THE EFFECT OF REPEATED WETTING-DRYING ON THE HYDRAULIC PROPERTIES OF KONNOS CLAY

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ABSTRACT Effect of climatic changes on the structure of a compacted calcareous marine clay was investigated. The most important climatic factor, repeated wetting and drying changed the macro and the micro fabric. The influence of these structural changes on the soil-water characteristic curve (SWCC) and the permeability function were studied. The models of Brooks and Corey and van Genuchten were used to describe the SWCC. The best fit to the experimental data of SWCC, obtained during desorption of saturated samples of three wetting cycles, was van Genuchten's model using variable m and n parameters. The relative coefficient of permeability was predicted by applying van Genuchten's equation with m = 1-1/n constraint, to the model of Muallem. Repeated wetting-drying reduced the pore-size distribution and increased the water capacity. The relative coefficient of permeability, however, is almost the same at lower suction values and decreases if repeated wetting is applied.

RÉSUMÉ L'effet abstrait des changements climatiques sur la structure de l'argile marine calcaire compactée était recherché. Le facteur le plus important, la répétition d'humidification et séchage, a changé les caractéristiques de l'argile aux niveaux micro et macro. L'influence des changements structuraux sur la courbe caractéristique de l'eau du sol (SWCC) et la fonction de perméabilité était étudiées. Les modèles de Brooks et Corey et van Genuchten était utilisés pour décrire le SWCC. La modèle de van Genuchten, qui s'est servi des paramètres m et n, s'est accordé le mieux avec les données expérimentales du SWCC, obtenues pendant la désorption des échantillons saturés de trois cycles d'humidification. L'application de l'équation de van Genuchten, contraint avec m = 1-1/n, au modèle de Muallem a prédit le coefficient de perméabilité relatif. La répétition d'humidification et séchage a réduit la distribution des tailles des pores, et a augmenté la capacité de l'eau. Pourtant, le coefficient de perméabilité relatif était presque le même aux valeurs de succion plus basses, et a diminué aux valeurs plus hautes à cause de l'application de l'humidification répétée.

1. INTRODUCTION

Semi-arid soils of marine origin are heavily structured and with high concentrations of salt precipitates due to prolonged periods of dryness. The changes of chemical and physical properties of such soils due to environmental or manmade factors influence their engineering behavior. To understand the factors influencing the engineering behavior, the soil structure, the crystallization or dissolution of salts and other chemical changes, and the hydraulic properties must be studied (Wheeler, 1994). Soil structure include both fabric and the inter-particle bonding due to existence of cementing materials precipitated during the time of deposition. The changes in fabric and the inter-particle bonding, due to repeated wetting and drying, is indirectly observed by routine soil mechanics tests, such as one-dimensional swell and consolidation tests on fully saturated samples (Bilsel and Tuncer, 1999). The changes in percent swell, swell pressure, apparent pre-consolidation pressure, coefficient of saturated permeability, and the volume of the saturated and desiccated samples, at the end of each wetting and drying cycle, were indirect implications of change in the structure. Furthermore, the structural changes were also observed at macro level as cracks were formed after the second wetting cycle and increased in number with repeated drying. At micro level, pore size analysis and scanning electron microscopy were used after several drying cycles. These structural changes are attributed to softening and weakening of the bonds created by the cementation materials and on the dissolution of the soluble salts during each wetting period. Reduction in salt content changes inter-particle forces and causes an increase in double layer thickness (Mitchell, 1993).

Semi-arid soils are unsaturated soils and their hydraulic properties must be obtained to help design earth dams, highway embankments, soil covers, etc. A change in the climatic environment (i.e. wetting and drying) changes the matric suction hence changing the stress history also. Stress history is of equal interest to artificially compacted soils as well as the natural soils (Nishimura et al., 1998). It is a measure of structure.

