Turkish Journal of Earth Sciences

http://journals.tubitak.gov.tr/earth/

Research Article

Turkish J Earth Sci
(2014) 23: 330-338
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doi:10.3906/yer-1302-13

Experimental investigation of mixtures of bentonite and dredged sediments from Chorfa dam in Algeria

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Received: 28.02.2013 • **Accepted:** 26.11.2013 • **Published Online:** 21.03.2014 • **Printed:** 18.04.2014

Abstract: Geotechnical properties of dredged sediment from Chorfa dam in Algeria and their mixtures (5%, 10%, 15%, 20%, and 25%) with bentonite were investigated through a series of laboratory experimental tests in order to investigate possibilities of their usage as a barrier against the spread out of the Sebkha of Oran in the northwest of Algeria. Grain size and Atterberg limits tests, chemical and mineral analyses, and compaction, vertical swelling, and horizontal and vertical permeability tests were performed on the soils and their mixtures using tap water and the salty Sebkha water. The results indicate that the bentonite specimens remolded and inundated with Sebkha salty water have less swell potential than those prepared with tap water. The addition of bentonite to Chorfa sediment increases the density, limit liquid, specific surface, and swell potential of the mixtures. Compaction tests show a decrease in the optimum moisture and an increase in maximum dry densities as the bentonite content increases. The horizontal and vertical permeabilities decrease relatively with the addition of bentonite.

Key words: Dredged sediment, bentonite, salty water, barrier

1. Introduction

The world's reservoirs are currently filling with sediments at a rate of approximately 1% per year (World Commission on Dams, 2000; De Vente et al., 2005). This implies that within about 50 years, the world's water storage in reservoirs will be half of the current storage, which will have large economic and environmental consequences, especially in semiarid environments where many reservoirs have been built for water supply, irrigation, flood control, and production of electricity. This sediment storage can also have large implications for ecosystem and coastal development downstream of large river systems (World Commission on Dams, 2000; De Vente et al., 2005). Sediment dredging is a lake-restoration technique that removes the surface sediment layer rich in pollutants in order to decrease their release from the sediments to the water column (Semcha, 2006). Dredging is currently the most commonly selected option for remedying contaminated sediments (Gustavson et al., 2008).

The management of dredged material has become an environmental and economic concern for a large number of countries since international and European laws have become more stringent (Marot, 1998; Samara et al., 2009). Various alternatives to the disposal of the processed material, such as sea deposit, landfilling, and treatment processes, have been investigated. The effect of disposal in open-water has been widely studied (Krieger and Barber, 1970; Rosenberg, 1977; Samara et al., 2009). Landfilling requires large spaces and long-term monitoring; however, it is less accepted by public opinion (Samara et al., 2009). On the other hand, treatment processes reduce the toxicity and volume of dredged material, but in comparison with open-water and upland disposal, the treatment cost is not yet competitive enough (Rosenberg, 1977; Samara et al., 2009; Tribout and Husson, 2011; Zri et al., 2011). This underlines the necessity to find ecological valorization paths for processed material to make these alternatives economically competitive (Samara et al., 2009).

The Sebkha of Oran (northwestern Algeria), which is 56.870 ha at 35°22′N, 000°48′W, is a large endorheic depression of tectonic origin with a seasonal saline lake and flats characterized by halophilic vegetation and periodic flooding (Khaznadar et al., 2009).

This work aimed to examine the possibility of using a mixture confected with dredged sediment of Chorfa dam and bentonite as a barrier in the proximity of the airport of Oran (Algeria) in order to stop the spread of the Sebkha. Chorfa sediment, bentonite, and Sebkha water were analyzed, and then mixtures were confected. Compaction, vertical swelling, and horizontal and vertical permeability tests were done using Sebkha and tap water.

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2. Experimental investigation

2.1. Materials used

Two soils of different origins and physical properties were used to achieve the clay barrier. Samples were obtained from dredged sediment of the Chorfa dam (northwestern Algeria). The used bentonite was manufactured by the Bental factory in Maghnia (northwestern Algeria).

Both soils were subjected to several laboratory identification tests using standard procedures adopted by the French standard. The results are shown in Table 1.

