# Effect of the moisture and compaction on SWCC

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## ABSTRACT

This paper analyses the soil-water characteristic curve (SWCC) of a soil sampled from a subgrade used on an Accelerated Pavement Testing Facility (PaveLab), consisting of a Heavy Vehicle Simulator (HVS Mark VI) and a set of 8-test tracks of bituminous pavement materials at the National Laboratory of Materials and Structural Models of the University of Costa Rica (LanammeUCR).

The analyzed soil corresponds to a silt (MH, A-7-6) with high plasticity index in relation to the liquid limit. This type of soil, readily found in the central valley of the country, can result in extremely large volume changes due to moisture. Furthermore, this type of material is typically used as subgrade material in pavement construction at the national level.

The main objective of the project is to assess the effect of the moisture content using different levels of compaction in the SWCC. The curves were obtained using an equipment known as Richard´s pressure chamber (suction chamber): the samples were subjected to upward pressure stages allowing for simulation of a dry process in which the value of the suction matrix increases gradually.

The relationship between optimum compaction moisture content and compaction energy was evaluated in a range between 90 to 100% relative to the maximum dry density. A SWCC model was developed in order to assess with accuracy the local data obtained.

## INTRODUCTION

The soil-water characteristic curve (SWCC) is defined as the relationship between the degree of saturation (i.e. gravimetric or volumetric water content) and the soil suction (i.e. matric suction at low suction and total suction at high suction). Therefore, it corresponds to the relationship between the amount of water in the soil and its suction. Many properties can be obtained from the SWCC (mechanical and hydraulic), such as the coefficient of permeability, shear strength and volume strain, pore size distribution and the amount of water contained in the pores for any given level of suction (Zhou et al. 2012, Zhoun et al. 2005 and Marinho, 2005).

The density or porosity of one soil can change considerably, depending on the stress and suction states as well as the stress and suction history of the soil (Zhou et al. 2012). On the other hand, the SWCC is characteristic for a given soil only at a specific density and specific stress level. As stated by Assouline (2006), a change of soil density can lead to a significant change of the SWCC, and such a change in soil density is a common feature of natural soils (Zhou et al. 2012).

An SWCC is J- or S-shaped (Figure 1) and is hysteretic; that is, for a given water content, higher matric suctions exist due to desorption (drying) than sorption (wetting) (Tinjum et al. 1997).

Because of experimental difficulties inherent in measuring the sorption curve, only the desorption portion of the curve is usually measured (Hillel 1980, Tinjum et al. 1997).

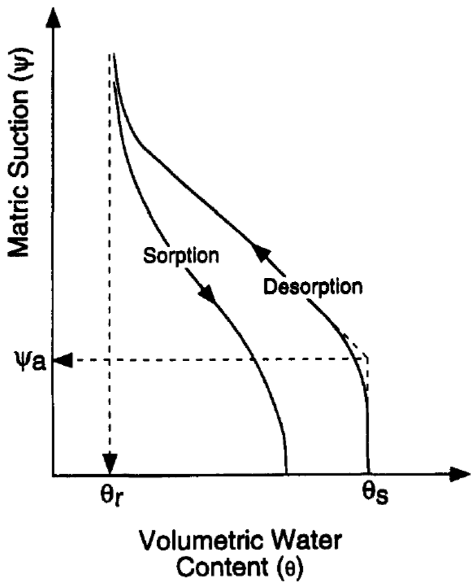



**Figure 1. Typical Soil-Water Characteristic Curves for Desorption and Sorption (Zhou et al., 2012)**

Figure 2 shows that a typical de-saturation (desorption) curve for a soil usually consists of three stages: capillary saturation, de-saturation and residual saturation. When the suction value exceeds the air-entry value (AEV), the degree of saturation decreases rapidly at relatively low suction values and then reduces more gradually when the suction becomes high (Zhoun et al. 2005).

