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Shrinkage Curve: Experimental Study and Modelling

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ABSTRACT

In order to study the shrinkage process of clayey soil, we perform a modified laboratory test allowing to measure simultaneously and continuously the vertical displacement and the weight of natural state specimen. The experiment was conducted on undisturbed clayey specimen. Using the experimental results, and on the basis of the existing relation between the soil water content and its structural evolution, we propose an analytical model allowing the analysis of the soil shrinkage curve.

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1. INTRODUCTION

The abundance of the expansive soils at the global scale generated too many efforts in order to better understand their behavior. In the field, these kinds of soils are non-homogeneous; and it is globally recognized that their volume changes are water content depending and closely related to the amount and the type of clay minerals. Indeed, the soil's hydro-mechanical properties are argillaceous phase depending. Most studies of the clay soil volume change are focused on their swelling character, but the shrinkage character still lacks study.

In addition to the conventional laboratory tests allowing to describe the axial variation, the shrinkage curve analysis seems to be the best way to follow up the evolution of the hydro-structural soil's properties during the drying process. Indeed, the shrinkage curve analysis is one of the rare methods which makes it possible to describe the quantitative evolution of the clay soil hydro-structural properties.

The aim of this paper is to study and to model the shrinkage process of a Moroccan clayey soil, by performing a modified laboratory tests. On the basis of the existing relation between the evolution of the shrinkage process and the structural variations which accompany it; the experimental results were used to develop an analytical approach to describe the soil's shrinkage process, from the wet state to the dry one. Because there is no conventional model unanimously used to describe the shrinkage curve, an analytical model to describe the clay soil's behavior during the desaturation phase is proposed in this paper.

2. THEORY

2. 1. Shrinkage Curve Description

Usually, the superficial clay soils are non-rigid and non-homogeneous and the transfer of water through this system is done via the argillaceous matrix porosity and its cracks network caused by the shrinkage. So, the knowledge of the shrinkage rate of these soils requires understanding their hydro-mechanicals behavior.

The clay volume is moisture depending. During the drying process, the clay volume decreases when the medium moisture decreases with a rearrangement of the particles and the aggregates. These modifications of the soil structure influence the displacement of the interstitial solution in the soil matrix, making its transport more complex compared with the rigid soils.

To determine how the soil's volume decreases during the drying process, the behavior of the soil shrinkage can be characterized either by its void ratio according to its moisture state [1- 4] or by its specific

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*Corresponding Author Email: *Saad.bensallam@gmail.com* (S. Bensallam) volume according to its water content [5, 6]. In the present study, it is intended to use the variation of the void ratio (e) according to the water content (W).

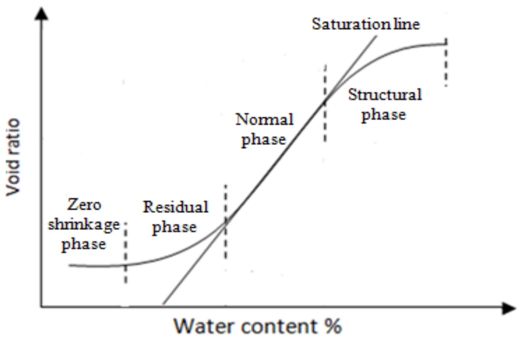

Figure 1. Shrinkage curve representation**.**

The shrinkage curve is characterized by four clear-cut phases (Figure 1). From the wet state of an undisturbed clay specimen to the dry one, four phases can be distinguished : the Structural shrinkage, the Normal shrinkage, the Residual shrinkage and the Zero shrinkage. In the zone of structural and residual shrinkage, the soil's volume reduction is smaller than the quantity of water extracted from the medium. In the structural phase, the water extracted is exclusively the free water localized in the inter-aggregate pores. And in the residual shrinkage phase air enters to the intra-aggregate pores. In the zone of normal shrinkage, the volume reduction is almost equal to the quantity of extracted water, and during this stage the air volume in the medium remains constant in the soil's matrix [4, 6] and the intra-aggregate pores still saturated. In the zone of zero shrinkage, the soil particles have reached their densest configuration and the volume does not change any more, except if there is a disintegration of particles creating a new micro-porosity and leading to a new rearrangement of particles. However, all the clay soils do not always show those four shrinkage zones. In some cases the shrinkage curve does not present the zone of structural shrinkage [7]; in other cases, it is the phase of zero shrinkage which is absent [6].

