Soil-Water Characteristic Curves and Evolution of the Tensile and Unconfined Compression Strength of Drying Slurried Soils

Michail Bardanis and Sofia Grifiza

Abstract. The experimental work presented in the paper explores the soil-water characteristic curve and the evolution of tensile and unconfined compression strength of drying slurried soils. The axis translation technique and the saturated salt solutions method were employed for matric and total suction control respectively. Tensile strength was determined using the splitting tensile (brazilian) test.

Keywords: soil-water characteristic curve, drying, tensile strength, unconfined compression strength, slurries.

1 Introduction

The motivation for studying the drying of slurried soils was the on-going research in the field of constitutive modelling of unsaturated soils, in this particular case of reconstituted soils in the form of slurries drying without any loading prior to the beginning of drying. In this paper fundamental properties of unsaturated slurried soils measured on four fine-grained soils from Greece such as the soil-water characteristic curve (SWCC), the unconfined compression and splitting tensile strength are presented. The tests performed are part of a larger programme on the particular subject and the properties mentioned will eventually be used for constitutive modelling of these soils during drying along with other properties measured.

Michail Bardanis
Edafos Consultant Engineers, Athens, Greece
e-mail: lab@edafos.gr

Sofia Grifiza
Edafos Consultant Engineers, Athens, Greece
e-mail: sgrifiza@edafos.gr

2 The Soils Tested

The soils tested by this stage of the ongoing research are the Corinth and Chalkoutsi Marls, the Parnitha weathered siltstone and the Maroussi Clay. The index properties of the soils are summarised in table 1. The Corinth Marls are a very well-studied formation (Kavvadas et al. 2002) through which the Corinth Canal was excavated until put in operation in 1893. Various experimental investigation programmes have been undertaken in order to investigate the properties of this material including the SWCC of the undisturbed marl and its recomposed counterpart (Bardanis & Kavvadas 2008), where recomposed is the material consolidated from a slurry condition to a desired value of void ratio (preferably that of the undisturbed soil) and then unloaded to zero stress. In this paper the results on reconstituted low plasticity Corinth Marl are presented for the first time. The Chalkoutsi Marl is a formation found 35km north of Athens. High, steep slopes are formed in the formation by sea erosion of their toe with occasional landslides occurring along the 5km coast that the formation outcrops in the highest slopes. The SWCC of the undisturbed material and its recomposed counterpart have been reported by Bardanis & Grifiza (2011). Parnitha weathered siltstone is found in mount Parnitha 30km north of Athens close to the ground surface. Finally, samples of Maroussi Clay came from boreholes drilled as part of a site investigation in the suburb of Maroussi in Athens close to the 2004 Olympic Games complex.

3 Experimental Method

Two methods were employed for suction control; the axis translation technique as applied in a SoilMoisture pressure extractor with 1500 kPa air-entry value porous ceramic disks for matric suction control and the salt solutions method for total suction control. Saturated solutions of the salts presented in table 2 were used. The saturation molalities were measured experimentally. This involves gradual addition of salt increasing the concentration by one m at a time until salt appears as sediment at the bottom of the jar holding the solution. This appearance of sediment is not the definite factor as sediment may appear during and after stirring but finally dissolve after a certain time. The solution prepared at each concentration therefore must be left for the time necessary for chemical equilibrium (typically 48h) and if the sediment at the bottom of the jar has not dissolved it is then recorded that this particular concentration leads to the appearance of sediment. Molalities of the solutions prepared for actual use for total suction control were increased by 1 m relative to the threshold values that sediment appeared for the first time, in order to ensure the ability of the solutions to remain saturated after applying the required suction value to the soil samples. Total weight of the solution was monitored and the required amount of salt was added in order to maintain the concentration constant. This was necessary as the samples placed in the solution chambers were saturated slurries. Water vapour from their drying therefore adds to

Table 1. Index properties of the soils examined.

Soil Name	Abr.	Grain Size Distr. (%)			Atterberg Limits (%)			G_s	USCS Clas.
		Sand	Silt	Clay	w_L	w_P	I_P		
Corinth Marl	CM	8.8	84.7	6.5	30.5	25.0	5.5	2.67	ML
Parnitha Weathered Siltstone	PWS	21.3	47.1	27.5	33.0	16.5	16.5	2.69	CL
Maroussi Clay	MC	18.0	41.9	40.1	47.0	19.0	28.0	2.66	CL
Chalkoutsi Marl	CHM	15.0	64.2	20.5	51.0	21.0	30.0	2.69	CH

Table 2. Characteristics of salt solutions used for total suction control.