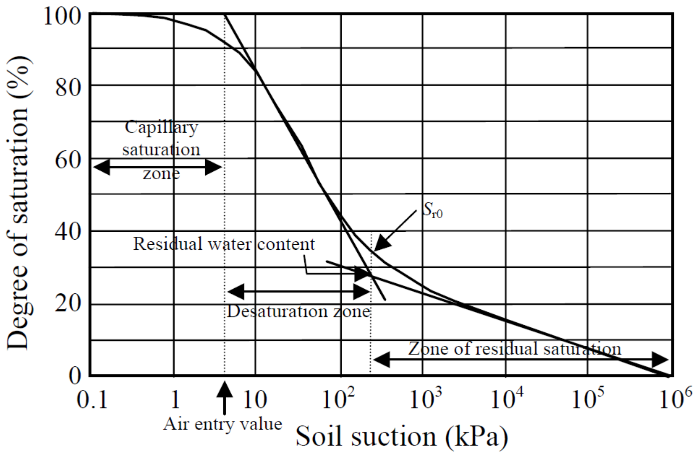



**Figure 2. Soil-water characteristic curve showing the regions of de-saturation (Sillers et al, 2001)**

The shape of the SWCC depends on the pore size distribution and compressibility of the soil in relation to suction as shown in the Figure 3 (Marinho 2005). Material with larges variation in pore sizes should present a more gradual reduction in water content with an increase in suction. These materials typically have an S shape curve.

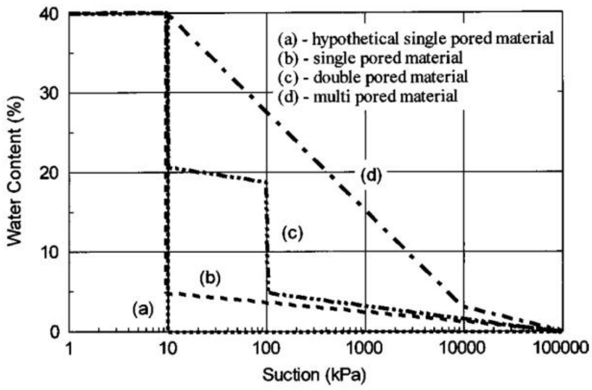
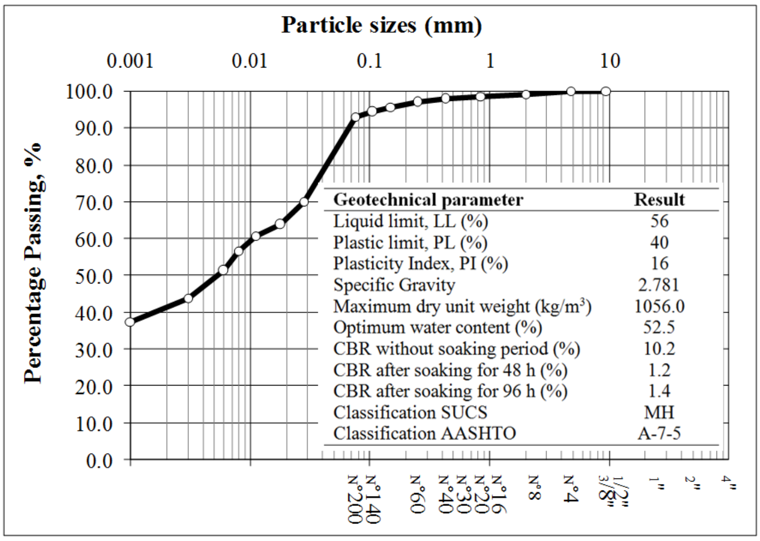



**Figure 3. General shape of soil-water characteristic curve according to pore size distribution (Marinho, 2005)**

## SOIL CHARACTERIZATION

This paper analyses the soil-water characteristic curve (SWCC) of a soil sampled from a subgrade used on an Accelerated Pavement Testing Facility (PaveLab), consisting of a Heavy Vehicle Simulator (HVS Mark VI) and a set of 8 test tracks of bituminous pavement materials at the National Laboratory of Materials and Structural Models of the University of Costa Rica (LanammeUCR). This soil is very typical type of material found in the central valley of the country, and is generally used as subgrade material for pavement construction. The results of the geotechnical characterization and the particle size distribution of the soil under analysis are shown in the Figure 4.