Each shrinkage phase is delimited by a boundary limit and corresponds to a particular configuration of the soil with a particular rearrangement and properties at the microscopic and the macroscopic scale.

As it was stated before, the use of the shrinkage curve allows to evaluate the volume changes according to the water content, and to determine the active specific volume in the soil mass by the means of the active argillaceous particles sorption ratio; it can also be used to describe the medium kinetics for a given configuration.

According to Braudeau et al. [8], the diagram shown in Figure 2 presents the soil's microstructural evolution according to its water content. The soil-structure is composed of aggregates and empty spaces (Vpma) which separate their assembly. The specific volume of the interparticles porosity (Vpmi) can be defined by the quantity of water in the air entrance point (point B) following this equation: Vpmi= WB/ρw. The points A, B, C, D and E represent the transition points between the different shrinkage phases. It is admitted that during the drying process, water leaves gradually the macropores then the micropores. Indeed, from a saturated state, the macroporosity loses its water up to point C which represents the transition point from the phase of structural shrinkage to the normal shrinkage. Microporosity however, starts retracting from point D by losing its water without any air intake (from point B up to point D). According to Braudeau et al. [8], the water removal from the porous systems (micro and macro porosity) is done according to two stages: A first stage where water leaves the porous systems without any air intake, bringing closer both the aggregates and the particles (shrinkage phase D-B). A second phase where we have a replacement of water by the air when water still leaves the porous systems; the aggregates and the particles are connected to each other (shrinkage phase E-C B-O). In the shrinkage curve, the zones which cover these two stages are the curvilinear part (CD & BA).

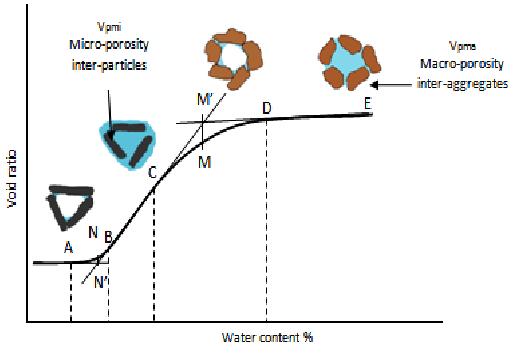

Figure 2. Representation of the soil structure evolution during the drying process

Points M and N represent the water contents at the intersections points of the tangents of the shrinkage curve quasi-linear parts. These parameters are important characteristics for the porous system, because they allow to calculate the minimal and maximum volume of microporosity, and the swelling capacity (CG) of the porous system according to the following equations [8]:

$$\max(V_{Pmi}) = \frac{W_M}{\rho_w} \tag{1}$$

$$\min(V_{Pmi}) = \frac{W_N}{\rho_w} \tag{2}$$

where, W_M , W_N are respectively the moisture ratio at

points M and N, and ρ_w is the density of water.
At the particles scale, the swelling capacity can be defined as a micro swelling capacity (CG^{μ}):

$$CG^{\mu}(\max V_{Pmi} - \min V_{Pmi}) = \frac{W_M - W_N}{\rho_w} \tag{3}$$

where, $\min V_{Pmi}$, $\max V_{Pmi}$ are respectively the minimal and the maximal volume of the microporosity. At the aggregates scale, the macro swelling capacity (CG) is:

$$CG = K_{bs}(W_M - W_N) = K_{bs}\rho_W CG^{\mu} \tag{4}$$

where, K_{bs} is the slope of the normal shrinkage phase.

It should be noted that the sample size influences the shrinkage curve slope. Indeed, the smaller the clay sample, the more important the shrinkage curve slope is. That can be explained by the fact that the more important the volume considered is, the higher the existence of macroporosity. So, this needs a great quantity of water before reaching its saturation line.

According to Peng et al. [9], the authors proposes to use the end points of the differently characterized shrinkage phases to express them as a percentage in relation to the total shrinkage ($W_{ss}, W_{ps}, W_{rs}, W_{zs}$, $e_{ss}, e_{ps}, e_{rs}, e_{zs}$), according to the changes in moisture ratio and void ratio during the drying process. The Equations (5) and (6) allowing to calculate this percentages are:

$$W_{ss}\% = \frac{W_s - W_w}{W_s - W_0} \times 100 \tag{5.1}$$

$$W_{ps}\% = \frac{W_w - W_p}{W_s - W_0} \times 100 \tag{5.2}$$

$$W_{rs}\% = \frac{W_p - W_z}{W_s - W_0} \times 100 \tag{5.3}$$

$$W_{zs}\% = \frac{W_z - W_r}{W_s - W_0} \times 100 \tag{5.4}$$

$$e_{ss}\% = \frac{e_s - e_w}{e_s - e_r} \times 100 \tag{6.1}$$

$$e_{ps}\% = \frac{e_w - e_p}{e_s - e_r} \times 100 \tag{6.2}$$

$$e_{rs}\% = \frac{e_p - e_z}{e_s - e_r} \times 100 \tag{6.3}$$

$$e_{zs}\% = \frac{e_z - e_r}{e_s - e_r} \times 100 \tag{6.4}$$

where,

W_w, e_w: the maximum curvature point at the wet side of the shrinkage curve;

W_p, e_p : the transition point from the normal to the residual shrinkage (can be defined by the intersection of the two phases tangents)

W_z, e_z: the transition point from the residual to the zero shrinkage (can be defined by the intersection of the two phases tangents)

W_0, e_r: the residual shrinkage point, which represents the limit of the shrinkage curve on the dry side.

W_s, e_s : the saturation point.

In Figure 3, the description of the structural evolution is proposed taking place in the soil's skeleton during the saturation and the desaturation phases, as well as an estimation of the different types of water present in the soil.

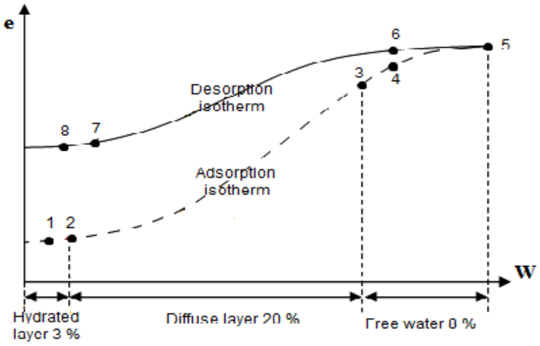

Figure 3. Hydro-structural evolution of an expansive soil.
1: Van der Waals, Crystallization, condensation and cementing links development; 2: Colloidal, inter-molecular, and coagulation links development (steps 1 and 2 represents the structural links destruction phase); 3: End of the diffuse layer development; 4: End of inter-particular porosity water filling; 5: End of adsorption, swelling limit; 6: Free water move out, air enter to the macro-pores; structural links development between closest particles, air enter to the micro-pores; 8: Shrinkage limit.

2. 2. The Existing Models Allowing to Describe the Shrinkage Curve

In the literature, several models were proposed to describe the shrinkage curve that can be represented experimentally. The models presented here describe the relationship between the water content and the void ratio [10, 11] (Table 1).

3. MATERIALS AND METHODS

To reproduce the soil's shrinkage curve experimentally, we must measure the change of the volume and the weight during all the test process simultaneously. To perform this experiment, we use the measurement device basically used to carry out the desiccation test according to Norme Française et al. [12] (Figure 4).

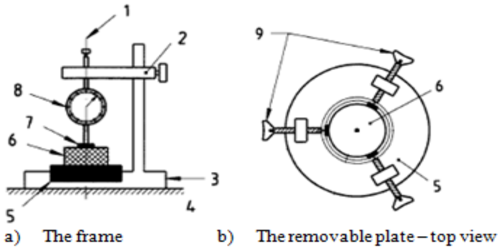

Figure 4. Measurement device of the volume changes.
1. Centering axis; 2. Measurement device; 3. Base; 4. Horizontal support; 5. Removable plate; 6. Test tube; 7. Sensor; 8. Displacement sensor; 9. Centering screw.

This measurement device is usually used to measure the axial deformation during the drying process, but in our study we use it to measure the axial deformation in both wetting and drying processes.

