



Experimental Study and Modeling of Water Retention Curve of a Silty Soil Compacted and Treated with Cement

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Abstract – The evaluation of unsaturated soils' fundamental properties is ensured by the characteristic water retention curve for a wide range of soil suction values. However, a minimal number of research works have focused on studying the water retention properties of natural soils and treated with hydraulic binders using soil-water characteristic curves (SWCC). The present work is motivated by the lack of experimental evidence of this type. Firstly, experimental measurements of soil-water characteristic curves of a natural loam soil from the region of Sidi Bel Abbes (Algeria), treated with cement and compacted at Standard Optimum Proctor at an ambient temperature of 20 °C, Were carried out using the methods of the imposition of suction, namely the osmotic method ranging from 0 to 0.05 MPa and the method of saline solutions over a suction range from 0.05 MPa to about 343 MPa respectively. The suction used were applied to four studied mixtures (natural soil, + 2%, + 4% and + 6% cement). At the end of the tests on the drainage-humidification path, the water retention curves for the treated soil at different cement dosage allow us to determine the different state parameters of the treated soil: Degree of saturation (S_r), dry weight (ρ_d), void ratio (e) and water content (w). The suction imposition range and the cement dosage significantly influence the water behavior of the material studied. On the other hand, we develop a model of the water behavior of soils treated with cement. This model makes it possible to correctly predict the retention curves at different cement dosage from the experimental measurements performed on samples compacted at Standard Optimum Proctor represented in the plans [suction, degree of saturation] and [suction, moisture content].

Keywords: Treated soil, Cement, Water retention curve, Degree of saturation.

Introduction

Treatment with lime has been widely used to improve clay soil's geotechnical properties, such as increased workability of high plasticity soils during construction and stabilization of the improved formation layer and base layer. Research initiated on the stabilization of clay with lime has historically focused on plasticity, CBR or compressive strength, and shear strength. There is, however, very limited information in the literature based on drainage-humidification path tests that can be used to describe the behavior of soils treated with binders, particularly water retention curves. The water retention curve of a porous medium is a conceptual tool allowing us to understand soil's water behavior over a range of suctions of increasing values, from the saturated state to the assumed dry state. The retention curve has been the subject of numerous studies in recent decades. The works of Gardner (1958); Brooks and Corey (1964); Van Genuchten (1980); Fredlund and Xing (1994) integrate the mathematical adjustment function of the experimental points. The prediction of its allure from the soil's

physical characteristics, particularly from its granulometric curve, was studied by Gimenez *et al.* 1997; Fredlund *et al.* 2002 and Chertkov (2003).

On the other hand, analytical modeling of characteristic curves of natural soils without treatment, parameterized in dry density, has been approached by several authors (Van Genuchten, 1980; Fredlund and Xing, 1994; Fredlund *et al.*, 1996; Fredlund *et al.*, 1997; Kosugi, 1997; Bachman *et al.*, 2002; Sugii *et al.*, 2002; Zhang and Chen 2004; Pham *et al.*, 2005; Salager *et al.*, 2007; Francois and Laloui, 2008; Pedroso *et al.*, 2009; Salager *et al.*, 2010; Sheng, 2011 and Satyanaga *et al.*, 2013). The authors have shown that if the particle size distribution is uniform, it is possible to deduce its characteristic curve. The different successive empirical approaches are based on functions of power-law and exponential law. In general, these models have found on the hypothesis that the shape of the characteristic curve depends on the soil's pore size distribution.

On the other hand, developing a model that predicts the water retention curve of a mixture (soil-cement) has not yet been mentioned. There are few results from the literature that describe the water behavior of soils treated with hydraulic binders. There is also a lack of information on the properties of these soils in the partially saturated state, although they are typically compacted and therefore partially saturated and the results reported are still far from conclusive (Rahardjo *et al.*, 1995; Likos *et al.*, 2003; Puppala *et al.*, 2006). Nowamooz *et al.* 2010, Show on a mixture of bentonite/silt treated with lime the extreme sensitivity of hydro-mechanical properties to drainage for a range of suctions ranging from 0 to 8 MPa. They concluded that water content increases with increasing lime dosage. The experimental works of Mavroulidou *et al.* 2011, and Wang *et al.* 2013 show the favorable effect of lime on the soil's volumetric stability. Zhang *et al.* 2015 studied the effect of lime treatment and suction on the volume behavior of compacted, partially saturated, highly plastic clay.

On the other hand, the work carried out by Alasledj *et al.* 2009 notes that the initial void ratio of the treated samples is similar to that of the untreated sample and decreases very little with the increase in lime dosage. However, the work reported above shows that the treatment of soils with binders presents an unavoidable variable in studying the water behavior of unsaturated porous media. Therefore, it is necessary to control the influence of the treatment effect on the water retention curve.

This research's main objective is to study the effect of suction and cement treatment on the response of the chemical and water behavior of unsaturated soil. Indeed, a series of tests of the water retention curves were carried out on natural samples and treated with cement using the imposition of suction and measurement of the initial suction. On the other hand, to present the numerical modeling of the retention curve of treated soils. Based on the experimentally obtained water retention curve, we will adapt the Van Genuchten (1980) water model, which can predict, by numerical simulations, the retention curve of a soil treated from the Characteristic curve of the untreated soil while evaluating the parameters of the model. This allows us to reduce the number of experimental tests required to obtain the retention curve at different binders' dosages. The coupling model of the effect of suction and the modified cement treatment is validated experimentally in a compacted loam soil compacted at standard Optimum Proctor, which can be used in road infrastructures.

Materials and Method

Materials

The experimental study involved Loamy soil taken from a site 50 km from Sidi Bel-Abbes west of Algeria, at a depth of about 65 cm. A complete characterization of the material classified as A1h has been studied by Dadouch *et al.* 2014 and Ikhlef *et al.* 2015 for use in embankments and the improved formation layer of a roadway. Table 1 shows the essential geotechnical properties of the material used.

Table 1. Geotechnical properties of the material studied

Properties	Values
Passing 80 μm (%)	56.80*
Specific gravity, Gs (-)	2.74
Liquid limit, LL (%)	33*
Plasticity index, PI (%)	11.97*
Proctor optimum moisture, wopt (%)	16.00
Proctor maximum dry density, $\gamma\text{d-max}$	16.50

Soil water characteristic curves test procedures

Soil samples designed for the tests on drainage and humidification paths were statically compacted in a mold of 50 mm diameter and of 2 mm thickness at a dry density and water content corresponding to 80% of the dry side of the optimum water content of the standard Proctor test. During compaction, soil samples were treated with dosages of 0; 2%; 4%, and 6% of cement type CEM I, 32.5; previous results of Daddouch *et al.* 2015 and Ikhlef *et al.* 2015 have shown that the effective cement dosage is between 0 and 6%. The principle consists of statically compacting about 2/3 of the sample height, then inserting a Whatman No. 42 filter paper disc protected on two sides by two other common filter papers in the mold and compacting the 1/3 remaining. To ensure proper hydration of the cement under handling conditions, the water content corresponding to the dry density ($w = 16\%$) was increased to 18.6% with a corresponding dry density of $\gamma_d = 16.50 \text{ kN/m}^3$. Table 2 presents the results obtained from the Standard Proctor compaction tests of soil mixtures (w_o and γ_d -max), the density of solid particles (γ_s), the initial values of the void ratio), The degree of saturation (Sr_0), and the initial suction (u_{ci}). The average initial suction values of each mixture are measured by the filter paper method, which is widely used in the literature (Fawcett and Collis-George, 1967; Chandler and Gutierrez, 1986; Chandler *et al.*, 1992b; Houston *et al.*, 2004; Likos and Lu, 2002; Leong *et al.*, 2002; Ghembaza *et al.*, 2007; ASTM Standard D5298-10, 2010 and Bicalho *et al.*, 2015).