2.1.1. Chorfa sediment

Chorfa specimens are river sediments, generally cohesive brown and gray soils; their major clay minerals are calcite, quartz, and a small amount of kaolinite. The grain-size distribution and chemical composition of these soils are given in Figure 1. Their engineering and chemical properties are summarized in Tables 1 and 2, respectively. The chemical analysis of Chorfa sediment and bentonite was carried out in accordance with NF EN 1744 (AFNOR, 2010) and the results are presented in Table 2. The main constituents of Chorfa sediment are silica (as SiO_2), calcium oxide (as CaO), aluminum (as Al_2O_3), and iron oxide (as Fe_2O_3). The total amount of SiO_2, CaO, Al_2O_3, and Fe_2O_3 is 78.7%, which is less than the determined value for bentonite (89.55%).

Sediments can absorb various chemicals contained in industrial and domestic wastewaters and can be polluted. Run-off water often contains many chemical constituents, including heavy metals (e.g., Cd, Cr, Cu, Fe, Pb, As, and Zn), organometallic species, polycyclic aromatic hydrocarbons, fossil fuels (petrol and diesel), lubricating and transmission oils, grease, and anticorrosion and antifreeze agents (Ward, 1995). The Chorfa sediment seems to be unpolluted.

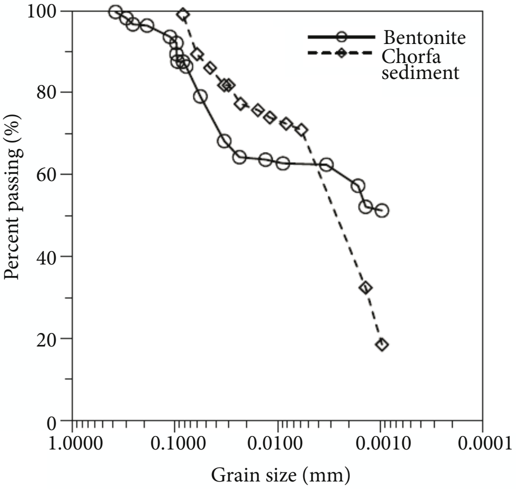


Figure 1. Grain–size distributions for used materials.

The particle size analyses were performed by sieving and hydrometer method (NF P94-056 and NF P94-057; AFNOR, 1992; AFNOR, 1996). The grain size distribution curve indicated that Chorfa sediment is predominantly silt-sized with 38% clay; the percentage of particles whose diameter is less than 80 µm is about 99.59%.

The limit liquid is about 71% (NF P94-051; AFNOR, 1995a), and the plasticity index is about 31%. This soil (Chorfa sediment) is defined as inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts (MH) or organic clays of medium to high plasticity, or organic silts (OH), according to the Unified Soil Classification System (USCS). The organic matter content, defined by ignition test at 450 °C (XP P94-047; AFNOR, 1998b), is

Table 1. Engineering properties of soils used in the study.

Property	Sediments of Chorfa	Bentonite
Density (mg/m^3)	2.67	2.34
Grain size		
Sand (%)	2	-
Silt (%)	60	15
Clay (%)	38	85
Liquid limit (%)	71	141
Plastic limit (%)	40	48
Plasticity index	31	93
Shrinkage limit (%)	9	-
Specific surface area *SST* (m^2/g)	147	462
Volume of blue *VB* (cm^3)	7	22
Optimum moisture content (%)	29	32
Maximum dry density	1.36	1.21

Table 2. Chemical compositions of soils used in the study.

Property (%)	Chorfa Sediment	Bentonite
SiO_2	44.27	65.2
Al_2O_3	12.17	17.25
Fe_2O_3	4.97	2.10
CaO	17.29	5
MgO	1.92	3.10
Na_2O	0.181	3
K_2O	1.477	1.7
SO_3	0.09	-
Na_2O	0.181	-
K_2O	1.477	-
OM	4.4	2.5
Loss in ignition	16.39	-

about 7.3% for Chorfa sediments samples. The loss on ignition, at 750 °C, is about 16.39%. The chemical method gives a value of 4.4% of organic matter for Chorfa sediment and 2.5% for bentonite. The specific gravity, obtained using a pycnometer (NF P94-054; AFNOR, 1991), is about 2.67. The maximal and minimal void ratios were calculated theoretically using solid constituent and dry unit weight according to $e = \frac{\gamma_s}{\gamma_d} - 1$. The void ratio values range between 1.03 and 2.02.