Salt	K_2SO_4	$BaCl_2$	KCl	NaCl	$Mg(NO_3)_2$	$MgCl_2$
Total suction measured	4.10	14.1	23.6	39.0	85.5	151.7
Salt saturation molality	1	2	5	6	9	15

the amount of water in the solution as with any sample, but in this case much more as much more water evaporates from the slurries, given their very high initial water content. Therefore by knowing the initial amounts of water and salt in the solution and monitoring the weight of the samples in the chambers one could add the salt necessary to keep the solution saturated as drying of the slurries continued. Saturation molalities are presented in table 2 along with the total suction corresponding to the equilibrium relative humidity of the salt solutions that was measured in a Decagon Devices chilled-mirror hygrometer. Similarly, rather than relying on temperature measurements and Kelvin's law, the total weight of the soil samples placed in solution chambers was monitored until stabilisation and then the samples were taken out and cut in three pieces; one for total suction measurement using the chilled-mirror hygrometer, one for water content measurement and one for immersion in molten paraffin wax for total volume measurement and therefore calculation of void ratio.

All slurries were prepared at an initial water content of $1.5 \times w_L$ using deaired, deionised water, left for hydration for two days in a humidity chamber with occasional stirring in order to avoid sedimentation of coarser particles in the slurry and then placed for at least half an hour under vacuum for removal of air. Samples were placed in lubricated plastic tubes taped on the porous stone of the pressure extractor or tin holders for placement in the salt solutions chambers. Given that samples were slurries in their initial condition, volume decrease during their drying was large. Careful lubrication of the inner surfaces of the tubes was crucial so as to avoid cracking of the samples during shrinkage as any inhibition of the diameter decrease by adhesion to the inner surface of the tubes resulted in cracking.

4 Soil-Water Characteristic Curves

The soil-water characteristic curves measured for all soils are shown in fig. 1 expressed in terms of degree of saturation vs suction. Maroussi clay practically did not desaturate up to 1500 kPa while all other three soils had already desaturated at 100 kPa of suction (at lower values immersion in molten paraffin wax was impractical as the samples were still very soft to handle). Regarding the second inflection point corresponding to residual water content, it appeared only on the curve of the Corinth Marl close to 800 kPa. Finally, regarding the capability of the samples to hold water in their pores this was found to be the lowest for Corinth Marl, becoming higher for Chalkoutsi Marl, even higher for Parnitha weathered siltstone and the highest for Maroussi clay. Another interesting observation is that curves for both Chalkoutsi Marl and Parnitha weathered siltstone appeared quite flat which will make their modelling very interesting. Modelling of the curves at this stage of the research was avoided until all the curves for reconstituted soils in the research programme are measured and a study of the evolution of their curve-fitting parameters by correlation with the index properties of the soils can be performed.

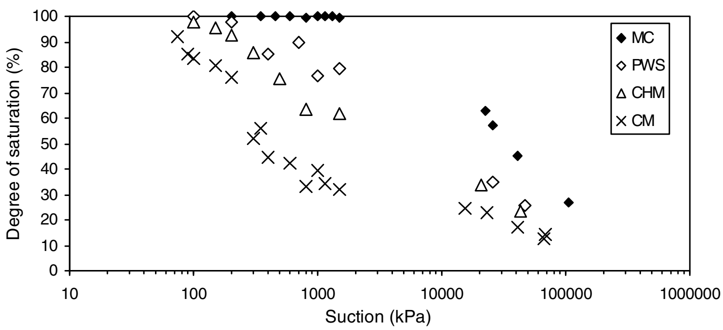

Fig. 1. Soil-water characteristic curves of the four soils dried from an initial condition of slurry.

5 Unconfined Compression Strength and Tensile Strength

Samples for measuring the unconfined compression strength and the tensile strength were prepared in the same manner as already described but were large enough at the beginning of drying in order to provide samples of sufficient size after suction was applied. Plastic tubes used for preparing samples for unconfined compression tests had an internal diameter of 46mm and 110mm height and tubes used for preparing samples for splitting tensile (brazilian) test had an internal diameter of 72mm and 60mm height. These dimensions were selected after several tests were performed as samples placed in them ended up with the required length over diameter ratio at the end of drying. A limited control over the height could be applied by filling the tube up to a certain point in the tubes. Fig. 2a depicts empty tubes taped on the porous stone, fig. 2b the same tubes filled with slurry of