Figure 1 positions initial suction values at the standard optimum proctor on the filter paper calibration curve (Bicalho *et al.*, 2015). It is noted that the suction values of low cement dosages are within the range of high water contents. On the other hand, the suction values of high dosages are localized in the domain of low moisture contents.

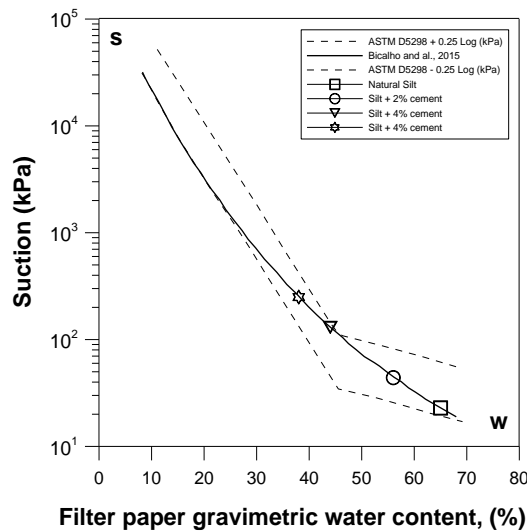


Figure 1. Initial suction of the test samples shown on the calibration curves of the Whatman No. 42 filter paper

Table 2. Initial properties of the studied mixtures

Silt Mixtures	γ_s (kN/m^3)	γ_d -max (kN/m^3)	w_o (%)	e_0	Sr_i (%)	$w_{\text{papier filtre}}$ (%)	u_{ci} (MPa)
Untreated Silt	27.40	16.91	16.40	0.66	77	65	22.94
Silt + 2% cement	27.45	17.22	14.94	0.62	75	56	44.03
Silt + 4% cement	27.50	17.19	14.23	0.66	76	44	130.27
Silt + 6% cement	27.55	17.85	11.95	0.63	79	38	250.51

It should be noted that the initial suction is a measured value after static compaction of each specimen prepared for different cement dosage ranging from 0% to 6%. For the initial water content and the initial void ratio, the values given in Table 2 are the values measured after 48 hours of sample preparation. In Table 2, the decrease in the water content as a function of the cement content can be explained by the manifestation of water in the cement's hydration. On the other hand, the increase in the degree of saturation is a function of the void ratio because the hydrated cement fills the voids, and the number of pores decreases. We do not need a method to quantify the hydration of cement for a first approximation because our goal is to study the treated soil with water contents imposed on the standard Proctor.

The specific mass of the treated samples is calculated with the relationship developed by Saadeldin *et al.* 2013 using the total density of the soil-cement mixture, which can be determined as the average value of the combination of specific densities of soil and cement. The following relation gives it:

$$G_{SC} = (1 - C)G_S + C.G_C \quad (1)$$

With G_{SC} : the density of the mixture (treated soil), G_S : the density of the soil, G_C : the density of the cement, and C : the cement content. Once removed, the samples treated and equipped with the filter paper were wrapped in sealed plastic bags for 48 hours. They were conserved and stored under controlled environmental conditions (temperature and humidity constant) before the drainage-humidification test to achieve the highest saturation level, concerning the evaluation of all-natural (control) soil water retention properties and treated samples, osmotic methods, and saline solutions following drainage or humidification paths from the initial state of the material. When the water balance is reached at a given suction value, the samples are weighed and then immersed in a non-wetting oil (Kerdane) with a density of 0.785 to fill the large pores without bulging the sample. This oil is immiscible with water and evaporates in an oven at 105°C. The sample's external volume is deduced from the difference between the weight of the sample soused with oil and that of the sample immersed in the oil (weight of the displaced volume). Finally, its dry weight is measured after evaporation of water and oil in a study at 105°C for 24 h. We consider that the method of weighing kerdane is acceptable given the size of the sample (1 cm³).

Table 3. Physico-chemical properties of used cement (Cement works of CHLEF-Algeria).

Chemical composition	Values (%)
Insoluble	0.97
Loss on ignition	5.14
Free CaO	0.70
SiO ₂ (%)	20.71
Al ₂ O ₃	5.29
Fe ₂ O ₃	3.47
CaO	62.07
MgO	1.12
SO ₃	1.66
Physical characteristics	Values
Specific surface area	3500
Consistency (%)	19
Initial setting time (h, min)	2:13
Hot expansion on paste	1.51
Specific density	3.1

This operation is repeated for each measuring point. It should be noted that the measurement is made systematically on two samples, at least for each value of suction imposed. The time required to reach the equilibrium between the imposed suction and that of the sample depends on the tested material's properties and the sample's initial suction (Ghembaza *et al.*, 2007).

However, the cement added to the mixture of silt is Portland cement of class CEM I 32.5. It follows the grinding of clinker with about 5 % gypsum for the regularization of the setting. Clinker is of the cement works

of CHLEF in western Algeria. The chemical study revealed no evidence of disruptive agents (Table 3). The percentage of organic matter measured is low, of the order of 1.03 %, and cannot be disruptive to the setting. We recall that beyond 3%, there is a risk of disruption (NF P94.011).

Experimental device

Two methods are used to determine the studied soil's water retention curves at an ambient temperature of 20°C. These tests consist of imposing on the soil a series of increasing capillary pressures (u_c) until complete drying (drainage) from the initial state of the material:

The first method is called the osmotic method (Figure 2). It is used for low suctions between 0.05 MPa and 1.5 MPa. In this technique, the sample is in contact with a solution of polyethylene glycol (PEG) organic molecules of molecular weight 20000 through a semi-permeable membrane, which allows only water to pass.

The whole (sample + membrane) is immersed in a desiccator (osmotic solution) of osmotic solution at each concentration, and the membranes are then pinched at their ends (Figure 3). The semi-permeable membrane is tubular, as shown in Figure 2; it is properly sealed against leaks using the pliers. At equilibrium, the hydration potential of PEG is equal to that of the soil, and it is possible to establish equivalence between the concentration of the osmotic solution in PEG and the suction. For reliable and representative results, we performed at least three trials of each sample at equilibrium.

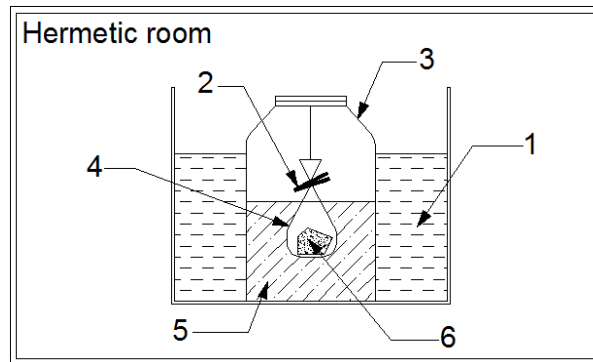


Figure 2. The osmotic method; 1. Water bath, 2. Clamp, 3. Desiccator, 4. Semi-permeable membrane (SPECTRAPOR 4), 5. Osmotic solution (PEG 20,000), 6. Sample (treated or untreated) enveloped and immersed.