| Geotechnical parameter | Result |
|---|---|
| Liquid limit, LL (%) | 56 |
| Plastic limit, PL (%) | 40 |
| Plasticity Index, PI (%) | 16 |
| Specific Gravity | 2.781 |
| Maximum dry unit weight (kg/m$^3$) | 1056.0 |
| Optimum water content (%) | 52.5 |
| CBR without soaking period (%) | 10.2 |
| CBR after soaking for 48 h (%) | 1.2 |
| CBR after soaking for 96 h (%) | 1.4 |
| Classification SUCS | MH |
| Classification AASHTO | A-7-5 |

**Figure 4. Geotechnical characterization and particle size distribution**

The importance of analyzing this soil, lies in the mechanistic analysis to be carried out for the accelerated pavement testing facility. Due to this condition, it was decided to utilize a range of compaction percentages at which to obtain the SWCC and then, be able to compare the results and derive parameters (such as strength, permeability) under unsaturated conditions.

## EXPERIMENTAL PROGRAM

The soil water characteristic curves (SWCC) were developed using the axis translation method with a pressure plate apparatus for controlling suction in soils (Richard, 1947). In this case, saturated soil specimens are placed in contact with a saturated porous membrane resting on a screen disk installed within a high-pressure chamber (Figure 5). The bottom of the membrane-screen assembly is maintained at atmospheric pressure by means of a small drain tube or opening through the bottom of the pressure chamber. A desired air pressure admitted to the pressure chamber, and consequently to the top of the membrane, creates a pressure drop across the membrane. The saturated soil specimens on the membrane establish equilibrium with the water in the membrane. The water, held at a tension less than the pressure drop across the membrane, will then move out of the soil, through the membrane, and out through the drain hose. When water has ceased to flow from the specimen and membrane, indicating equilibrium for that particular tension, the moisture content of each specimen is determined.

A series of tests at various tensions are required to prepare a complete curve of capillary-moisture relationship for any particular soil (Johnson, 1970).

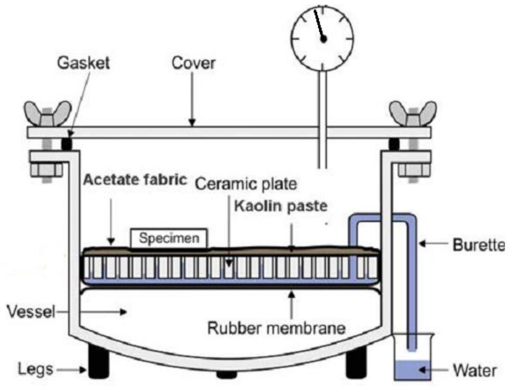



**Figure 5. Pressure Plate Test Apparatus (ASTM C1699-09)**

As part of this study, the samples were subjected to upward pressure stages with different steps at different pressure levels. The first set of those steps uses air pressures of 20, 40, 60, 90, 120, 150, 200 and 300 kPa. The second uses air pressures of 200, 250, 300, 450, 750 and 1200 kPa. The third uses air pressures of 490, 980 and 1370 kPa. The fourth and fifth set use air pressures of 0.1, 6, 10, 16 and 30 kPa. Three samples at three degrees of compaction (90%, 95% and 100% of maximum dry unit weight) at the optimum compaction moisture content were compacted for each series of pressure levels. In this regard, each specimen is first weighed after a 24 hour saturation period, and afterwards its weight is measured after each pressure level. Once the entire pressure application over the selected levels is completed, the specimen is then oven dried, as required and its weight is measured. The gravimetric water content, and hence, the volumetric water content can then be calculated from the differences in the weights at the various pressure levels and the oven-dry weight. In this method, the process in which the value of the suction matrix increases gradually is simulated. The SWCC generated by drying the soil sample (desorption curve) was obtained for each degree of compaction (Figure 6).