Since fabric changes with alternate wetting and drying, the climatic changes would have an effect on the hydraulic properties of unsaturated soils. The soil hydraulic properties consist of soil water characteristic curve (SWCC), and permeability function. SWCC describes the relationship between the volumetric water content, θ, and the matric suction, ψ; and the permeability function relates θ to the relative coefficient permeability, K_r (the ratio of coefficient of unsaturated permeability to coefficient of saturated permeability, $K_r(\psi)= K(\psi)/K_s$). Because experimental determinations of SWCC and unsaturated coefficient of permeability are very expensive, tedious, and time-consuming, numerous empirical equations have been proposed to describe SWCC and to define the permeability function in terms of SWCC (Meerdink et al., 1996; Tinjum et al., 1997). Therefore, SWCC can be considered one of the most fundamental hydraulic characteristics of unsaturated soils. In this study, characterization of the SWCC and the change in the permeability function are studied at the end of each wetting period of three wetting-drying cycles, using the models of van Genuchten and Brooks and Corey. To predict the permeability function van Genuchten's closed-form expression obtained by substitution of his equation in Mualem's model is used.

2. MODELS OF BROOKS AND COREY, van GENUCHTEN, AND MUALEM

Various research works have shown that there is a relationship between the soil-water characteristic curve of soils and their unsaturated properties (Fredlund and Xing, 1994). One important property estimated empirically, is the permeability function for an unsaturated soil obtained by using the saturated coefficient of permeability and the soil-water characteristic curve.

One of the earliest empirical equations for modeling the SWCC has been proposed by Brooks and Corey (1964), given as;

$$[1a]\ \Theta = \frac{q - q_r}{q_s - q_r} = \left(\frac{y_a}{y}\right)^{l} \quad y \geq y_a$$

$$[1b]\ \Theta = 1 \quad \text{and} \quad q = q_s \quad y < y_a$$

where Θ = normalized volumetric water content or relative degree of saturation, λ = pore size distribution index, which is a function of the distribution of pores in the soil, θ_s = saturated volumetric water content, θ_r = residual volumetric water content, ψ_a = air-entry suction (de-sorption) which is assumed to be related to the maximum size of pores forming a continuous network of flow paths within the soil (Assouline et al.,1998).

Another widely used model for the SWCC is the van Genuchten (1980) relationship:

$$[2]\ \Theta = \frac{q - q_r}{q_s - q_r} = \left\{\frac{1}{[1 + (ay)^n]}\right\}^m$$

where α, n, and m = fitting parameters. This is a more flexible equation than Brooks and Corey model. When the parameters m and n are variable, usually an excellent fit to the observed soil water characteristic data can be obtained for most soils, provided there are enough data in the dry range. If incomplete data is available, restrictions of m = 1-1/n or m = 1-2/n give better fits. The variable m, n and m = 1-1/n constraint are employed in this study.

Reliable estimates of the unsaturated permeability function of unsaturated soils may be predicted by using the statistical model of Mualem (1986), given by Eq.3, using the saturated coefficient of permeability and the soil-water characteristic curve.

$$[3]\ K_r(q) = \Theta^q \left(\frac{\int_{q_r}^{q} \frac{dq}{y(q)}}{\int_{q_r}^{q_s} \frac{dq}{y(q)}} \right)^2$$

where Θ^q = correction factor.

Substitution of van Genuchten's equation (Eq. 2) in Mualem's model, a closed-form solution for permeability function can be obtained. In this study, Equation 2 with variable m,n values will be used with Mualem's model to predict the relative coefficient of permeability.

3. MATERIAL AND METHODS

Konnos clay is derived from the marine sediments of Kythrea flysch, a Miocene formation tightly compressed afore deep and covers an extensive area in the north of Cyprus. "Konnos" is a local name given to this abundantly found calcareous clay used as a water isolation material, on the roofs of light buildings in the rural areas. It has varying amounts of calcite and dolomite and an appreciable amount of soluble salts due to prolonged periods of desiccation and short periods of rainfall. Konnos clay possesses high to very high swell potential. The mineral composition and the physical properties are given in Table 1 and Table 2 respectively.

