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Estimation of soil strength using the adsorption soil-water characteristic curve

RONALD ROOPNARINE[1], GAIUS EUDOXIE[1] AND DEREK GAY[2]

[1]*Department of Food Production, University of the West Indies, St. Augustine, Trinidad.*
[2]*Department of Civil Engineering, University of the West Indies, St. Augustine, Trinidad.*

ABSTRACT. Adsorption soil water characteristic curves can serve as a means of predicting the minimum contribution of soil suction to soil strength. This is essential to assessing slope stability and provides a means of determining the lower threshold of soil strength, which allows for an estimation of the minimum stress that a soil can withstand. A total of 26 soil series of varying clay content and mineralogy was sampled and their adsorption curves developed. Soils were grouped into four categories of increasing clay content and the relationships subjected to non-linear regression. Standard, linear by linear curves (rectangular hyperbola) were found to be the best fit in all instances, explaining the relationship between water content and suction. Suction values were combined with soil strength indices; namely friction angle and normal force, to determine the minimum strengths of soil series over a range of moisture contents. For similar water contents, soil suction increased with increasing clay content. Similarly, R^2 values increased with clay content, with distinct parameter estimates explaining the behavior of each clay group. Clay content and mineralogy played a crucial role in establishing accurate adsorption curves with predictive capabilities. Understanding and grouping soils based on these relationships provides a viable alternative in the assessment of potential instances of soil instability negating the exorbitant cost and time associated with traditional laboratory testing methods. The adsorption curves can provide valuable insight into, and allow the interpolation of the suction/cohesion component of soil shear strength.

Key words: soil suction, SWCC, Trinidad, soil

1. INTRODUCTION

The soils of Trinidad are dominated by expansive clays, which are structurally weak and susceptible to various forms of mass movement, such as, landslides (Wuddivira, 2008, Roopnarine et al., 2013). Annually, there are numerous cases of slope failure in the form of mass movement, triggered mostly by moisture content changes. Pertinent information on soil physical and engineering properties associated with slope failure is meagre. Existing information is aligned to agriculture and of limited use to other disciplines. Local soil engineers undertake costly and time consuming tests to determine the soil strength properties needed to address land use and slope stability issues. Understanding and utilising the Soil Water Characteristic Curve (SWCC) for strength estimation will improve both cost and resource efficiency.

SWCCs have been used extensively since the introduction of the concept of apparent cohesion by Haines in 1927 (Barbour, 1999). The nature of these curves has also been investigated by Yang et al. (2004) who reported on the factors that influence the SWCCs and indicated that the main determinants were grain size distribution and dry density. Botha and Eisenberg (1993) showed that SWCCs can be estimated accurately from clay content and cation exchange capacity. The increased specific surface (surface area per unit mass of soil) of clays offers a superior capacity for adsorption with the latter increasing with increasing clay content. Water molecules possess adhesive properties, have a dipolar charge (Adamson, 1982), and are organized in a double layer around the negatively charged clay colloids (Bolt, 1955; Efremov, 1960). The work of these authors illustrates that there is a direct relationship between clay content, mineralogy and water holding capacity of a soil, which ultimately affects the nature of the SWCCs.

SWCCs have been used for estimation of unsaturated soil property functions including permeability, water storage, shear strength and thermal property functions (Fredlund et al., 2011). The relationship between pore water suction and water content, as presented in a SWCC is one of the fundamental relationships used to describe unsaturated behaviour of a soil (Miller et al. 2002). Increasing suctions generally result in high resistance to flow and increases in effective stress. Terzaghi (1943) demonstrated that the shear strength of unsaturated soils could be better understood from studies related to the distribution and geometry of the pore-water combined with pore-water pressure. Describing and appreciating the relationship between soil suction and moisture content is critical to understanding its contribution to soil shear strength. Efficient and accurate assessment of soil shear strength is essential in addressing soil instability issues, including the maximum shear stress a soil can withstand.