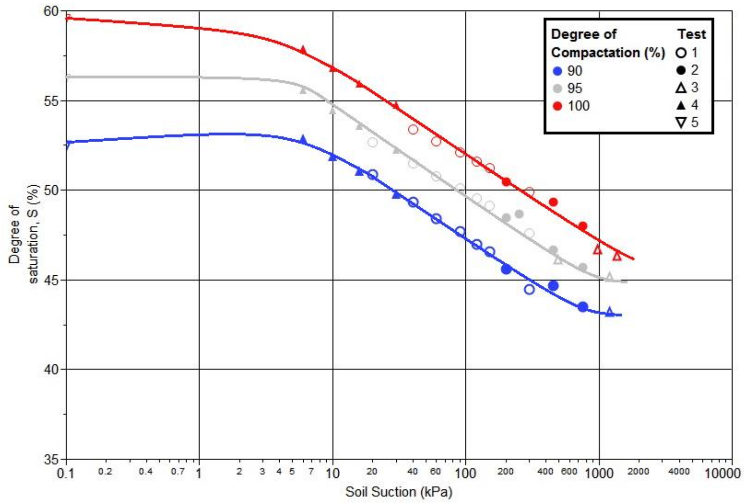



**Figure 6. Soil water characteristic curves of soil studied by different degree of compaction**

## MATHEMATICAL MODELS

Due to the different SWCC shape associated with various soil types, it is essential to fit a general mathematical expression for practical use. Many researchers have tried to find an adequate structural form (Zhou et al. 2005). Table 1 shows some of the mathematical models used to fit the experimental data found in the literature. However, this equations have been validated for a limited range of soils and suctions. The equations with three and four parameter have been identified as the more suitable to represent the SWCC. (Zapata et al. 2000)

**Table 1. Soil-water characteristic curve models**

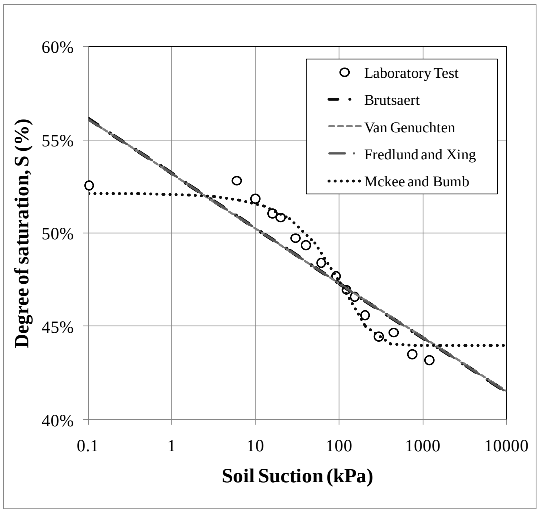
| Model Name | Model | Parameter Description |
|---|---|---|
| Brutsaert (1966) | $S = \dfrac{1}{1 + \left(\frac{\psi}{a}\right)^n}$ | S, degree of saturation |
| Van Genuchten (1980) | $S = \dfrac{1}{(1 + (a\psi)^n)^m}$ | Ψ, soil suction |
| Mckee and Bumb (1987) | $S = \theta_r + \dfrac{\theta_s - \theta_r}{1 + e(1)^{\left[\frac{\psi - a}{b}\right]}}$ | $\theta_r$, residual volumetric water content |
| Fredlund and Xing (1994) | $S = \dfrac{1}{\left(Ln\left(e + \left(\frac{\psi}{a}\right)^n\right)\right)^m}$ | $\theta_s$, saturated water content |
| | | *a*, *b*, *n* and *m* are fitting parameters |

Currently, it has not been possible to define a particular structural form that is capable of adequatly fitting every soil encountered (Zapata et al. 2000). As shown on Figure 7 (a), (b), and (c), the Mackee and Bumb (1987) model is the only one that adequately fits the shape of the curve obtained experimentally. However, it is clear from the figure that prior to modifying the structural form of the model, the Mackee and Bumb model over predicts the degree of saturation when the soil suction is high and under predicts the degree of saturation for low soil suction, when fit using data from the evaluated soil. Based on these results, it was necessary to propose a new SWCC structural form in order to reduce the differences between predicted and measured data. The proposed model is as follows:

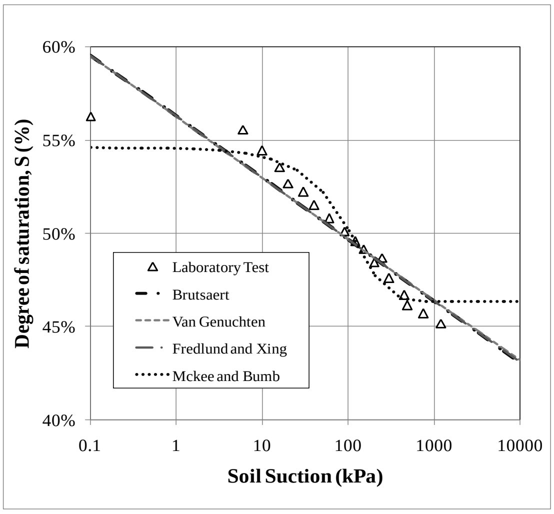
$$S = \theta_r + \frac{\theta_s - \theta_r}{1 + e^{a + b\log(\psi)}} \quad ^*$$

*Parameters defined on Table 1.

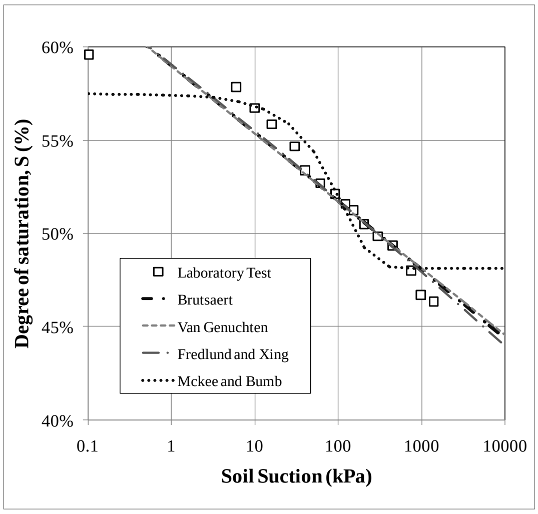
The model uses two fitting parameters; namely, *a* and *b*. Parameter *a* does not affect the curve shape, but shifts the curve towards the higher or lower suction regions of plot, and is related to the air entry value of the soil. The parameter *b* is related to the pore size distribution index. More uniform pore sizes in soil have larger *b* values. Larger magnitude *b* values are also associated with a steeper curve in the de-saturation zone. In other words, the *b* parameter is related with the slope of the SWCC curve. Figure 8 shows the model fit to the experimental data, and Table 2 shows the parameters and statistical data associated with the SWCC proposed model. In can be seen that the new model is suitable for the soil analyzed.




