Savanna soil water content effect on its shear strength-compaction relationship

Efecto del contenido de agua de un suelo de sabana sobre la relación resistencia cortante-compactación

Américo José HOSSNE GARCÍA ✉**, Yosmer Noel MAYORGA JAIME, Ángela Maryelis ZASILLO CONTRERAS, Luis Daniel SALAZAR BASTARDO and Fernan Andrés SUBERO LLOVERA**

Universidad de Oriente, Departamento de Ingeniería Agrícola, Núcleo de Monagas, Maturín, estado Monagas, Venezuela. E-mails: americohossnegarcia@gmail.com y americohossne@cantv.net ✉ Corresponding author

ABSTRACT

Soil resistance, expressed as shear strength (τ) according to Coulomb-Mohr-Terzaghi theory, is most often supplanted by bulk dry density (ρ_S) when measuring soil compaction; frequently, without providing soil wetness records. The savanna sandy loam soils have low organic matter, low kaolinite content, low power of shrinkage and expansion, deformable, perturbed, erodible, compactable, and its tenacity and consistency is achieved at low water content because of the cementation tendency of its particles. The objectives were to evaluate the relationship between the shear strength and compaction under eight (8) water content levels (w) of two savanna sandy loam agricultural soils at two depths. Methodologically, it was used a manual paddle device for *in situ* shear test, the Proctor compaction unit, regression analysis, ANOVA, LSD and statistical response surface to interpret the variance proportion between the parameters. Amongst the results, the 100 kPa mean maximum shear strength, lied between 6.5 and 7.3% soil water contents and 1.77 g·cm^{-3} bulk density. The dry bulk density showed a maximum of 1.84 g·cm^{-3} at optimum moisture between 9 and 10% with 84.24 kPa shear strength. Superimposing the two curves of dry density and shear strength versus moisture content, respectively, gave the best compromise moisture content within the friable range between 7.6% and 9.5%. The peak value of the optimal shear strength was reached before the optimum dry bulk density peak. It was concluded that the effect of moistness weakening the shear strength was greater than the effect of dry bulk density strengthening shear strength. The results of this study support the argument that the resistance of the compacted soil is a function of water content.

Key words: shear strength, optimum bulk density, soil wetness, savanna soil, soil compaction

ABSTRACT

La resistencia del suelo, expresada por la tensión cortante (τ) de acuerdo a la teoría de Coulomb-Mohr-Terzaghi, es más a menudo sustituida por la densidad aparente seca (ρ_S) en la medición de la compactación del suelo, con frecuencia, sin proporcionar los registros de humedad. Los suelos franco-arenosos de sabana tienen poca materia orgánica, bajo contenido de caolinita, baja potencia de contracción y expansión, deformables, perturbables, erosionables, compactables y su tenacidad y consistencia se consigue a bajo contenido de agua debido a la tendencia de la cementación de sus partículas. Los objetivos fueron evaluar la relación entre la resistencia al corte y compactación con ocho (8) niveles de contenido de agua (w) de dos suelos de sabana franco arenosos agrícolas a dos profundidades. Metodológicamente, se utilizó un dispositivo manual para ensayo de corte *in situ*, la unidad de compactación Proctor, el análisis de regresión, Andeva, la MDS y superficie de respuesta para interpretar la proporción de varianza entre los parámetros. Entre los resultados, la resistencia al esfuerzo cortante máximo de 100 kPa, se produjo entre 6,5 y el 7,3% de humedad del suelo y densidad aparente seca de 1,77 g•cm^{-3}. La densidad aparente seca mostró un máximo de 1,84 g•cm^{-3} a la humedad óptimo entre 9 y 10% con resistencia a la cizalladura de 84,24 kPa. La superposición de las dos curvas de densidad seca y resistencia al cizallamiento con respecto al contenido de humedad, produjo el mejor contenido de humedad dentro de la gama friable entre 7,6% y 9,5%. El valor máximo de la resistencia al corte óptimo se alcanzó antes del óptimo de la densidad aparente seca. Se concluyó que el efecto disminuyente de la resistencia al cizallamiento por la humedad fue mayor que el efecto de fortalecimiento del cizallamiento por la densidad aparente seca. Los resultados de este estudio apoyan el argumento de que la resistencia del suelo compactado es una función del contenido de agua del suelo.