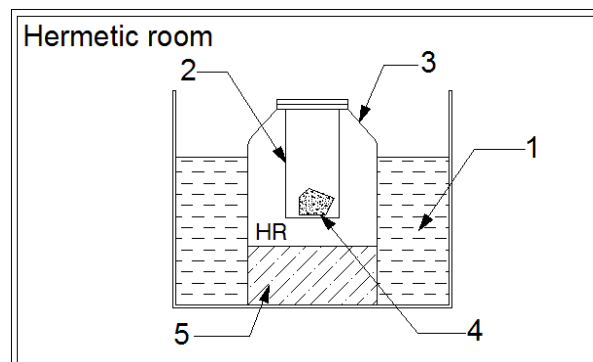


Figure 3. Saline solution method; 1. Water bath, 2. Support, 3. Desiccator, 4. Soil, 5. Solution Saturated salt

The second procedure is called the saline solution method (Figure 3). It is used for higher suction values between 2 and 1000 MPa); the transfer of water takes place in the vapor phase. Indeed, this pressure is governed by Kelvin's law. The control of the air's relative humidity is ensured by the competition between the water's tendency to saturate the atmosphere of the closed precinct of the desiccators in which the saline solution is

placed and that of the salts to be hydrated (Ghembaza *et al.*, 2007). Each sample placed on suspended cradles in the desiccator's atmosphere (hermetic jar) reaches, after several weeks, a capillary pressure equilibrium, which depends on the nature and the concentration of the saline solution. The salts used to make it possible to obtain relative humidity whose suction is between 4.2MPa and 343MPa. In both processes, the desiccators are placed in a controlled temperature and humidity precinct (Figures 2, 3).

Results

Figure 4 shows the relative variation of the mass in function with the tested samples of about 1 cm³. When the balance of the liquid phase of the sample is reached, at the end of the test, the state parameters of the various natural and treated models are determined again by hydrostatic weighing, namely: moisture content (w), dry weight (γ_d), void ratio (e) and degree of saturation (S_r).

The equilibrium between the liquid phase and the sample is reached after a certain duration of the test. After equilibrium, we move on to the measurement of the state parameters by the hydrostatic weighing method, which consists of immersing the samples studied in a non-wetting oil which is "Kerdane" having a density of the order of 0.785, used to fill large pores without causing swelling in the sample. This oil is immiscible with water and evaporates in an oven at 105 ° C. This method was used by Tessier (1975) and taken up by Zerhouni (1991) (cited by Bourabah, 2012).

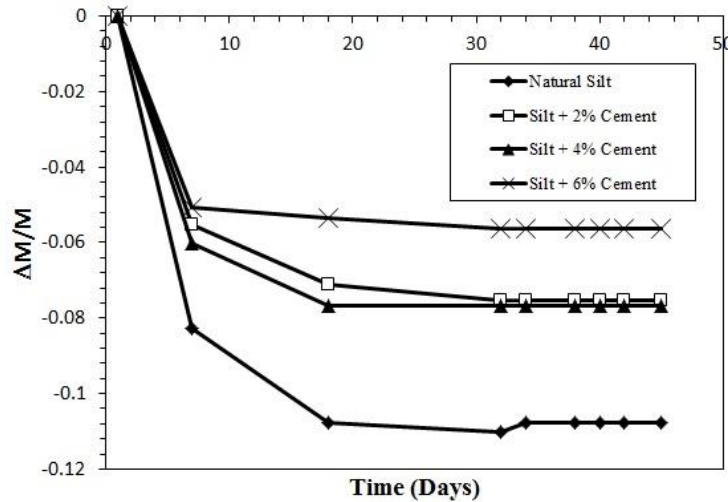


Figure 4. Evolution of the weight of the samples in the function of time during a drain to an imposed suction of 7 MPa

The ratio $\Delta M/M$ in Figure 4 represents the variation in the mass of the sample during the test with respect to the initial mass. The measurement of equilibrium times varies from one sample to another; each sample is weighed delicately every 24 hours with a precision balance (0.01 g). The time required to reach equilibrium between the imposed suction and that of the sample depends on the properties of the material tested and the sample's initial suction (Ghembaza *et al.*, 2007). We can say that equilibrium is reached if there is no variation in the mass of the sample; that is to say, the $\Delta M/M$ ratio remains constant for several days.

After equilibrium, it is possible to determine the different parameters (water content (w), dry weight (γ_d), void ratio (e), and degree of saturation (S_r), and the results of the soil drainage-moistening liners.

Figure 5 shows the response of the silt control soil retention curve obtained experimentally at 20°C. And that of the treated soil at various cement dosages ranging from 2% to 6%. The initial state (OPN), treated, and unprocessed samples follow a drainage path for suction values greater than the initial suction SOPN of each treatment dosage determined by the filter paper method. The different initial suction values are listed in Table 2, and a humidification path for suctions below these initial values. The results which give the variation of the degree of saturation as a function of the suction of the treated soil at different percentages of cement show that the degree of saturation at a given density depends appreciably on the cement content "C." In other words, for

small given suctions, the increase of the cement content to a threshold of 4% has the effect of increasing the saturation degree value in relatively large proportions (of the order of 10 %). The 6% cement dosage shows a slight decrease in the degree of saturation in the same suction range.

On the other hand, for high given suctions, this increase in the degree of saturation is considerably reduced when the cement dosage varies from 0% to 6%. It can also be seen in the plane $[\log (s), S_r]$ that the treated soil has a point of curvature indicating the air entry value at high suctions relative to the untreated soil (this is expected as a result of the flocculation of cement-induced particles). This critical value is a measure of soil's maximum pore size because the larger pores drain the water first. On the other hand, the slope of the drainage paths of treated and untreated soils beyond these points of curvature is similar. This is probably related to the microporosity of soils. In any case, as long as the soil is becoming desaturated, the suction is increased, and the degree of saturation drops rapidly from the initial negative pressure to attain 3% for a suction value of about 100 MPa, whatever the cement dosage, especially when the air entry point is reached.

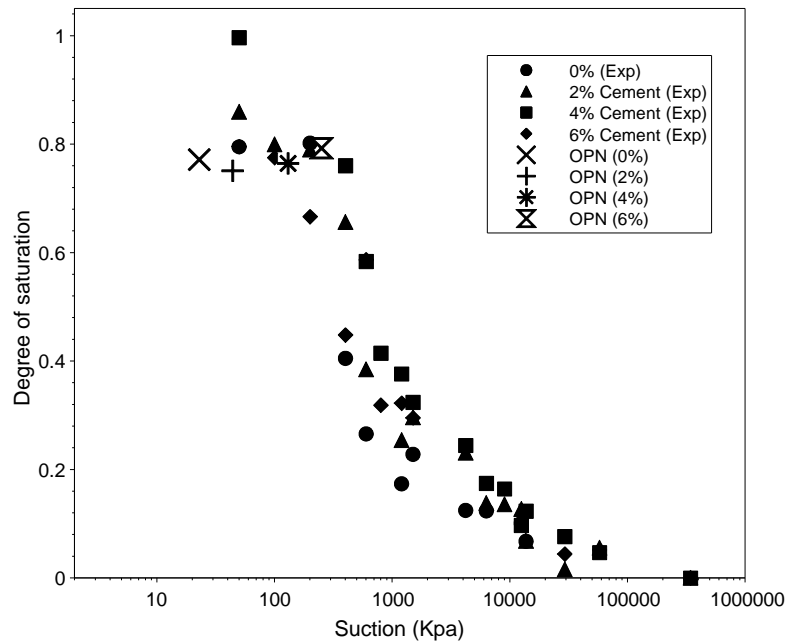


Figure 5. Water retention curve in the $[s, S_r]$ plane of a compacted loam and treated at different cement contents

Figure 6 shows the same observations in the plane $[\log (s), w]$. Indeed, an increase in moisture content is observed when the cement percentage increases, especially in the range of low suction. This phenomenon is already shown in the results of the compaction characteristics. However, there is an increase in optimal moisture content and a decrease in maximum dry density when the cement dosage increases (Ikhlef *et al.*, 2015). On the other hand, this moisture content decreases as the suction increases for each cement dosage. The water retention curves (SWCC) of samples prepared at different initial compaction moisture contents tend to converge to the same degree of residual saturation (S_{rres}) (Figure 5) and the residual moisture content (w_{res}) (Figure 6) for large suction values.

