

Soil-Water Characteristics Curves for Reddish Brown Tropical Soil

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ABSTRACT

Soil-water characteristics curves (SWCCs) are presented for three compacted reddish brown tropical soils that were prepared at different compaction water contents (dry, wet and optimum water content) and compactive efforts (reduced Proctor, standard Proctor, West African Standard and modified Proctor). The SWCCs were measured in the laboratory using pressure plate extractors. The shape of the SWCC depends on the soil structure, compaction water content and compactive effort. Compaction at higher compaction water content or with greater compactive effort results in larger air entry. Changes in the shape of the SWCC are consistent with changes in pore size that occur by varying compaction conditions. These changes in the SWCC are also reflected in the van Genuchten and Brooks-Corey parameters, which were obtained from fits to the SWCC data.

KEYWORDS: Soil-water characteristics curve, reddish brown tropical soils, compaction water content, compactive effort

INTRODUCTION

Unsaturated soil mechanics has become a necessary tool for analyzing the behaviour of soils in the vadose zone and the flux boundary conditions as required in many geotechnical and geoenvironmental problems (Fredlund and Rahardjo, 1993a). Compacted natural soils used as hydraulic barriers in waste containment facilities such as engineered landfills are often unsaturated and modeling of flow and transport through these soils require the knowledge of their unsaturated hydraulic properties. It is the water content versus matric suction relationship which becomes an important additional relationship in qualifying unsaturated soil behaviour (Fredlund and Rahardjo, 1993b)

The soil – water characteristics curve (SWCC) defines the relationship between (pore water suction) matric suctions (ψ) and water content [gravimetric (w) or volumetric (θ) or degree of saturation (S)] (Tinjum et al., 1997). The soil – water characteristics can be described as a measure of the water holding capacity (i.e storage capacity) of the soil as the water content

changes when subjected to various values of suction. The *soil – water characteristics* is a conceptual and interpretative tool through which the behaviour of unsaturated soils can be understood. As the soil moves from the saturated state to drier states (unsaturated states), the distribution of the soil, water and air phases change as the stress state changes. The relationships between these phases take on different forms and influence the engineering properties of unsaturated soils (Fredlund and Rahardjo, 1993a; Fredlund, 1996; Vanapalli et. al. 1999).

The relationship between pore water suction and water content, as presented in a SWCC is one fundamental relationship used to describe unsaturated behaviour of a soil. Suction is inversely proportional to the water content in a soil. Suction generally increases as the soil desaturates. Increasing suction generally results in high resistance to flow and increase in effective stress. Desiccation is a by-product of the increased effective stress (Miller et al., 2002). Increasing suction in compacted clays due to decrease in water content modifies the flow behaviour of covers. During desiccation, the saturation of a liner is reduced and the remaining pore water is held at increasingly large suction. The relationship between saturation and suction during desiccation is described using the SWCCs. Knowledge of suction and corresponding water content in the soil can be used to predict cracking potentials of liners. The onset and resulting amount of cracking can be correlated to a soil-specific critical suction level (Miller et al., 1990). Hence, the SWCC provides critical input to the design of a compacted clay cover liner due to its potential impact on flow rates and the desiccation process.

A typical SWCC is shown in Fig. 1. Several defining parameters of the curve include the matric suction which correspond to the break in the curve (near the saturated water content, θ_s) is referred to as the air entry suction (ψ_a). This air entry suction corresponds to the matric suction required to remove water from the largest pores (Brooks and Corey, 1966). The water content corresponding to the asymptote of the SWCC at low degrees of saturation is called the residual water content (θ_r). It is also the degree of saturation, or gravimetric water content, or volumetric water content beyond which it becomes increasingly difficult to remove water from a specimen by drainage.

The traditional soil – water characteristics has been defined over a range of suction that is limited from 0 to 1500 kPa. A suction value 1500 kPa has taken on significance as ‘residual suction’ because it corresponds to the wilting point for many plants (van Genuchten, 1980). However, this arbitrary value may not actually correspond to a residual state of saturation condition (Vanapalli et. al., 1999). At zero water content the soil matric suction is appropriately 1,000,000 kPa (Fredlund et. al., 1994). This dry condition is achieved by oven drying the soil. It is necessary to define the residual state of saturation hydraulic conductivity (Brooks and Corey, 1964; van Genuchten, 1980).

The shape of the SWCC is a function of the soil type. Soils with smaller pores have higher air entry pressure (ψ_a). Soils with wider ranges of pore sizes exhibit greater changes in matric suction with water content (Hillel, 1980; Fredlund and Rahardjo, 1993a). The SWCCs of compacted clay soils depend on the compaction water content, compactive effort and plasticity index (Tinjum et al., 1997). Several models have been used to describe the SWCC, commonly used one includes the Brooks-Corey (1964); van Genuchten (1980); Fredlund and Xing (1994); and these were reviewed by Leong and Rahardjo (1997a). The two most common models are the Brooks – Corey equation (Brooks and Corey, 1964, 1966) and van Genuchten equation (van Genuchten 1980). These two models have been used in this work to describe the unsaturated behaviour of the test soils.

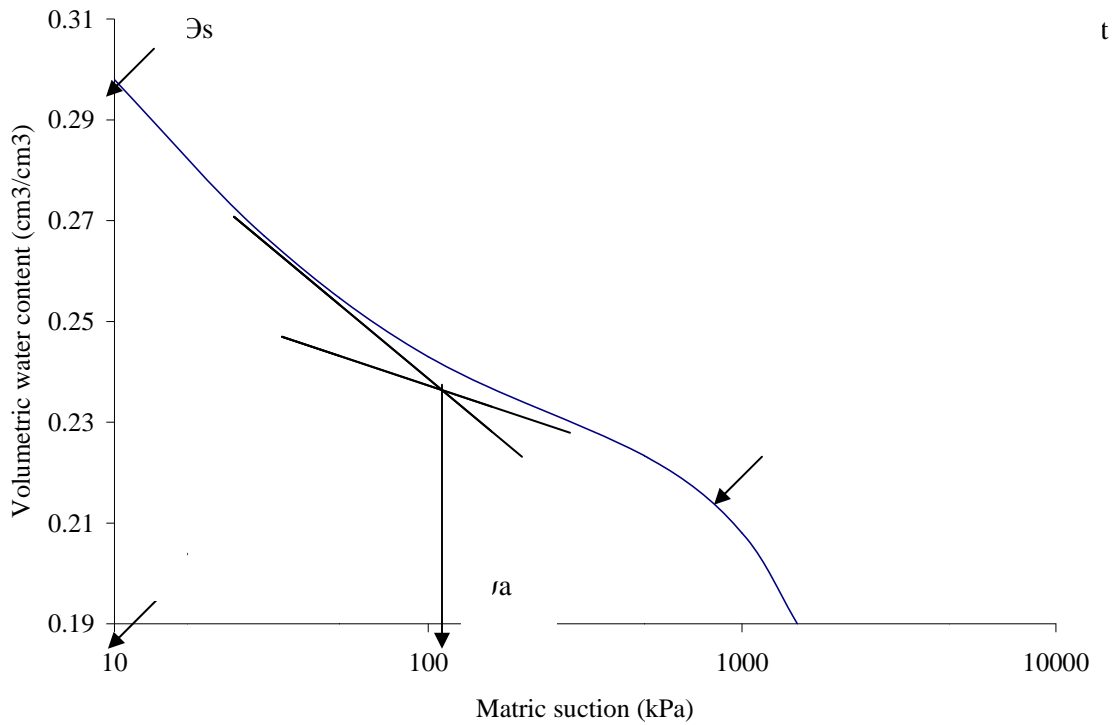


Figure 1: Typical Soil Water Characteristics Curve

The Brooks – Corey model is expressed as:

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left(\frac{\psi_a}{\psi} \right)^\lambda \quad \psi \geq \psi_a \quad (1)$$

$\Theta = 1$ and $\theta = \theta_s$ where $\psi < \psi_a$

where Θ is a normalized, dimensionless volumetric water content; and λ = a fitting parameter called the pore-size distribution index, θ_s is the saturated volumetric water content, θ_r is the residual volumetric water content, θ is the actual volumetric water content (Corey, 1994).

The van Genuchten model is expressed as:

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left\{ \frac{1}{[1 + (\alpha\psi)^n]} \right\}^m \quad (2)$$

where α , n and m are fitting parameters and m is equal to $1 - n^{-1}$. α = a soil parameter related to the air entry value of “bubbling pressure”; parameter m , rotates the sloping portion of the curve. As m increases, the range of the curve between ψ_a and the knee (the point of inflection at the lower portion of the curve as it approaches a horizontal position) of the SWCC decreases. The parameter is the pivot point of the curve and its value is related to the value of the air-entry suction. As α increases, the air- entry suction increases. The parameter n controls the slope of the SWCC about the pivot point, which occurs at normalized volumetric water content (Θ) of 0.5. As n increases, the sloping portion of the curve between ψ_a and the knee of the SWCC becomes steeper (Miller et al., 2002). Each of these parameters is described by Leong and Rahardjo (1997a, b).

Equations describing the SWCC have been classified into three-parameter and four-parameter equations while the classification of SWCC equations into unimodal and bimodal SWCC functions are presented by Burger and Shackelford (2001). Dual porosity models are also available (Burger and Shackelford, 2001). Thus, other models are those of Mckee and Bumb (1984, 1987).

The factors which influence the SWCC of soils include texture, structure and clay mineralogy (Williams et al., 1983), compaction energy (Marinho and Stuermer, 2000), as well as stress state (Ng and Pang, 2000). Many researchers (Arya and Paris, 1981; Arya et al., 1999a, b; Fredlund et al., 2000) have shown that the SWCC of soil can be predicted from grain size distribution (GSD) function as well as other soil index properties. Zapata et al. (2000) showed that the SWCC, whether measured or estimated, is highly variable. The variability of SWCC and the associated uncertainty is viewed to have some effect on any model for unsaturated soil behaviour that makes use of this relationship.