Palabras clave: Resistencia al corte, la densidad aparente óptima, humedad del suelo, suelo de sabana, la compactación del suelo

INTRODUCTION

Mechanical stability of soils is an important property for resisting mechanical disturbance and erodibility. It consists of several primary factors, in which the packing density is probably the most critical. For the experimental sandy loam soils, contents of silt and clay particles were more influential than organic matter and calcium carbonate in forming their structural stability (Chen and Fryrear, 2010). The strength of structured soils is a property of interest for applications in both agriculture and engineering. In the case of agricultural use, the inherent soil strength is useful to describe the susceptibility to deformation by pressure caused by farm machinery. It is also important to specify the tilling machine to be used to change the soil structure at plowing to improve agricultural production (Ohu *et al*., 1986). At low moisture content the soil grains are surrounded by a film of water, which tends to keep the grains apart even when compacted. The finer the soil grains the more significant is this effect. When more water is added when achieved optimum compaction, then excess water begins to push the particles apart so that bulk density is reduced: little or no more air is displaced by compaction and bulk density continues to decrease (Arvind and Dhananjay, 2003).

It is believed that a proper understanding of soil resistance could contribute to better management of agricultural soils (Horn, 2004; Horn and Lebert, 1994). Soil resistance is the result of Mohr-Coulomb-Terzaghi-Peck theory, and compaction is the consequence of the air-filled pore space reduction with little or no decrease in water content. The soil-water characteristic curve is the relationship between matric suction and water content, and reflects the ability to withstand the water under the matric suction (Tan Yun-zhi *et al*., 2005). Much important information on soil permeability, tenacity, volume change, state of tension and granular distribution are obtained from soil-water relationship (Zhou Jian, 2005). The unsaturated soil-water characteristic curve is the main content of its constitutive relation. Inquire about soil-water has engineering and theoretical importance (Chen Zheng-Han *et al*. 2003; Chen Zheng-han, 2001). Soil resistance and compaction produce unacceptable conditions for agricultural soils. The shear strength of soil has been shown to decrease with increasing moisture content and increase with compaction (Panwar and Siemens1972). Ohu *et al*., (1986) reported that the shear strength of compacted

soils is affected by many factors including soil density, overburden pressure, moisture content, energy applied for compaction and soil type.

Soil compaction increased the shear strength of the soils irrespective of moisture content, while organic matter incorporation decreased their shear strength. Adekalu *et al*., (2007) working with Ultisols sandy loam soils, sandy clay loam Entisols and sandy loam Alfisols found that higher levels of compaction increased the bulk density and shear force, while the shear force decreased with increasing soil water content; for all levels of compaction, the bulk density increased with increasing water content up to a maximum and decreased with progressive water aggregation. The rate of increase in shear strength with depth decreased with increasing moisture content level. The decrease in shear strength with increasing moisture content that is accompanied by decreasing in the solid particles and dry bulk density is attributed to the smaller bounding forces due to lower suction. Consequently, moisture content is the most important factor affecting the value of shear strength in addition to dry bulk density, which can be considered as a secondary influencing factor, Zhao *et al*. (2009); Rezaei *et al*., 2012. Bachmann *et al*. (2006) interpreted the depth dependent penetration resistance characteristics, and compared it with soil vane shear data to prove the plausibility of both methods.

Saarilahti, (2002) stated that vane tester is one of the most used devices to record direct shear of soil *in situ* conditions; even, it is used also in some laboratory methods. In simpler versions, only the maximum torque is read, based on that, soil maximal shear strength, soil vane strength is calculated. Ekanayake and Phillips (1999) reported that soil layers *in situ* test showed high shear strength under field moisture content (undrained field vane shear test greater than 80 kPa), often shear strength reduced to as low as 2 kPa when the layers became saturated. According to Schjùnning and Rasmussen (2000) findings, the vane will over-estimate soil cohesion; noticeable for silty loam soils that displayed a higher cohesion than the vane estimate of strength. This may be due to anisotropy of the soil, the vane shearing the soil primarily in a vertical plane of failure, while the loaded annulus in the laboratory shears the soil in a horizontal plane. Vane shear strength measured in the field at depth of 4.8 cm and 14.8 cm, produced for sandy loam soil 46.3 kPa (1,53 g·cm⁻³, 12.3 %) and 52.7 kPa (1.52 g·cm⁻³, 29.1 %), and for silt loam soil

72.3 kPa (1.38 g·cm⁻³, 31%) and 66.1 kPa (1.40 g·cm⁻³, 34.5 %), respectively as a function of depth, bulk density and soil wetness. Similar to the field vane measurements, the laboratory shear annulus estimates of strength remained unchanged from the first and second sampling date.

