Relationship between Soil-Water Characteristic Curves and the As-Compacted Water Content versus Soil Suction for a Clay Till

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ABSTRACT: The soil-water characteristic curve relationship is commonly determined on a single specimen from a fully saturated condition to a suction value of interest in the laboratory using pressure plate equipment. The soil suction in an individually compacted unsaturated specimen with a particular density and initial water content can be determined using the axis-translation technique on a null pressure plate apparatus. The relationships obtained by the above two procedures are different. The soil-water characteristic curve is mainly dependent on the soil structure that is in turn dependent on the initial moulding water content. However, the influence of initial moulding water content on the structure (and aggregation) can be evaluated by comparing the soil-water characteristic curve data with data obtained from individually compacted specimens. This paper summarizes the above comparisons on a statically compacted clay till at three different water contents that represent different structure (and aggregation).

KEYWORDS: Unsaturated soils, soil-water characteristic curve, suction, soil structure

1 INTRODUCTION

The soil-water characteristic curve defines the relationship between the soil suction and gravimetric water content, w, or the volumetric water content, θ, or the degree of saturation, S. The soil-water characteristic curve has been found to be a conceptual and interpretative tool by which the behavior of unsaturated soils can be understood. As the soil moves from a saturated state to drier conditions, the distribution of the soil, water, and air phases changes as the stress state changes. The relationships between these phases take on different forms and influence the engineering behavior of unsaturated soils. For example, in some cases the behavior may be primarily related to the volume of the separate phases (e.g., water content), or the continuity and tortousity of the liquid phase (e.g., coefficient of permeability, molecular diffusion) or the air phase (e.g., coefficient of vapor or oxygen diffusion). In other cases it is the nature of the interphase contact area controlling stress transfers (e.g., shear strength, volume change) or interphase mass transfers (e.g., chemical adsorption, volatilization) which control behavior (Barbour 1999).

Fredlund and Rahardjo (1993) have provided a rational approach for interpreting the engineering behavior of unsaturated soils in terms of stress state variables based on experimental results. However, compared to this approach estimating unsaturated soil properties from interphase relationships using the soil-water characteristic curve data is attractive to engineering practitioners because rigorous laboratory tests on unsaturated soil are difficult, time consuming and, therefore, costly. Several theoretical and empirical relationships have been developed in the last five years to model the unsaturated soil properties such as the coefficient of permeability and shear strength using the soil-water characteristic curve and the conventional saturated soil properties (Fredlund et al. 1994, Vanapalli et al. 1996, Fredlund et al. 1996).

Several factors influence the soil-water characteristic curve such as soil structure (and aggregation), initial moulding water content, void ratio, type of soil, texture, mineralogy, stress history, method of compaction, etc. Specimens of a particular soil, in spite of having the same texture and mineralogy can have different soil-water characteristic curves. As a result, the engineering behavior of each of the specimens will also differ. Of all these factors initial moulding water content and stress history seemingly have the most influence on the soil structure (and aggregation) which in turn dominates the nature of the soil-water characteristic curve for fine-grained soils. Vanapalli et al. (1998) studies have shown that shear strength of an unsaturated soil can be reasonably well predicted without considering the influence of stress state for a fine-grained soil compacted at optimum and wet of optimum conditions.

In this paper, the influence of initial moulding water content on the structure (and aggregation) is evaluated by comparing the soil-water characteristic curve data with data obtained from individually compacted specimens. The matric suction of the individually compacted specimens was determined using the axis-translation technique on a null pressure plate apparatus. Soil-water characteristic curves were developed on statically compacted clay till specimens prepared at three different "initial" water contents. The initial water contents selected for this study represent the dry of optimum, optimum and wet of optimum conditions with corresponding densities determined from the standard AASHTO test.

2 SOIL AND TESTING PROGRAM

A sandy clay till obtained from Indian Head, Saskatchewan, Canada was used in this testing program. This soil is classified as a CL according to the Unified Classification System. The liquid limit and plastic limit are 35.5% and 16.8% respectively. Sand, silt and clay fractions are 28%, 42%, and 30% respectively. The clay fraction consists mainly of a calcium montmorillonite. The AASHTO standard compacted maximum density is 1.80 Mg/m^3 at an optimum water content of 16.3%. The relative density of the soil solids is 2.73.

