MEASUREMENT OF HYDRAULIC PROPERTIES OF SOILS USED FOR ROAD CONSTRUCTION UNDER SATURATED AND UNSATURATED CONDITIONS

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***Abstract*— Road structures are more often found in unsaturated conditions. Despite this, at present there is a limited volume of literature on the hydraulic properties of soils used for road construction evaluated under unsaturated conditions. In this context, this paper presents the characterization and measurement of the hydraulic properties of different soils used for road construction in the city of Santander, Northern Spain. The soils were extracted from a road structure. The hydraulic properties of soils have been measured under saturated and unsaturated conditions, in order to determine the saturated hydraulic conductivity (Ks) and the Soil Water Characteristic Curve (SWCC), according to the van Genuchten model of four-parameter. Finally, the procedures followed in this particular study case can give guidelines for the determination of the hydraulic parameters of soils used for road construction, especially when unsaturated conditions needs to be take into account. Besides, the hydraulic parameters obtained with the described methods can be effectively used for modeling the water flow and contaminants through road structures using FEM-based numerical simulation.**

***Keywords*— Road materials; Unsaturated soils; Matric suction; Water content; Hydraulic conductivity.**

I. INTRODUCTION

Road structures are more often found in unsaturated conditions as opposed to saturated ones. Under unsaturated conditions water flow is primarily by capillarity, while under saturation gravity is the primary force causing water movement. Therefore, suction measurements in soils plays an important role in the study of the water flow through road materials under unsaturated conditions (Alonso, 1998). Suction measurements are employed in order to developing the Soil Water Characteristic Curve (SWCC), which is a graphical relationship between soil matric suction and water content or degree of saturation of a soil type (Fredlund, 2006). As shown in Fig.1, the SWCC form is characterized by singular points where the slope of the curve changes abruptly. These points are called the air-entry value (AEV) and the residual water content value (θ_r). The air-entry value corresponds to the value of matric suction at which the air begins to enter into the larger pores of the material. The residual water content (θ_r) is defined as the minimum volumetric water content and therefore requires large changes in the suction to cause a further reduction of water content. Another characteristic value of the SWCC is the saturated water content value (θ_s) which represents the point where all the available spaces in the pores of the soil matrix are filled with water and the suction at this point is zero (Zhai and Rahardjo, 2012).

Additionally, the SWCC form (Fig. 1) can be divided into three zones according to the state of water retention, such as Song *et al.* (2012): the capillary fringe zone, the continuous capillary zone, and the residual zone; where the water content is almost zero. Therefore, direct measurements of the SWCC using experimental techniques, for example a null pressure plate apparatus or pressure cell can be used to obtain data which defines the relationship between matric suction and water content (Fredlund, 2006; Marinho *et al.*, 2008; Vanapalli *et al.*, 2008). However, modeling the behavior of unsaturated soils using numerical simulation requires the relationships between suction and water content to be described by continuous mathematical functions (Sreedeep and Singh, 2011). For this reason, many mathematical equations have been proposed to describe the SWCC based on experimental data (Fredlund and Xing, 1994).

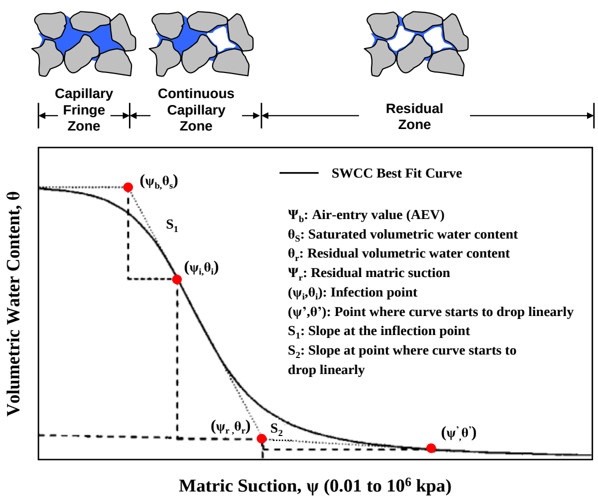

Fig. 1. Soil Water Characteristic Curve form and its variables (modified from Zhai and Rahardjo, 2012).

Table 1. Physical properties of soils.