MATERIALS AND METHODS

Soils

The soil samples used in this research work are a natural material that is reddish brown lateritic soil obtained from borrow pit at Moniya, Akinyele Local Government, Ibadan (latitude $7^{\circ}27'$ and longitude $4^{\circ}59'$), South western Nigeria using the method of disturbed sampling. Lateritic soils in Ibadan area are often found in the area of peneplain (primary) laterite and are developed in-situ from different parent materials with or without the introduction of externally derived iron. The method of disturbed sampling was employed in obtaining soil samples for laboratory testing. The soil samples designated as MP1, MP2 and MP3 were obtained at depths of 0.80 – 2.90m. The soils are classified as A-7-6 according to the Association of American States Highway and Transportation Officials Classification System (AASHTO, 1986) and lean clay with sand (CL), according to the Unified Soil Classification System (BS, 1990). The specific gravities of the soils are in the range 2.62- 2.66, while their pH is in the range 6.10 - 6.20. The percent passing BS No. 200 sieve are in the range 59.2 - 66.4%. The summary of the index properties of the soil samples are summarized in Table 1. The results of the particle size distribution are shown on Fig.1. The plasticity indices and activity were generally in the ranges 13 - 16% and 0.70 - 0.75, respectively. These values of activity, A (plasticity index, PI/clay fraction) are typical of those reported for kaolinitic soils by Mitchell (1976), Holtz and Kovacs (1981) as well as Oweis and Khera (1998).

All the soil samples are classified as A-7-6 according to the AASHTO classification system, while the Unified Soil Classification System (USCS) classifies the samples as CL, which is an indication of low plasticity clay (Bowles, 1992; Coduto, 2003; Punmia et al., 2005). On the basis of the Casagrande plasticity chart, these soils are inorganic clays of low to medium plasticity or sandy silty clays (Holtz and Kovacs, 1981). According to the engineering use chart (Wagner, 1957; Lambe and Whitman, 1979), these soils are impervious with respect to their permeability when compacted. The soils should be of medium compressibility when compacted and saturated and should be of good to fair workability as construction materials.

Table 1: Index properties of the soil samples

Properties	Soil Samples		
	MP1	MP2	MP3
Natural moisture content, %	5.2	5.9	5.6
Specific gravity	2.66	2.62	2.65
Liquid limit, %	43	48	44
Plastic limit, %	29	32	28
Plasticity index, %	14	16	16
Linear shrinkage, %	8.60	7.80	6.25
% Passing BS No. 40 sieve	80.1	77.25	81.55
% Passing BS No. 200 sieve	63.55	59.2	66.4
% < 2 μ m	23.63	21.57	25.39
AASHTO classification	A-7-6	A-7-6	A-7-6
USCS classification	CL	CL	CL
Group index	8	9	8
Activity	0.55	0.68	0.74
Derived parameters			
Grading modulus	0.61	0.67	0.60
Plasticity product	889.7	947.2	982.4
Plasticity modulus	1121.4	1236.0	1304.8

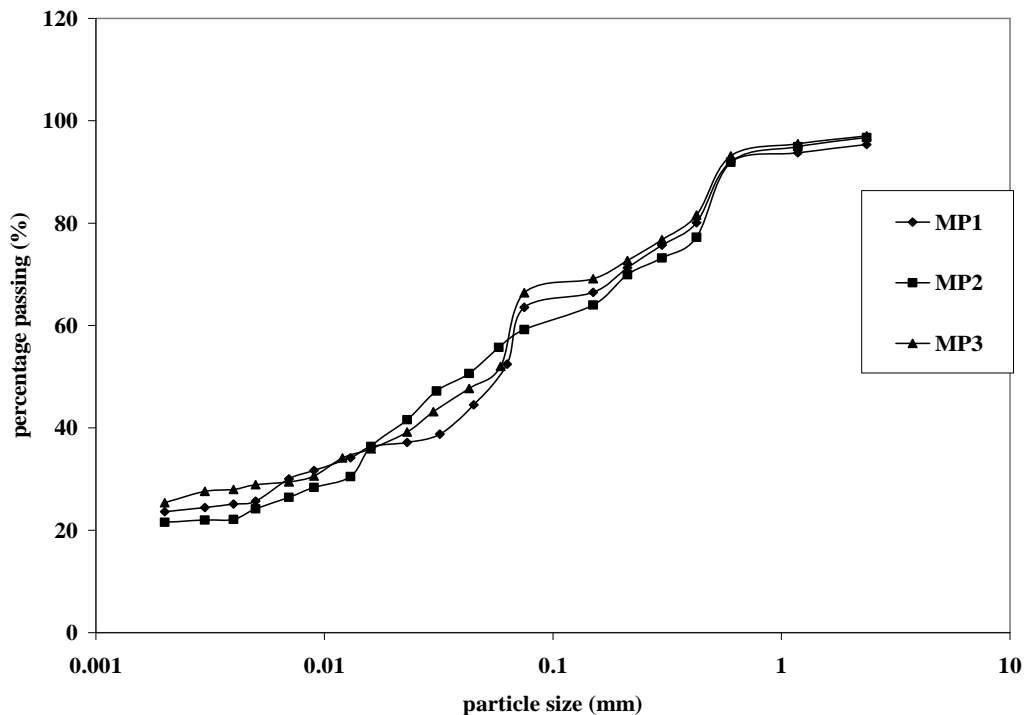


Figure 1: Particle-size distribution curves for the soil samples

Compaction

The sample specimens tested were prepared by mixing the relevant quantity of dry soil samples previously crushed to pass through BS No.4 sieve with 4.76 mm aperture as outlined by Head (1992) as well as Albrecht and Benson (2001). The specimens were moulded at water content in the range 5.25 - 25.5% and four different compactive efforts similar to those that might be achieved in the field.

The compaction methods used included the reduced Proctor (RP) effort described by Daniel and Benson (1990) as well as Benson and Trast (1995) which is equivalent to the Reduced British Standard Light (RBSL). The standard Proctor (SP) or British Standard Light (BSL) and modified Proctor (MP) or British Standard Heavy (BSH) are in accordance with BS 1377 (1990). The West African Standard (WAS) compaction is outlined in the Nigerian General Specification (1997).

Five to seven batches of soil each weighing 2.5 kg was placed in a tray and mixed with tap water. The reduced and standard Proctor compactions utilized 3 layers applying 15 and 27 blows each of a 2.5kg rammer falling from a height of 300mm using 1000cm³ mould respectively. The modified Proctor compactive effort involved the use of the same mould with a 4.5 kg rammer falling from a height of 450 mm applying 27 blows each and compacting in 5 layers. For the West African Standard compactive effort which is the conventional energy level commonly used in the region (Ola, 1980; Osinubi, 1998) consist of energy level derived from a 4.5 kg rammer falling through 450 mm height onto five layers using 10 blows each.

The calculation of dry densities and moisture contents followed procedures described in Head (1992). Calculated values were used to obtain the appropriate compaction curves, from which the maximum dry densities (or maximum dry unit weights) and the corresponding optimum water contents were estimated. The summary of the compaction characteristics are shown in Table 2.

Table 2: Compaction characteristics of soil samples

Properties	Samples		
	AB1	AB2	AB3
Maximum dry density, Mg/m ³			
Reduced Proctor	1.79	1.78	1.67
Standard Proctor	1.84	1.84	1.75
West African Standard	1.88	1.87	1.81
Modified Proctor	1.92	1.90	1.82
Optimum moisture content, %			
Reduced Proctor	14.9	15.0	14.5
Standard Proctor	14.4	14.5	14.2
West African Standard	14.3	14.1	14.0
Modified Proctor	13.8	14.0	13.5

Preparation and testing of specimens

Soil water characteristics curve (SWCC) specimens were prepared with four compactive efforts (reduced Proctor, standard Proctor, West African Standard and modified Proctor) at -2, 0 and +2% from the dry to the wet side of the line of OMC. 2.5kg of each specimen was moistened with tap water, mixed thoroughly and compacted in BS moulds and later cored into stainless steel rings with inside diameters of 50mm and heights of 50mm with the aid of a mallet. Each of the 36

specimens was covered with caps at both ends before saturation. The samples were subjected to full saturation by capillary action for a period of 3 weeks.

Volumetric pressure plate extractor

The SWCC is measured in the laboratory using volumetric pressure plate extractor. Pressure plate extractors work on the principle of axis translation which employs matric suction (pressure difference across the air-water interfaces, $\psi = u_a - u_w$

where u_a is the pore air pressure and u_w is the pore water pressure). In the pressure plate extractor, u_w is maintained constant ($u_w = 0$) and u_a is increased to obtain the desired matric suction (Tinjum et al.; 1997; Wang and Benson, 2004).

A pressure plate extractor consists of two main components: a porous plate air-entry pressure higher than the maximum matric suction to be applied during the test and a sealed pressure cell (Fredlund and Rahardjo, 1993). The porous plate is made of either ceramic or polymeric membranes. In the drying test, the soil starts at a saturated condition and the matric suction is gradually increased leading to a reduction in the water content in the soil specimen. The air-entry ceramic disk and the soil are first saturated. After saturation, excess water is removed from the cell. The soil specimen is placed on the high air-entry ceramic disk inside the retaining cylinder. The cell cover is then mounted and tightened into place and air-pressure is applied to the soil specimen in series of increments to achieve different matric suction (ψ). Each increment in air-pressure cause water to be expelled from the specimen until an equilibrium state is reached for the ψ that has been established. Additional increments in outflow are applied only and increment is measured (gravimetrically or volumetrically) to define the water content corresponding to each suction (Benson and Gibb, 1997; Kasim et. al., 1999; Miller et al., 2002; Wang and Benson, 2004).

Application of pressure

Pressure was applied in three batches as the pressure plate equipment has capacity for only 16 specimens. The entire pressure application lasted about 2 weeks, while the entire process from specimen preparation, saturation and pressure application lasted about 3 months. Pressure was applied using regulated compressed air from a compressor. The soils were subjected to pressures of 10, 30, 100, 500, 1000 and 1500 kPa, respectively. On completion of the test, the equipment was disassembled, the soil specimen removed and placed in an oven to determine its final gravimetric water content. All computations made were based on the original as-compacted soil volumes.

RESULTS AND DISCUSSION

Effect of compaction molding water content

The SWCCs showing the effect of molding water content for specimens prepared using reduced Proctor compactive effort are shown in Fig. 2a-c. Similar trends were observed at other compactive efforts as shown on Figs. 3a-c - 5a-c. Compaction water content affects the shape of the SWCC as shown in the plots. The resistance to water discharge is relatively lower in the dry of optimum specimens compared to optimum and wet of optimum specimens. This is due to the soil structure at compaction, since fine-grained soils 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, while the arrangement of the soil aggregates is referred to as the macrostructure (Mitchell, 1976). In compacted clayey soils, both structures are present. When soil samples are compacted at different molding water contents at the same compactive efforts, the resulting macro-structure is different.