The soil was air-dried for several days, pulverized using a rubber mallet and passed through a 2 mm sieve. A prescribed amount of distilled water was sprayed on the air-dried soil in several layers and left over night in tightly covered plastic bags in a humidity controlled room. The soil was then thoroughly hand mixed. To help prevent the formation of soil-water clods, the mixed soil was again passed through a 2 mm sieve. The mixed soil was placed in plastic bags and kept in a humidity controlled room for at least 48 hours. All samples were statically compacted (100 mm diameter and 21 mm high). The samples were prepared in a single layer using a constant volume mould to obtain the required initial conditions of water content and density. A specimen 63.5 mm in diameter was cut from the 100 mm diameter sample using a stainless steel sharpened consolidation ring. The prepared specimens were sandwiched between filter paper and porous stones in consolidation rings and were subjected to a nominal seating load of 3.5 kPa in a conventional oedometer. These specimens were submerged in distilled water allowing access to drainage at top and bottom for about 36 hours. The degree of saturation of these specimens was checked using waxed trial samples that were weighed in air and water. The degrees of saturation of specimens were greater than 99% for all the samples. These specimens were then used to obtain data for the soil-water characteristic curve data from a pressure plate apparatus. In a pressure plate apparatus, the prepared specimen sits on a high air-entry ceramic disk in a sealed air pressure chamber. Water in a compartment beneath the disk is maintained at zero water pressure while an applied air pressure induces a matric suction under which the specimen is allowed to come to equilibrium.

The matric suction of the individually compacted specimens (100 mm diameter and 21 mm high) were measured with a null pressure plate using the axis translation technique. Each set of individually compacted specimens were prepared at the same dry density (i.e., constant void ratio with varying initial water contents). These test results were used to evaluate the role that soil structure (and aggregation) plays in determining soil suction.

Three sets of specimens were prepared with initial water contents ranging from 12.5% to 19.2%. Matric suction measurements for specimens with water contents lower than 12.5% could not be made due to the limitations of the air-entry value of the porous stone in the null pressure plate (i.e., 500 kPa). It was difficult to prepare the specimens with water contents greater than 19.5% because the specimens were soft and difficult to handle. In some cases a film of water developed on the surface of the specimen suggesting that positive pore-water pressures might have been developing in the specimens at these higher water contents. Therefore, it was decided to restrict the study of matric suction measurements for individually compacted specimens to a water content range of 12.5 to 19.2%.

3 RESULTS AND DISCUSSIONS

3.1 Soil-water characteristic curve behavior

Soil-water characteristic curves with different initial water contents and densities are shown in Figure 1. Fine-grained soils, such as this clay till, typically have two levels of structure: a macro level structure and a micro level structure. The soil micro structure is described as the elementary particle associations within the soil, whereas the arrangement of the soil aggregates is referred to as the macro structure (Mitchell 1976). Typically both the macro and micro levels of structure are present in natural and compacted clayey soils. The resulting macro structure of specimens prepared at different initial water contents is different in spite of their identical mineralogy, texture and method of preparation. The resistance to water flow (i.e., desaturation) is relatively low in the dry of optimum specimens in comparison to optimum and wet of optimum specimens. The dry of optimum initial water content specimens contain relatively large pore spaces which are located between the clods of soil as compared to the pore spaces within the clods. The relatively low suction values associated with removing water from the large pores are significantly different from the large suctions required to remove water from the microscopic pore spaces between soil particles within the clods of clay. As a result, the macro structure controls the initial desaturation of compacted clayey specimens with initial water contents that are dry of optimum.