Specific surface area of the sediment was determined with methylene blue test (NF P94-068; AFNOR, 1998a). The specific area is about 147 m^2/g, and the volume of methylene blue is about 7 cm^3. The soil is compacted with standard Proctor energy (NF P94-093; AFNOR, 1999); the optimum moisture content is about 25%, which greater than the determined value for the bentonite (32%). The maximum dry density of Chorfa sediment is about 1.36.

2.1.2. Bentonite

The grain-size distribution of the bentonite is shown in Figure 1. Its chemical and index properties are summarized in Tables 1 and 2, respectively. The main constituent of the bentonite is silica at 65.2%; the SiO_2/Al_2O_3 ratio equals 3.78. The clay is dominant (Table 2) at 85%, and the plasticity index of the bentonite is 93%, which is 3 times the plasticity index of the Chorfa sediments, The specific area is about 462 m^2/g, and the bentonite contains a high percentage of clay. According to the USCS, the bentonite of Maghnia is defined as clay with high plasticity (CH) (Trouzine et al., 2012).

2.1.3. Sebkha water

All tests were performed using salty Sebkha water, which is, according to the World Health Organization, far from drinkable (Table 3).

2.2. Mixture designs

Geotechnical barriers are often constructed with bentonite. The high cost of bentonite led to the idea of mixing bentonite with sediment. The Chorfa sediment sample and bentonite were dried in an oven at approximately 105 °C before grinding. They were then blended to prepare mixtures under dry conditions. The mixture design of the Chorfa sediment and bentonite was based on dry weight percentages of total mixture. The amounts of bentonite were chosen to be 5%, 10%, 15%, and 25% by dry weight of mixtures. The mixture design is given in Table 4.

Table 3. Sebkha water quality.

Minerals	World Health Organization requirements (mg/L)	Sebkha water (mg/L)
NO_3	6	>5
SO_4	400	>1000
Cl	500	>1000
Na	200	>600
K	20	>600
Ca		>500
Mg		>500
Ca+Mg	500	

In many research studies, mixtures are prepared at optimum Proctor water content or at a content corresponding to the limit liquid. In the present study, the sediment–bentonite mixtures were mixed with the required amount of water according to the optimum Proctor moisture content. All mixing was done manually and proper care was taken to prepare homogeneous mixtures at each stage.

The Chorfa sediment and bentonite mixtures were compacted at their optimum water contents. The compaction processes were performed by standard Proctor tests in accordance with NF P94-093. Compacted samples were used for permeability and swelling tests.

2.3. Compaction tests

The mixture compaction parameters, such as the maximum dry unit weight and the optimum moisture content, were obtained by standard Proctor tests in accordance with NF P94-093. To determine the compaction parameters, Chorfa sediment–bentonite mixtures were blended with various amounts of water. Each material was evaluated at 4 different water concentrations in 3 steps. To ensure uniform compaction, the required quantities of Chorfa sediment–bentonite mixtures were placed inside mold-collar assemblies and compressed alternately in 3 steps from the 2 ends until the samples were reached.

2.4. Vertical swelling tests

The samples of mixtures were all initially compacted at their optimum moisture content in a standard Proctor mold and extruded using a cutting ring before the one-dimensional consolidation tests. The compressibility and swelling behaviors of the Chorfa sediment–bentonite mixtures were assessed from one-dimensional consolidation tests. These samples were confined in a consolidation ring, Sebkha water was added to the samples, and they were allowed to swell freely. Other series of tests were performed using tape water for remolding and inundating bentonite specimens.

Swelling tests were performed according to AFNOR XP P94-091 (AFNOR, 1995b) on all compacted specimens. These tests were conducted in a conventional odometer, 50 mm in diameter and 20 mm thick. The following equation was used for calculation of the vertical swelling percentage:

$$G(\%) = \frac{v_f - v_i}{v_f}.100\% = \frac{h_i - h_f}{h_f}.100\% = \frac{\Delta h}{h_i}.100\% \quad (1)$$

Table 4. Mixture design and property.