TABLE 1: Results of X-ray diffraction

Mineral	**Percentage**
Calcite	24
Dolomite	2
Illite	1
Kaolonite	32
Montmorillonite	12
Quartz	9
Plagioclass	24
Chlorite	3

Samples compacted to maximum dry density at optimum water content, were kept airtight at least for a week for the structure destroyed by compaction to be recovered at least to a certain extend. Swell tests were conducted on fully inundated samples under an overburden stress of 7 kPa in a standard oedometer test system. Identical samples were used to achieve alternate wetting and drying, while consolidation tests were conducted at the end of each wetting period. Swell pressure required to bring the samples to their original void ratio before swell was determined during the loading stage. The consolidation test results were analyzed to obtain the apparent pre-consolidation pressure, the compression index and the coefficient of saturated permeability. The drying cycles were also carried out under 7 kPa load at 40° C and the samples are dried to water content well below the shrinkage limit.

TABLE 2: Physical properties

Specific gravity	2.8
Liquid limit	65
Plastic limit	24
Shrinkage limit	15
Linear shrinkage	21
Clay (%)	60
Silt (%)	28
Sand (%)	12
Maximum dry density (kg/m3)	1620
Optimum water content (%)	22

To directly see the structural change in samples scanning electron micrographs of the originally compacted sample before wetting and drying and of the samples after the third wetting and drying were taken.

To determine the soil-water characteristic curve samples saturated in oedometer rings under 7 kPa pressure, were dried to different water contents at 40° and packed in airtight containers in perfect contact with 5.5 cm Whatman No. 42 filter papers. The filter papers were sandwiched between the samples and the load necessary for applying 7 kPa.

This procedure was repeated at the end of first three wetting cycles. The boxes were kept in a temperature-controlled room, for a period of 7-10 days upon sealing. After the equilibration time was completed for each sample, at different water contents each, the filter papers were weighed with an accuracy of 0.0001g and the water content and the volume of the samples were determined. The filter paper water contents were used to determine indirectly the matric suction using the filter paper calibration chart for Whatman No. 42 filter papers (Fredlund and Rahardjo, 1993). The volumetric water content, θ, which is the mass of water content divided by the volume of the sample, was determined for each sample.