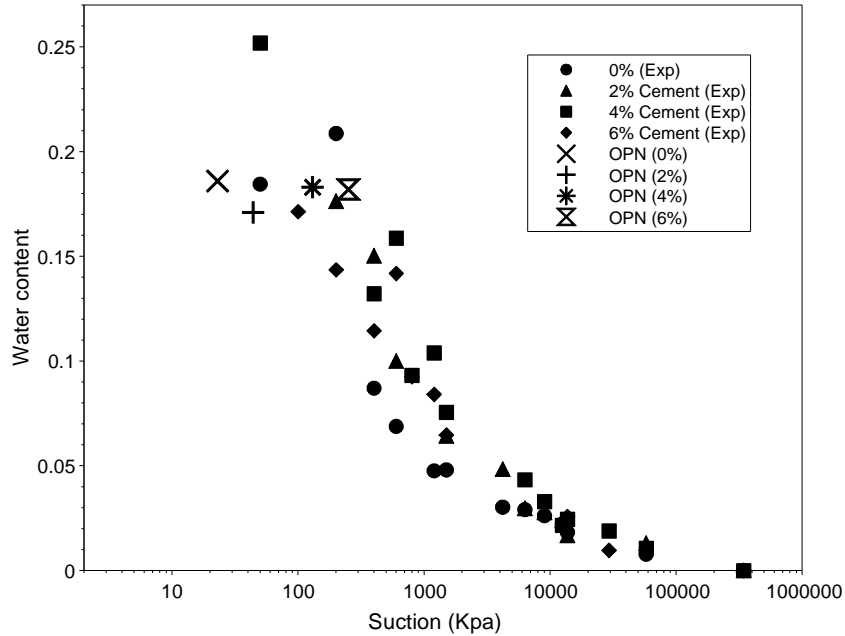


Figure 6. Water retention curve in the $[s, w]$ plane of a compacted loam and treated at different cement contents

Moreover, it is interesting to present an important parameter for unsaturated soils, namely the air entry point (AEV), from which the degree of saturation begins to decrease rapidly.

Figure 7a shows the air entry value (i.e., air entry suction S_d) and the air entry water content (w_d) as a function of the cement percentage. It should be noted that the determination of the air entry values and the air entry saturation degree values are made using the water retention curves in the saturation degree (Figure 5). In general, when the treatment dosage percentage increases to a threshold of 4%, the air entry value increases and then decreases slightly for a cement dosage of 6%. It can be said that the increase in air entry suction is related to the initial moisture content of the sample. Concerning the degree of saturation of the air entrance, a marked increase is observed when the percentage of cement increases.

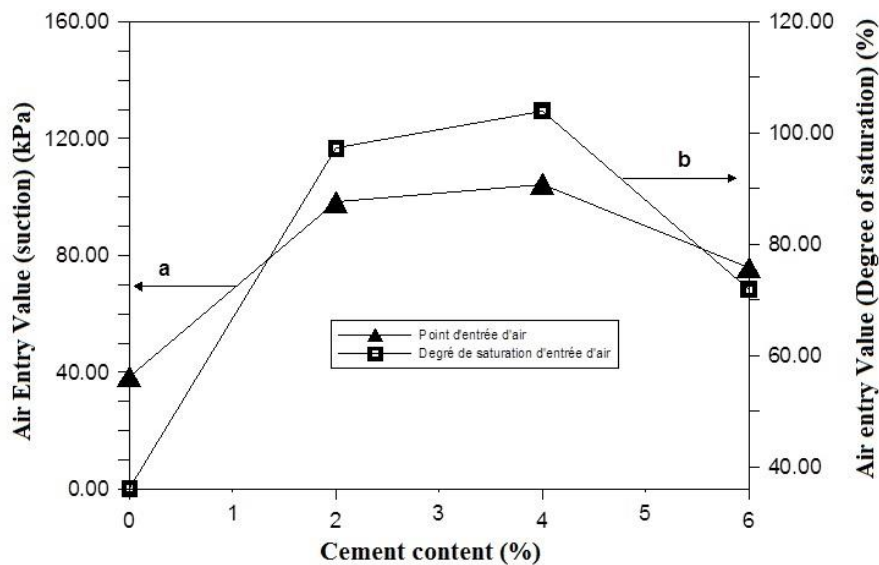


Figure 7a. Air-entry values: a - Soil suction, b - degree of saturation

The method used to determine the air entry value (AEV) is the graphical method illustrated in Figure 7b. It should be noted that the air entry value corresponding to 6% cement is less than that of 4%. This can be explained by the incomplete hydration of the 6% cement quantity in the mixture, knowing that the amount of water used initially is chosen in the optimum Proctor's vicinity.

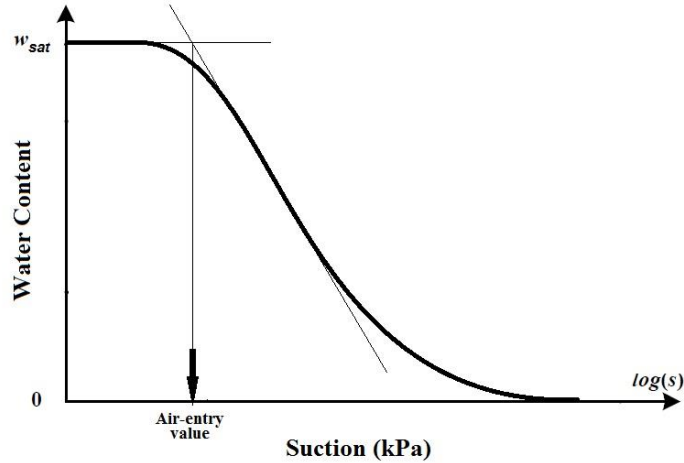


Figure 7b. The graphical method determination of the air entry value (Fredlund and Xing (1994))

Analytical modeling

Model of treated soils

Experimental suction data for different soil moisture contents are adjusted by an empirical expression defining the soil water retention curve (SWRC). There are many models available in the literature to describe the experimental results of the soil water retention curve (SWRC) (Gradner (1958); Brooks and Corey (1964); van Genuchten (1980); Fredlund and Xing (1994)). Each model has its advantages and disadvantages when applied to a given soil. The research by Leong and Rahardjo (1997) and Sillers *et al.* 2001 and Agus *et al.* 2003 showed that experimental data for various soils over a wide range of soil suction could be well adjusted using the Model of Fredlund and Xing (1994) in terms of three parameters designated a , n and m .

She and Sleep (1998); Bachmann *et al.* 2002 using the van Genuchten (1980) model, modified by Grant and Salehzadeh (1996) by integrating only the temperature. This model has been successfully applied to experimental results for a wide variety of soils but without chemical treatment. The literature is abundant on the use of the van Genuchten (1980) model for treated soils.