Engineering properties	Mixture 1	Mixture 2	Mixture 3	Mixture 4
Chorfa sediment (%)	95	90	85	75
Bentonite (%)	5	10	15	25
Density (mg/m^3)	2.38	2.53	2.56	2.59
Liquid limit (%)	72	73	79	81
Plastic limit (%)	41	42	43	44
Plasticity index	31	31	36	37
Methylene blue values				
Volume of blue V_B (cm^3)	6.6	7.3	8.3	10
Specific surface *SST* (m^2/g)	138.6	153.3	174.3	210
Optimum moisture content (%)	28	27	25	25
Maximum dry density	1.37	1.38	1.39	1.40

where V_i is the initial volume of the soil, V_f is the final volume of the soil, h_i is the initial height of the soil, and h_f is the final height of the soil.

2.5. Permeability tests

2.5.1. Vertical permeability

Vertical permeability was first measured using compaction permeameter (mold with the same dimension of standard Proctor mold). Specimens were first prepared with Sebkha water at the normal optimum Proctor energy then compacted in 3 layers in a standard Proctor mold using dynamic compaction (NF P94-093). The upper and lower plates of the Proctor mold were replaced by compaction permeameter ones in order to allow the flow of water through the compacted sample. The compacted specimens were first saturated for a period of about 1.5 to 2 months. Full sample saturation was confirmed by water coming out of the water outlet portal of the compaction permeameter equipment. Coefficient of permeability (k) values were calculated as follow:

$$k = \frac{a.L}{A\left(t_1 - t_2\right)}.\ln\left(\frac{h_1}{h_2}\right) \tag{2}$$

where *a* is the inner cross-section of the standpipe, *L* is the length of the specimen, *A* is the cross-sectional area of the compacted soil specimen, h_1 is the head at time t_1, and h_2 is the head at time t_2.

2.5.2. Horizontal permeability

The flow of water through a porous medium is governed by Darcy's law: if we consider a cylindrical tube with section S, and this cylindrical tube is filled with a porous material over length L, which is circulated water over a total height ΔH (constant) when the medium is saturated with water, then:

$$Q = k.\frac{\Delta h}{l}.A \tag{3}$$

where Q is the flow (m^3/s), k is the permeability or hydraulic conductivity (m/s), A is the surface perpendicular to flow (m), l is the length of the sample (7 cm), and Δh is the level difference between upstream and downstream.

Horizontal permeability tests were done using drainage and seepage tank model HM 169, as shown in Figure 2.

3. Results

Basic properties of mixtures samples are summarized in Table 4. Figures 3a and 3b show, respectively, the effect of bentonite content on consistency limits of Chorfa sediment and the location of the samples of sediments, bentonite, and their mixtures on Casagrande's chart by plotting plasticity index (%) against liquid limit (%).

Figures 4a and 4b show the effects of bentonite on the optimum moisture contents and maximum dry unit weights normalized by setting these values for Chorfa sediment.

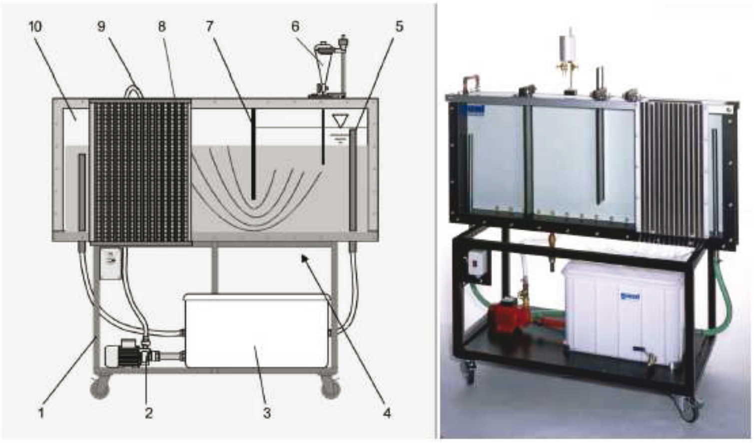
The amount of swelling of Chorfa sediment, bentonite, and their mixtures is shown in Figure 5.