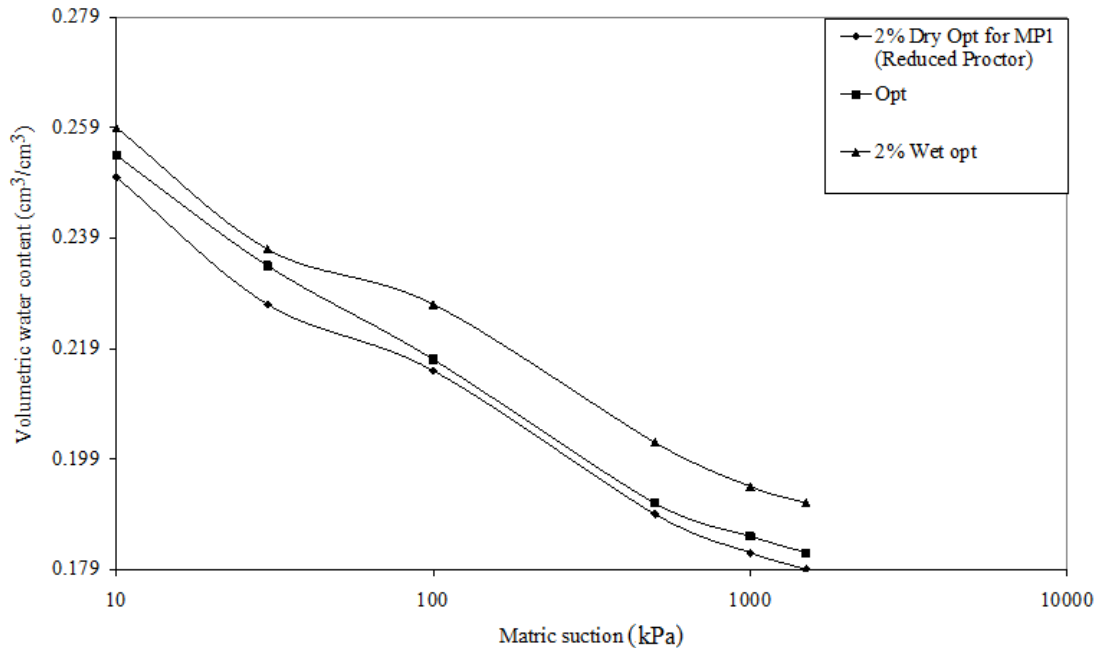


Figure 2a: Variation of soil water characteristics with matric suction for MP1 at reduced Proctor compactive effort

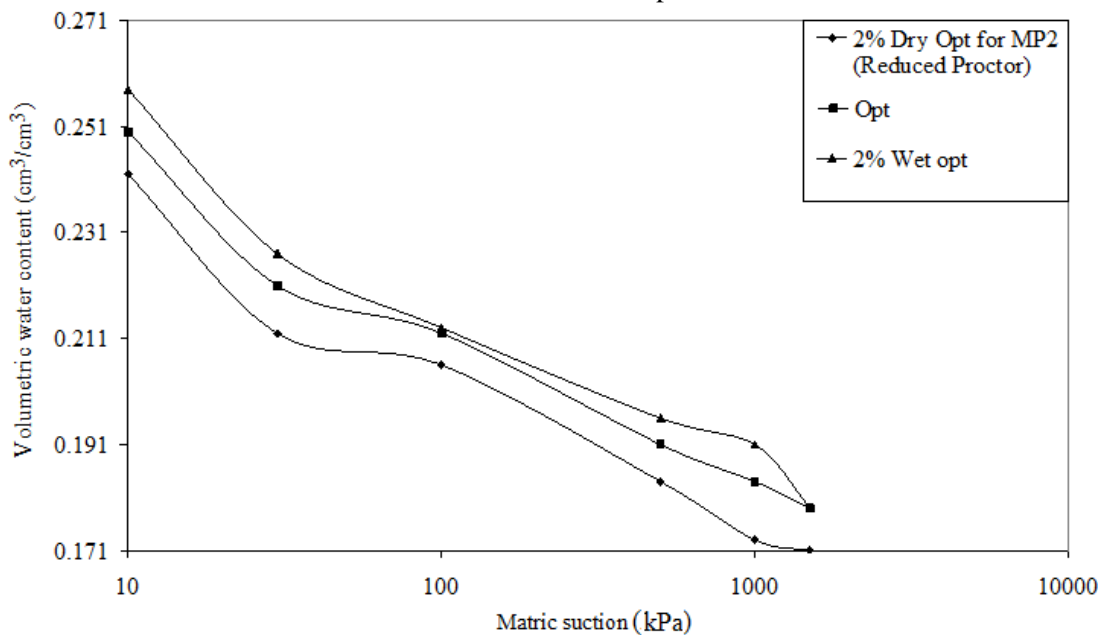


Figure 2b: Variation of soil water characteristics with matric suction for MP2 at reduced Proctor compactive effort

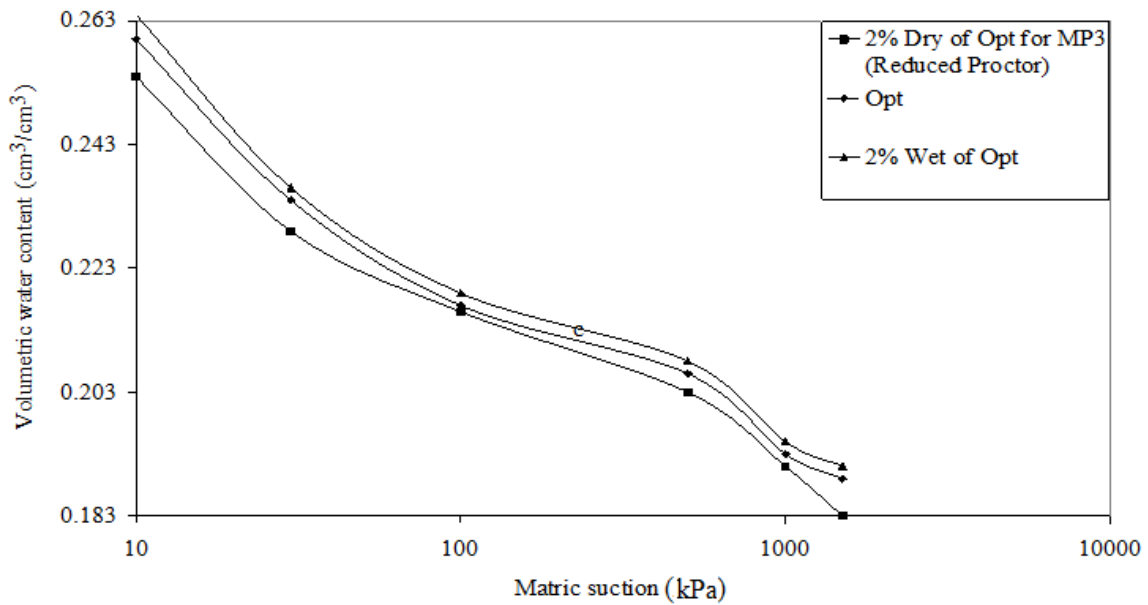


Figure 2c: Variation of soil water characteristics with matric suction for MP3 at reduced Proctor compactive effort

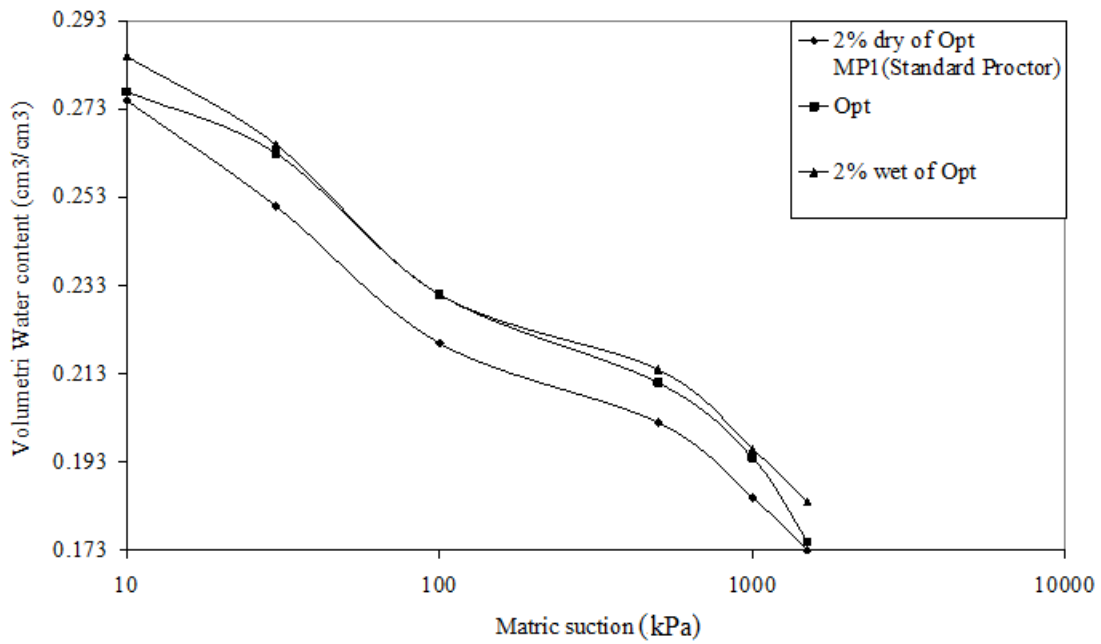


Figure 3a: Variation of soil water characteristics with matric suction for MP1 at standard Proctor compactive effort

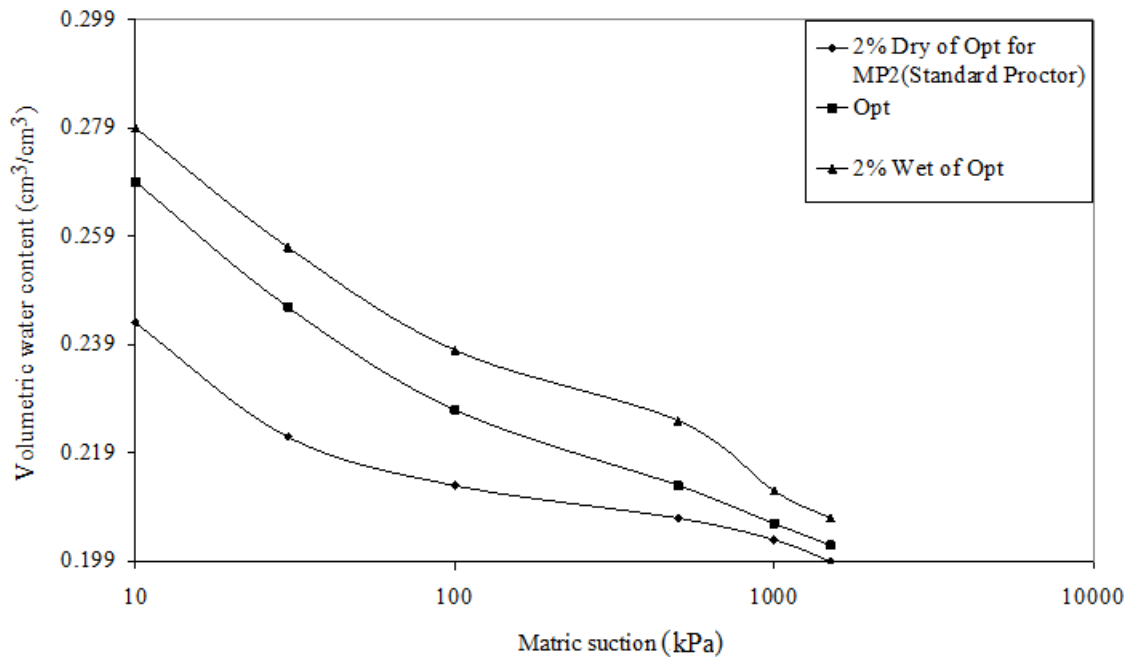


Figure 3b: Variation of soil water characteristics with matric suction for MP2 at standard Proctor compactive effort