The pore spaces in a clayey soil compacted at an initial water content wet of optimum are not generally interconnected or are in an occluded state. These soils are more homogeneous and have a higher storage capacity due to their different structure. They have no visible interclod pores and offer more resistance to desaturation under an applied suction in comparison to those specimens compacted dry of optimum. In contrast to the specimens compacted dry of optimum, the micro structure in the specimens compacted wet of optimum controls and resists the desaturation (drying) characteristics of the soil. Hence, the slope of the soil-water characteristic curve is relatively flatter for the wet of optimum specimen in comparison to the dry of optimum initial water content specimen. The boundary between the occluded pore space and the open pore conditions occurs at water contents approximately equal to the optimum water content (Marsall, 1979), and, hence, the specimen prepared at optimum water content condition lie in between these two.

The relationship between the degree of saturation versus matric suction obtained from individually compacted specimens is different from the soil-water characteristic curve behavior, which is the variation of degree of saturation with suction for a single specimen. Moreover, the resulting soil structure (and aggregation) of the individually compacted specimens at various initial water contents will be different from specimens with a corresponding water content on the soil-water characteristic curve.

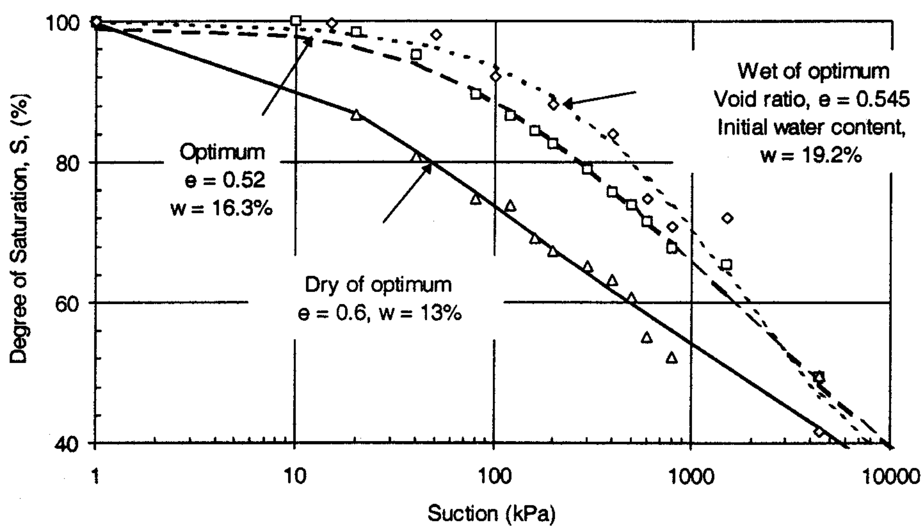

Figure 1. Soil-water characteristic curves for specimens compacted at three different initial water contents

3.2 Dry of Optimum Initial Water Content Conditions

Figure 2 shows the best-fit soil-water characteristic curve for a specimen with dry of optimum initial water content conditions ([] symbols). The degree of saturation versus matric suction results of individually compacted specimens are also shown (Δ symbols). The initial void ratios for all specimens are the same. Matric suction and corresponding degrees of saturation greater than 75% for individually compacted specimens lie above the best-fit soil-water characteristic curve.

The specimens with degrees of saturation greater than 75% have water contents above 16%. The resulting soil structure (and aggregation) at this water content and higher should be similar to the specimens at optimum and wet of optimum conditions.

The matric suction values of the individually compacted specimens with degrees of saturation less than 68% and corresponding water content of 14.5% are comparable to the values of suction and degree of saturation of the specimens used to determine the soil-water characteristic curve. At these water contents of approximately 14.5%, the individually compacted specimens and the specimen used for the soil-water characteristic curve can be considered to be "identical" due to their "similar" soil structure (and aggregation).

It is apparent that the individually compacted specimens at higher saturations are different from the specimens used to determine the soil-water characteristic curve. In these cases, the initial water contents of the specimens are different, and the resulting soil structure (and aggregation) is different. Over the selected range of water contents (i.e., from 12.5% to 19.2%) the degrees of saturation of the individually compacted specimens varied from 58.8% to 90.3%. These specimens are different from one another because they have different soil structures (resulting from the inter-particle aggregations) based on their initial water content.