Soil property	Material tested		
	Soil cement	Natural soil	Top soil
USCS classification	CL	CL	MH
Specific gravity, G_s (kg/m^3)	2720	2700	3060
Maximum dry density, γ_d (kg/m^3)	2040	2160	1558
Optimum water content, w_{opt} (%)	10	7.8	30
Total specific surface area, SSA (m^2/g)	7.104	3.473	20.333
Limit liquid, LL (%)	37	27	56
Limit plastic, LP (%)	18	18	32

Among these approaches the van Genuchten model (van Genuchten, 1980) which has been the most widely used for the setting of experimental results in different types of soils used for road construction. Among them numerical modeling of rainwater infiltration, contaminant transport, use of recycled materials, pavement structures, and embankments (Apul *et al.*, 2005; Beyer *et al.*, 2009; Canelon and Nieber, 2009; Gardner *et al.*, 2002; Hansson *et al*., 2005; Norambuena-Contreras *et al.*, 2012; 2014). However, as the SWCC form is highly nonlinear and the determination of the characteristic curve parameters requires nonlinear fitting of the equation. Several commercial codes such as RECT (van Genuchten *et al.*, 1991) or SWRC-Fit (Seki, 2007) are available to allow the determination of the characteristic parameters of van Genuchten equation. Finally, despite the fact that water flow in road structures is an important topic in civil and geotechnical engineering (Gardner *et al.*, 2002), at present there is a limited volume of literature on the hydraulic properties of soils used for road construction evaluated under unsaturated conditions (Norambuena-Contreras, 2015), unlike agricultural soils (Nemes *et al.*, 2001), in which there are diverse databases on unsaturated soil hydraulic parameters, e.g., the UNsaturated SOil hydraulic DAtabase (UNSODA).

Moreover, under unsaturated conditions the equations describing water flow into soils are highly nonlinear, showing a higher difficulty in its numerical solution. For all these reasons, this paper has been prepared with the objective of characterize and measure via two experimental processes, the hydraulic properties (SWCC and saturated hydraulic conductivity) of three different soils under saturated and unsaturated conditions.

II. MATERIALS AND METHODS

A. Description of materials

Three different soils were analysed in this study. The soils were extracted of the construction of a road structure located in the city of Santander, Northern Spain. Thus, a subgrade improvement of soil cement with 3.5% of Portland cement, a subgrade of natural soil, and topsoil used in the embankment zone, have been evaluated. In addition, Unified Soil Classification System (USCS) and the main physical properties and of the three soils evaluated are indicated in Table 1. It is noticeable the great specific surface area and plasticity of the topsoil.

B. Test specimen preparation

Compacted test specimens were prepared in order to measure the matric suction and saturated hydraulic conductivity of the three soils. For the matric suction test a total of 24 specimens were prepared: 8 undisturbed specimens of soil cement and 16 remoulded specimens of natural soil and topsoil. For the saturated hydraulic conductivity test a total of 9 samples were prepared: 3 undisturbed specimens of soil cement stabilized soils and 6 remoulded specimens of natural soil and topsoil. Finally, test specimens were preconditioned in two different ways before testing, and according to the following configuration:

1) *Undisturbed specimens*: specimens were extracted directly from the corresponding field sample, with unaltered structure and water content.

2) *Remoulded specimens*: were compacted in laboratory at the optimum water content and maximum dry density according the modified Proctor Test (ASTM D1557, 2009). For the matric suction specimens, each soil was compacted into a rigid device containing an oedometer steel ring-mould of 70 mm diameter and 20 mm height. The compacting process was static in order to obtain the desired dry density. For hydraulic conductivity samples, each soil was compacted using a cylindrical three-part split mould, of 38 mm diameter and 76 mm height. Finally, each specimen was confined laterally using two elastic membranes and kept in an airtight container until the test.