TABLE 1. The existing models allowing to describe the shrinkage curve [10]

Shrinkage Curve Model	Equation	
Model of Giraldez et al. [11] Describe the phases zero, normal and residual of the SC. Using 2 parameters.	$e = 0{,}7429\,\varphi\, W_B + 0{,}23 \frac{\varphi}{W_B} W^2 + 0{,}0267 \frac{\varphi}{W_B^2} W^3$	
Model of McGarry and Malafant. [6] Does not describe the zero deformation zone. Using 5 parameters.	$e = e_0 + \frac{W}{W_B}(W_B - e_0 + e_n)$ for $0 < W < W_B$ $e = e_n + W$ for $W_B < W < W_C$ $e = e_s + \frac{W}{W_C}(W_C - e_s + e_n)$ for $W_C < W < W_D$	
Model of McGarry and Malafant [6] Describe the four phases of the SC, using 4 parameters	$e = e_0 + \frac{e_v}{1+\exp[-\beta(W-W_i)]}$	
Model of Kim et al. [3] Does not take into account the structural part of the SC. Represents the normal part of the SC as a line, and the parts of zero and residual shrinkage by a reverse exponential function.	$e = e_0 \exp(-\beta W) + \varphi W$	
Model of Tariq and Durnford. [4] The authors extended the model of McGarry and Malafant by using 7 parameters to describe the shrinkage curve. Describe the four phases of the SC.	$e = e_0$ for $0 < W < W_A$ $e = a_0 + a_1 W + a_2 W^2 + a_3 W^3$ for $W_A < W < W_B$ $e = e_B - W_B + W$ for $W_B < W < W_C$ $e = W_0 + c_1 W + c_2 W^2$ for $W_C < W < W_D$	$a_0 = e_0 + \frac{A}{2} W_A^2 + \frac{B}{3} W_A^3$ $a_1 = -AW_A + \frac{B}{2} W_A^2$ $a_2 = \frac{A}{2}$; $a_3 = \frac{B}{6}$; $c_0 = e_c - W_c + \frac{C}{2} W_C^2$ $c_1 = 1 - CW_C$; $c_2 = \frac{C}{2}$ $A = \frac{1}{W_B - W_A} - \frac{B}{2}(W_B + W_A)$
Model of Olsen and Haugen. The authors used an hyperbolic equation where the positive solution represents the side between the zero and the normal parts of the SC. However, the negative solution represents the part between the normal and the structural shrinkage. Using 6 parameters.	$e = \frac{1}{2}\left[\varphi W + e_0 + \sqrt{(\varphi W + e_0)^2 - 4e_0(1-\eta)W}\right]$ for $W < W_t$ $e = \Delta(W_t) + \frac{1}{2}\left[\varphi W + \varepsilon + \sqrt{(\varphi W + \varepsilon)^2 - 4\varepsilon(1-\lambda)W}\right]$ for $W > W_t$	
Model of Braudeau et al. [5] The authors propose 7 parameters for an exponential equation. They divided the structural part into two parts: a linear part and another curvilinear by including a point of friability.	$e = e_A + (e_A - e_0)W_{OA}$ for $0 < W < W_A$ $e = e_A + (e_B - e_A)\frac{K_{BC}[\exp(W_{AB}) - W_{AB} - 1] + K_{OA}[2.1718 W_{AB} - \exp(W_{AB}) + 1]}{0.718 K_{BC} + K_{OA}}$ for $W_A < W < W_B$ $e = e_B + (e_C - e_B)W_{BC}$ for $W_B < W < W_C$ $e = e_D + (e_C - e_D)\frac{K_{BC}[\exp(W_{CD}) - W_{CD} - 1] + K_{DS}[2.1718 W_{CD} - \exp(W_{CD}) + 1]}{0.718 K_{BC} + K_{DS}}$ for $W_C < W < W_D$ $e = e_D + (e_S - e_D)W_{DS}$ for $W_D < W < W_S$	$K_{OA} = \frac{e_A - e_0}{W_A}$ $K_{BC} = \frac{e_B - e_C}{W_B - W_C}$ $K_{DS} = \frac{e_D - e_S}{W_D - W_S}$
The model of Chertkov [2] This model was developed for a clay matrix only.	$e = e_0$ for $0 < W < W_A$ $e = e_0 + \mu(W - W_A)^2 \frac{\rho_w^2}{\rho_s}$ for $W_A < W < W_B$ $e = W$ for $W_B < W < W_L$	

C :Shrinkage curve

W_B *: the water content corresponding to the air entrance point,*

W_C *: the water content corresponding to the swelling limit,*

W_D*: the maximum water content,*

e_0 *: the void ratio corresponding to a zero water content null,*

e_n *: the void ratio corresponding to the air entrance point,*

e_s *: the ordinate at the origin of the structural part of the shrinkage curve,*

e_v *: the difference between the saturation void ratio and the void ratio after drying with the oven,*

β *: a slope parameter which air entrance point depending,*

W: is the water content corresponding to the inflection point (the point from which the shrinkage curve starts to move away from the saturation line).