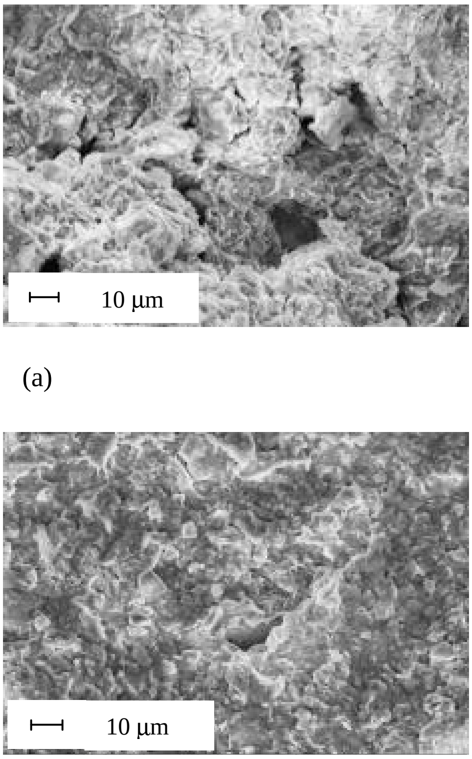
4. RESULTS AND DISCUSSION

The structure of the compacted samples change after repeated wetting-drying which can be observed by the changes in mechanical properties such as swell potential, swell pressure, compressibility, apparent pre-consolidation pressure and saturated permeability. It was concluded earlier that the changes in structure of calcareous, saline marine clays are due to change in soil chemistry and softening and breaking of cementation bonds developed by carbonates and salt (Bilsel and Tuncer, 1999). Structure of fine-grained soils consists of the macrostructure and microstructure. The macrostructure is the arrangement of soil aggregates and the microstructure is the elementary particle associations (Vanapalli et al., 1999). Both types of structure exist in natural and compacted clayey soils, which are influenced by repeated wetting and drying, manifesting in increase of swell potential, compressibility and saturated coefficient of permeability, and decrease in the apparent pre-consolidation pressure. After the second drying cycle a change in the macro fabric occurs in the form of macro pores or cracks as shown in Figure 1. The size and number of cracks increase progressively after each drying cycle. The volume of the dried samples decrease as the particles arrange at a closer configuration, hence the dry density increases after each cycle and the fabric gets more homogeneous as the micro pores decrease in size. Figure 2 shows scanning electron micrographs of originally compacted sample, and of the sample undergone three cycles of wetting and drying, in their dry states.

FIGURE 1: Compacted soil samples showing increase in macropores after cyclic drying

All these studies justify the expected structural changes in cemented saline marine sediments, which would be even more significant, in their natural state. To show the effect of structural changes on the soil-water characteristic curve and the permeability function, especially important in the design of soil covers and barriers in semi-arid climates, filter paper method is used to obtain water retention data. Filter paper method is especially chosen since it gives good results for a wide range of suction values of 0-1000 MPa. A computer program RETC developed by van Genuchten is used to fit several analytical models to the observed water retention and/or unsaturated permeability data (Genuchten et al., 1991). In this study the soil-water characteristic data are obtained as volumetric water content versus matric suction and are used to predict the unsaturated permeability function. Only desorption data were used as sorption data might be misleading due to possible air entrapment in the samples during saturation. Figure 3 shows the fits of Brooks and Corey model to the experimental data for three cycles of wetting and drying.

FIGURE 2: Scanning electron microscopy results of (a) original sample, (b) after third wetting-drying



(a)

(b)

The saturated volumetric water content, θ_s, is generally assumed equal or very close to the soil porosity (Assouline et al., 1997), and is observed to increase after each wetting. The residual water content, θ_r, is the maximum volumetric water content, at which the water capacity (the rate of change of volumetric water content with respect to matric suction) approaches zero and the unsaturated coefficient of permeability becomes zero. Table 3 summarizes the fitting parameters of Brooks and Corey model for samples after each wetting cycle. The soil water characteristic curves become steeper with repeated wetting-drying applied, which is also reflected by the pore-size parameter, λ, in Table 3. Increase in λ means a relatively narrow pore or particle size distribution, and an increase in the water capacity $C(\psi) = d\theta/d\psi$. The reduction in pore-size distributions were also justified by the scanning electron microscopy and the increase in water capacity by the changing mechanical behavior after each wetting-drying cycle.

FIGURE 3: SWCC's defined by Brooks and Corey

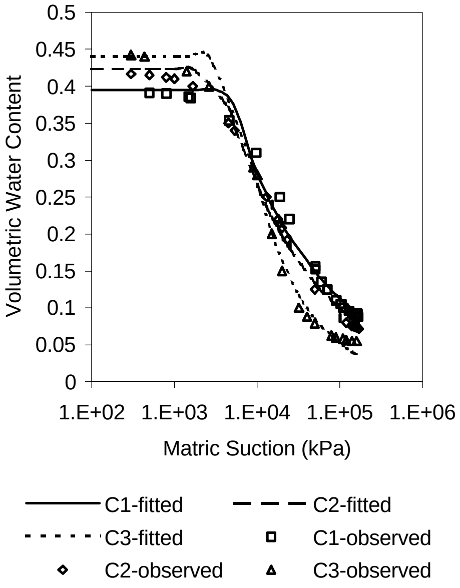


TABLE 3: Brooks and Corey parameters for SWCC

C	θ_s (%)	θ_r (%)	λ	ψ_a (kPa)	R^2
1	0.395	0	0.397	4348	0.9883294
2	0.423	0	0.4239	3333	0.9907662
3	0.440	0	0.7151	5000	0.9905508