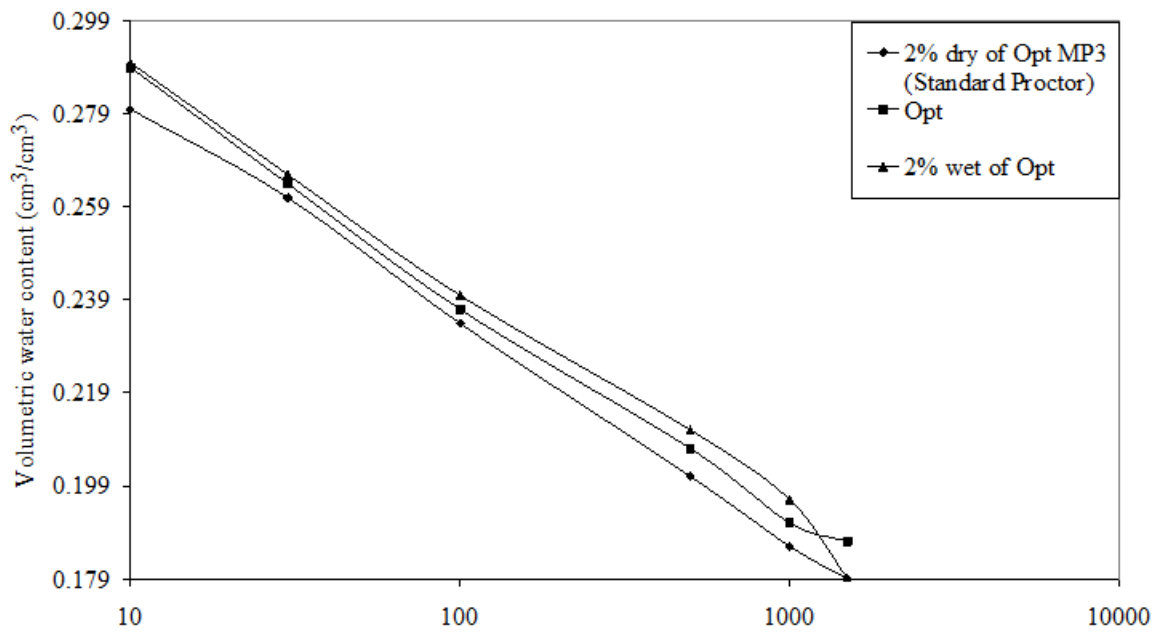


Figure 3c: Variation of soil water characteristics with matric suction for MP3 at standard Proctor compactive effort

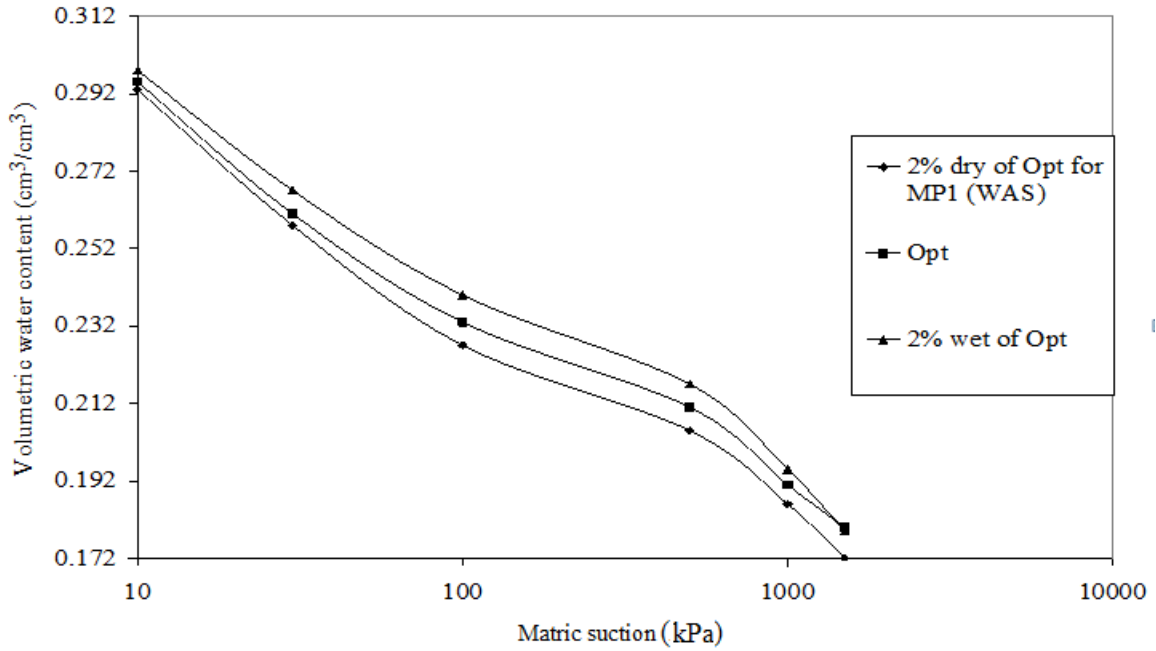


Figure 4a: Variation of soil water characteristics with matric suction for MP1 at WAS compactive effort

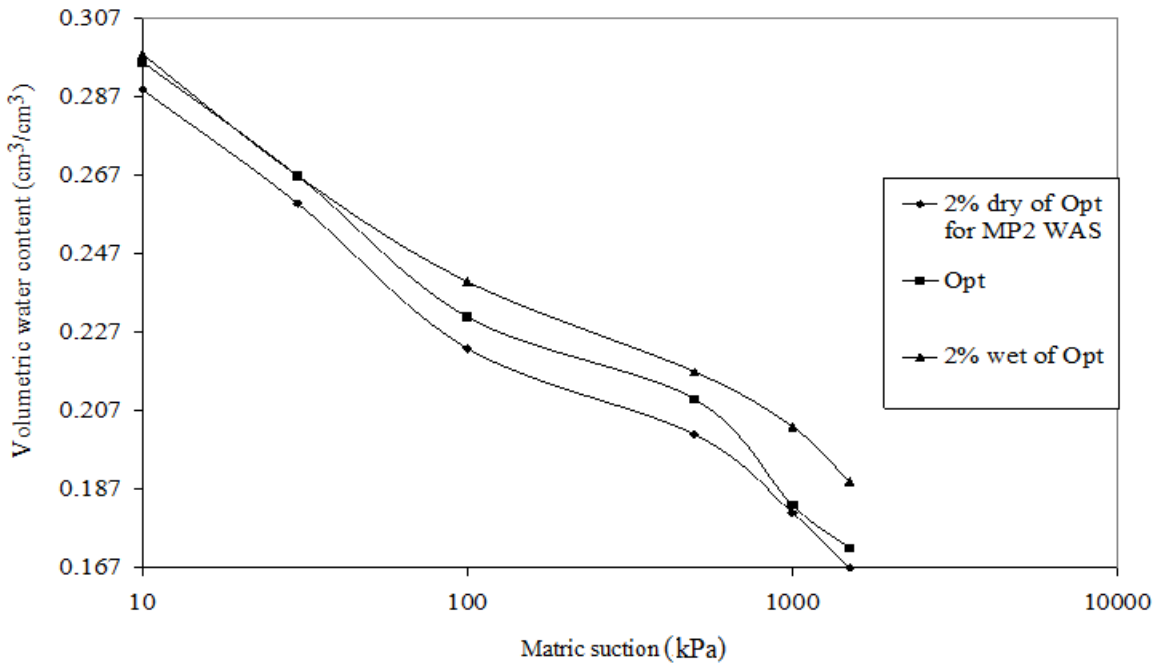


Figure 4b: Variation of soil water characteristics with matric suction for MP2 at WAS compactive effort

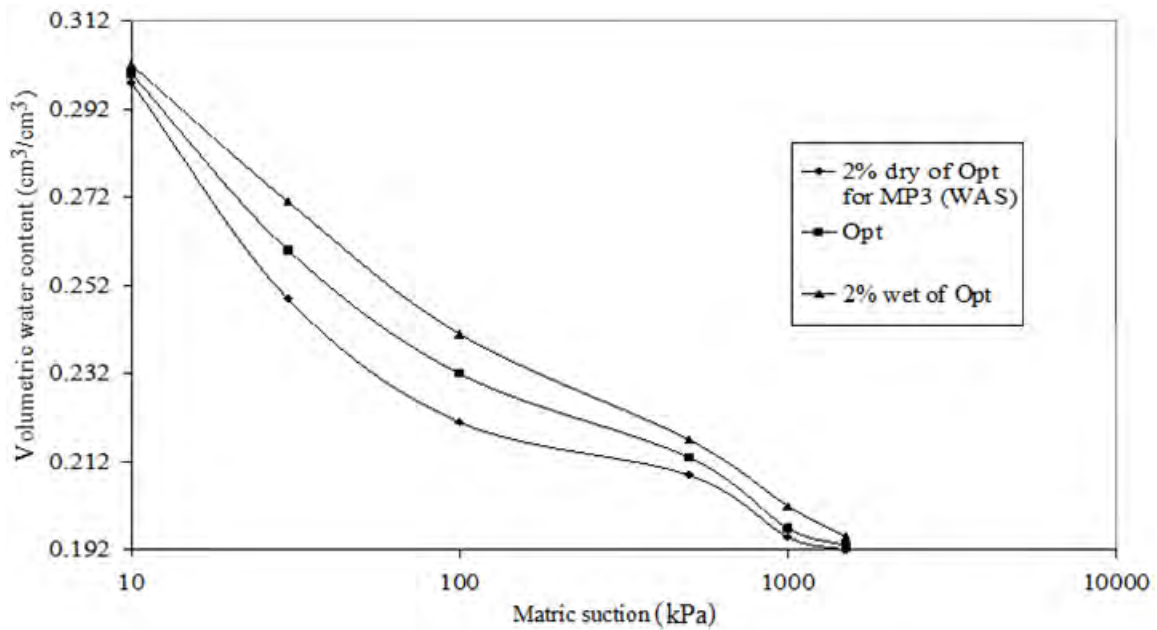


Figure 4c: Variation of soil water characteristics with matric suction for MP3 at WAS compactive effort