Results of vertical and horizontal permeability tests of the mixtures are shown in Figure 6.

4. Discussion

Liquid limit, plasticity index, and specific surface area increase gradually as the bentonite is added (Table 4). This can be explained by the increase of clay content in the mixtures (Figure 3a).

The change in consistency limits of the mixtures may be due to the mixture type (Bell, 1993), the cation exchange capacity (Okagbue and Onyeobi, 1999; Sivapullaiah et al., 2000), or the relative amount of clay mineral in the mixtures (Schmitz et al., 2004). The location of mixtures



1 laboratory trolley, 2 pump, 3 supply tank, 4 measuring gland, evenly distributed over the base of the tank, 5 adjustable overflow pipe, 6 device for injecting the contrast producing medium, 7 pile planking, 8 fourteen tube manometer, 9 water feed, can be positioned as required, 10 tank with viewing window made of special glass

Figure 2. Drainage and seepage tank.

on Casagrande's plasticity chart is given in Figure 3b. The main aim is to determine whether fine soil is silt or clay. Clay plots are present above the A-line and silt below. Generally, high liquid limit values correlate with high plasticity. Silts and organic soils have a low plasticity index compared to their liquid limit. Clay soils have a high plasticity index in relation to their liquid limit. Clay minerals have the capacity to take in moisture and still retain some cohesion (USCS). According to Casagrande's chart, Chorfa sediment and their mixtures are classified as OH (organic soil of high plasticity) or MH (silt of high plasticity), whereas bentonite is classified as CH (clay of high plasticity).

Casagrande (1948) suggested that the effect of increasing the organic content of a soil is to increase the liquid limit with no appreciable change in the plasticity index, thus causing the soil to shift below the A-line. Holtz and Krizek (1970) suggested an increase of the plasticity index with the increase in the liquid limit for materials with increasing amounts of organic content.

The optimum moisture content of Chorfa sediment–bentonite mixtures decreased with the addition of bentonite contents (Figure 4a). However, it was observed that the maximum dry unit weights of Chorfa sediment–bentonite mixtures increased for the same compaction effort (Figure 4b). Bentonite changed the particle size distribution and surface area of the composite samples. Decreases in the optimum moisture contents are due to the change in surface area of composite samples. In the same way, the reason for the increase in the maximum dry unit weights of the mixtures is the addition of higher amounts of bentonite, which filled the voids of the composite samples. Holtz and Krizek (1970) studied such soils and found that the maximum dry density of compaction decreased with increasing organic content, whereas the optimum moisture content increased with increasing organic content. Similar behavior was also observed by Schmidt (1965).

Interestingly, Jesmani et al. (2008) studied the variation of γ_{dmax} and ω_{opn} versus the clay content with various compaction energy levels. Study of the γ_{dmax} vs. clay (%) curve shows that, at all compaction energy levels, the curve ascends with a steep slope to a certain percentage of clay and then descends to hold a mild slope. On the other hand, there is an optimum percentage of clay for different energy levels at which γ_{dmax} is obtained. At low energy levels the effect of optimum clay value is more outstanding, but at high energy levels this effect is less considerable. At low energy levels, the present clay content of the mixture fills out the pores between the coarse particles and, thus, at the

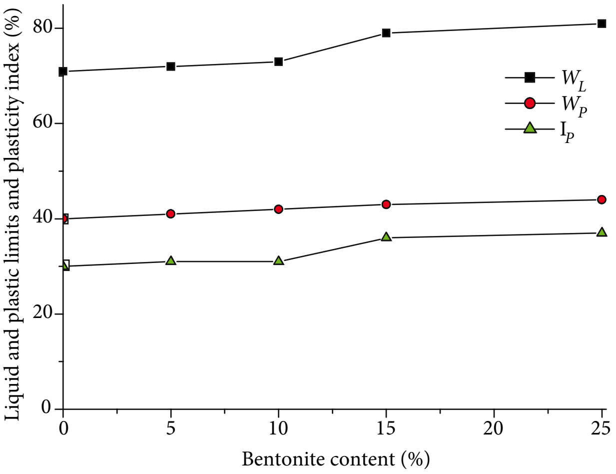


Figure 3a. Effect of bentonite content on consistency limits of Chorfa sediment.