van Genuchten's model with no restriction on parameters n and m, and with m =1-1/n restriction are applied to the water retention data, as shown in Figure 4 and Figure 5 respectively. The air entry value, ψ_a, is the matric suction where air starts to enter the largest pores. It can be obtained as the reciprocal of the empirical parameter, α, which increases at each wetting-drying cycle. Therefore, the air-entry value decreases with increasing wetting-drying cycles. This might be due to formation of macro pores as the samples start to crack and eventually weather after many repetitions of wetting-drying process. The fitting parameters for variable m,n and m= 1-1/n constraint are given in Table 4 and Table 5. The increasing n parameter in Table 5 is consistent with the λ values in Table 3, as they are directly proportional. The increase in α, which is inversely proportional to ψ_a, in Table 4 is also consistent with the conclusion derived earlier that the air entry decreases after repeated wetting, with the development of macropores. Macropores allow easier access of air in to the micro pores, hence faster desorption and the SWCC curves become steeper with increasing wetting-drying cycles.

FIGURE 4: van Genucten's SWCC's (m, n variable)

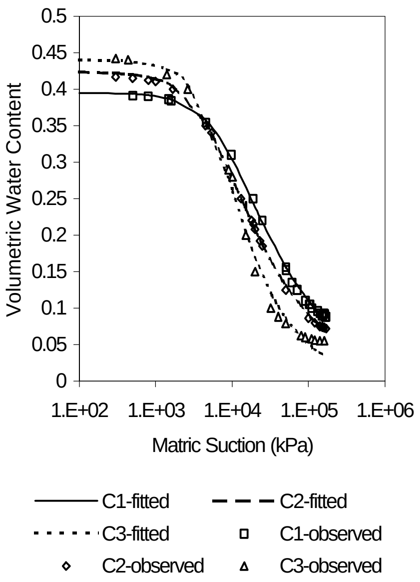


TABLE 4: van Genuchten parameters for SWCC (variable m, n)

C	m	n	α	ψ_a (kPa)	R^2
1	0.330	1,594	0.00011	9091	0.9986180
2	0.399	1.408	0.00015	6667	0.9995062
3	0.356	2.095	0.00018	5556	0.9931576

Though it was observed that at each wetting cycle the samples act more plastic, with increasing swell capacity and compressibility, during each drying phase they become more brittle and fragmented. Therefore, the compacted samples subjected to repeated wetting-drying, with the changing structure, will behave, as far as the soil water characteristic properties are concerned, like a coarse-grained material during desorption. It is believed that the hysteresis between sorption and desorption curves could be more emphasized in calcareous marine soils due to chemical and physical changes in the structure, which reflect themselves differently during wetting and drying phases.

One more interesting feature of SWCC of different wetting-drying cycles is the intersection of the curves at a point corresponding to matric suction of about 4000 kPa and volumetric water content of 36%, indicating that the void ratio in all three cases is the same. For void ratios bigger than this critical value, the rate of change of water content, with respect to suction is low and increases considerably for smaller void ratios. Furthermore, this rate of change of water content increases even more with each desorption phase.

Based on the R^2 for regression of observed versus fitted values, van Genuchten equation, with variable m and n values, represents a better model for the observed behavior of compacted samples subjected to alternate wetting and drying.