Escario and Seaz (1986), Gan and Fredlund (1988) and Escario and Juca (1989) performed studies over a large range of suction values and concluded that shear strength varied with respect to soil suction in a non-linear manner. Abramento and Carvalho (1990) and De Campos and Carillo (1995) further extrapolated on this idea and suggested relationships that were elliptical and hyperbolic between shear strength and SWCC.

Vanapalli et al. (1996a), Fredlund et al. (1996), Oberg and Salfours (1997), Khallili and Khabbaz (1998) and Bao et al. (1998) proposed modifications to existing equations. These modifications involved an extension of the initial equation proposed by Bishop (1959) by the inclusion of a fitting parameter, as well as considerations for non-clayey soils and the degree of saturation. Overall it is well established in the literature that there is a relationship between SWCCs and shear strength of unsaturated soils. However, SWCCs have not proven to be a reliable means for estimating *in situ* soil suctions, and their usage for this purpose has been discouraged (Fredlund et al., 2001; Fredlund, 2002). This is primarily because of the hysteretic nature associated with the drying (desorption) and wetting (adsorption) SWCCs (Fredlund et al., 2011). The nature of the *in situ* field moisture content cannot be distinguished, i.e., whether it is on the wetting curve or the drying curve. This limits the use of empirical models to accurately predict the *in situ* soil suction from field based moisture content values. However the SWCCs can give reasonably accurate prediction of the maximum (desorption) and minimum (adsorption) range of suction (Fredlund et al., 2011). Thus the adsorption curve can be used to estimate the minimum contribution of soil suction to apparent cohesion. This is essential to assessing slope stability as it provides a means of determining the lower threshold of soil strength, which allows for an estimation of the minimum stress that a soil can withstand.

The Mohr Coulomb failure criterion expresses soil shear strength as:

$$\tau = \sigma \tan \varphi + c$$

where τ is the shear strength, σ is the normal stress, c is the intercept of the failure envelope with the τ axis, and φ is the slope of the failure envelope. The quantity c is called the cohesion factor and the angle φ the angle of internal friction. Thus it is possible to calculate the minimum value of the soil shear strength once the normal stress and the friction angle are known. The calculated value will be the minimum value if the cohesion value is not known. Theoretically the Mohr coulomb failure criterion indicates that a soil will fail if it exists at an angle greater that its intrinsic friction angle, providing that there is no cohesion (Krahn et al., 1989). The use of the SWCCs can allow for a numerical value to be attributed to cohesion based on easily measured moisture content values. The study presented here focused on the application of adsorption curves towards prediction of *in situ* soil shear strength.

2. METHODOLOGY

Soil Selection and Sampling

A total of 26 soil samples was selected to encompass a range of textural classes and taxonomical families (**Table 1**). Samples were taken across Trinidad with at least 4 soil series in each of the five physiographic zones proposed by Suter (1960). For each of the 26 soil series, two undisturbed samples and one disturbed sample were taken at a depth of 1.6 - 2.0 m. Comparable depths were used by Roopnarine et al. (2012) to determine soil friction angles of Trinidadian soils. Undisturbed samples were taken using a core (height - 0.15 m, diameter - 0.073 m) that was inserted vertically using a core sampler. The core sample was sealed in plastic wrap and stored in a cool dry area prior to laboratory analysis. Undisturbed samples were used to measure bulk density (**Db**) following Grossman and Reinsch (2002). Disturbed samples were collected using an auger and were prepared for subsequent laboratory analysis by air drying and grinding to pass a 2 mm sieve. Samples were stored in plastic containers until analysed. Particle size distribution was measured using the hydrometer method (Gee and Or, 2002).