Corinth Marl, and fig. 2c tubes with slurries of Corinth Marl and Maroussi Clay after applying suction. Short 46mm diameter tubes were used only for water content and total volume measurement (by immersion in paraffin wax) –fig. 2a and 2b- while short 72mm diameter tubes were used for splitting tensile (brazilian) tests samples and long 46mm diameter tubes for uniaxial compression test samples –fig. 2c. Occasional leaks observed through the tape at the bottom of the tubes were sealed with plasticine like that indicated by the arrow on fig. 2c. After application of the required suction in the pressure extractor for a minimum of 72h the samples were taken out, weighed immediately and then subjected to loading. After failure the samples were retrieved from the loading frame, carefully enough to collect all small pieces that may have fallen during loading, and weighed again for comparison with their weight before loading. The difference between the initial and the final total weight of the samples was considered a measure of the suction change between removal from the pressure extractor and finishing the loading stage as there was no suction control during this stage.

The tensile strength of unsaturated soils has been thoroughly researched as it gives insight into the modelling of the shear strength of unsaturated soils, whether that is limited to simple models like the extended Mohr-Coulomb failure criterion (linear on non-linear) or more complex constitutive models based on critical state theory extensions for unsaturated soils. Most researchers however have performed tensile strength tests of some sort on compacted soils (e.g. Tang & Graham 2000, Nahlawi et al. 2004) or reconstituted soils which were not undergoing drying (Nahlawi et al. 2004), or soils having undergone combined compression and drying paths (Vesga 2009). The series of tests presented in this paper have been performed on samples of slurry soils subjected to drying without any loading prior to the beginning of drying.

A review of research efforts into the measurement of unconfined strength of unsaturated soils is out of the scope of this paper given the very large number of researchers having studied the subject. For the purpose of completeness the results of Kato et al. (2002) and Pineda & Colmenares (2006) are reported.

Also a clarification of the various types of ‘tensile’ strength is considered useful. If a sample of soil is isotropically loaded in tension (fig. 3a) then the isotropic tensile strength is obtained, denoted σ_{ti}. To the authors’ knowledge no experimental array set up to measure this property has ever been reported. If a sample of soils is uniaxially loaded in tension (fig. 3b) then the uniaxial tensile strength is obtained, denoted σ_{tu}. Another type of tensile strength is the splitting tensile (brazilian) test. In this case a disk-shaped sample is loaded by a linear load on its periphery and the stress condition corresponding to the centre of the sample at failure involves tension in the direction vertical to the external linear load, combined however with a compressive stress in the direction of the external linear load. The stress condition at the centre of the disk-shaped sample is plotted in fig. 3c and the tensile stress at failure is denoted $\sigma_{tb} = -2F/\pi dh$, where F is the external linear load, d and h the diameter and the height of the sample. Except for the tests described already, the stress state corresponding to the uniaxial compression strength is plotted in fig. 3d. Vesga (2009) reported a new type of test combining the ability to apply direct shear under tensile loading of a specimen (called the direct tensile-shear test). Any combination of two of the stress state conditions shown in fig. 3 and described in this section can yield the cohesion intercept, the angle of friction and the isotropic tensile strength on the assumption of a model for the failure envelope. More combinations of these stress state conditions can offer insight into the appropriate model of the failure envelope to be selected for each soil.

The unconfined compression strength and splitting tensile strength were measured for all soils up to a suction of 1500 kPa applied using the axis translation technique. In fig. 4a the unconfined compression strength is plotted against suction for all four soils, while in fig. 4b the splitting tensile strength. Conventional equipment was used. There was no suction control during the actual loading of the samples. Still the change in their total weight was less than 0.1% before and after loading indicating a minimum change of suction. An important observation on fig. 4 is that both the unconfined compression and the splitting tensile strength obtain finite values after a certain value of suction. This is a critical observation as it indicates that reconstituted soils obtain strength after a value of suction that seems to be a function of the air-entry pressure (AEP) of the slurries. Also although the trend of the tensile strength is dubious, still it seems that the unconfined compression strength tends to stabilise for all soils after 900 kPa of suction.

Sheng et al (2008) reported on a new approach into constitutive modelling of unsaturated soils. They formulated their new model by examining the mechanical

(a) (b) (c)

Fig. 2. a) Empty plastic tubes taped on the surface of the porous plate, b) tubes filled with slurried Corinth Marl, and c) tubes and slurried Corinth Marl and Maroussi Clay after drying.