Schjønning (1990) reported that the strength of a sandy and a loamy soil was measured using a vane tester and a torsional shear box in the field and an annulus shear method and a drop cone penetrometer in the laboratory. Soil shear strength was found to be dependent on the method used for its measurements as well as on the history of the soil specimen. Perhaps data obtained from a particular soil unit for a specific property from two different tests, e.g. field vane shear tests and lab unconsolidated undrained tests did not agree. Results of field vane shear tests may be used to determine undrained shear strength for deep clays instead of laboratory unconsolidated undrained tests because of the differences in stress states between the field and lab samples. Shear vane testing can be useful to obtain *in situ* undrained shear strength of soft cohesive soils. The vane shear test may also be performed in very soft to soft cohesive soil (Geotechnical Design Manual, 2012). Hossne *et al*. (2003) working with Ultisols savanna soils showed the inverse influence of soil water on shear strenght, and that the soil resistance was less than 100 kPa near field capacity water content.

Terzaghi (1936) introduced the concept of effective stress (σ-u_w) for the particular case of saturated soils bellow the ground water table followed by other major contributions (Skempton, 1960; Nur and Byerlee, 1971). Initial attempts to extend such a theory to unsaturated soils or vadose zone had limited success (Bishop *et al*., 1960; Burland, 1964). The stress state, considered uniquely represented by the effective stress, is valid only for the limit states of full saturation of pores with one fluid alone, namely water or air, a need for extending the effective stress principle to unsaturated states raised (Nuth and Laloui, 2008). Fredlund, (2006) reported that laboratory studies revealed fundamental differences between the behavior of saturated and unsaturated soils. Unsaturated soils are recognized in geotechnical engineering as a four-phase material composed of air, water, soil skeleton, and contractile skin (air-water interface) (Fredlund and Morgenstern, 1977). The soil-water characteristic has emerged to be the key soil property which is of value in characterizing the behavior of unsaturated soil for civil engineering application. Various forms of effective stress equations for unsaturated soils have been proposed; e.g. by Bishop (1959), Fredlund *et al*., (1978) and Gitau *et al*., (2008). In agricultural, a vadose zone with exceptional geo-mechanical characteristics conditions, the water is obviously a mixture of water and dissolved air rather than pure water (Nuth and Laloui, 2008).

It is necessary in geotechnical engineering practices, in order for unsaturated soil mechanics to be implemented to be aware of that a particular agricultural soil for every water content produces different mechanical condition; i.e. a different soil mechanical property. The relationship between soil suction and water content was originally used in predicting the soil water available for plant growth. The agricultural soil physical-chemical variability is practically infinite even without taking into account the grate variability of its water and organic matter content, hamper in civil engineering. Because of this, it has been difficult to describe an appropriate stress state variable for unsaturated soils (Towner 1983; Hettiaratchi and O'Callaghan 1985). Fortunately, the agricultural soil wetness produces different soil consistency (important in soil agricultural administration) as, for example, the friable state with mechanical characteristics favorable for agricultural management: root growth, plant development, and machinery and equipment use in the field with minimal structural damage (Gitau *et al*., 2008; Hossne, 2008; Hossne and Salazar, 2004).

The pore-water pressures are negative and it is a change in the pore-water pressure that produces behavior which has been difficult to predict. The primary deterrent to their application was the difficulty associated with measuring negative pore-water pressure *in situ*, matric suction (Fredlund and Rahardjo, 1988). In agricultural soil sciences have long been recognized that soil suction contributes to soil strength, both shear and tensile (e.g. Greacen 1960; Chancellor and Vomocil 1970; Koolen and Kuipes 1983; Mullins and Panayiotopoulus 1984; Mullins *et al*., 1990; McKyes *et al*., 1994); however, there has not been a rigorous theoretical framework quantifying the contribution of soil suction. The influence of these factors cannot be readily perceived because of the very large number of interacting effects. Wulfsohn *et al*., (1996) in their conclusion, reported that the use of the soil-water characteristic to relate matric suction and water content or degree of

saturation to soil strength is only valid for the soil structure for which the soil-water was obtained. If the structure alters significantly under wetting o drying or due to mechanical disturbance, the saturated strength parameters, as well as the soil-water characteristic, will all change. Predicting these structural changes requires an understanding of the effect of the stress variable on the soil deformation characteristics and the soil-water characteristic. Most real agricultural problems, however, engage the shear and compressive strength and deformation responses of soil simultaneously. The effective stress parameter χ would attains boundless values between unity and zero in unsaturated soil.

Adams *et al*., (1994) reported that while water content is easier to measure, the soil suction determination usually takes considerable time and effort. These concepts should be well thought-out for the determination of agricultural soil mechanical property. There would not be a general formulation for agricultural soil as there is for saturated cohesive soil and possibly for unsaturated soil civil engineering application, an agricultural soil must be maintained under the soil water condition for plant requirements; and under these condition, soil geo-environmental engineering and soil mechanical knowledge should be applied to know the best soil stress state. Agricultural soils should not be allowed to shrink or expand due to its effect of compaction increase, root breakage, water deficit, leaching of fertilizers and chemicals below the root zone, reduced soil organism activity, and breaking of capillary flux of water. The main objective of this investigation was to present the effect of soil water content, on the relationship compaction/strength, and when the best condition happens for soil management.