3. LABORATORY ANALYSIS

Development of SWCCs

For each soil series 5 g of oven dried soil was placed in 12 metal cups of known weights (Mc). To each cup varying amounts of water was added using a dropper, ranging from 2 drops to complete saturation. The cups were then sealed and allowed to equilibrate for 24 hrs. Each cup was then reweighed (Mf) and placed in a Decagon, WP4-T dew point potentiometer to determine the soil suction value. Gravimetric water content for each cup was then calculated by using equation 1 (Topp and Ferré, 2002). SWCCs were developed by plotting water content against soil suction.

$$\mathbf{(Mf-(Mc+5g))/5g} \qquad \textit{Equation 1}$$

Statistical analysis

Soil series were grouped based on clay content; <30% clay, 31 to 59% clay, 60- 90% clay and >90% clay. The moisture content (%) vs. soil suction (***pF***) for each of the four clay groups was plotted and subjected to nonlinear regression analysis in GenStat (VSN International, 2010 statistical software, 13th Edition), to determine the best-fit curves. Best fit curves are a range of standard curves, which accurately represent the pattern of the input data. Associated parameter estimates are selected based on maximizing the correlation of the best fit curve and the input data. R^2 values and equations for each curve were determined. The data for all soil series was also pooled removing the clay grouping factor and subjected to similar analysis to investigate the variation in the data. All regressions were done at the 95% confidence interval level.

Table 1: Properties of selected soils

Soil Series	Taxonomic Family†	% Clay	FA-P (°)
San Souci	fine, mixed	35	24.53
Anglais	clayey, kaolinitic	53	28.56
Diego Martin	coarse-loamy, carbonatic	13	52.4
Maracas	clayey, oxidic	35	35.19
Piarco	clayey, kaolinitic	52	29.44
Bejucal	very-fine, mixed, acid	96	11.70
River Estate	fine-loamy, micaceous	31	40.43
Tacariqua	Coarse-loamy, micaceous	45	29.84
St.Augustine	Clayey, kalonitic	45	30.19
Arena sand	Coated, mixed	11	54.12
Freeport	Fine-loamy, mixed	29	41.15
Pasea	Fine, mixed	16	47.30
Montserrat	fine, oxidic	35	36.78
Biche	very-fine, mixed	66	20.78
Brasso	very-fine, montmorillonitic, non-acid	62	23.92
Marac	very-fine, mixed	96	9.23
Golden Grove	fine, loamy, mixed	29	37.58
Mt. Harris	Clayey, mixed	65	21.66
Cleaver	Clayey, kaolonitic	62	24.99
Princess Town	very-fine, montmorillonitic, non-acid	91	11.8
Moruga	fine-loamy, mixed	40	33.84
Talparo	very-fine, mixed, acid	93	11.33
Ecclessville	very-fine, mixed, acid	72	19.47
Sevilla	Very-fine, montmorillonitic	63	24.12
San Francique	very-fine, mixed, acid	67	20.98
Tarouba	Very-fine, montmorillonitic	91	13.58

*Friction angle data sourced (Roopnarine et al., 2012)
†Smith (1983)

Soil Suction Model

Db was used to calculate the normal force (***Db**** Depth) which was then combined with suction values at associated moisture contents and the respective friction angles for five soil series known to have stability issues. Friction angle data was sourced from the work of Roopnarine et al. (2012). Resultant data was used to estimate shear strength at various moisture contents according to the Mohr Coulomb failure criterion for five soil series.

4. Results and Discussion

The range of properties of the sampled soil series which was used to develop the SWCCs is shown in **Table 1**. Results show that a wide cross-section of taxonomical classes was sampled with an extensive range of clay contents. The latter ranged from a low of 11% to a high of 96%. Roopnarine et al. (2012) reported similar clay content values for the respective soil series. Such variation was vital to accurate and reliable development of SWCCs that are useful for a range of soil types. Fredlund et al. (1996) investigated the relationship between grain size distribution and SWCCs. The findings indicated that the predicted SWCCs for silt and sand were reasonably accurate but were not so for clays. This can be attributed to the hysteretic effect that is more pronounced in clays, resulting in larger variations between the adsorption and desorption curves. In this study only adsorption curves were considered, eliminating the hysteretic effect, which resulted in improved predictive capabilities for clay soils.