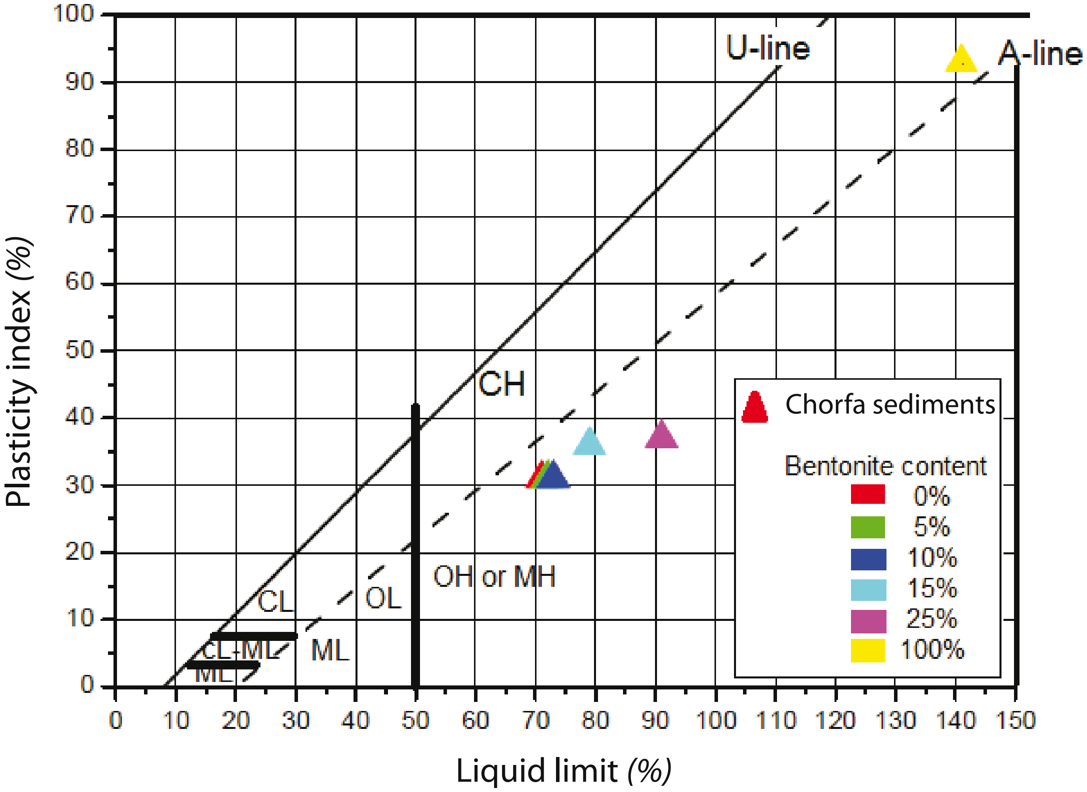


Figure 3b. Location of studied samples on Casagrande's plasticity chart.

outset, increasing the clay content results in an increasing γ_{dmax}. Passing over an optimum clay content, the repulsive effect between the layers of clay prevents optimum compaction. More increase in fine grains causes the coarse grains to be away from each other; this changes the soil state from semibuoyant to buoyant and, as a result, γ_{dmax} decreases (Jesmani et al., 2008).

At high energy levels, the effect of this optimum clay content is less considerable. It seems that the high compaction energies have a more important effect on obtaining higher maximum dry unit weight. The optimum water content keeps a rising trend due to the increase in clay content of the mixtures (Jesmani et al., 2008).