According to Utomo and Dexter, 1981; Dexter and Kroesbergen, (1985); Kay & Dexter, 1992; Watts *et al*., 1996; Dexter, (1988 and 1997); Dexter and Watts, (2000); Walters, 2012 tensile strength is probably the most useful measure of strength of individual soil aggregates, and has been used in soil friability and tillability or workability studies. A friable soil is defined as a soil where large aggregates have a low tensile strength; that must not be too great, and small aggregates a relatively large strength which is necessary if soil is to retain its structure against imposed stresses as required in civil practices. Numerous researchers have placed great emphasis in performing tillage operations when soils are at the friable states hence minimizing compaction.

It is also worthwhile to measure the soil mechanical characteristics over a range of water regimes, and to continue such experiments for mid- and long-term periods for the possible beneficial effects of conservational tillage systems on the soil tilth and friability. The universally accepted indices for quantifying tilth soil friability should be tested in every agricultural soil locality in collaboration between the farmer/user of the tillage tool and the designer for effective crop production and soil/water conservation. Timing of tillage and traffic as it relates to soil water conditions. When soils are tilled or trafficked in their plastic state they are highly sensitive to compaction, while the soils are sensitive to rutting in their liquid state. In the friable state soils are less sensitive to compaction. This means that a friable soil that is ideal seen from a soil fertility/productivity point of view may also be desirable seen from an environmental point of view, i.e. low energy input in tillage and low erodibility.

Soils are usually in a most friable state when the moisture content is near field capacity. The studied soils depending on the water content has divergent characteristics: Hossne (2008) reported a friable ranged between 7.63 and 9.52%. Espinoza (1970) investigated the field capacity for the Ultisols savanna soil of Monagas, founding: 11.70% (0 - 0.2 m), 13.49% (0.2 m - 0.5 m), 16 , 89 (0.5 m - 1.0 m) and 19.48% (1.0 m - 3.50 m) with an overall average of 15.39% and 12.6% from 0.0 m - 0.5 m. Hossne (2008) reported the field capacity approximately from 10.3 to 12.8%. Hossne and Salazar (2004) determined: the shrinkage limit from 4.22 to 5.20%, plastic limit from 12.92 to 14.04%, liquid limit from 16.94 to 19.43%, the plasticity index of 3.59 to 5.78% and the friability of 8.63 to 9.37%. The wilting point found by Gaspar (1983) was 6.19% and Fermin (1971) was 5.53% for the soils under study.

Unsaturated soils for testing have been performed using a conventional triaxial and direct shear equipment modified to allow for the control and measurement of pore-air and pore-water pressures (Uchaipichat, 2010; Toll, 1990; Oloo and Fredlund, 1996; Peterson, 1988; Gan, 1986; Ho and Fredlund, 1982; Escario, 1980; Satija, 1978; Fredlund and Morgenstern, 1977; Gibbs *et al*., 1960; Bishop *et al*., 1960; Donald, 1956). The vane shear test (VST) has also being used for laboratory and *in situ* undrained shear strength evaluation (Geotechnical Design Manual, 2012; Saarilahti, 2002; Schjùnning and Rasmussen; 2000; Ekanayake and Phillips 1999;

Carter, 1990; Schjønning, 1990; Ohu *et al.*, 1986; Fountaine and Brown, 1959; Manuwa and Olajide, 2012; Ekwue and Stone, 1995; Rezaei *et al.*, 2012; Bachmann *et al.*, (2006); Zhao *et al.*, 2009).

The objective was, with soil samples obtained in two savanna agricultural soils sites at two depths, to evaluate the correlation among the shear strength, soil vane strength calculated, compaction, Proctor tester calculated, and the interaction of the soil water content.

MATERIALS AND METHODS

The soil samples designated A, was collected in San Jacinto Sector Costo Arriba, Maturin, Monagas State (Figure 1), in the area at 58 meters above sea level, with location North 1,088,572 and East: 474,602, annual rainfall of 1127 mm and an average temperature of 27.5 °C. The soil samples designated B, was collected in Jusepin, Monagas State (Figure 1), in an area situated at 147 meters above sea level, with location 9°41'3" north latitude and 63°26' west longitude, with an average annual rainfall of 1,127 mm and an average temperature of 27.5 ° C. With a typical savanna vegetation: Chaparro (*Curatella americana*, Dilleniaceae), Manteco (*Byrsonima crassifolia*, Malpighiaceae), Mastranto (*Hyptis suaveolens*, Lamiaceae), Grasses and Cyperaceae. The selected areas belong to the Oxic Paleustult Isohipertermic in virgin soil conditions.