This paragraph describes the proposed model for describing the water behavior of treated soils. It is a water model coupled with a hydraulic binder's chemical effect, noted (HC). The main objective of this model is to highlight the influence of treatment with cement, denoted "C," the dry density (γ_d), the moisture content (w), and the void ratio (e) on the water retention curve of loamy soil. Therefore, it is interesting to extend the van Genuchten (1980) model by adding to the latter the chemical effect on the initial water retention curve established at an ambient temperature T_0 and zero cement content "C₀". Although it is recognized that suction in soils is not a process of capillarity alone, the Laplace equation is a good approximation to explain the processes of water retention in unsaturated soils:

$$s = u_a - u_w = \frac{2\sigma \cdot \cos \theta}{r} \quad (2)$$

With: s : Capillary pressure, u_a : Air pressure, u_w : Water pressure, σ : Water-air surface tension (surface pressure), θ : Connection angle between the meniscus and the solid and r : the mean pore radius. The analysis of the motion of the moisture in the porous media is affected in the case where this medium is treated with a hydraulic binder. The partial derivative of the suction with respect to a cement content "C" deduced from the Laplace Eq. (2) is:

$$\frac{\partial s}{\partial C} = \frac{\partial s}{\partial \sigma} \cdot \frac{\partial \sigma}{\partial C} + \frac{\partial s}{\partial \theta} \cdot \frac{\partial \theta}{\partial C} + \frac{\partial s}{\partial r} \cdot \frac{\partial r}{\partial C} \quad (3)$$

The relation (3) takes into account the fact that the surface tension, the wetting angle, and the mean pore radius depend on the cement content. In Figs. 5 and 6, we see that the SWCC varies according to treatment; we observe a shift of the curves with treatment (2%, 4%, and 6%) towards the right side compared to the untreated curve (0%), so we can say that the suction (s) is changed depending on the cement content (C). Therefore and since the suction is a function of σ , r and θ (Laplace equation), we can assume that the quantities σ , r and θ are a function of the cement content (C), where comes the hypothesis of the function (3).

The lack of experimental data makes it impossible to consider the variation of the wetting angle and the pore radius as a function of the cement content. These considerations lead to a simplified expression of relation (3) in the form:

$$\frac{\partial s}{\partial C} = \frac{\partial s}{\partial \sigma} \cdot \frac{\partial \sigma}{\partial C} \quad (4)$$

Eq. (4) shows the mechanical relationship between the cement content and the surface pressure physically translated by the addition of cement and water to the soil crystallization and creation of the new granular structures in the mixture, reflecting the rearrangement of the pore system. As a result, the surface tension is affected.

After the mathematical derivation of Eq. (3), it is possible to obtain the variation of the suction as a function of the cement content " C " for a known degree of saturation, in the following expression:

$$\frac{\partial s}{\partial C} = \frac{2 \cos \theta}{r} \cdot \frac{\partial \sigma}{\partial C} \quad (5)$$

To derive Eq. (3), it is supposed that the suction coincides with the capillary pressure u_c , and we can write:

$$\frac{s}{\sigma} = \frac{2 \cos \theta}{r} \quad (6)$$

By replacing Eq. (6) in Eq.(5), we can write the variation of suction as a function of the cement content in the planes $[s, w]$ and $[s, S_r]$ in the following form:

$$\frac{\partial s}{\partial C} \Big|_{S_r, w} = \frac{s}{\sigma} \cdot \frac{\partial \sigma}{\partial C} \quad (7)$$

With: (S_r, w): the degree of saturation and the soil studied's moisture content.

Extension of the van Genuchten model in the case of treated soils

The model used to simulate the reference water retention curve of a soil is the model of Van Genuchten (1980), given by the following expression:

$$S_r = \left[1 + \left(\frac{s}{a_0} \right)^n \right]^m \quad (8)$$

With: a_0 , n , and m : are smoothing parameters determined from the experimental results,

Where $m = 1 - \frac{1}{n}$

The parameters m and n in the Van Genuchten (1980) model relate to the linear part of the water retention curve's inclination. The simplicity of the calculations assumes that the parameters n and m do not vary with the cement content. Index 0 in the parameter a_0 indicates the percentage of the cement content (untreated soil).

The retention curve deduced by Eq.(8) corresponds to an initial temperature ($T = T_0$) and an initial void ratio ($e = e_0$). In the Van Genuchten (1980) model, the density's effect is included in parameter a_0 . It should be noted that as the density increases, the more the value of a_0 increases (Al-Mukhtar *et al.* 1999; Vanapalli *et al.* 1999; Romero and Vaunat (2000); Pang (2009)). For the partial inclusion of the influence of the treatment for a cement content (C) on the water retention curve, the variation of parameter " a " as a function of (C) must first be

determined. Based on the experimental tests results, mathematical smoothing was performed with Eq. (8) by varying the parameter "a" of the retention curves at different cement dosages. There is a variation that represents a bell curve (Figure 8).

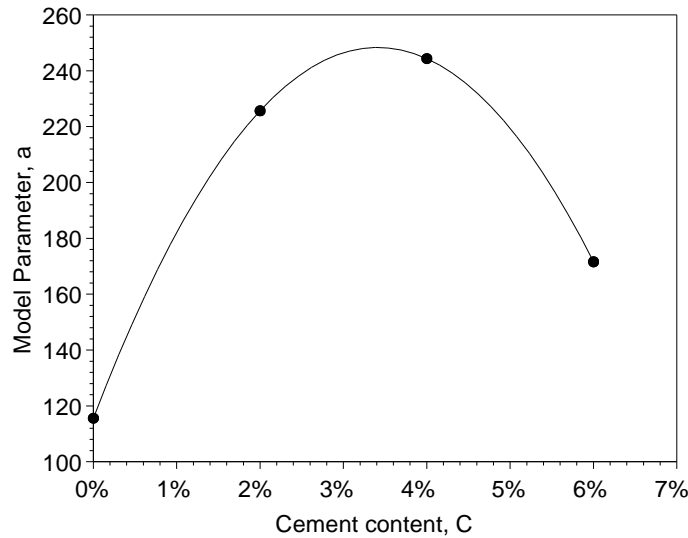


Figure 8. Variation of the parameter "a" as a function of the cement dosage "C."

The curve shows that the parameter "a" varies increasingly between the values of 0% and 3.4% and then decreases for cement contents higher than 3.4%; this gives us an idea of the optimum percentage of the cement content, which varies between 3% and 4%. For the first approximation, we adopt a polynomial equation for the variation of the parameter "a" as a function of the cement content "C." This relationship is written as follows:

$$a = b'_1.C^2 + b'_2.C + b'_3 \quad (9)$$

With: b'_1 , b'_2 and b'_3 are parameters where $b'_1 = -113.6$, $b'_2 = 7.744$ and $b'_3 = 0.11492$

As for the variation in the surface tension of the water σ as a function of the cement content "C," we opt for the following relation, which will be detailed below:

$$\sigma = b_1.C^2 + b_2.C + 1 \quad (10)$$

With $b_1 = b'_1/b'_3$ and $b_2 = b'_2/b'_3$, the surface pressure σ is in (N/m), and the cement content (C) is in percentage (%). From Eqs. (7) and (10), a relationship between suction and variation in cement content C can be deduced:

$$\frac{ds}{s} = \left[\frac{2b_1.C + b_2}{b_1.C^2 + b_2.C + b_3} \right] dC \quad (11)$$

By integrating Eq. (11), we have:

$$s = \frac{s_0 \cdot \sigma}{\sigma_0} \quad (12)$$

With: s suction, s_0 initial suction, σ and σ_0 , are the surface pressures that correspond to treated and untreated soil, respectively. By introducing Eq. (12) into Eq. (8) of the water retention characteristic curve, a new relation is obtained, which generally introduces the variation of the cement content "C" in the water retention curve.

$$Sr = \left[1 + \left(\frac{s}{a} \right)^n \right]^m \quad (13)$$

With: "a" is a parameter that considers the effect of the treatment in the model.