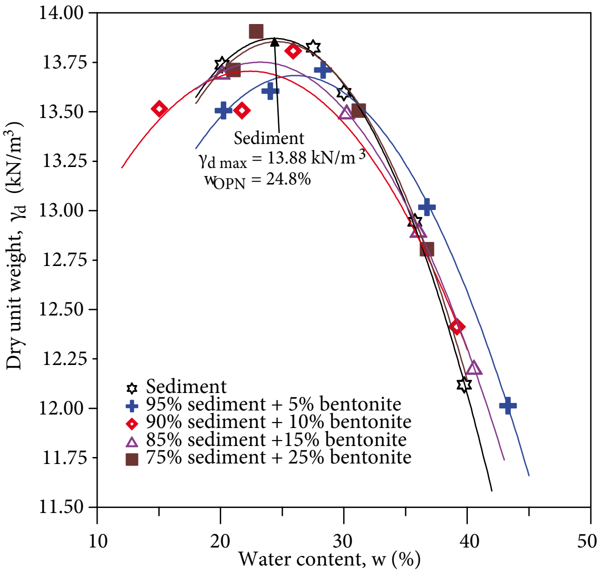


Figure 4a. Compaction characteristics of Chorfa sediment and their mixtures.

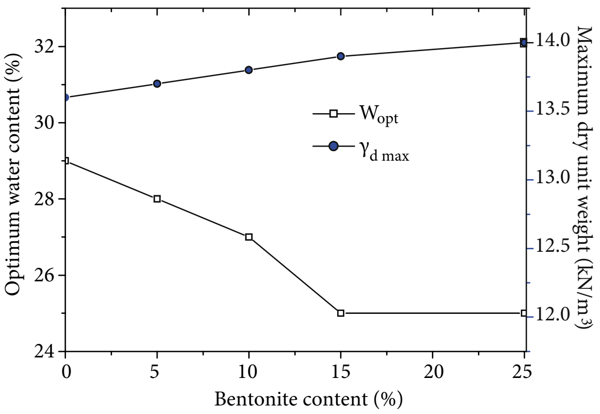


Figure 4b. Effect of bentonite on the compaction characteristics of Chorfa sediment.

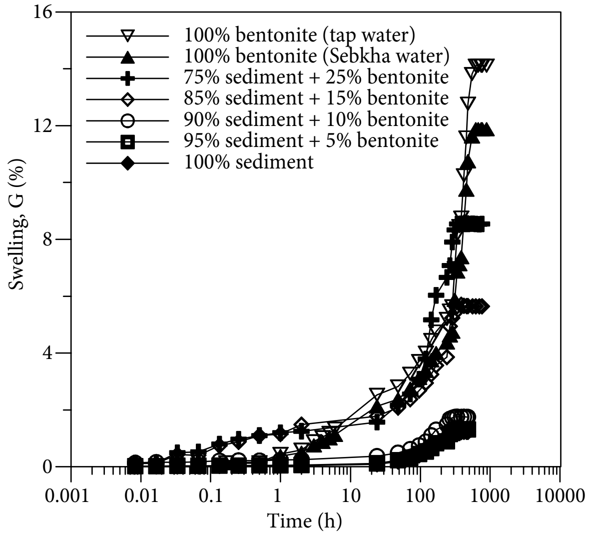


Figure 5. Swell potential of bentonite, Chorfa sediment, and their mixtures.

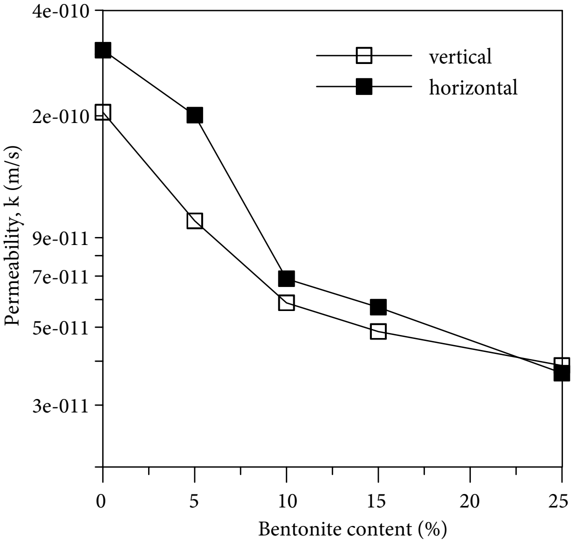


Figure 6. Effect of bentonite content on vertical and horizontal permeability of Chorfa sediment.