(a) 90% of Compaction

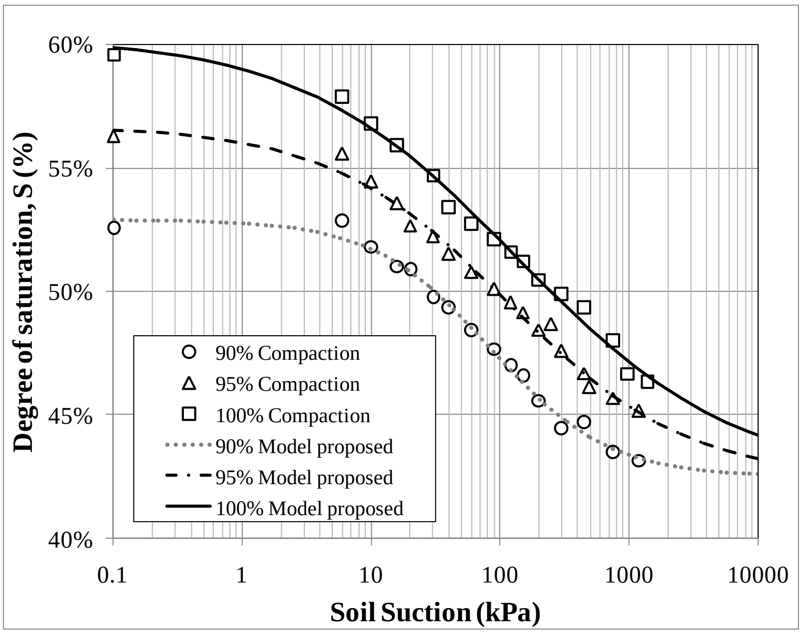



(b) 95% of Compaction




(c) 100% of Compaction

**Figures 7. Soil-water characteristic curves model for the laboratory test results**




**Figures 8. Soil-water characteristic curves model fitted to the experimental data**

**Table 2. Parameters of soil-water characteristic curve models fitted to the experimental data**

| **Parameter** | | $\theta_r$ | $\theta_s$ | *a* | *b* |
|---|---|---|---|---|---|
| **90% of Compaction** | **Estimate** | **0.425** | **0.529** | **-4.256** | **2.211** |
| | **N** | 16 | 16 | 16 | 16 |
| | **Std Err** | 0.004852 | 0.003001 | 0.432937 | 0.241474 |
| | **t statistic** | 87.59 | 176.40 | -9.83 | 9.16 |
| | **p-value** | 0.000 | 0.000 | 0.000 | 0.000 |
| **95% of Compaction** | **Estimate** | **0.424** | **0.567** | **-2.967** | **1.438** |
| | **N** | 18 | 18 | 18 | 18 |
| | **Std Err** | 0.013119 | 0.004474 | 0.297857 | 0.197766 |
| | **t statistic** | 32.35 | 126.80 | -9.96 | 7.27 |
| | **p-value** | 0.000 | 0.000 | 0.000 | 0.000 |
| **100% of Compaction** | **Estimate** | **0.424** | **0.603** | **-2.526** | **1.182** |
| | **N** | 16 | 16 | 16 | 16 |
| | **Std Err** | 0.020103 | 0.005898 | 0.257833 | 0.189061 |
| | **t statistic** | 21.10 | 102.15 | -9.80 | 6.25 |
| | **p-value** | 0.000 | 0.000 | 0.000 | 0.000 |

All of the parameters estimated for the proposed model at the three compaction levels are virtually significant at any confidence level. In general, the parameter with a larger effect on the model is the residual volumetric water content ($\theta_r$). This is to be expected since the parameter directly correlates to the range of saturation that can be associated to a soil at a given level of compaction. The same can be stated with regards to the saturated water content ($\theta_s$). However, note from the model that $\theta_r$ is inelastic to changes in compaction, while this is not the case of $\theta_s$. The shift factor (*a*) and the slope parameter (*b*) are also elastic with respect to the level of compaction. However, note that the elasticity of the parameters decreases with an increase in the level of compaction.

Furthermore, the model allows to quantify the effect of compaction and suction. It was identified that on average, a 5% increase in compaction can be associated to a 3.7% increase on the degree of saturation for a given suction. Similarly, even thought the effect of compaction on suction is not linear, it can be recognized that for lower degrees of saturation (eg. 45%) a 5% increase in compaction can be associated to an increase in suction in a range between 700 to 3000 kPa, while for high saturation levels (eg. 55%) a 5% increase in compaction can be associated to an increase in suction of 25 kPa.

## CONCLUSION

The SWCC is very important in the research of partially saturated soils. However, high variability and numerous sources of error associated to the measured values can lead to difficulties in obtaining a unique SWCC for a given soil.

More tests are needed to grasp the general features of the SWCC, especially to provide information about soil structure, microstructure and macrostructure. However, it is not practical to test samples under every condition. For this reason a minimum series of test for each type of soil should be performed to establish the effects and influence of different factors on the SWCC of the soil.

It was shown that the initial density has a significant impact on the SWCC due to the reduction of the amount of voids in the soil, therefore a decrease on the amount of voids allows a gain on the degree of saturation (*S*). Additionally, the saturated water content ($\theta_s$) increases due to the density and the residual volumetric water content ($\theta_r$) has little variation at high suctions values (higher than 1000 kPa) for all the evaluated densities.

An adequate model for the SWCC is essential to further perform constitutive modeling. In this regard, an updated model is proposed to predict the SWCC curve for a Costa Rican soil. Comparisons between measured and modeled SWCCs proved the model's capability and accuracy. Further studies are required to analyze the relationship between the SWCC and other geotechnical and soil parameters such as void ratio, initial water content, stress state, grain size, and plasticity among other variables.

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