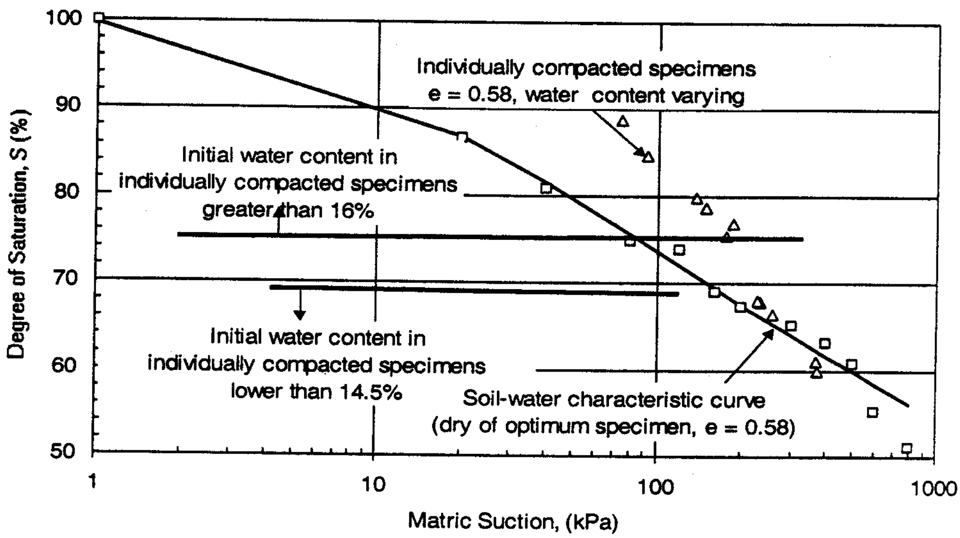

Figure 2. Comparison of soil-water characteristic curve for specimen compacted at dry of optimum water content and those compacted at the same initial void ratio

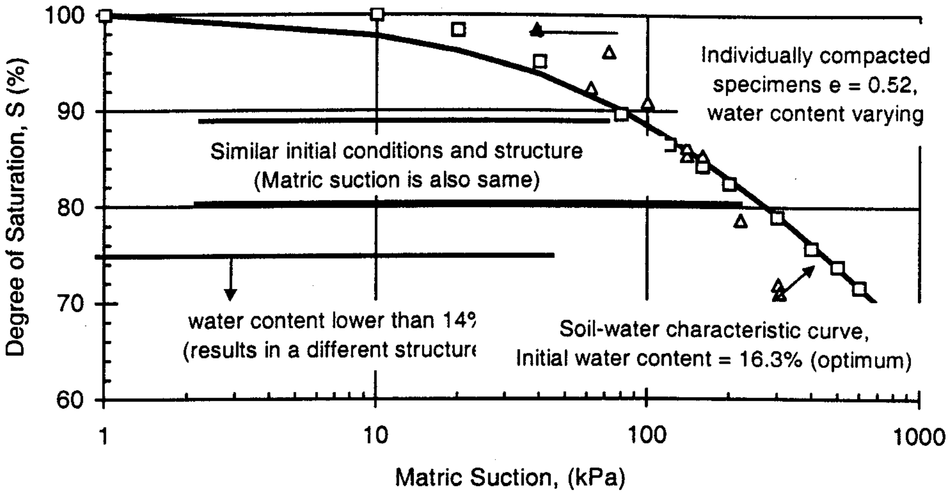

Figure 3. Comparison of soil-water characteristic curve for specimens compacted at optimum water content and those compacted at the same initial void ratio