The groupings based on clay content resulted in no less than four soil series being placed in each of the four categories. The 30-59% clay content category contained the most soil series. The majority of the soils present in Trinidad belong to clay loams (Brown and Bally, 1967, 1968, 1970).

Statistical analysis revealed that the best fit adsorption curve in each instance was defined by a rational function (ratio of polynomials) in the form of a linear-divided-by-linear curve or rectangular hyperbola (**Figures 1 to 4**). The regression equation $Y = \{A + B/(1 + D*X)\}$ was found to be significant ($p < 0.001$) in all cases. "A", "B" and "D" are the parameter estimates that provide the best possible fit based on the empirical data. "Y" represents the dependant variable ***pF*** (soil suction) and "X" represents the independent variable ***Mc*** (moisture content). There was an exponential decrease in suction with increasing water content. The decrease was more pronounced in soils that contained lesser amounts of clay, as seen with the constant decline in the slope coefficients from 0.367(<30% clay) to 0.0188 (>90% clay).

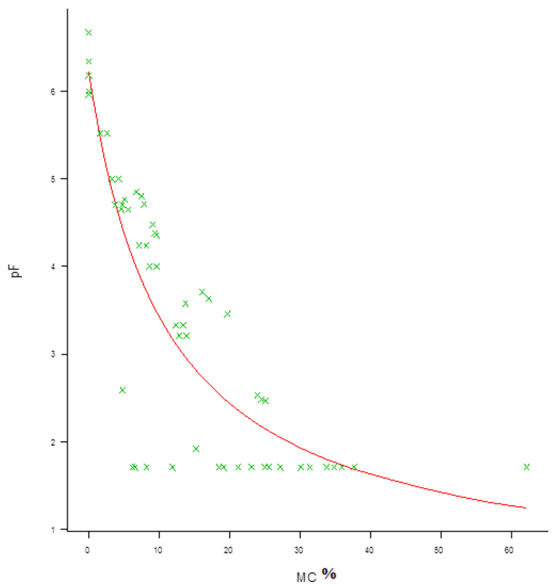

Figure 1. Moisture content vs. pF for soil series with less than 30% clay.