In the van Genuchten (1980) model, the effect of porosity must be included in parameter "a."

Therefore, the following relationship is proposed (Jacinto et., 2009):

$$a = a_0 \cdot f \left(\frac{\rho_0}{\rho} \right)^\beta \quad (14)$$

With: ρ and ρ_0 ; Are the porosities which correspond to the cement content C and C_0 , respectively.
 Knowing that :

$$\rho = \frac{e}{e+1} \quad (15)$$

e and e_0 are the voids ratio, which corresponds to the cement contents C and C_0 , respectively. For the function f , Eq. (16) is proposed:

$$f = \left(\frac{\rho_0}{\rho} \right)^\beta \quad (16)$$

With: β is a parameter to be defined experimentally.

Considering Eqs. (15) and (16), the relation between the void ratio and the cement content, which depends essentially on " a ," is defined as follows:

$$a = \frac{a_0 \cdot \sigma}{\sigma_0} \left(\frac{\rho_0}{\rho} \right)^\beta \quad (17)$$

Hence, only the cement content's effect on the suction is considered in Eq. (8). However, part of the suction is attributed to the physicochemical interaction between water, the solid soil structure, and cement. Therefore, it is clear that other mechanisms are present and must be considered in Eq. (17) if unsaturated soils' hydro-chemical behavior is analyzed. Concerning the study of the influence of cement on the void ratio, Figure 9 presents the variation of the void ratio as a function of the cement content at different suctions. A very slight decrease in the voids ratio is observed when the cement dosage increases for a given suction. In a first approach, the variation of the void ratio as a function of the cement content will be neglected. The relevance of this choice will be discussed later. This consideration leads to a simplified expression of the relation (17) in the form:

$$a = \frac{a_0 \cdot \sigma}{\sigma_0} \quad (18)$$

In this model, the void ratio is assumed to be constant (nondeformable soil); therefore, the water content or degree of saturation is proportional. For this purpose, we can use the relation (19) to model the water retention curve.

$$w = w_{sat} \left[1 + \left(\frac{s}{a} \right)^n \right]^m \quad (19)$$

with: w_{sat} is a saturation water content.

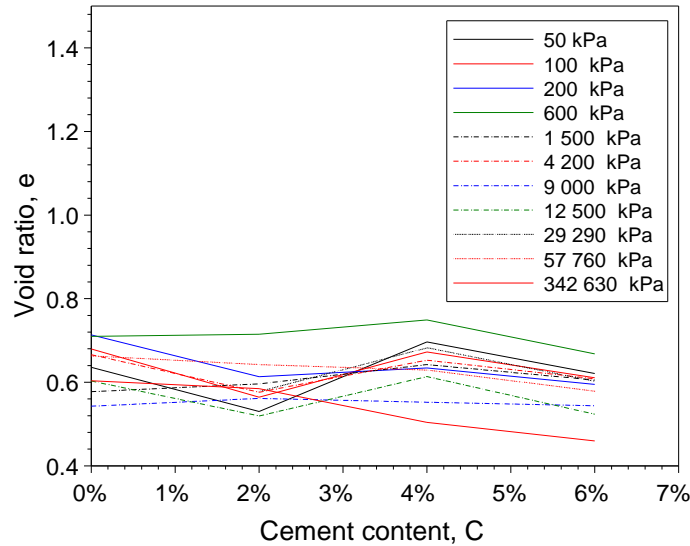


Figure 9. Variation of the void ratio as a function of the cement content of a compacted loam parameterized in successions

Discussion

Experimental validation of the relationship

This part is devoted to illustrating the capacities of the adapted water model, which makes it possible to take into account the effect of the treatment on the retention curve and model the path of drainage and humidification of compacted soils. Concerning the simulations, an adjustment of the experimental points is carried out using the proposed model. The untreated soil retention curve ($C = 0$) is used as the reference curve for the calculation described in Eqs. (13) and (19). The results of the modeling of the SWCC curves represented by lines for the different cement measurements (0%, 2%, 4% to 6%) in the $[\log(s), S_e]$ and $[\log(s), w]$ are also shown in Figures 10 and 11. The proposed model adequately reproduces the retention curves resulting from the experiment using the model parameters (Table 4) for all retention curves. Figure 10 shows that for a given suction value (for example, 500 kPa), an increase in the dosage from 0% to 4% causes an increase in the silt's saturation degree from 40% to 60%. For the same suction value, in Fig.11, there is also an increase in water retention capacity of 10% to 15%.

Comparisons between modeling and experimentation on water paths of treated and untreated soil show the ability of relationships (13) and (19) to predict the retention curve at a given cement content from a single Parameter of the proposed model " a " measured on the retention curve at a given cement content C_0 . The hypothesis which led to neglecting the void ratio of the relation (17) appears acceptable. Although the variation in the void ratio may be significant overall in the tests, it does not seem necessary to take this variation into account in the calculation explicitly.

Indeed, the determination of the expression of " a " of the retention curve implicitly integrates the contribution of the material's progressive deformation during the loading of water. The results presented in this article make it possible to consider the retention curve's generalization to a retention surface, expressing the degree of saturation or the moisture content as a function of the suction and the cement dosage.

Table 4. Model parameters deduced from the experimental points

Dosage	W _{sat}	a	n	m
0%	0.24	115.6000		
2% Cement	0.23	222.0572	1.601	0.375
4% Cement	0.24	236.9408		
6% Cement	0.23	160.2508		

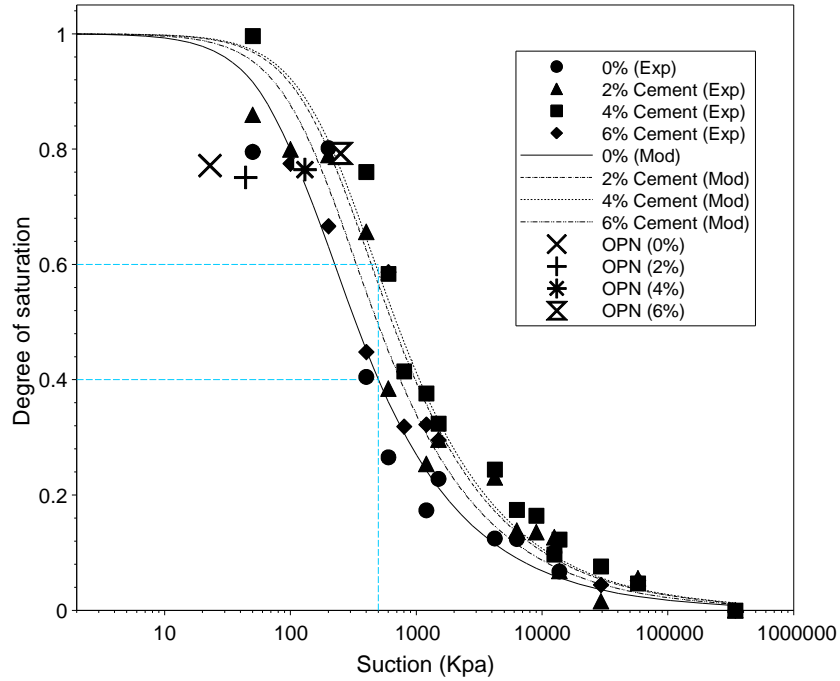


Figure 10. Experimental results and fitting curves obtained by using the model for silt samples compacted on $[\log (s), S_r]$