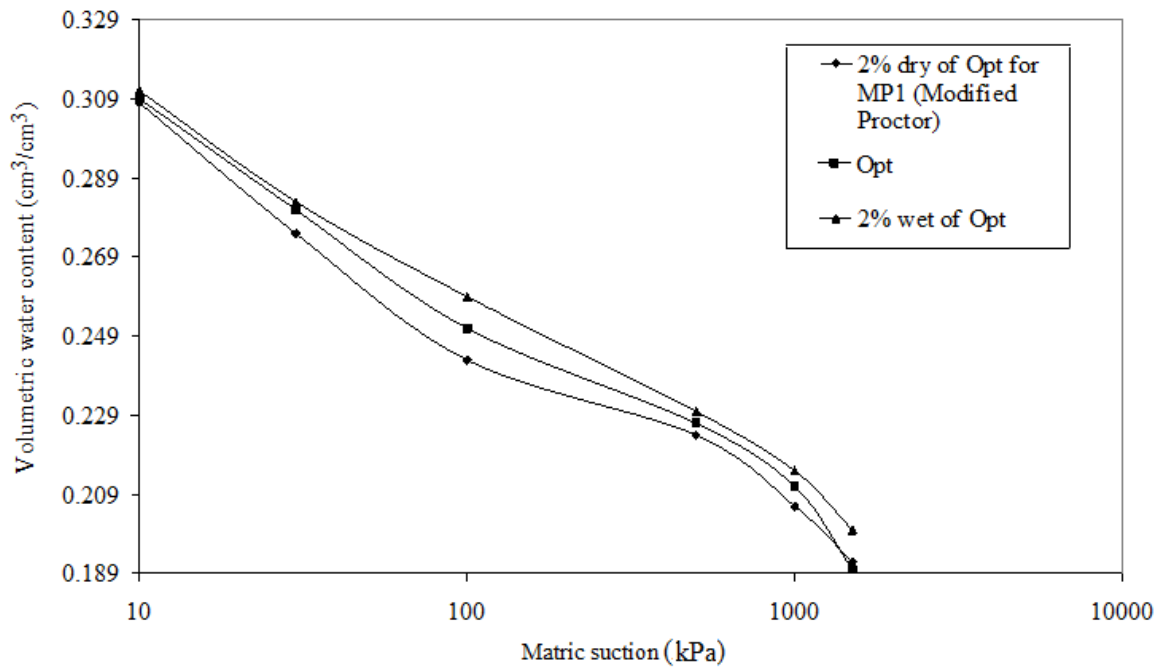


Figure 5a: Variation of soil water characteristics with matric suction for MP1 at modified Proctor compactive effort

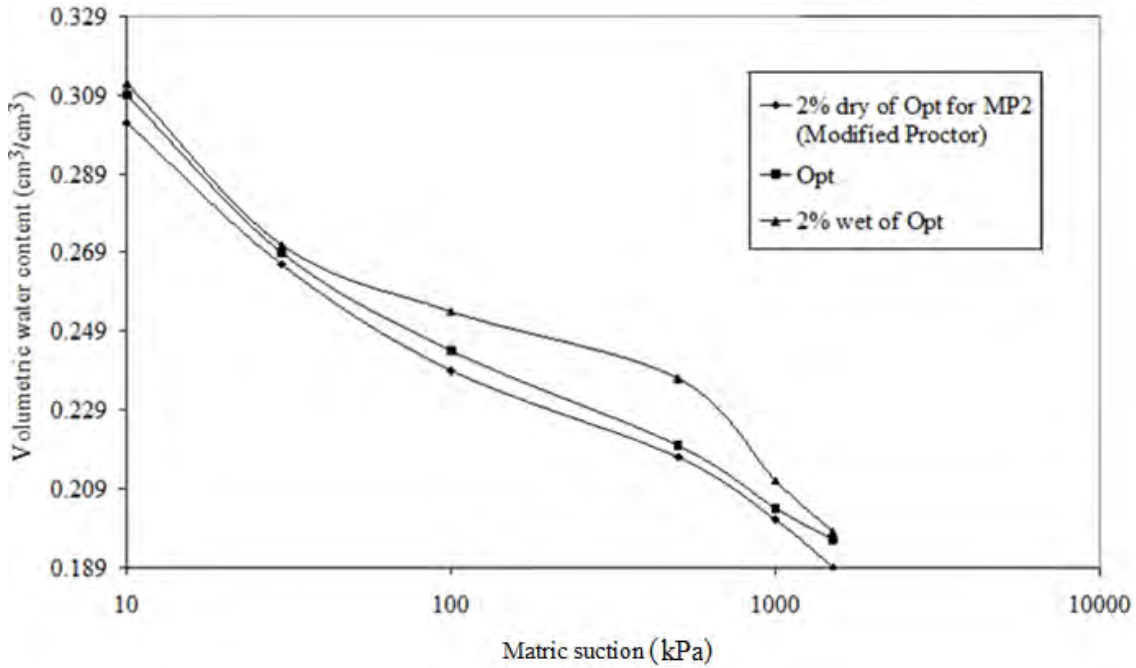


Figure 5b: Variation of soil water characteristics with matric suction for MP2 at modified Proctor compactive effort

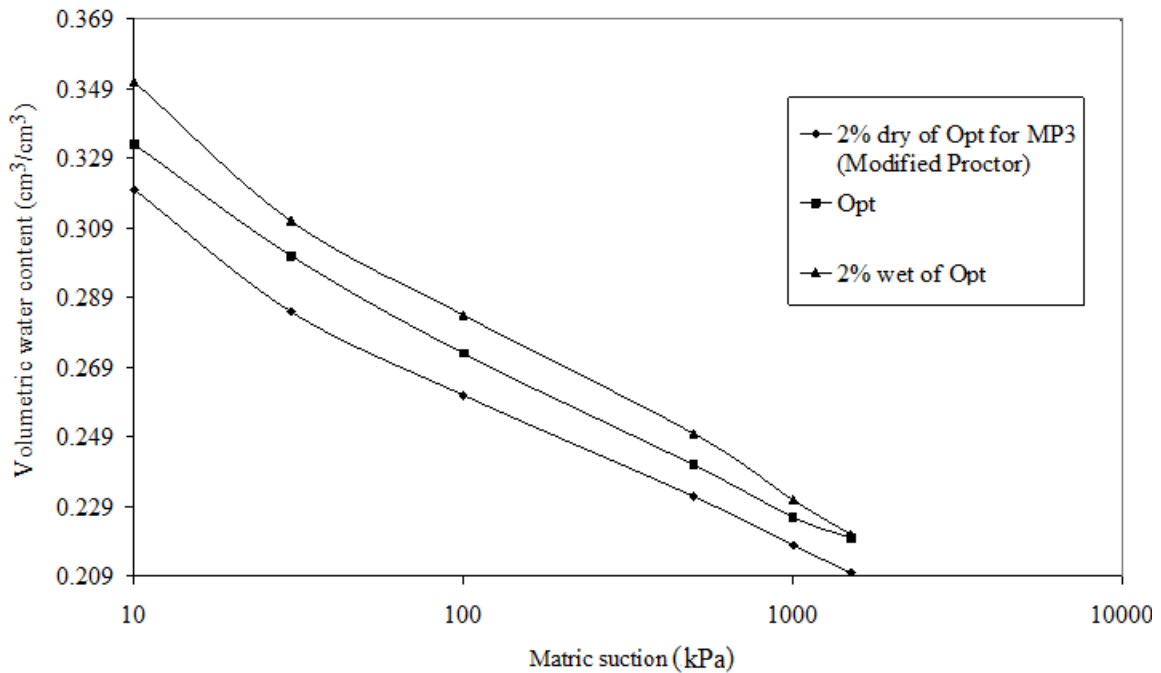


Figure 5c: Variation of soil water characteristics with matric suction for MP3 at modified compactive effort

The dry of optimum samples have bimodal pore-size distribution, with relatively larger pores (macro pores) which are located between the clods of the soil which were not remoulded during compaction. Relatively low suction values would be required to remove water from these larger pores, while higher suction would be required to remove water from microscopic pore spaces

between soil particles within the clods of clay. Hence the macro structure controls de-saturation of compacted clayey specimens prepared at water contents dry of optimum.

The observed trends in Figs. 2a-c through 5a-c can be attributed to differences in soil fabric and pore-size distribution at different molding water contents and compactive efforts. Compaction of soil dry of optimum results in flocculated soil fabric while those compacted wet of optimum have fabrics that are more oriented or dispersed for a given compactive effort (Holtz and Kovacs, 1981). A soil compacted at the same water content dry of optimum but with a higher compactive effort will be more oriented than that compacted at a lower effort as well as those compacted with a lower effort but at near the optimum. According to Diamond (1971) and Yong and Warkentin (1975), soil compacted at a given effort will have greatest pore size dry of optimum, followed by that compacted wet of optimum and then least pore size when compacted at optimum water content. Also, pore sizes reduce when a soil is compacted at the same water content but with a higher compactive effort. It then follows that at nearly all the compactive efforts and for matric suction values of 15,000 kPa, specimens of soils compacted dry of optimum have the least volumetric water contents. This is because of the large pore sizes due to the randomness in particle arrangement.

Moreover, samples compacted wet of optimum typically have broad unimodal pore-size distributions, primarily containing micro scale pores. The pore spaces are not generally interconnected; the increasing water content helped in deflocculating the particle structure thus, reducing the voids. These soils have higher water storage capacity due to their structure. They have no visible inter-clod pores and offer more resistances to de-saturation under an applied suction in comparison to specimen compacted dry of optimum. Hence the micro structure controls and resists the de-saturation characteristics of the soil. Samples compacted at optimum fall between both, since the boundary between the closed pore and open pore conditions occurs at water contents approximately equal to the optimum water content (Garcia-Bengochea et. al., 1979; Acar and Oliveri, 1990; Benson and Daniel, 1990; Vanapalli et. al., 1999; Tinjum et al., 1997; Nwaiwu, 2004).