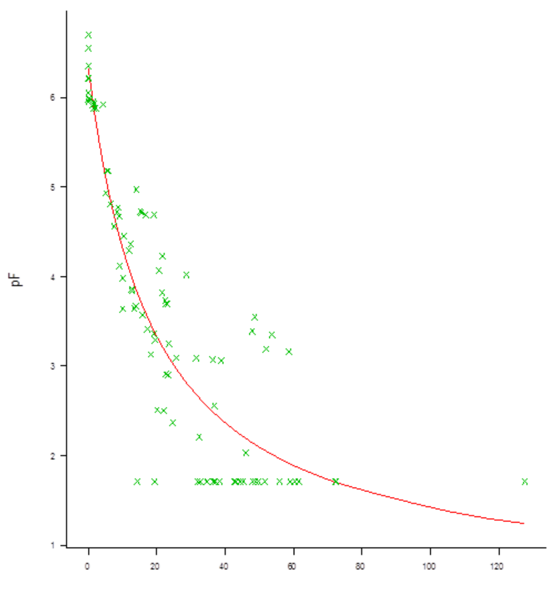

Figure 2. Soil suction (pF) Vs % Moisture content for soils with 30-59% clay

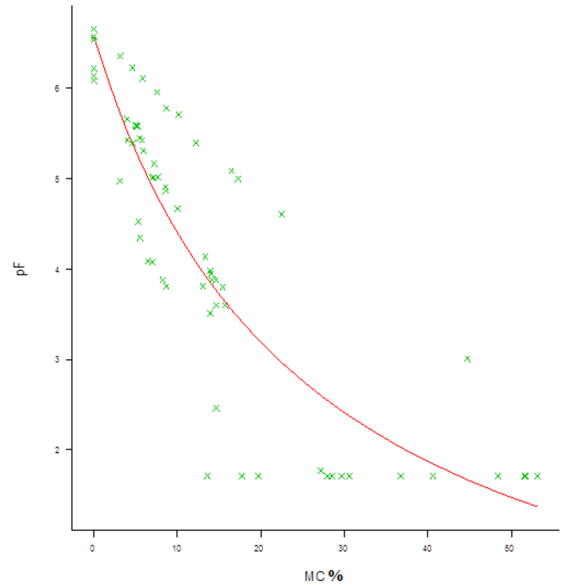

Figure 3. Soil suction (pF) Vs % Moisture content for soils with 60-89% clay.

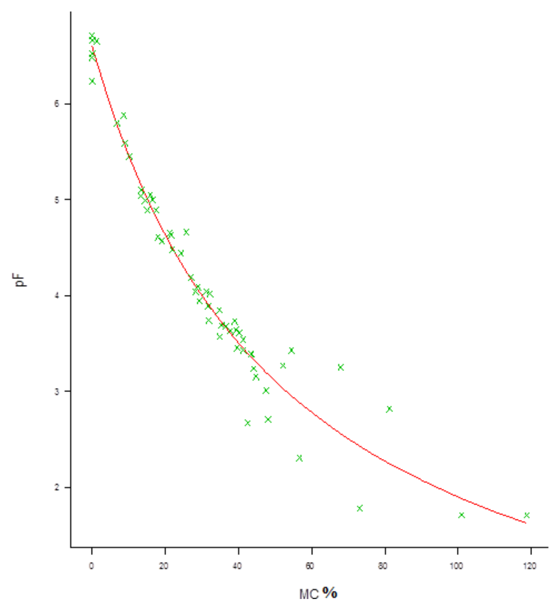

Figure 4. Soil suction (pF) Vs % Moisture content for soils with >90% clay.

In all instances R^2 values of greater than 0.6 were noted (**Table 2**). Amongst the categories, the strongest R^2 was seen for the soil series in the >90% clay category (0.959) while the lowest R^2 was seen in group <30% clay category (0.723). Increasing clay content along with the presence of expanding minerals augments water holding capacity and results in a wider range of soil suction. Increased clay content generally leads to an augmentation in the amount of water retained at certain suction (Miller et al., 2002). The overall R^2 (65.6) and regression analysis for the pooled data (no grouping factor) was the weakest indicating that it may be impractical to have a generalized adsorption curve that covers all the textural classes (**Figure 5**). The accumulated regression analysis for the pooled data (**Figure 6**) indicated that separate curves were needed for each of the clay categories, and the non-linear coefficient ("D") was found to be significantly different in each instance where clay content was included as a grouping factor. There was also an increase in the R^2 and a decrease in the standard error, which supports the notion that clay content influences the nature of the regression equation (Botha and Eisenberg, 1993).

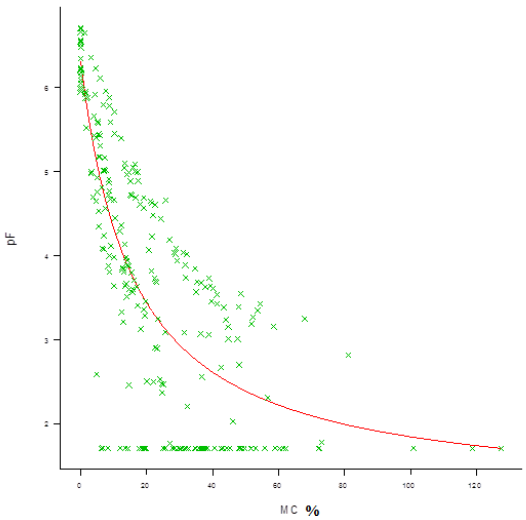

Figure 5. Pooled data (no grouping factor)