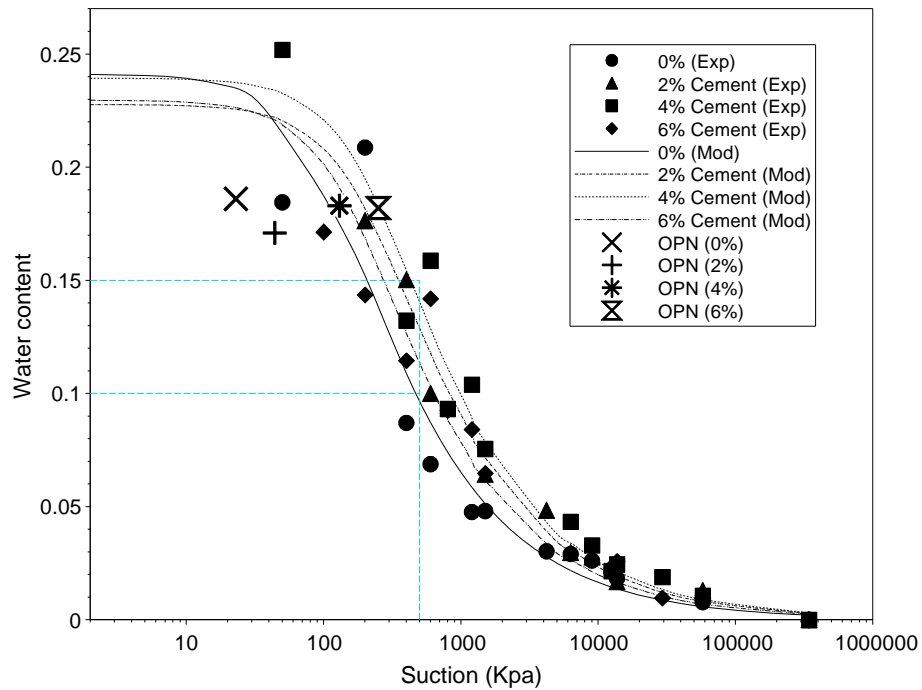


Figure 11. Experimental results and fitting curves obtained by using the model for silt samples compacted on $[\log (s), w]$.

Other experimental results from the literary works are simulated to validate the generalization of the extension of the presented model. We show a very good concordance between modeling and experimentation. For example, Figures 12,13, and 14 show the results of simulations of the water retention curve of recent work by several researchers (Hoyos *et al.*2007; Lesladj *et al.* 2009 and Mavrouludou *et al.* 2013) presented in the plane

[log (s), w]. It is found that the extension of the van Genuchten model is well adapted and more relevant for the modeling of the water behavior of unsaturated treated soils of different natures. Figure13 shows the numerical simulation response to a drainage path of highly plastic swelling clay from southern Arlington, Texas, compacted at OPN (Hoyos *et al.* 2007). Before the drainage test, the samples are completely saturated. A better adaptation of the adapted model's parameters was successfully developed during the simulation (Table 5) with a soil treatment of 0%, 2%, and 5% cement. The moisture content reduction is observed when the cement dosage increases; this is due to solidifying the cement between the particles. It can be said that the model is capable of predicting experimental retention curves.

Table 5. Model parameters deduced from the experimental points (Hoyos *et al.* 2007)

Dosage	w_{sat}	a	n	m
0%	0.46	760		
2% Cement	0.42	1483.75	1.65	0.393
5% Cement	0.4	1442.49		

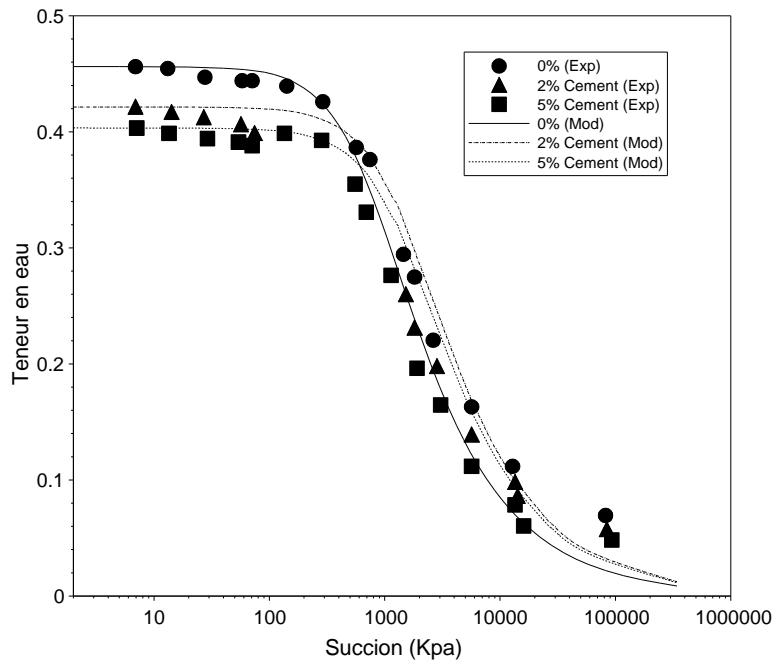


Figure 12. Simulation of the water retention curve of the work of Hoyos *et al.* 2007

Table 6: Model parameters deduced from the experimental points (Mavrouludou *et al.* 2013)

Dosage	w_{sat}	a	n	m
0%	0.23	3932.00		
4% Lime	0.27	8311.53	1.598	0.374
6% Lime	0.32	5837.09		

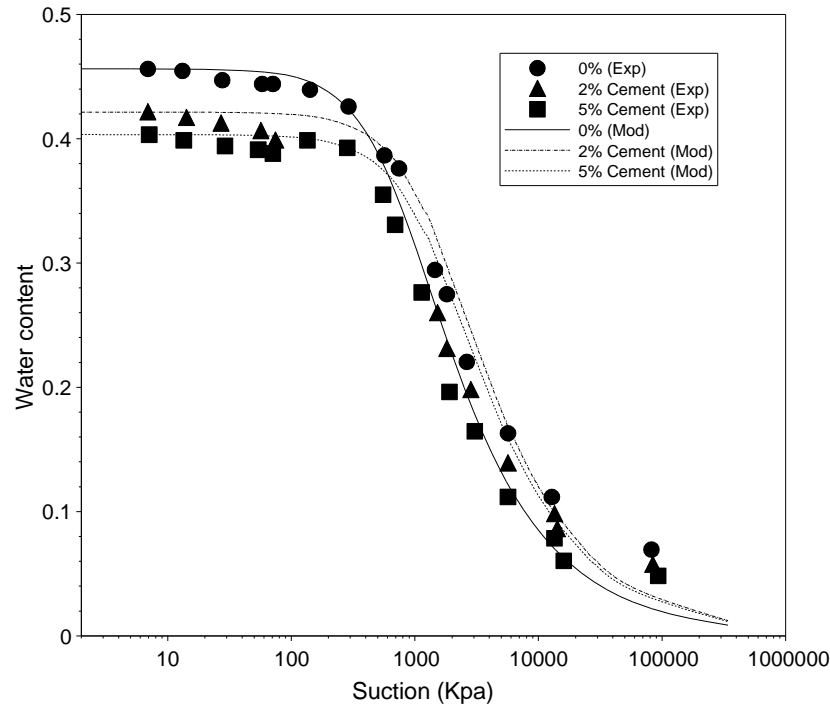


Figure 13. Simulation of the water retention curve of the work of Mavrouludou *et al.* 2013

To further illustrate the advantage of the proposed model in Mavrouludou's work, 2013, the moisture content is drawn as a function of suctions. Figure 13 shows the results provided by the developed water model and compared to the experimental data. This figure shows a good agreement between the predictions of the variation of the retention curve for different lime dosages and the experimental data on the drainage path. The numerical and experimental results show that the moisture content, for the same suction, increases with the increase of the percentage of lime. After the suctions greater than 10,000 kPa, the rate of change of moisture content with suction is similar for treated and untreated samples (this is confirmed by the slope of the treated samples' curves). On the other hand, for the same high suction range, it can be seen that the moisture contents of the different samples converge towards the residual moisture content. The parameters of the model are summarized in Table 6.