3.3 Optimum Initial Water Content Conditions

Figure 3 shows the best-fit soil-water characteristic curve with optimum initial water content conditions (void ratio equal to 0.52 and initial water content of 16.3%). The degree of saturation versus matric suction of individually compacted specimens is also shown for comparison. The soil-water characteristic curve lies below the results of individually compacted specimens in the region of 0 to 150 kPa matric suction. The initial water content in individually compacted specimens for this range of matric suction is higher than 16.3% (i.e., degree of saturation greater than 86%). With the increased water content in the compacted specimens, the soil aggregations differ and result in a different soil structure. As the water content in the individually compacted specimens decreases, the values of matric suction fall below the soil-water characteristic curve. This discrepancy is expected because the specimens with lower water contents exhibit a different soil structure based on their aggregation, which in turn depends on the water content. The resulting structure (or aggregation) is similar to the soil structure expected for specimens with dry of optimum conditions. At a degree of saturation around 86% (i.e., at 16.3% water content), both the individually compacted specimens and the specimen used for the soil-water characteristic curve show similar matric suction values. This correspondence is possible as both the structure and density in the two specimens are approximately the same or essentially "identical".

3.4 Wet of Optimum Initial Water Content Conditions

Figure 4 gives the comparison of the soil-water characteristic curve obtained using wet of optimum initial conditions (i.e., initial water content equal to 19.2%) with individually compacted specimens. The individually compacted specimen results fall below the soil-water characteristic curve. The individually compacted specimens were tested with water contents in the range of 13 to 19.2%. It can be seen that as initial water contents in the individually compacted specimen increases, the agreement with the soil-water characteristic curve also increases.

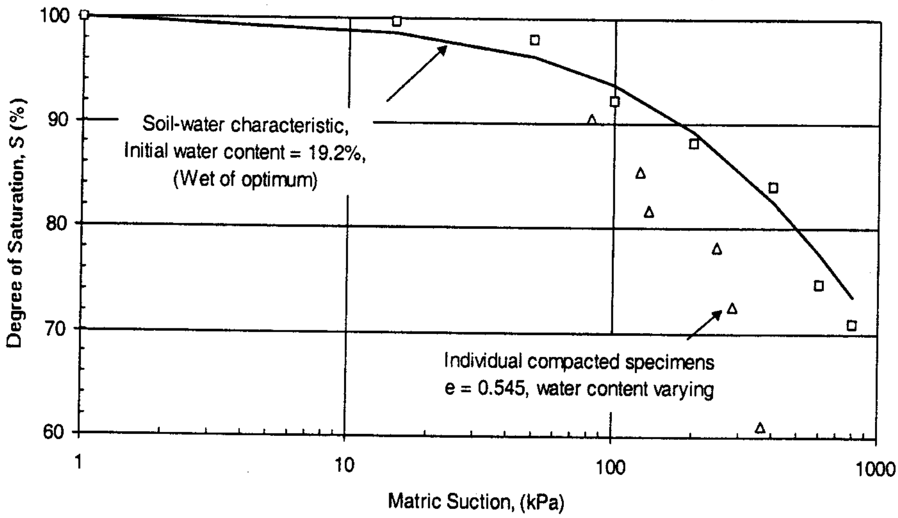

Figure 4. Comparison of soil-water characteristic curve for specimens compacted at wet of optimum initial water content and compacted at the same initial void ratio

Figure 5 shows the degree of saturation versus matric suction for all of the individually compacted specimens with different initial water contents for the three void ratios (i.e., dry densities) tested. The figure shows that the results fall within a narrow band. The same data, when plotted as gravimetric water content versus matric suction, show a clearer relationship (Figure 6). Olson and Langfelder (1965) and Krahn and Fredlund (1972) reported similar observations for a wider range of void ratios (i.e., dry densities). Thus, for the void ratios used in this study (i.e., 0.52 to 0.58), it is the initial water content which governs the matric suction of individually compacted specimens, and not the initial void ratio.