Effect of compactive effort

The effect of compactive effort on soil water characteristics curve (SWCC) for each of the samples compacted at optimum moisture content is shown in Figs.6a-c. Generally, for each of the samples, SWCCs of specimens prepared at higher compactive efforts plot below those prepared at lower compactive efforts. This trend is line with the results reported by Tinjum et al. (1997) and Miller et al. (2002). Soils compacted with higher compaction energies have smaller pores but as the compactive effort increases, the optimum moisture content reduces leading to smaller amount of water being contained in the specimen at the same water content. There might probably be other factors responsible for this behaviour. A similar trend was observed for samples compacted at water content dry of optimum and wet of optimum as shown on Figs 7a-c - 8a-c, respectfully. SWCCs for different compaction energies overlap at different points where the relative positions of the curve are reversed.

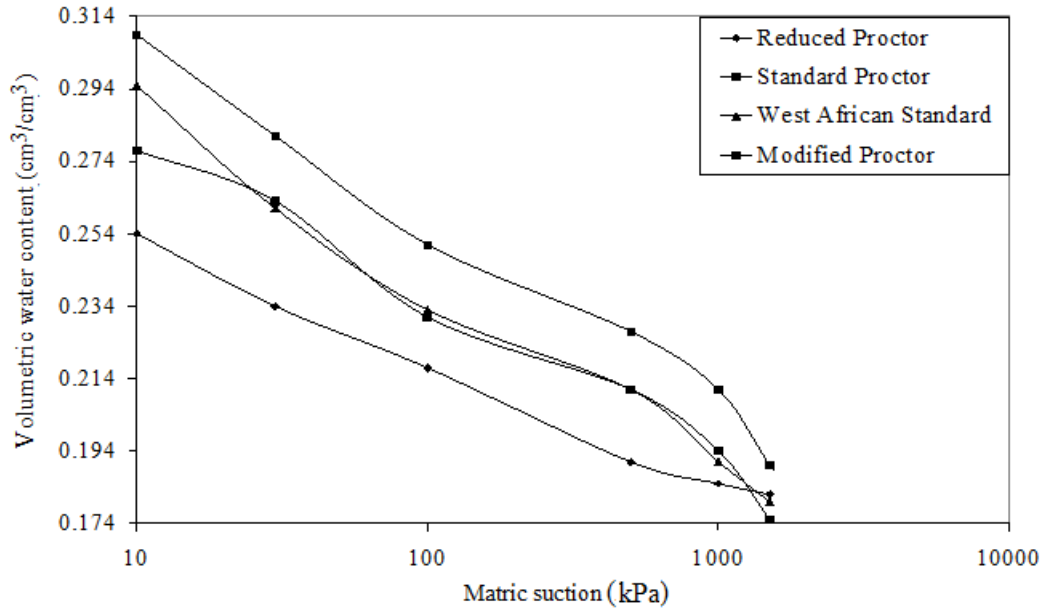


Figure 6a: Variation of soil water characteristics with matric suction at optimum moisture content for MP1 at different compactive efforts

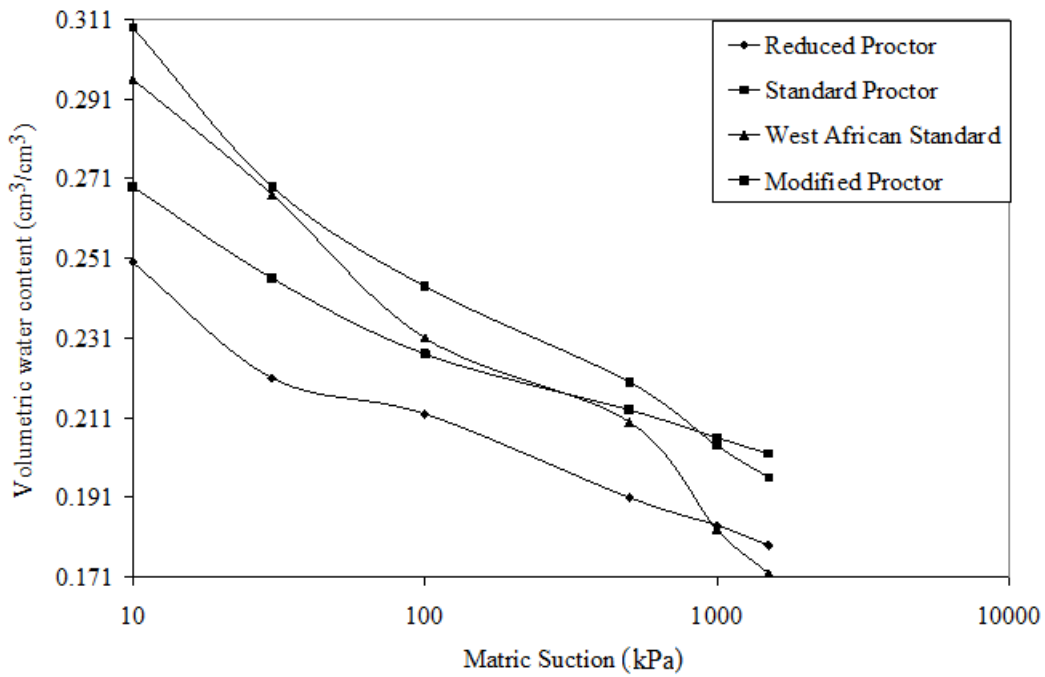


Figure 6b: Variation of soil water characteristics with matric suction at optimum moisture content for MP2 at different compactive efforts

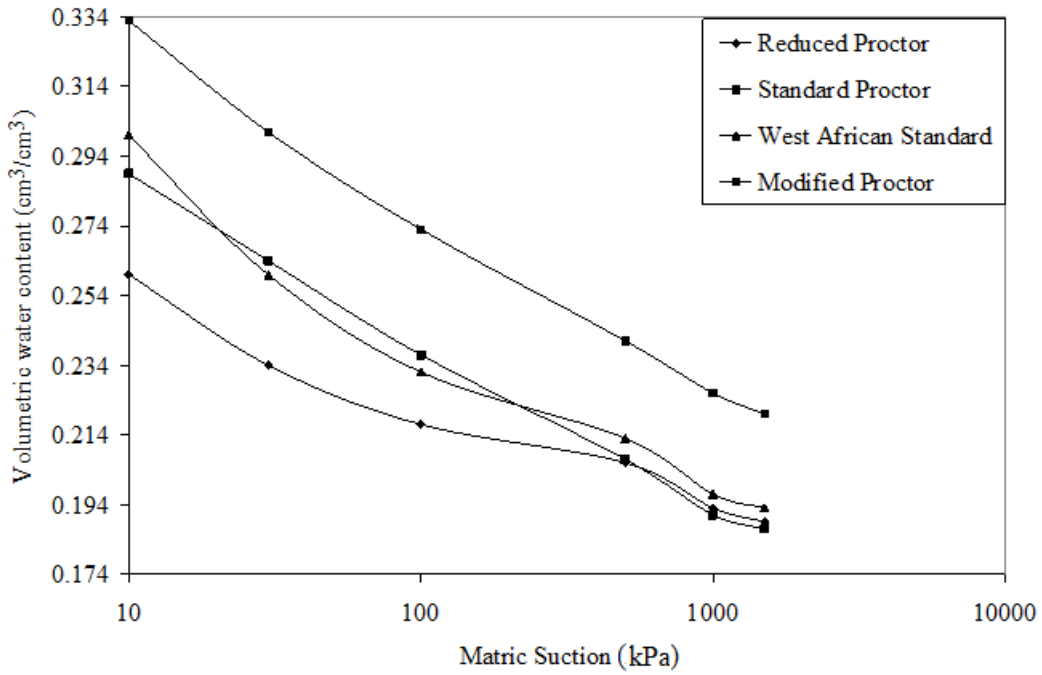


Figure 6c: Variation of soil water characteristics with matric suction at optimum moisture content for MP3 at different compactive efforts

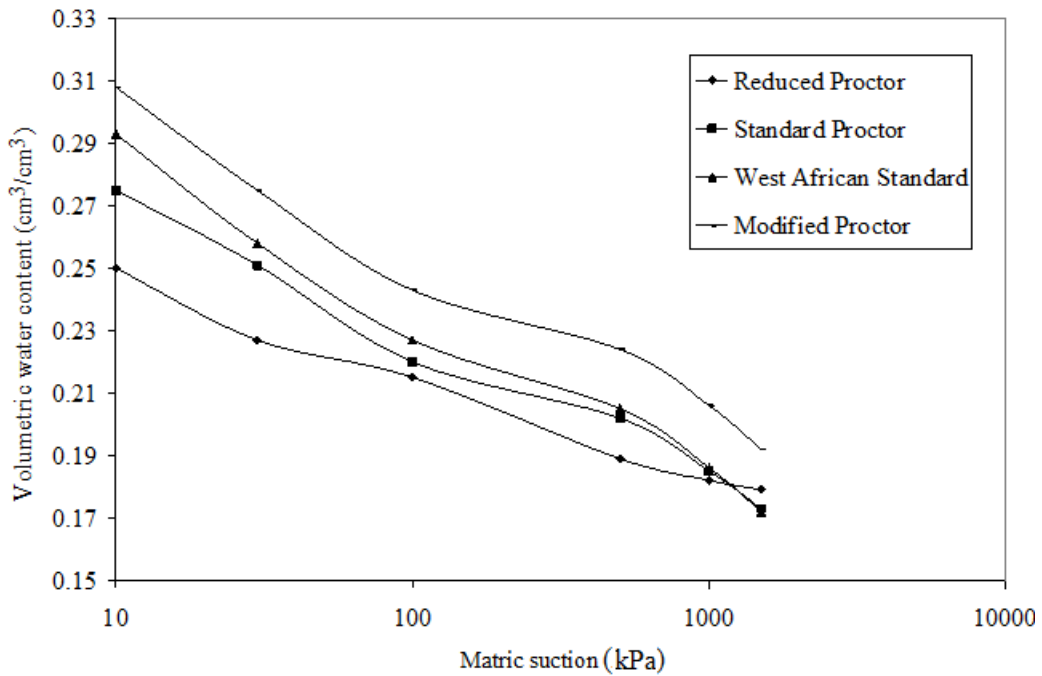


Figure 7a: Variation of soil water characteristics with matric suction dry of optimum moisture content for MP1 at different compactive efforts