The simulations of the water retention curves (SWCCs) obtained by Lesladj *et al.* 2009 on compacted samples of Impersol treated with lime are shown in Figure 14. It is found that moisture contents increase when suction decreases of untreated samples. This shows the high capacity of Impersol to absorb water. This observation explains the character of much-swelled soil. The model reproduces this phenomenon well and indeed gives an increase in moisture content at low suction.

On the other hand, in the same suction range, the numerical and experimental results show that the treated samples have moisture contents close but lower than those of the untreated samples. In strong suction, the comparison of the experimental results with those provided by the model shows that the moisture contents are slightly identical. It can be said that the treated and untreated Impersol exhibits the same behavior. The parameters of the model are determined and summarized in Table 7.

Table 7. Model parameters deduced from the experimental points (Lesladj *et al.* 2009)

Dosage	w_{sat}	a	n	m
0%	0.65	3.00		
4% Lime	0.51	6.34	1.601	0.375
6% Lime	0.45	4.45		

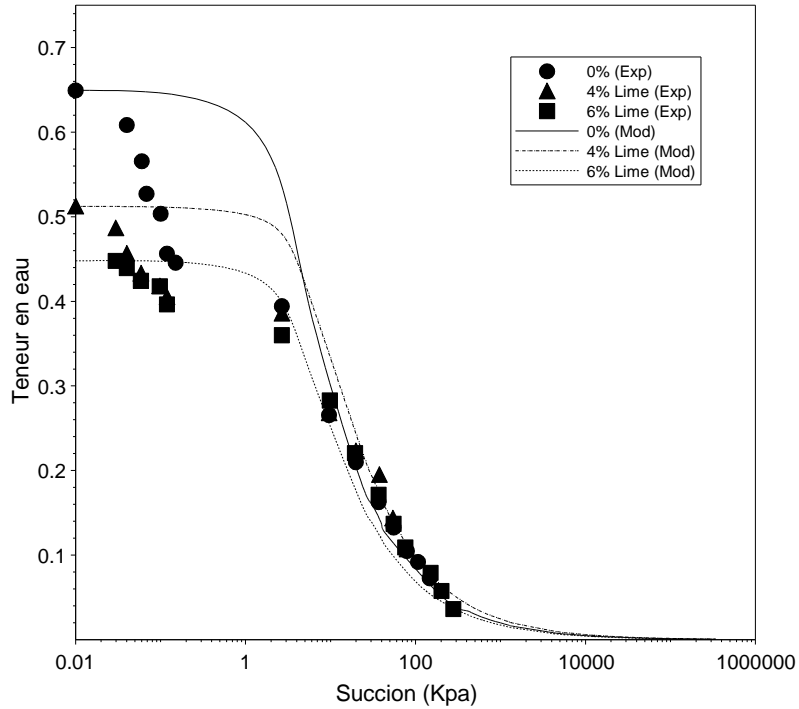


Figure 14. Simulation of the water retention curve of the work of Lesladj *et al.* 2009

Moreover, Figure 15 presents comparisons between the predicted and measured gravimetric moisture contents of the treated and untreated samples. In the treated soil, the predictions obtained from the proposed model were compared well with the gravimetric moisture content measured. It can be said that the relative variation between predictions and measurements is low in the treated soil than in the untreated soil. It should be noted here that small variations in moisture content lead to good correlations to predict treated soils' SWCC behavior. Given the absence of regression models for SWCCs of soils treated in the literature, it can be said that the developed model reasonably interprets the behavior of treated soils. Nevertheless, other experimental studies on treated soils should validate the correlations of the model.

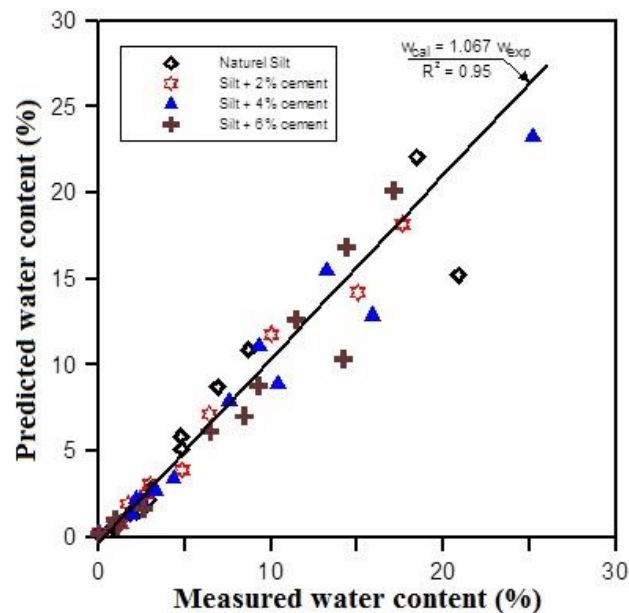


Figure 15. Comparison of predicted and measured moisture contents of treated soil

Conclusions

The work presented in this paper is part of the study of the hydraulic behavior of soils treated with hydraulic binders. In this framework, a model has been proposed to characterize the compacted loam soil's coupled chemo hydric behavior. This model integrates the main properties encountered in the water retention curves of unsaturated soils.

The developed water model takes into account the effect of chemical treatment on the properties of water retention. It makes it possible to predict, from experimental measurements carried out on untreated silt, the water retention curves for the same soil but treated with a few cement dosages. Indeed, quantitative simulations carried out by the proposed model at different cement contents (0%, 2%, 4%, and 6%) make it possible to validate the modifications made to the Van Genuchten (1980) model and to confirm the effectiveness of the model proposed in the simulation of the water retention curves of treated soils. Depending on the model parameters, the water retention curve's intrinsic shape is defined and correlated well with experimental data on different compacted samples.

The latter follows a drainage and humidification path from the initial state (OPN) of the material. The different properties of the water behavior are highlighted and predicted by the adapted model, namely: 1 - The air entry point (AEV), which increases when the cement dosage increases to a level of about 4%, 2- The gravimetric moisture content or degree of saturation which also increases as a function of the dosage and conversely decreases when the suction increases and, 3 - The determination of the residual moisture content (w_{res}) and the degree of residual saturation (S_{rres}). Moreover, given that there are few parametric studies on water paths, varying the binder dosage and the moisture content as a function of the nature of the soil and linking the formulation properties with the physical and hydric properties, curves of water retention in the literature in terms of moisture content were simulated. These studies showed the relevance of the proposed model for modeling the water retention curves of a treated soil subjected to a drainage and humidification cycle. The research presented here indicates that water retention properties can better understand the effects of binder-based treatment on coupled chemical and water behavior.

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