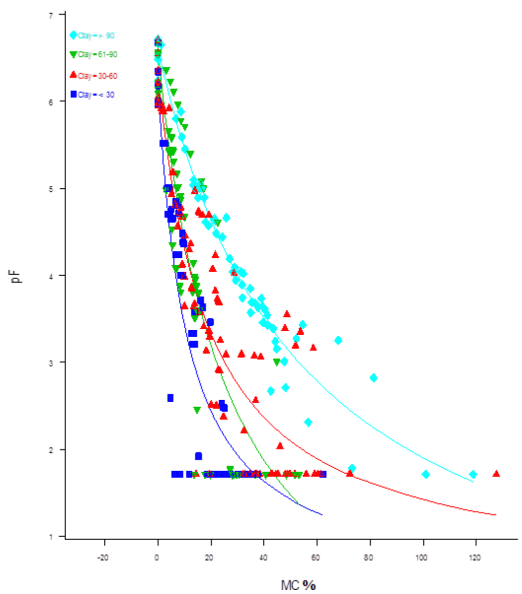

Figure 6. Pooled data for all groups (grouping factor: clay content).

This is also supported by the increased strength of the R^2 values when the soils were grouped. In addition the strongest R^2 (0.959), was associated with the >90% clay category which contained soil series with the least variation with respect to clay content, indicating that variation in clay content even within the chosen categories can be influential on the accuracy of the regression models. A similar trend was seen with the standard errors of the regression models. The smallest standard error was seen in the >90% clay category (0.252), while the largest was seen in the pooled data (0.907), in all cases standard errors <1 are noted, emphasizing the limited variability between the fitted and the observed values.

Table 2. Regression equation, parameter estimates and R^2 for all groups

Group	Parameter estimates	% variance accounted for (R^2)	Standard Error (SE)
1 (<30% clay)	A:0.367	72.3	0.819
	B:5.850		
	D:0.367		
2 (30-60 % clay)	A:0.483	82.6	0.653
	B:5.837		
	D:0.0526		
3 (61-90 % clay)	A: -1.14	75.7	0.792
	B:7.70		
	D:0.039		
4 (>90% clay)	A:-0.593	95.9	0.252
	B:7.191		
	D:0.01888		
Pooled data, all groups combined	A:1.126	65.6	0.907
	B:5.181		
	D:0.0620		
Clay, constant parameters separate	D: 0.04618	79.7	0.694
	B: 6.258		
	A Clay 30-60:0.1049		
	A Clay 61-90:0.06319		
	A Clay < 30 :-0.6840		
	A Clay > 90 :1.169		
Clay, all linear parameters separate	D:0.04410	80.4	0.682
	B Clay 30-60:6.078		
	A Clay 30-60:0.1514		
	B Clay 61-90:7.407		
	A Clay 61-90:-0.7677		
	B Clay < 30:6.967		
	A Clay < 30: -1.213		
	B Clay > 90:5.460		
	A Clay > 90:1.501		

Soil Strength Model

The ***Db*** for the five soil series considered (**Table 3**) were consistent with those reported by Roopnarine et al. (2012). The highest ***Db*** were noted for the Bejucal and Tarouba soil series: 1580 and 1550 kg/m^{-3} respectively. These series are predominantly sedimentary clay soils dominated by 2:1 expansive clay minerals, which allows for greater compaction and thus higher bulk densities, noting the depth within the profile at which the samples were taken. However, these values all fall within the normal range for clay soils. The Princes Town series although consisting of over 90% clay has a shallow profile, and parent material is encountered at the sampling depth which possibly reduced compaction and consequently the bulk density.