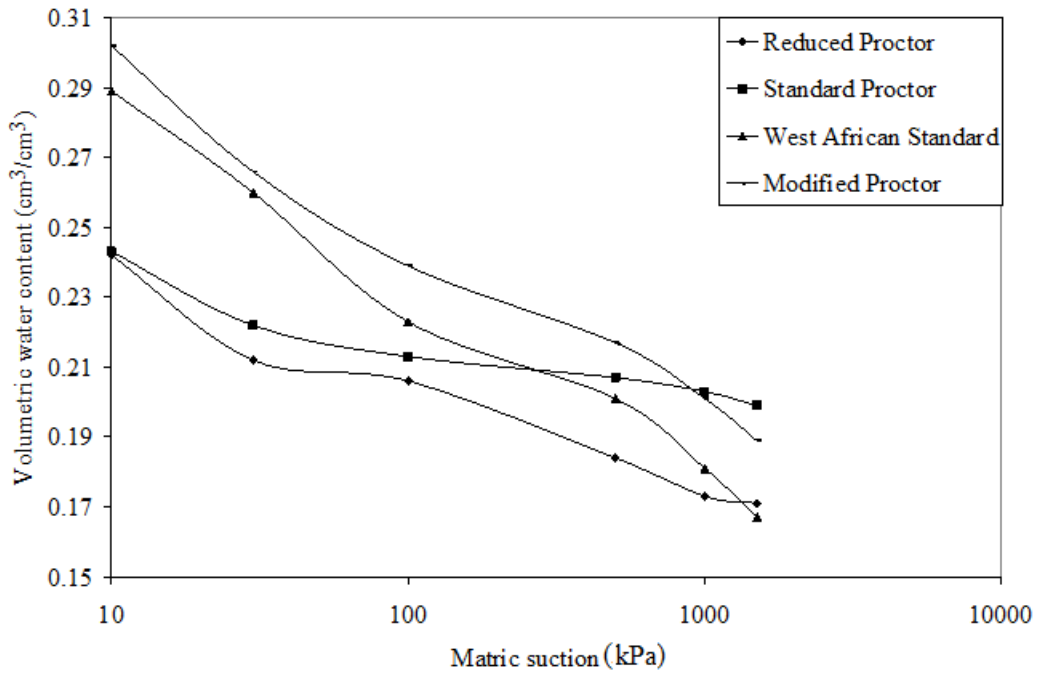


Figure 7b: Variation of soil water characteristics with matric suction dry of optimum moisture content for MP2 at different compactive efforts

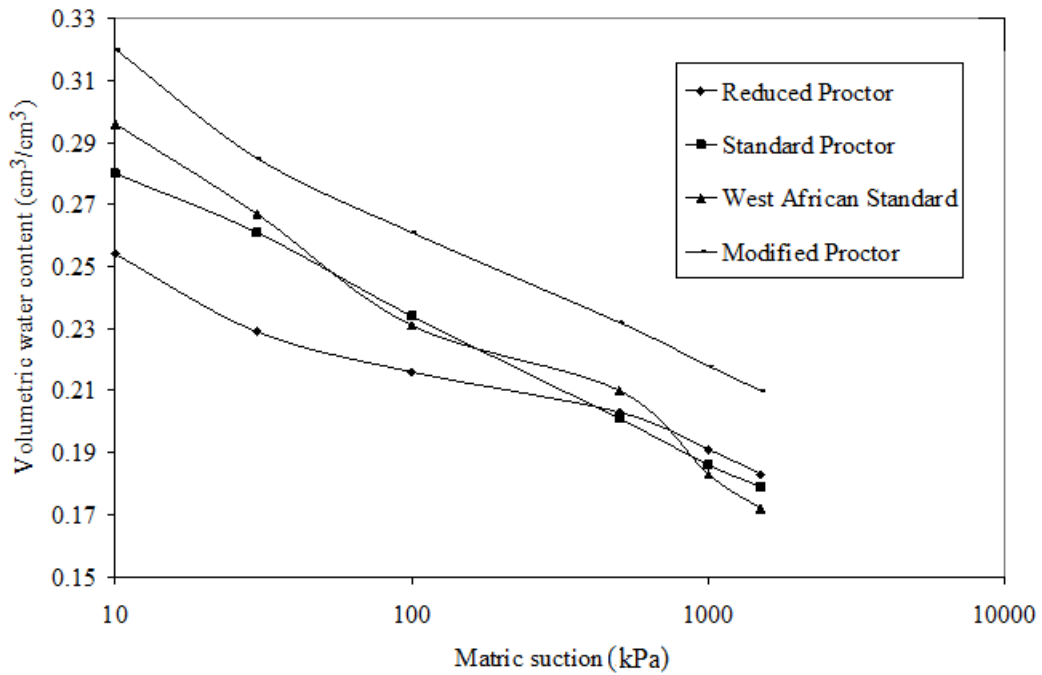


Figure 7c: Variation of soil water characteristics with matric suction dry of optimum moisture content for MP3 at different compactive efforts

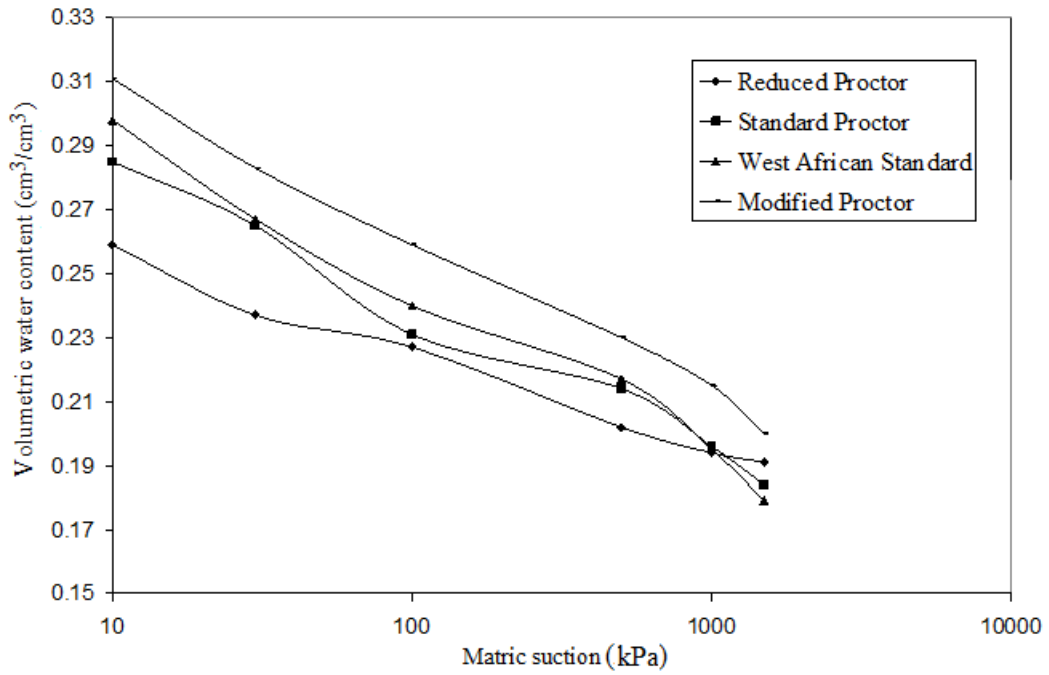


Figure 8a: Variation of soil water characteristics with matric suction wet of optimum moisture content for MP1 at different compactive efforts

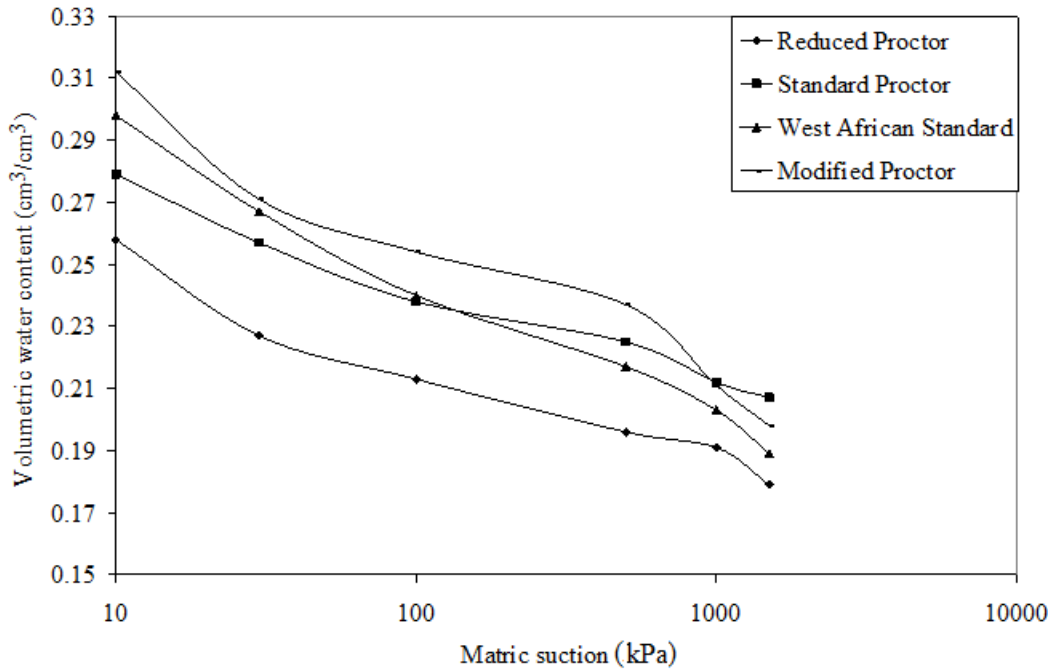


Figure 8b: Variation of soil water characteristics with matric suction wet of optimum moisture content for MP2 at different compactive efforts