To collect the representative soil samples from the two different sites (Table 1) the Uhland sampler (Figures 2a and 2b) was used, the sampler cylinders were previously identified, weighed, where three different height measures (l) and diameter (φ)

were taken with a digital caliper. The cylinder volume (V_C), that represented the *in situ* sample volume (V_T), was determined with Equation 1.

$$V_C = V_T = \frac{\pi * \varphi^2}{4} * \ell \qquad (1)$$

A random sampling, of the areas of study, were proceeded with the excavation of five test pits spaced at 30 m with an area of 100 by 80 cm (Figure 1). Samples were taken with the Uhland type sampler at two different sites, at three depths in five pits with five replicates per depth (2 * 3 * 5 * 5), this produced a grand total of 150 samples, 75 samples per site, which were subjected to the determination of the *in situ* bulk density and gravimetric moisture content. A portion of the oven dried subsamples crumbled and mixed, was employed to determine the physicochemical components (Table 1) and the remainder was passed through 2 mm sieve used in the

Figure 1. Sampling area North: 1078422,0; 1078979,0; 1079445,0; 1079698,0; 1079821.0; 1079772,0: East: 451257,0; 451018,0; 451394,0; 451555; 451486,0; 451276,0 respectively.

Table 1. Physical characteristics of a sandy loam soil of two different sites at two depths at Monagas State, Venezuela.

Components (%)	Horizons of two sites			
	San Jacinto, Sector Costo Arriba		Jusepin	
	0-30 cm	30-60 cm	0-30 cm	30-60 cm
Very course sand	1.03	0.37	1.77	0.50
Course sand	9.18	1.93	22.43	0.58
Medium sand	25.61	7.49	24.01	16.94
Fine sand	30.10	7.22	22.13	27.74
Very fine sand	12.60	14.06	6.33	8.39
Total sand	78.42	31.07	76.67	54.15
Silt	8.400	52.73	15.23	29.65
Clay (kaolinite)	13.151	16.2	5.2	10.2
Organic matter	1.632	0.86	0.49	0.45
Textural class	SaL	SL	SaL	SaL

compaction and shear test sufficient to meet the experimental soil needs, 14.4 kg per moisture measure with 4 replications, for eight (8) moisture levels, for a total of 115.2 kg.

The instruments used in the tests were: (a) Balance, (b) Uhland sampler of 8235 g total mass (Figure 2a, and Figure 2b), (d) 2 mm sieve mesh (No. 10), (e) A manual hand held shear vane *in situ* testing device apparatus for measurement the unconfined maximal shear strength (Figure 3c), with a reading log head with scales 0-120 and 0-28 kPa, a pointer type no return, cutting blades (19 and 33 mm in diameter) and 300 mm extension bar and 0-28 kPa for a 33 mm in diameter palette (Figure 3c) and (f). Proctor compaction tester with 152.5 mm diameter cylindrical extension, 4.54 kg hammer modified piston compactor, with a 457.2 mm free fall and 50.8 mm diameter piston face stroke (Figure 3b). Figure 3a shows the three layers and the two surfaces (Su) (top (1) and bottom (2)) where sampling, after compaction, were taking for evaluating water content, bulk density, and the vane shear tester was operated. Manuwa and Olajide (2012) to determine the shear strength of the soils, compaction was carried out at 25 blows of standard (2.5 kg) Proctor hammer at moisture contents between 14.2 and 17.2 %. The moisture contents were chosen according to the consistency limits of the soils. Shear strength readings were taken at two depths (5 cm from top and bottom of the mould) with a 19 mm vane size shear vane tester.

The sample initial soil water content (w_0) was found with Equation 2 using the water mass (M_W) and dry mass (M_S). Dry mass was calculated using Equation 3. The water volume (V_W) was determined with Equation 4 for each moisture selected level according to the four replicates and a total soil mass (M_T) of 14.4 kg/replicate used in the test. The capsule mass plus mercury (M_{CA+HG}) was obtained by weighing the flushed mercury filled capsule. The capsule volume (V_{CA}) and the mercury mass (M_{HG}) were obtained with Equation 5 and Equation 6, respectively, where ρ_{HG} symbolized the mercury density. The dry bulk density (ρ_S) was calculated with Equation 7.