β *: a parameter of slope which depends on the air entrance point,*
φ *: the slope of the line of saturation.*
e_B *and* e_c *: the voids ratio corresponding respectively to the entrance point of air (in the pores intra-aggregates) and to the swelling limit,*
η *: the curvature in the zone of transition between the residual and the normal shrinkage,*
λ *: the curvature in the zone of transition between the normal and the structural shrinkage,*
ε *: a parameter depending on the saturation void ratio* ($e_D = e_0 + e_v$)
W_t *: the water content where the two fields of the shrinkage curve meet.*
μ*: a coefficient of model,*
ρw *: water density,*
ρs *: solid particles density,*
W_L *: the liquid limit.*

The intact sample submitted for testing was a clayey soil with a little carbonate nodules (7%) from Moulay el Bergui (Morocco). The intact samples were taken from 1.8-2.4m depth.

The tests were performed as follows:

First, undisturbed samples were taken from field using a sampling box, in order to preserve its natural state. Then, test tubes of 3.6cm diameter were carefully cut from the undisturbed bloc, and placed in the testing apparatus. Once the test tube was fixed in the receptacle, we place all the mechanism over a balance in order to measure the weight and the volume change both at the same time. After a first reading at its natural state, we begin supplying water by stages and at each stage the weight and the axial deformation were taken after the stabilization of the axial deformation.

During the wetting process, we protected the upper plane of the test tube by a thin plastic film to avoid water evaporation, and all the mechanism was placed in a box whose the temperature and the humidity were controlled.

After saturation and total stabilization of the axial deformations, we begin the drying process. We start to take measurements along the free air dehydration, then when the axial deformations were stabilized, we place the sample in the oven (105°C) for 72 hours, taking its weight and deformations values every 6 hours.

The temperature of the testing room was 20°C and its humidity was 50%.

4. THE SHRINKAGE CURVE MODELING

In our testing approach, we study the one-dimensional volume variation of three test-tubes, considering that the tested soil is non-rigid and homogeneous and that there is no shearing between the soil particles. The choice of the physical parameters for our model was based on the fact that the value of the soil's deformation is the result of the spacing between the particles following the thickness variations of the diffuses layer. This is the variation of the void ratio according to the water content of the medium.

The shrinkage curve model integrates only intrinsic physical parameters of the soil, and the model is described by a third degree polynomial equation as follow:

$$e = a_0 + a_1\left(\frac{W_i}{W_m}\right) + a_2\left(\frac{W_i}{W_m}\right)^2 + a_3\left(\frac{W_i}{W_m}\right)^3 \qquad (7)$$

The values a_0 , a_1, a_2 et a_3 will be deduced from the boundary conditions of the process as follow:

When the soil is dry:

W_i=0 so $a_0 = e_L$

When the soil is saturated:

$W_i = W_m$ so $e_m = e_L + a_2 + a_3$

By derivation of the Equation (7):

$$a_1\frac{1}{W} + +2a_2\frac{W_i}{{W_m}^2} + 3a_3\frac{{W_i}^2}{{W_m}^3} = \beta w \qquad (8)$$

When the soil is dry:

W_i=0 , $\beta w = 0$ so $a_1 = 0$

When the soil is saturated:

$W_i = W_m$ so $\beta w = 2a_2 + 3a_3 = 0$

We obtains the Equation (9) as follow:

$$e = e_L + (e_m - e_L)\left[3\left(\frac{W_i}{W_m}\right)^2 - 2\left(\frac{W_i}{W_m}\right)^3\right| \qquad (9)$$

Since the results obtained by the Equation (9) was not too accurate, we opted for a new water coefficient, where we deduced the shrinkage limit from both the maximal water content and the considered water content as follows:

changing $\frac{W}{W_m}$ by $\frac{W-W_L}{W_m-W_L}$

The analytical model of the soil's behavior during the desaturation phase:

$$e = e_L + (e_m - e_L)\left[3\left(\frac{W_i-W_L}{W_m-W_L}\right)^2 - 2\left(\frac{W_i-W_L}{W_m-W_L}\right)^3\right| \qquad (10)$$

where, e_L is the void ratio at the shrinkage limit; e_m is the maximal void ration in a saturated state; w_m is the maximal water content, and w_L is the shrinkage limit.