C. Matric suction measurement and SWCC according to van Genuchten model

Matric suction was measured according to the recommendations of the standard (ASTM D6836-02, 2003). Specimens were prepared at the optimum water content and the maximum dry density (Table 1). Pressure cells with semi-permeable regenerated cellulose membranes based on the axis translation technique were used (see Fig 2.(a)). Estimated discrete values of volumetric water content and matric suction of the soil tested using pressure cells were used to adjust the SWCC according to the van Genuchten model. The best fit parameters of the van Genuchten characteristic curve model were estimated using a nonlinear fitting program (Seki, 2007). For the fitting analysis, the value of saturated water content (θ_s) was considered equal to the soil porosity to a matric suction of 0.1 kPa. Finally, the quality of fit between the experimental water content results and the values estimated using the van Genuchten model have been verified via sum of squared residual values (SSR), given by:

$$SSR = \sum_{i=1}^{n} w_i (\theta_i - \theta_e)^2 \quad (1)$$

where, w_i is a dimensionless weighting factor equal to 1 in this study, θ_i is the volumetric water content measured experimentally for a given value of suction, and θ_e is the volumetric water content estimated by the fit model with a suction value equal to ψ_i. Finally, according the authors (Leong and Rahardjo, 1997; Miller *et*

(a) (b)

Fig. 2. Equipment for measurements of the hydraulic properties: (a) Pressure cells apparatus to measure matric suction based in axis translation technique, and (b) triaxial cell apparatus to measure saturated hydraulic conductivity.

Table 2. Hydraulic conductivity via triaxial cell.

Sample description (unit)	Material tested		
	Soil cement	Natural soil	Top soil
Height (cm)	8.90	7.62	7.62
Diameter (cm)	4.80	3.81	3.81
Initial moisture content (%)	–	8.6	30.4
Final moisture content (%)	–	12.4	33.8
Dry density (kg/m^3)	–	2150	1540
Bulk density (kg/m^3)	1660	2340	2000
Test pressures[a]	Soil cement	Natural soil	Top soil
Top pore-water pressure (kPa)	588.6	588.6	588.6
Bottom pore-water pressure (kPa)	784.8	784.8	833.8
Cell pressure (kPa)	882.9	882.9	882.9
Cell effective pressure (kPa)	294.3	294.3	294.3
Average effective pressure (kPa)	196.2	196.2	171.7
Differential pressure (kPa)	196.2	196.2	245.2
Average saturated hydraulic conductivity (cm/s)	3.37×10^{-8}	2.50×10^{-8}	1.31×10^{-7}

[a]Average pressure values applied in the three specimens.

al., 2002) SSR values less than 0.001 can be considered satisfactory for a good fit using the van Genuchten model.

D. Measurement of saturated hydraulic conductivity

Saturated hydraulic conductivity was measured following the recommendations of the standard (B.S. 1377-6, 1990). For the tests on compacted soils specimens a triaxial cell was used (see Fig.2 (b)). To ensure the saturation of the specimen a pressure was applied at the top (top pore water pressure), which remained constant throughout the test. Once the specimen was saturated (after 48 hours approx.) it was laterally confined applying a side pressure (cell pressure). The pressure difference between the sample top and bottom (differential pressure) caused a hydraulic gradient which along with the geometrical properties of the specimen and the measured flow rates were used to determine the saturated hydraulic conductivity of each specimen according to Darcy's law given by Eq. 2. Finally, Table 2 shows the pressures values applied into triaxial cell for the different soils specimens tested.

$$K_s = \frac{\Delta QL}{Ah\Delta t} \qquad (2)$$

where, ΔQ is water volume flowing in [L^3] for a given time interval Δt, average of inflow and outflow, L is the height of sample in [L], A is the cross-sectional area of the test sample in [L^2], h is the difference in hydraulic head across the sample in [L], and Δt is the interval of time in [T] over which the water flow ΔQ occurs.

II. RESULTS AND DISCUSSION

A. SWCC according to van Genuchten model

Experimental data collection of matric suction and results of the best fit parameters (θ_r, θ_s, α, n) of the Soil Water Characteristic Curve according to van Genuchten model are shown in Fig. 2, for all the soils evaluated in this study. Thus, as shown in Fig. 3, coefficients of determination (R^2) for the materials soil-cement, natural soil and topsoil were 0.970, 0.913 and 0.992 respectively; they show a fairly good correlation with the van Genuchten retention model. Besides, according to Fredlund and Xing (1994) the suction corresponding to zero water content was considered equal for all the soils tested and equal to 10^6 kPa. On the other hand, the residual water content value of the topsoil (Fig. 3(c)) appears to be relatively high compared to natural soils. This fact could be due because the maximum suction during the determination was 1100 kPa, which was not great enough to encounter the inflexion point in the water retention function.