Figure 7 shows soil strength plotted against moisture contents for the chosen soil series. In all instances there was a drastic decrease in soil strength with successive increases in moisture content. Each curve came to a horizontal asymptote at the point where soil strength derived from soil suction is rendered negligible, and innate soil strength associated with soil friction angle and the normal force are the main contributors to soil strength. Of the five soils series, the highest strengths were noted for soils that contained over 90% clay. Clay soils especially those that contain 2:1 expanding minerals have high water holding capacity and would exhibit large suction values when dry. Though the clay soils possessed the highest strengths when dry, the initial reduction in strength is more pronounced with successive increases in water content, indicating that the affinity for water decreases significantly once small quantities of water enter the pores reducing suction/cohesion and consequently strength. Conversely the soils that contain less clay (Biche and Maracas series), have much lower suction when dry but the reduction in both suction and strength is less pronounced. This is related to clay mineralogical composition as well as lower clay content. The clay fraction of these soils consists mainly of 1:1 minerals (Hardy, 1974) consequently making it is more difficult for water to enter and to leave the pore spaces. The lowest strengths for all soils are noted at the highest moisture contents, which is consistent with the reduced contribution of soil suction with increasing moisture content. The Maracas series showed the greatest strength values at high water contents (>50%). This soil has the highest friction angle of the five soils (350), which accounts for the relatively high strength values at high moisture contents. Thus soils with high friction angles will be more resilient to failure at high moisture contents, regardless of their mineralogical compositions, however at low moisture contents, soils with particle size distributions dominated by clays will have much higher strengths that those with lesser amounts of clay, with mineralogy (expansive vs. non expansive) dictating the magnitude. Laboratory investigation of soil moisture content, however, do not reflect in actuality the range of soil moisture contents experienced in the field, in addition external factors such as vegetation (type and density) and precipitation inputs influence soil suction/cohesion by actively altering the water balance in soils (Norris and Greenwood, 2009). Field studies where *in situ* moisture contents are monitored will increase our understanding of the seasonal variations in soil moisture and its relation to soil strength. Sharp and sudden changes in soil strength may be the precursor to soil instability. This can be of particular importance in areas that are considered susceptible to mass movement. The pursuit of developed status has seen Trinidad, along with numerous other Caribbean countries, place emphasize on construction (buildings, highways, housing developments, etc.). In many cases these projects have encountered problems after completion due to soil related issues. The proposed method of estimating variations in soil suction and consequent strength can enable soil engineers and resource managers to assess the potential for soil instability based on the range of moisture contents that soils encounters.

Table 3. Bulk densities (*Db*) for selected soil series

Soil series	Bulk density (kg/m^3)
Maracas	1450
Bejucal	1580
Biche	1550
Princes Town	1210
Tarouba	1060

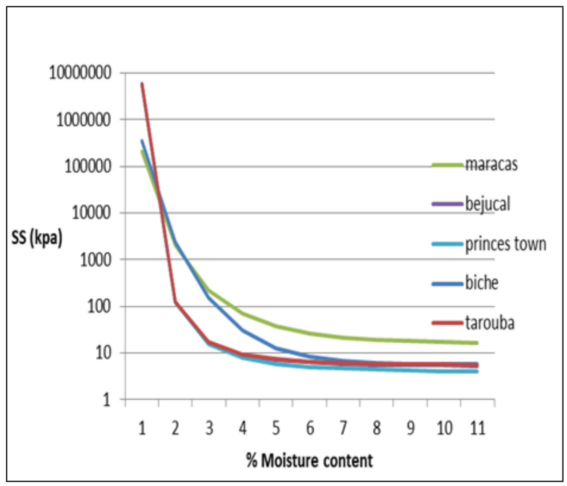

Figure 7. Soil strength (*SS*) vs % moisture content (MC) for chosen soil series.

CONCLUSION

Clay content was found to have a significant influence on the nature of the adsorption curves. R^2 for the adsorption curves increased with increasing clay contents. Linear by linear curves accurately explained the relationship between suction and moisture content and allowed the estimation of the minimum contribution of soil suction to soil strength. Soil strength was found to increase with decreasing moisture content, with the nature of this decrease dependent on the clay content and mineralogy. Knowledge of the minimum value of soil strength can aid in management and disaster preparedness of soils particularly those that are subjected to high levels of stress.

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