We also try to adapt this model to the saturation curve, according to the following formulation:

$$e = e_0 + (e_m - e_0)\left[3\left(\frac{W_i-W_0}{W_m-W_L}\right)^2 - 2\left(\frac{W_i-W_0}{W_m-W_L}\right)^3\right| \qquad (11)$$

where, w_0 is the natural water content.

5. RESULTS AND DISCUSSION

The experimental data and the corresponding soil's shrinkage curve are represented in Table 2 and Figure 5. Note that the data represented below are the average of three tests conducted on the same clayey soil.

TABLE 2. The tested soil water content and void ratio

Desorption curve		Adsorption curve	
W %	e	W %	e
36	0.947	18	0.6816
34	0.939	20	0.6937
30	0.9124	24	0.7446
26	0.879	26	0.7786
24	0.862	30	0.85
22	0.847	32	0.885
20	0.836	34	0.9145
18	0.828	36	0.9363
16	0.825	38	0.95

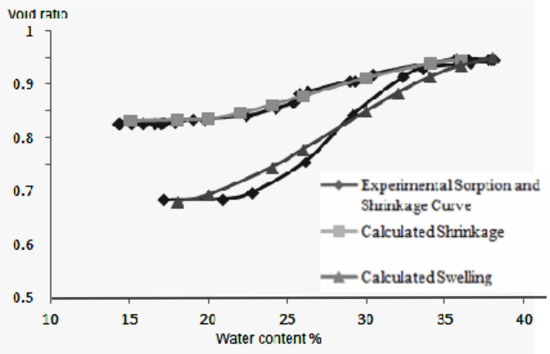

Figure 5. Adsorption and Desorption curves of undisturbed clay samples.

For the desorption curve, we observe that the measured shrinkage of the samples cover practically the complete water content range, from the shrinkage curve wet side to its dry one.

The comparison between the shrinkage curve experimentally performed and the one calculated by the previous model shows a good correlation between the two methods, and proves that this model is functional for this type of soil.

In order to compare the experimental and the analytical methods, and according to the Equation (5) proposed by Peng et al. [9]; we express the fourth shrinkage phases as a percentage of both, the experimental and the calculated shrinkage. The respective calculated values are:

For the experimental shrinkage curve (Figure 6):

- The structural shrinkage phase 29.54 %;
- The normal shrinkage phase 36.36 %;
- The residual shrinkage phase 25 %;
- The zero shrinkage phase 9.1 %.

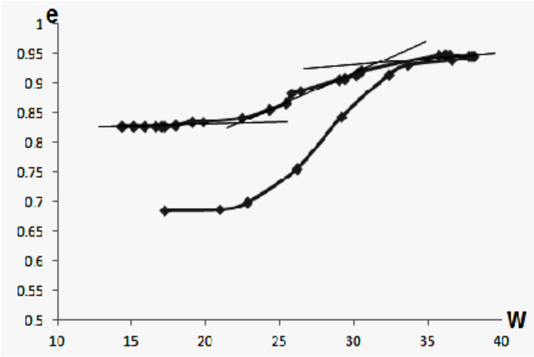

Figure 6. Experimental adsorption and desorption curves.

For the calculated shrinkage curve (Figure 7):

- The structural shrinkage phase 25.45 %;
- The normal shrinkage phase 38.18 %;
- The residual shrinkage phase 27.27 %;
- The zero shrinkage phase 9.1 %.

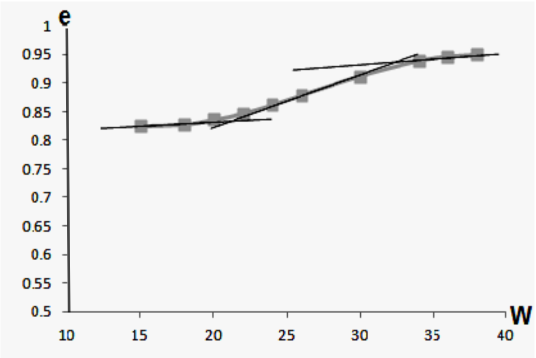

Figure 7. Calculated shrinkage curve.

The difference between the experimental and the calculated values, can be explained by the dispersion of some experimental values because of the testing progress; even if along the experiment we make sure that the test progress in a stable conditions. The comparison of the obtained values confirm the good correlation between the experimental and the analytical methods.

In addition, we try to evaluate the adsorption curve for the same soil with the same model, except that we change e_L by e_0. For the adsorption curve, the model does not follow the experimental curve perfectly; it did not give a perfect correlation between the experimental results and the analytical model.