Furthermore, Fig. 3 shown that the soils presented a high adsorption capacity for high water suction (greater than 100 kPa). This happened due to the high specific surface area of the soils selected in this study, especially in the case of the topsoil (Table 1). Thus, recorded air-entry pressure ranged from 53 to 83 kPa for the soils analyzed. For this reason, the soils used for road construction in the present study exhibited uniform grain-size, such is the case of soil cement and natural soil, that are characterized by flat characteristic curve from saturation to the air-entry point, because the majority of pores are drained within a narrow range of suction, showing a well-defined air-entry value (Fredlund and Xing, 1994). The central region of the characteristic curve generally has greater slope in soils with uniform pore-size distributions, as can be the case of a coarse granular soil, for example a crushed stone used as base layer in pavements.

However, soils with broad ranges of pore-size distribution have gentle slopes, as the topsoil. Moreover, the parameter n in the van Genuchten characteristic curve and given indicates greater uniformity in the pore-size distribution. Therefore, a higher value of *n* is associated with a greater slope of the curve in the central section, while a lower value is associated with a gentler slope. Thus, SWCCs shown in Fig. 3, the value of *n* decreases by following order: natural soil, soil cement and topsoil.

B. Influence of properties on the general form of the characteristic curve

As expected for the evaluated soils, the general form of the SWCCs is influenced by different parameters such as: the type of soil, texture and mineralogical composi tion, the structure and the stress history, tensional state

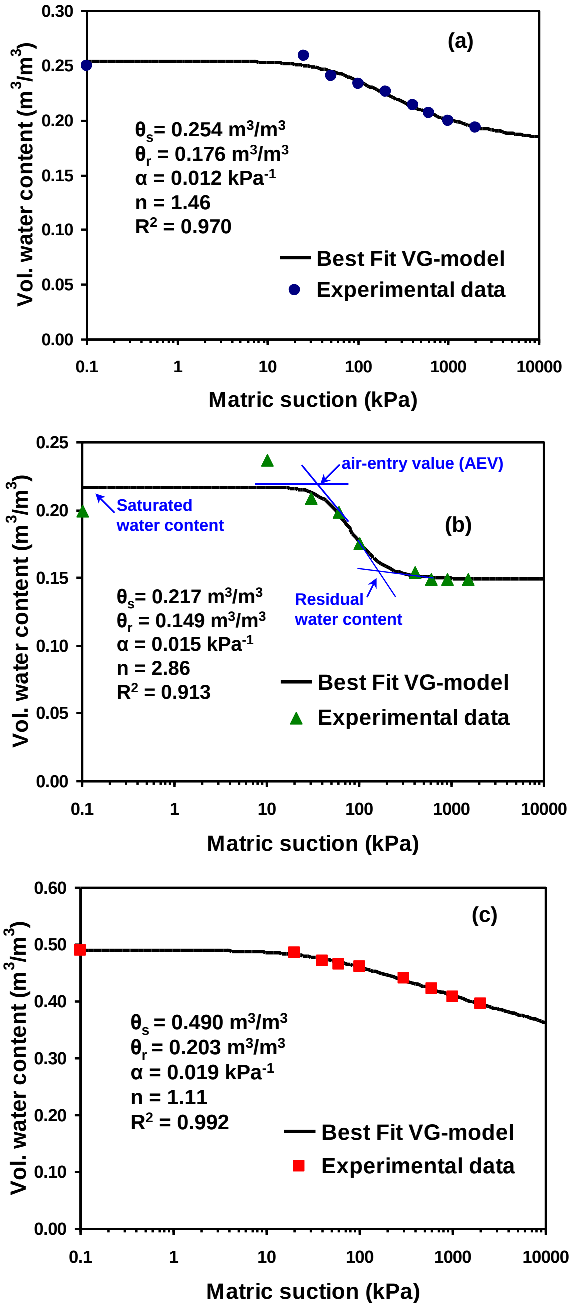

Fig. 3. Drying SWCCs and fitting parameter of VG-Model for: (a) Subgrade improvement, (b) subgrade of natural soil, and (c) topsoil.