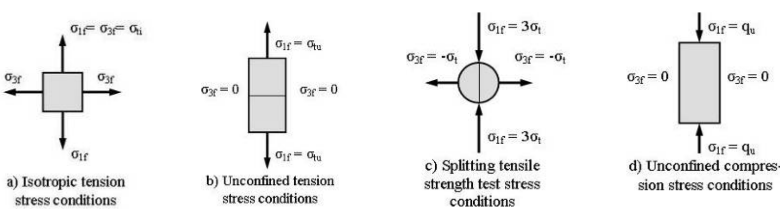

Fig. 3. Stress conditions during various types of tension applied in samples of soils and rock.

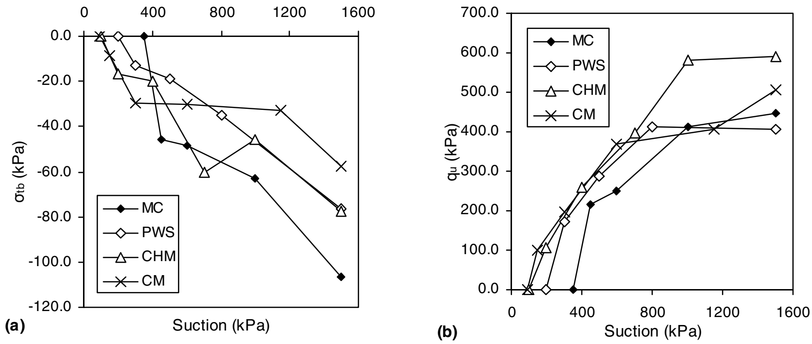

Fig. 4. a) Splitting tensile strength vs suction, & b) unconfined compression strength vs suction.

behaviour of a reconstituted soil that had been consolidated to a finite value of stress, it was then unloaded and started drying. This particular case examined by Sheng et al (2008) corresponds to a soil that when it undergoes drying lies at a distance from the yield locus. The focus of the ongoing research, part of which have been the tests presented in this paper, is to try and model the behaviour of a soil that lies on the yield locus since the beginning of each drying. A typical example of that is a reconstituted clay undergoing drying. This material has not developed any sort of structure, such as that developed due to loading and unloading, and since the beginning of its drying without any stress being applied on it, it undergoes plastic yielding since it obeys the principle of effective stress up to the suction corresponding to the air-entry value of the slurry. Up to that value of suction therefore it undergoes volumetric deformations corresponding to its compression index, therefore plastic volumetric deformation. As an indication of that two samples of Corinth Marl are shown in fig. 5. Both of them were dried and then splitting tensile strength tests were performed. A suction of 50 kPa was applied on the sample shown on the left in fig.5 and a suction of 400 kPa was applied on the

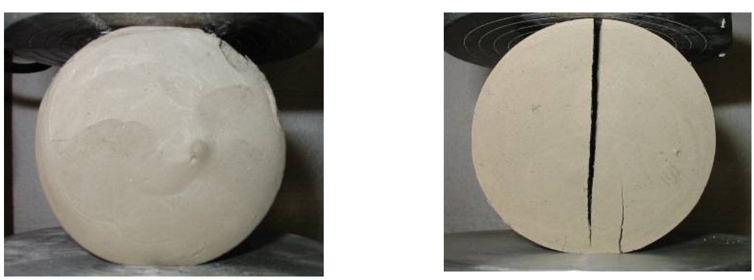

Fig. 5. Splitting tensile (brazilian) strength tests on reconstituted Corinth Marl subjected to 50 kPa of suction (left) and 400 kPa of suction (right).

sample shown on the right. 50 kPa of suction was a value lower than the AEP of the reconstituted Corinth Marl and 400 kPa a value higher than the AEP. The sample subjected to 50 kPa of suction deformed plastically as shown in fig. 5 without cracking or showing any resistance during loading. On the other hand the sample subjected to 400 kPa of suction failed after a minimum of strain was applied. The sample dried to a suction lower than the AEP therefore deforms plastically right from the beginning of loading without exhibiting the development of any strength due to drying. Similar observations were made for the samples of all the other soils dried to suction values below their AEP.

6 Conclusions

The soil-water characteristic curves, the unconfined compression strength and the splitting tensile strength were measured on four soils from Greece reconstituted to an initial water content of 1.5 times their liquid limit. The results presented constitute interim work part of a larger research programme on the properties of reconstituted soils drying without any loading prior to the beginning of drying. The most significant observation so far is that both the unconfined compression strength and the splitting tensile strength obtain finite values after a certain value of suction that seems to be a function of the AEP of the slurries.

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