$$w_0 = \frac{M_W}{M_S} * 100 \qquad (2)$$

$$M_S = \frac{M_T}{1 + w_0} \qquad (3)$$

$$V_W = \frac{w * M_T}{1 + w_0} \qquad (4)$$

$$V_{CA} = V_{HG} = \frac{M_{HG}}{\rho_{HG}} \qquad (5)$$

(a)   (b)
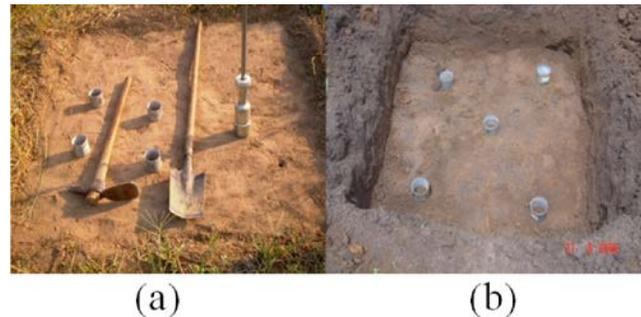
Figure 2. Uhland sample and field soil sampling, showing the pit.

(a)   (b)   (c)
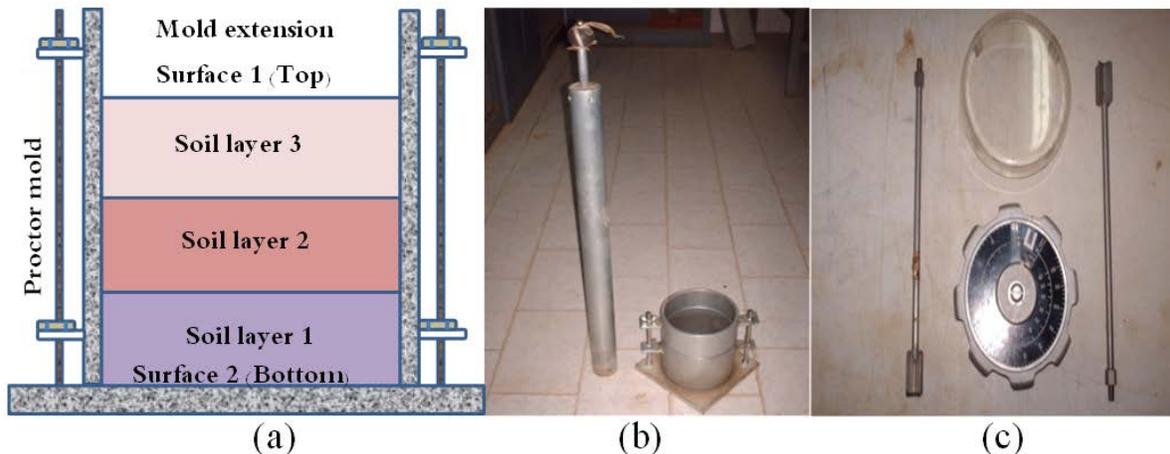
Figure 3. Proctor (a and b) and shear tests (c) equipment used in the experiment

$$M_{HG} = M_{CA+HG} - M_C \qquad (6)$$

$$\rho_S = \frac{M_S}{V_T} \qquad (7)$$

The experimental setup consisted on eight (8) selected wetness treatments (3, 5, 7, 9, 11, 13, 15, and 17) with three replications, for a total of thirty two (32) design treatments employing the same amount of Proctor cylinders. The Proctor cylinder was filled with three soil layers using 1.2 kg per layer, where 25 blows per layer were used. The shear strength, the dry bulk density and dampness were measured on the top (1) and bottom (2) of the Proctor cylinder surfaces (Su). The results were statistically analyzed by least significant difference (LSD) for each wetness level for the measured dependent variables (ρ_S and τ) and a regression analysis with representative scatter diagrams of the data trend line, linking shear tension and bulk density with soil water content. Three-dimensional plot and response surface methodology, introduced by Box and Wilson (1951), to relate optimally shear strength versus dry bulk density and soil wetness. The agricultural sandy loam soils of the Monagas state of Venezuela under water content variability conditions are: (a) Deformable, (b) Compactable, (c) Possess capillary cohesion, friction, elastic properties (Young modulus, shear modulus and Poisson ratio), friability, consistency properties, terramechanic resistance and shrinkage-expansion properties. Hossne (2011); Hossne (2008); Hossne (2008b); Hossne y Salazar (2004); Hossne (2004); Hossne *et al*. (2003).