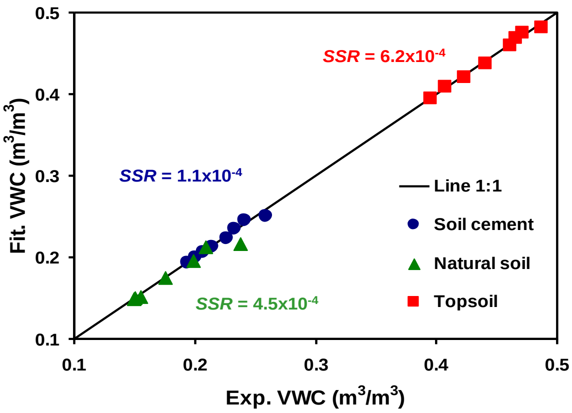

Fig. 4. Relationship between the values of volumetric water content (VWC) measured by experimental form and the calculated via a Fit program based in VG-model.

and the degree of compaction (Malaya and Sreedeep, 2011). However, authors as Miller *et al.* (2002) showed that SWCC for compacted soils in field and laboratory conditions can result very similar. This result suggests that the determination of characteristic curves in the laboratory, as in this research, adequately represents the behavior of soil under field conditions. However other published works (Miller *et al.*, 2002; Sillers *et al.*, 2001), showed an effect of the soil plasticity and mineralogy on the shape of the characteristic curve. The general trend is the air-entry value and the saturated water content are greater in fine-grained soils, such as clay or silt than in coarse-grained materials, such as sandy or gravel. Finally, Fig. 4 shown a really close correlation between the values of volumetric water content measured in laboratory and values adjusted by using the van Genuchten theoretical model. Thus, the Sum of Squared Residual values (SSR) ranged from 1.1×10^{-4} in the case of soil cement, through 4.5×10^{-4} for natural soil to 6.2×10^{-4} for topsoil. Therefore, as the values of SSR for all the analyzed soils in this study were less than 0.001, it confirms that the Fitting of the characteristic curves by van Genuchten model can be considered very satisfactory according to studies of (Leong and Rahardjo, 1997) ENREF_13 and (Miller *et al.*, 2002) ENREF_16 in fine soils of similarly texture.

C. Saturated hydraulic conductivity

Table 2 shows the average results of the saturated hydraulic conductivity measured using a triaxial cell apparatus (Fig. 2). From these results, it can be seen that all the values of hydraulic conductivity and for the three samples tested show a low scatter with very consistent data. For this reason, the hydraulic conductivity of the evaluated soils can be considered extremely low and similar to the typical values of compacted clays found in the literature. In this line, Kutílek and Nielsen (1994) reported that typical values of hydraulic conductivity for compacted clays ranged 10^{-7} to 10^{-9} cm/s. The major dispersion of the conductivity (Table 2) in soil cement could be due to a greater variability of this material and probably the existence of some fractures inside the material. Consequently, experimental data collection of hydraulic parameters, shown in Fig. 3 and Table 2, can be used to estimate the unsaturated hydraulic conductivity function by combining the van Genuchten function (van Genuchten, 1980) and the model of Mualem (Mualem, 1976). Besides, these experimental hydraulic parameters can be effectively used in order to modeling the water flow and contaminants through road structures using FEM-based numerical simulation. An example of this can be consulted in Norambuena-Contreras *et al.* (2014).

III. CONCLUSIONS

In this paper the hydraulic properties of three soils used for road construction have been measured under saturated and unsaturated conditions. Fitting parameters of the Soil Water Characteristic Curves have been determined according to Van Genuchten model. Additionally, saturated hydraulic conductivity values of soils also have been estimated. Finally, the following remarks can be made based on this research:

- Soil Water Characteristic Curves measured using pressure cells apparatus based in axis translation technique, and fitting four-parameters calculated according to the van Genuchten model (θ_r, θ_s, α, n) presented an excellent correlation for all the evaluated soils. This was evidenced by the high coefficients of determination (R^2) registered and the low values of Sum of Squared Residual (SSR) exposed. In addition, these Soil Water Characteristic Curves correspond to one of the few results published in Spanish soils used for road construction evaluated under unsaturated conditions.
- Moreover, saturated hydraulic conductivity values of the soils tested in this study using a triaxial cell apparatus, can be considered extremely low and similar to the typical values of compacted clays as found in relevant literature.
- Finally, experimental data collection of hydraulic parameters (SWCCs and Ks) can be used with the aim modeling the water flow and contaminants through road structures using FEM-based numerical simulation.

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