100 kPa is applied in the first time. In order to extrude the existing air bubbles between the membrane and the soil a low back pressure is applied at the base of the specimen (ue: back pressure at the base at the sample, ue =20 kPa, us: the pore pressure at the top at the sample, us=0 kPa). The progressive increase of the confining stress and the back pressure allows to free air bubbles from the connecting tubes (ue=30, ue=40 kPa) meanwhile preserving an average constant effective stress. The final confining stress applied on the sample during the saturation phase must be greater or equal to the swelling pressure of the mixture, which is around 180 kPa. The vertical deformation of the samples was recorded versus time and the samples were considered as saturated when the displacement of the piston became constant (less than 0,01 mm in 24 h) (Souli, 2008).

3.3. Measurement of the hydraulic conductivity in permanent mode (constant head)

The experimental program is carried out using two series-tests. The first one consists to investigate the effect of the average confining effective stress with a constant hydraulic gradient (Δu=constant), whereas the second consists to analyze the effect the hydraulic gradient with a constant average confining effective stress (σ3'=constant) (Table 3).

Table 3. Experimental program.

	σ_3 (kPa)	u_e (kPa)	u_s (kPa)	Δu (kPa)	*i*	σ_3' (kPa)
Constant hydraulic gradient	200	40	0	40	57,14	180
	420	240	200	40	57,14	200
	620	240	200	40	57,14	400
	820	240	200	40	57,14	600
	1020	240	200	40	57,14	800
	1220	240	200	40	57,14	1000
	1520	240	200	40	57,14	1300
Constant average confining effective stress	620	240	200	40	57,14	400
	640	280	200	80	114,28	400
	660	320	200	120	171,42	400
	675	350	200	150	214,28	400

4. Experimental results and discussions

4.1. Average confining effective stress effect

Figure 7 shows the variations of void ratio and the coefficient of hydraulic conductivity as a function of the average confining effective stress, respectively. It can be noted that the effect of the average confining effective stress on the hydraulic conductivity is more significant for values less than 200 kPa, beyond this stress the permeability seems to be almost constant, which in agreement with oedometer results. The measurement of the change in the volume of water throughout the test, allow deducing the final volume of voids. From the same figure, it can be seen that the void ratio decreases when the average confining effective stress increases and consequently result in a reduction of permeability.

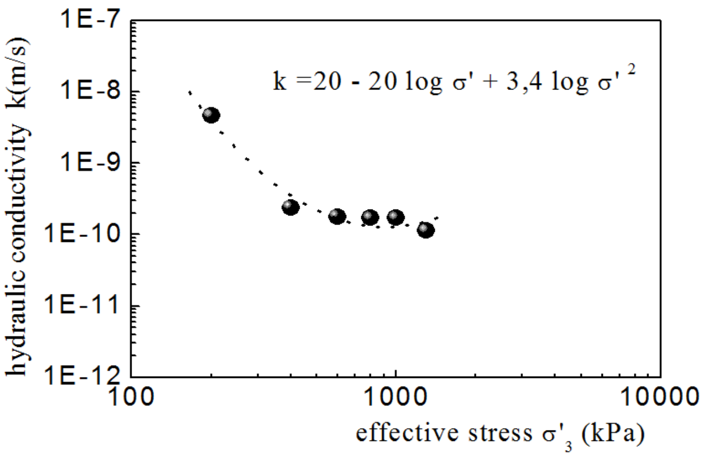

Fig 7. Hydraulic conductivity variation versus average confining effective stress.

4.2. Average hydraulic gradient effect

In the second case of the measurement of the saturated hydraulic conductivity, the average confining effective stress is kipped constant (σ_3'= 400 kPa) while varying the hydraulic gradient. Figure 8 presents the evolution of the hydraulic conductivity as a function of the hydraulic gradient. The experimental results can be approximated by a linear relation (see Figure 8). Similar results have been obtained by other authors (Kenney, 1992; Sayad-Gaidi, 2003).

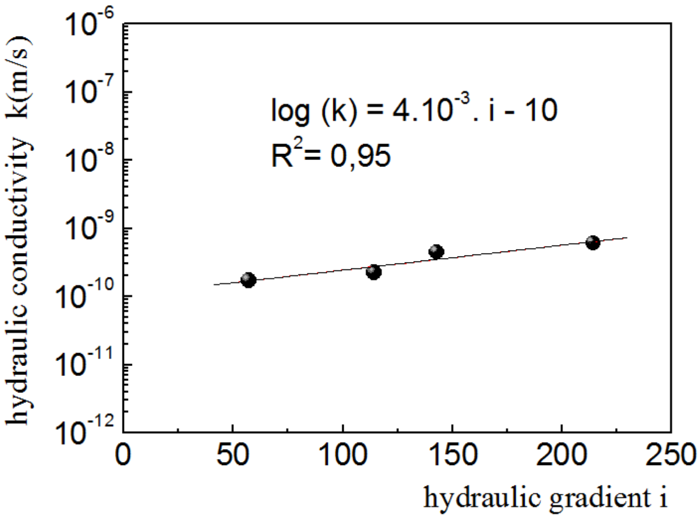

Fig 8. Hydraulic conductivity variation versus average hydraulic gradient.

5. Conclusions

In this research study we have shown that it is possible to obtain an adequate mixture intended for insulation barriers, using dune sand and a small amount of bentonite addition. According to the results obtained from this experimental study, we can advance the following conclusions:

- The common requirement on hydraulic conductivity (should be less than 10^{-8} to 10^{-10} m/s) is met for compacted soil with a minimum of 12% of bentonite addition.
- The results of the hydraulic conductivity obtained by the oedometric tests are lower than those obtained by the triaxial cell, this can be attributed to the lack of saturation of the specimen under oedometric conditions and some air bulbs may remain trapped within the soil.
- According to the results of permeability obtained by different methods, the adequate mixture proposed for the design of the worked barriers in the arid region (southern of Algeria) is 85% S+15% B. In addition such mixture presents a moderate swelling and shrinkage potentials and hence it will be less subjected to cracks under drying conditions.
- Finally, it can be stated that the use of dune sand, which is a local largely available material in the south of Algeria, with small quantities of bentonite additions can provide an economical insulation barrier for waste disposal management. The procedure on site for mixing and placing of sand-bentonite mixture along with strict control of compaction procedures play an extremely important role for the final quality of the barrier.

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