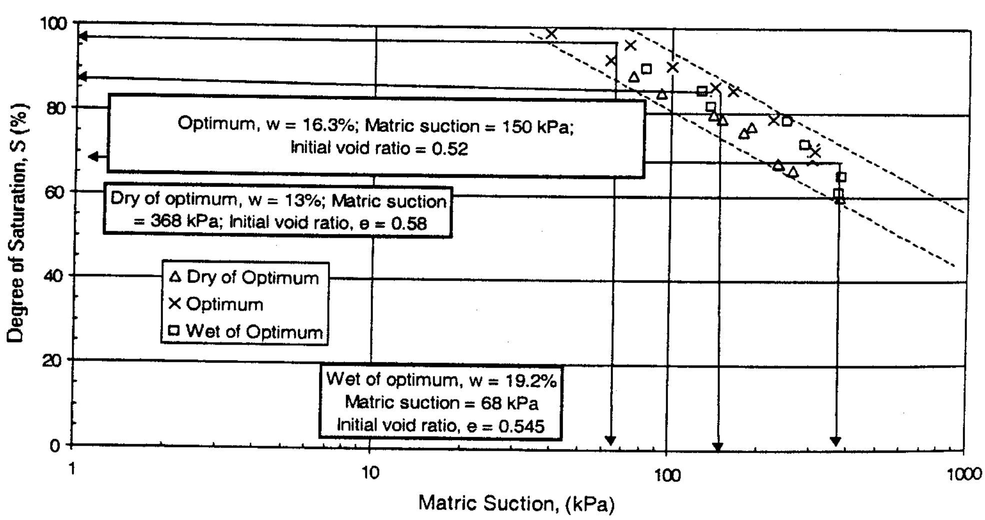

Figure 5. Degree of saturation versus matric suction values for compacted specimens

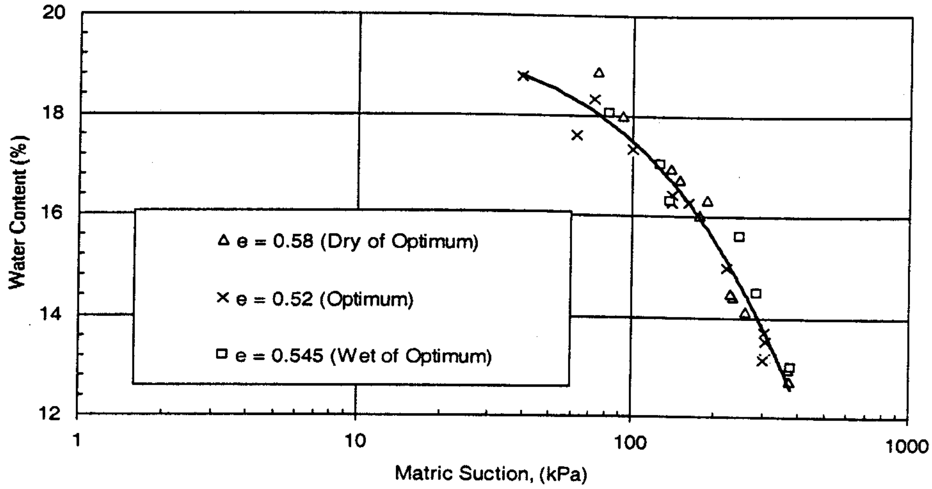

Figure 6. Gravimetric water content versus matric suction for compacted specimens

4 SUMMARY AND CONCLUSIONS

The initial moulding water content has a considerable influence on the resulting structure (and aggregation) of fine-grained soils such as the clay till used in this research program. Macro structure influences the soil-water characteristic curve for specimens compacted dry of optimum initial water contents, particularly in the low range of suction values. The dry of optimum specimen exhibits a steeper soil-water characteristic curve when compared with specimens compacted at optimum and wet of optimum water contents. The dry of optimum specimens act more like a coarse grained soil with a highly aggregated macro structure.

The matric suctions of individually compacted specimens determined from null pressure plates were dependent on the initial water content rather than the initial void ratio. At "identical" conditions (i.e., at similar densities, water contents and stress state conditions) the matric suctions corresponding to a particular degree of saturation were observed to be the same as those given by the soil-water characteristic curve. Re-analysis along similar lines for results of two different soils: a silty soil tested by Oloo (1994) and a clayey soil tested by Shuai (1995) have provided similar results. Hence, the conclusions of this study should be valid for most fine-grained soils.

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