RESULTS AND DISCUSSION

Figure 4 shows the shear strength and bulk density as affected by the soil water content in the Proctor compaction process of densification. The

Proctor soil compaction test was performed by measuring the bulk density of the soil being tested at different moisture content points. The bulk density obtained in a series of determination was plotted against the corresponding moisture. A curve was drawn between the water content and the bulk density to obtain the maximum bulk density and the optimum water content, for both soil site and depths. The position of the maximum on the curve corresponded to the optimal bulk density. It could be observed that the optimal compaction achieved was between 9.4 and 12.2% optimal compacting water content; instead, for the shear stress it was between 6.9 and 7.7%. It may be discerned that the wetness caused the optimum compaction and shear stress in different ranges of soil consistency. It may be perceived that soil wetness influenced much over shear stress than compaction. Each regression equation curve is shown in Table 2 with their respective optimal shear stress and bulk density values according to the optimum moisture. The regression equations show that the 117,22 kPa maximum shear strength at 7.67% optimal
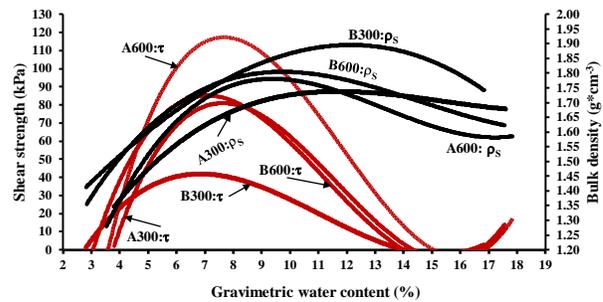
Figure 4. The shear strength (τ) and dry bulk density (ρ_S) versus moisture content for the two sites under study, at two depths 0-300 mm and 300-600 mm. In the notation from left to right, the capital letter represents soil side, the number represents depth in mm and the symbol represents the bulk density (ρ_S) and shear strength (τ).

Table 2. The regression equations of the displayed curves in Figure 4, showing the regression coefficient, optimum compaction wetness ($w_{optimal}$) and optimal shear strength ($\tau_{optimal}$) and optimal bulk density ($\rho_{Soptimal}$) of the two soil sites (A: San Jacinto, Sector Costo Arriba y B: Jusepin, Monagas, State, Venezuela) and two depths examined.

Soil	Regression Equations	R^2	$w_{optimal}$	$\tau_{optimal}$-$\rho_{Soptimal}$
A(300)	$\tau = 0.3386880\ w^3 - 11.8259619\ w^2 + 121.3100576\ w - 306.6718461$	0.89	7.63	80.90
A(300)	$\rho_S = 0.0003336\ w^3 - 0.0153724\ w^2 + 0.2225749\ w + 0.7036986$	0.82	11.69	1.74
A(600)	$\tau = 0.4249015\ w^3 - 15.0680686\ w^2 + 156.1616651\ w - 385.8240473$	0.94	7.67	117.22
A(600)	$\rho_S = 0.0008331\ w^3 - 0.0332296\ w^2 + 0.4035843\ w + 0.2307683$	0.91	9.39	1.78
B(300)	$\tau = 0.1498709\ w^3 - 4.9682102\ w^2 + 46.9566115\ w - 94.8844717$	0.94	6.85	41.82
B(300)	$\rho_S = -0.0001014\ w^3 - 0.0028020\ w^2 + 0.1128925\ w + 1.1192469$	0.87	12.14	1.90
B(600)	$\tau = 0.3181064\ w^3 - 10.7380857\ w^2 + 104.2140738\ w - 227.3488736$	0.87	7.08	85.12
B(600)	$\rho_S = 0.0004415\ w^3 - 0.0192927\ w^2 + 0.2499237\ w + 0.7921686$	0.65	9.72	1.81

water content happened in the 600 cm depth textured silt loam soil site A. Considering that soil consistency (measured for wet, moist and dry soil samples) is used to describe the resistance of a soil at various moisture contents to mechanical strength or farm machinery practices. Although the increase in bulk density caused increase in the shear strength of the soil as shown in Figure 5, the soil under study was exposed to maximum shear strength below the lower limit of the friable state, and the optimum bulk density above the upper limit of the friable state close to the soil field capacity. The optimal shear strengths were far achieved from the optimal bulk densities. JianQiang and Jing (2000) reported that the effect of moisture weakening the shear strength was greater than the effect of dry bulk density strengthening shear strength.

Figure 5 shows that the shear strength of the studied soil increased potentially versus soil bulk density but it pronounced when soil water content started to decline as function of soil bulk density. The strength increase with drying is normal in soils with fine particles as the effect of menisci forces in sandy soils (Barzegar *et al*., 1995; Seguel and Horn 2006).

Superimposing the curves of shear strength versus moisture content and those of the dry density versus moisture content, by optimization and solving the equations, gave the equilibrium moisture content of approaching the soils with the least shear strength and compaction, within the friable range between 7.6% and 9.5% soil wetness. Though these ranges and equilibrium moisture content values were obtained

using disturbed samples in the laboratory, they could be useful guides for identifying the moisture range for least draft and compaction on the field. Results herein reported also agreed with those obtained by Adekalu *et al*. (2007). By solving the system of equation formed with the shear strength and bulk density equations, the values of soil wetness corresponding to the crossing points equivalent to the same values of wetness, The points were achieved at values less than 4 % and higher than 14%; possibly indicating, that soil water content influenced separately the shear strength and bulk density results.