In order to check the proposed model for a second time, we used the shrinkage data sets presented by Tariq et al. [4] (Table 3). Even if the experimental device used by the authors was not the same as the one used for our testing, but both of them allows the volume determination according to the water contents; and they covers the full range of moisture contents. The full instrumental setup was described in Tariq et al. [4].

The experimental and the calculated shrinkage curves, for both the Nunn clay loam and the Nunn + 10% sand, were represented in the Figures 8 and 9.

The obtained shrinkage curves shows a pretty good correlation between the experimental and the analytical methods. The advantages of this analytical model are :

- The use of a single equation which covers all the phases of the shrinkage curve;
- A reduced number of physical parameters;
- A good correlation between the analytical and the experimental results during the drying process.

TABLE 3. Shrinkage data from Tariq et al. [4] for unadulterated Nunn clay loam, and the admixture of Nunn clay loam + 10% sand.

Nunn clay loam		Nunn + 10% sand	
W	e	W	e
0.876	0.876	0.676	0.676
0.768	0.787	0.605	0.619
0.679	0.714	0.535	0.562
0.614	0.657	0.461	0.523
0.537	0.605	0.390	0.489
0.461	0.560	0.323	0.480
0.362	0.528	0.270	0.472
0.304	0.505	0.187	0.456
0.261	0.493	0.114	0.440
0.215	0.482	0.084	0.436
0.141	0.463	0.050	0.436
0.092	0.459	0.002	0.436
0.061	0.459		
0.031	0.459		

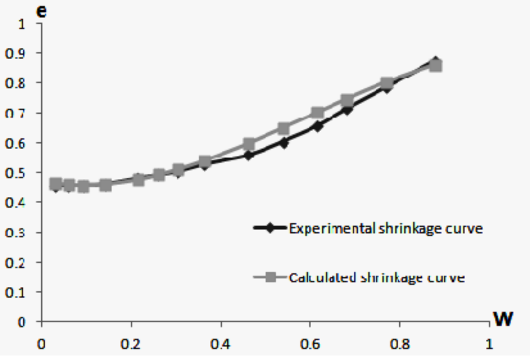

Figure 8. Nunn clay loam experimental and calculated shrinkage curves.

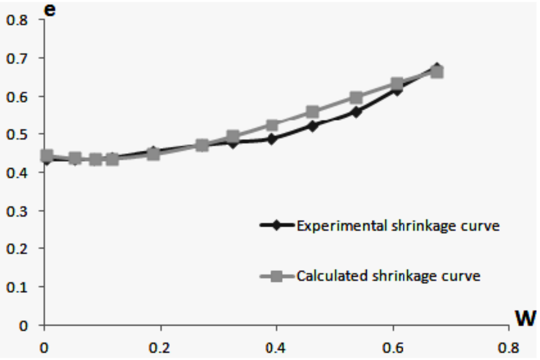

Figure 9. Nunn + 10% sand experimental and calculated shrinkage curves.

6. CONCLUSION

The current paper proposes a new model of the shrinkage curve on the basis of the soil's water content and its structural evolution. This single equation model is able to cover the fourth parts of the shrinkage curve (structural, normal, residual and zero shrinkage) by using only a third degree polynomial equation according to the limits of its hydro-structural boundaries. The comparison between the experimental results and the analytical results gives a good correlation between the two methods during the drying process (for the performed testing and the existing data).

In addition, a try was made to evaluate the adsorption curve with the same model (except that we changed e_L by e_0) , but it did not give a perfect correlation between the experimental results and the analytical model.

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Shrinkage Curve: Experimental Study and Modelling

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چکیده

برای مطالعه فرایند کاهش حجمی خاک رسی، یک تست آزمایشگاهی اصلاح شده انجام دادیم که می‌توان به صورت هم‌زمان و پیوسته، تغییرات مکانی عمودی و کیفیت وزن طبیعی نمونه را اندازه‌گیری نمود. آزمایش بر روی یک نمونه خاک رسی دست‌نخورده انجام گردیده است. با استفاده از نتایج آزمایش و بر اساس روابط موجود بین محتوای خاک آب و تغییرات ساختاری آن، یک مدل تحلیلی پیشنهاد کرده‌ایم که می‌تواند منحنی کاهش حجمی خاک را آنالیز و تحلیل نماید.

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