The mechanism of swelling is complex and is influenced by a number of factors, such as the type and amount of clay minerals present in the soil, the specific surface area of the clay, the structure of the soil, and the valence of the exchangeable cation and mixture type (Bell, 1993; Okagbue and Onyeobi, 1999; Sivapullaiah et al., 2000; Schmitz et al., 2004; Trouzine et al., 2012).

The maximum swelling of bentonite specimens (using tap water) was about 14% (Figure 5). Interestingly for specimens remolded and inundated with Sebkha salty water, the maximum swelling was only 12%; this could be due to the direction of salt diffusion during dissipation of osmotic suction difference, which has a significant bearing on the swelling behavior of unsaturated expansive clays (Rao and Thyagaraj, 2007). Swelling rapidly goes beyond 70% in 1 h and then 90% in 24 h, and then the evolution of swelling becomes very slow and stabilization begins to occur from the fourth day. The vertical swelling percentages of Chorfa sediment–bentonite mixture samples increased from 6% to 9%. It can be seen that the bentonite increased the vertical swelling of Chorfa sediment–bentonite mixtures.

The bentonite improved the permeability values of samples containing bentonite. The permeability values steadily decreased with increasing bentonite content and low values were finally reached in the composite samples containing 25% bentonite contents (Figure 6). The decrease in the permeability values was due to the decreasing void ratio of the samples containing bentonite. The vertical permeability coefficient ranges from 1.005×10^{-10} to 8.89×10^{-11}, and it increases with the percentage of bentonite added to the mixture (Figure 6). For a landfill site, the vertical permeability coefficient is required to be less than 10^{-9} (Ait Saidi, 2003).

The decrease in the permeability values was due to the decreasing void ratio of the samples containing bentonite.

The horizontal permeability values steadily decreased with increasing bentonite content and low values were finally reached in the composite samples containing 25% bentonite contents (Figure 6). For the composite samples containing 25% bentonite contents, the horizontal permeability is constant.

The following conclusions on the effect of bentonite content on the geotechnical and hydraulic characteristics for the Chorfa sediment that was investigated in this study were drawn:

- Geotechnical characteristics vary depending on the bentonite content: the liquid limit, the plasticity index, and specific surface increase with the increase of bentonite content.

- The bentonite content changed the compaction parameters of Chorfa sediment. The optimum moisture content values decreased with the addition of bentonite contents and the maximum dry unit weight values increased with increased bentonite contents.

- The bentonite content increased the swelling behavior of Chorfa sediment–bentonite mixture samples; however, the salty medium is likely to diminish the percentage of swelling.

- The bentonite content decreased the vertical permeability of Chorfa sediment–bentonite mixtures.

- As for the horizontal permeability, the bentonite content decreased the horizontal permeability of Chorfa sediment–bentonite mixtures.

- The organic matter contained in Chorfa sediment decreases when mixed with bentonite, thus making the mixture more efficient.

- The additive mixtures played an important role in improving the problem of permeability of the Chorfa sediment. These results demonstrate the possibility of using the dredged Chorfa sediment treated with bentonite as a geotechnical barrier to stop the spread of the Sebkha. This geotechnical barrier may be strengthened, in terms of permeability, by decreasing the bentonite content.

Nomenclature

Basic SI units are given in parentheses.

a	Cross-sectional area of the standpipe (m^2)
A	Cross-sectional area of the specimen (m^2)
e	Void ratio (dimensionless)
G	Vertical swelling percentage (dimensionless)
h_i, h_f	Initial and final height of soil (m)
h_1, h_2	Head (m)
I_p	Plasticity index (dimensionless)
k	Permeability or hydraulic conductivity (m/s)
l	Length of sample (m)
L	Length of the specimen (m)
Q	Flow (m^3/s)
SST	Specific surface (m^2/kg)
t_1, t_2	Time (s)
VB	Volume of blue (m^3)
V_i	Initial volume of soil (m^3)
V_f	Final volume of soil (m^3)
W_{OPN}	Optimum Water Content (dimensionless)
W_L	Liquid limit (dimensionless)
W_P	Plastic limit (dimensionless)
γ_d	Dry unit weight (N/m^3)
$\gamma_{d\,max}$	Maximum dry unit weight (N/m^3)
γ_s	Unit weight of solid constituent (N/m^3)

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