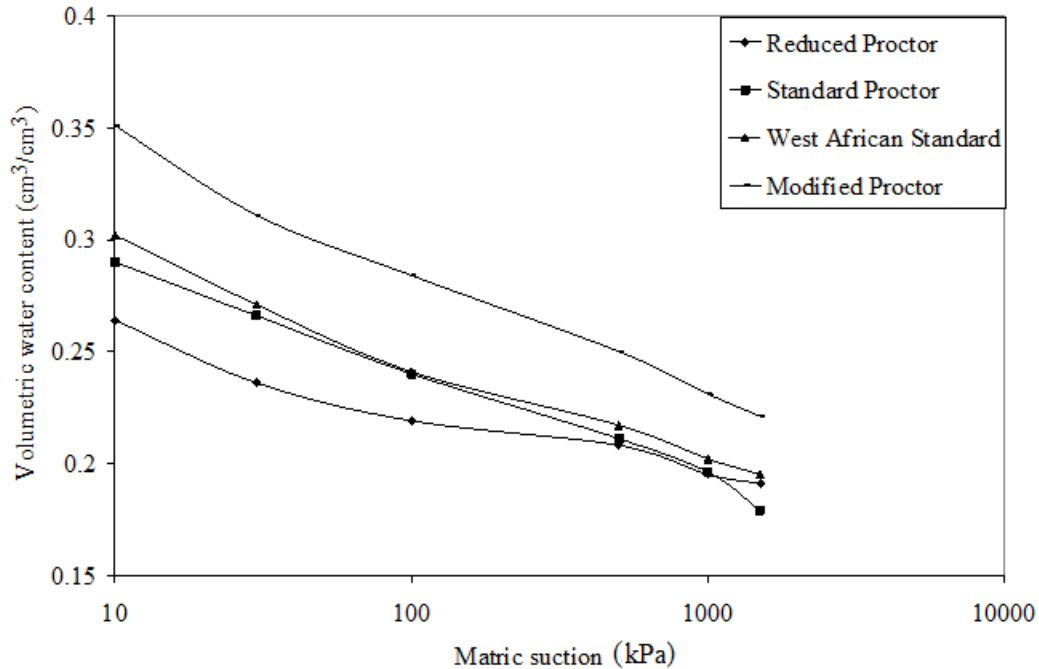


Figure 8c: Variation of soil water characteristics with matric suction wet of optimum moisture content for MP3 at different compactive efforts

SOIL WATER CHARACTERISTICS CURVE PARAMETERS

Effect of molding water content on SWCC parameters

The effect of molding water content on the soil water characteristics curve parameters (i.e., van Genuchten n and α) as well as Brooks-Corey λ) are shown in Fig. 10a-c. van Genuchten n and α decreased with higher molding water content (see Fig. 10a, b). The result is in agreement with data reported by Tinjum et al. (1997) and Miller et al. (2002). As the molding water content increased it became more difficult to de-saturate the specimen since the micro scale pores with minimal void ratio is dominant. Generally the Brooks-Corey pore size distribution index (λ) increased with higher compaction molding water content as shown in Fig. 10c.

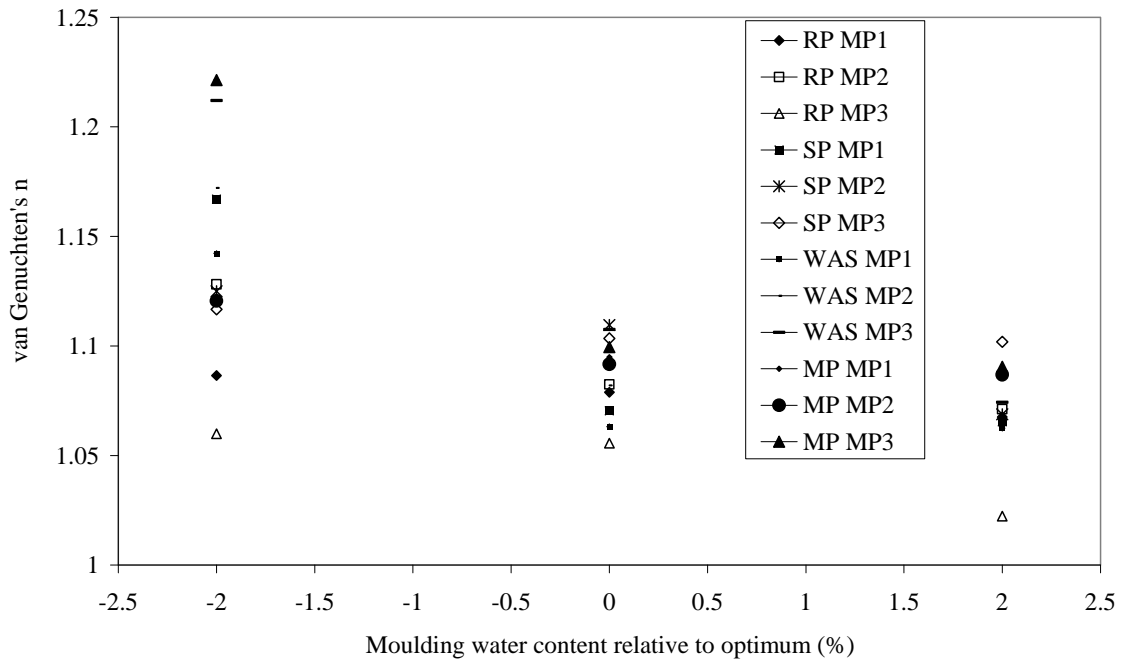


Figure 10a: Variation of van Genuchten n with water content relative to optimum for MP1, MP2 and MP3

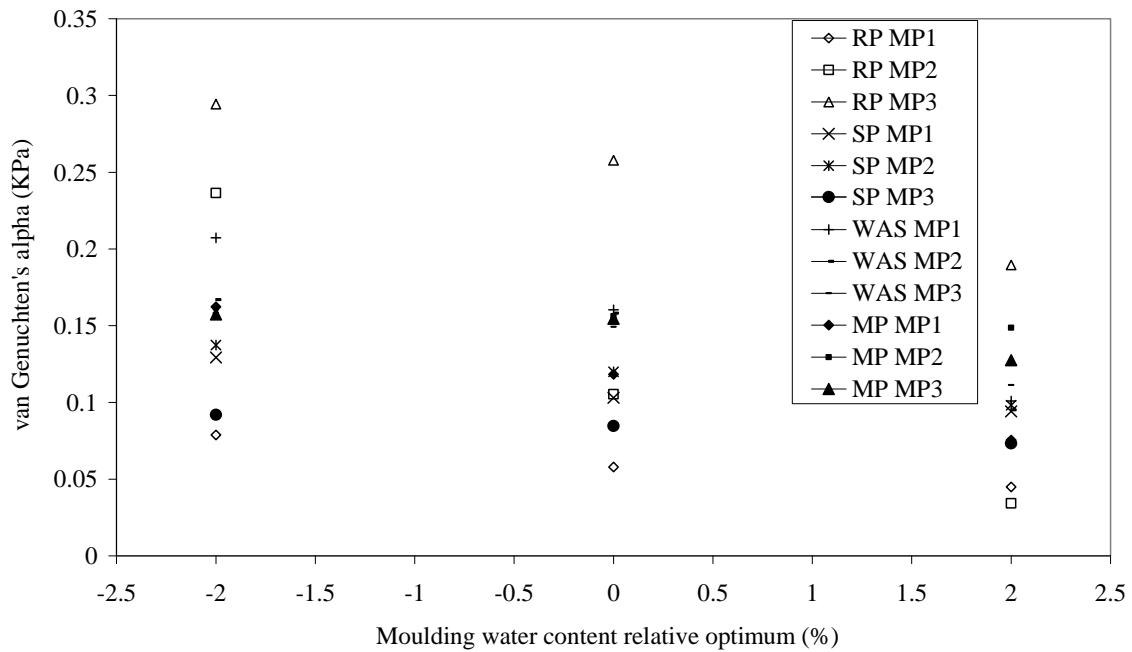


Figure 10b: Variation of van Genuchten α with water content relative to optimum for MP1, MP2 and MP3

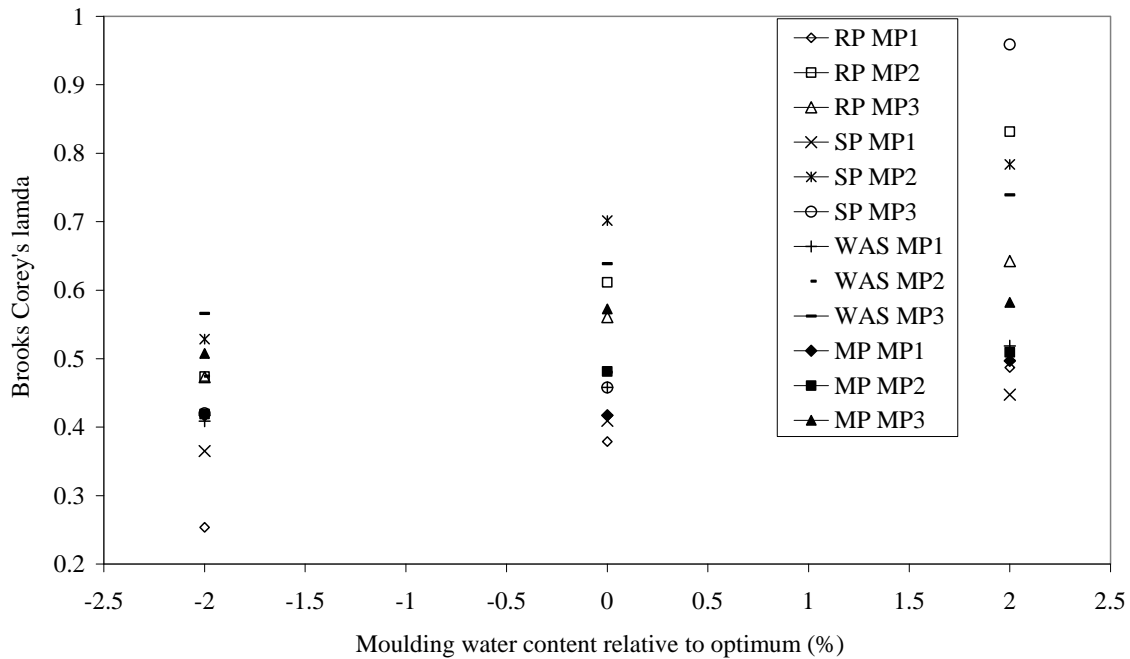


Figure 10c: Variation of Brook-Corey λ with water content relative to optimum for MP samples

CONCLUSIONS

The soil water characteristics curves (SWCCs) of seventy-two (36) specimens obtained from three tropical soil samples were developed based on data from laboratory pressure plate tests. The pressure plate extractor employs the axis translation technique to yield water contents. The SWCC data were used to determine the fitting parameters to two most commonly used soil-water retention models, the Brooks-Corey and van Genuchten models. These models also formed the basis for the prediction of volumetric water content (θ) for the soil specimens. The soil specimens were prepared dry of optimum, at optimum or wet of optimum water content using four compactive efforts stated above.

The initial molding water content has a considerable influence on the resulting structure (and aggregation) of soil particles such as tropical soil used in this research program. Macro structure influences the soil-water characteristics 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 characteristics 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. Specimen compacted at optimum water content had the least pore size distribution and those compacted dry of optimum had the highest pore size distribution. Smaller pore sizes were associated with high air-entry suctions. Soil composition and compaction conditions generally affected both the SWCCs and the model parameters. 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 characteristics curve. Hence, the conclusions of this study should be valid for most tropical soils.

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