FIGURE 5: van Genuchten' s SWCC's (m=1-1/n)

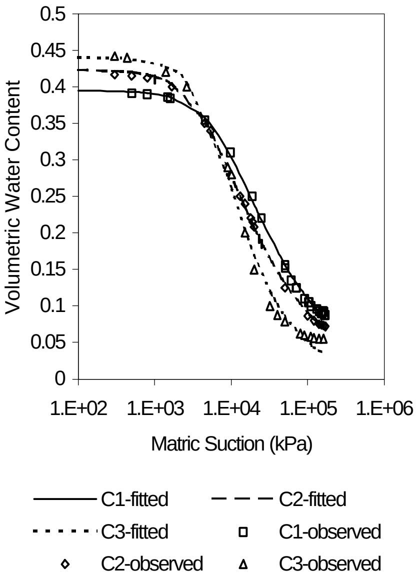
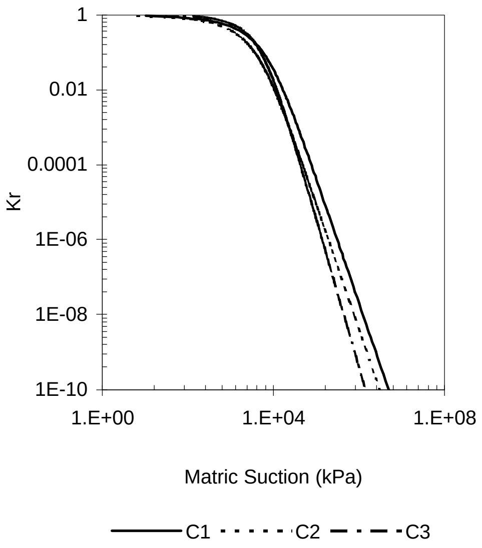


TABLE 5: van Genuchten parameters for SWCC (m=1-1/n)

C	m	n	α	ψ_a (kPa)	R^2
1	0.348	1.534	0.00011	9091	0.9986023
2	0.351	1.540	0.00017	5882	0.9993717
3	0.439	1.783	0.00016	6250	0.9928528

The closed-form solution of Mualem's model, using van Genuchten's equation with variable m and n (Figure 4), is used to predict the relative coefficient of permeability at three wetting-drying cycles. Figure 6 shows the predicted permeability functions for the three cases. At low suction values, the relative coefficient of permeability is nearly the same for the three wetting cycles. As suction increases the relative coefficient of permeability decreases, hence the unsaturated coefficient of permeability decreases. At high suction values, K_r versus ψ curves are steeper with alternate wetting and drying. Therefore, the rate of change of unsaturated coefficient of permeability increases with the effect of climatic effects, due to the significant changes in the chemical and physical behavior of the calcareous marine clay investigated. The coefficient of saturated permeability increases at the end of each wetting phase.

FIGURE 6: Predicted relative permeability curves (Mualem-van Genuchten, variable m,n)



CONCLUSIONS

The repeated wetting and drying has considerable influence on the resulting structure of fine-grained soils. The soil-water characteristic of such soils is mainly dependent on the structure, stress history and soil chemistry. Stress history, in the case of compacted soils is a measure of the degree of bond strength between the particles, which re-developes during aging. The bond strength between particles reduces as the compacted calcareous and saline marine soils undergo chemical and physical changes due to climatic factors. The micro and the macro structures undergo significant changes influencing engineering properties. For a more reliable design of compacted barriers, soil covers or highway embankments, which are unsaturated throughout a long period and subjected to only short periods of showers, effect of the climatic changes on the hydraulic properties must be studied. In this study, the effect of only three cycles of wetting and drying on the hydraulic properties is investigated. van Genuchten's model, with variable m and n values, provided the best fit for the desorption data obtained for samples subjected to different number of wetting-drying cycles. The rate of change of volumetric water content with respect to suction increased with each cycle, which was contributed to increasing surface area by the formation of macro pores, and fragmentation of compacted specimens. van Genuchten-Mualem model is used to predict permeability function. Saturated coefficient of permeability increases after each wetting, and the rate of change of unsaturated coefficient of permeability increases with number of wetting and drying applied. Clearly more research should be carried out on the effect of structural changes on the hydraulic properties of marine clays in a semi-arid climate, both in compacted and natural states.

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