Figure 6 shows the response surface of the optimized Equation 8 obtained from a thirteen terms polynomial, where the terms ρ_S, w, ρ_S*w, w^2, ρ_S^3, w^3, $\rho_S^3*w^2$ were eliminated for a 70.64% R^2 and 70.42% adjusted R^2, a 0.21943 (0.0000) Durbin-Watson statistic and a 19.86 standard error. The Durbin-Watson statistic is always between 0 and 4. A value of 2, mean that there is no autocorrelation in the sample. Values close to 0 indicate positive autocorrelation and values greater than 4, indicates negative autocorrelation (Durbin and Watson, 1951; Savin and White, 1977). As the value of P in the ANOVA was much lower than 0.05, there was a statistically significant relationship among the variables with 95% confidence level. The analysis of variance produced an F of 167.21 and P of 0.0000. It shows the influence of humidity in the range from 5% to 10% on the shear strength and the shear strength increased with increasing compaction, however, the preponderance of wetness reduced the effect of compaction on shear strength.

$$\tau = -80,2206 + 2,07175*\rho_S*w^2 - 38,5983*\rho_S^2 + 40,8795*\rho_S^2*w - 4,41358*\rho_S^2*w^2 - 5,52075*\rho_S^3*w + 0,0544451*\rho_S^3*w^3 \tag{8}$$
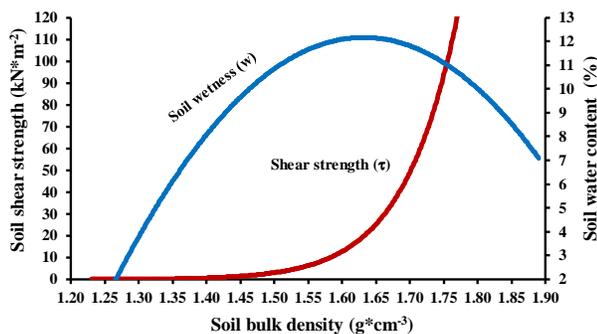
Figure 5. General relation of the shear strength (τ) and moisture content (w) versus dry bulk density (ρ_S).
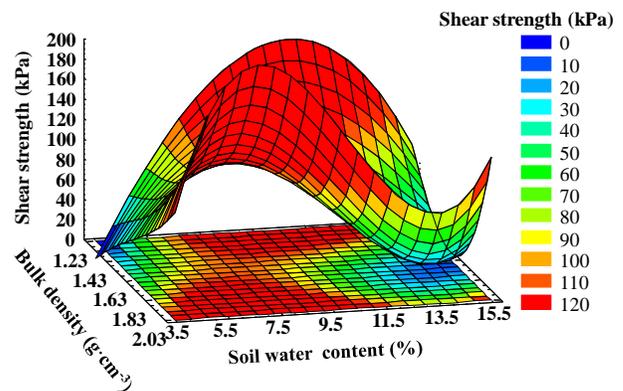
Figure 6. Response surface exhibiting the shear strength, soil water content and compaction relation.

Reported results here also agreed with those obtained by Panwar and Siemens (1972) and with those obtained by Hossne *et al*. (2003) who stated that the shear stress decreased exponentially with respect to increasing moisture for this soil. Farouk *et al*. (2004) affirmed that the results obtained from a series of triaxial tests performed on sand in its unsaturated form indicated that the shear strength of the samples increased as a result of increasing matric suction. Agodzo and Adama (2003) concluded that dry bulk density increased linearly with increasing soil strength for all the soils. However, dry bulk density had smaller effect than water content for determining soil strength, partly due to cementation changes that occur with soil wetting and drying.

Table 3 shows that there was no significance for the shear strength with respect to surface (Su) variable, and consequently no significant difference between the cylinder Proctor surfaces; however, with respect to the dry bulk density there was significant difference between the surfaces with a higher value in 0-300 mm depth samples on the lower surface of the Proctor cylinder. The maximum recorded value of the shear stress was between 7 and 8%. Agodzo and Adama (2003) concluded that the dry bulk density had a smaller effect on soil strength than moisture content. Panwar and Siemens (1972); Adekalu *et al*. (2007) and Agodzo and Adama (2003) demonstrated that shear stress increased with soil compaction. The difference may have been the result of the influence of moisture and texture on both parameters. The shear

stress and dry bulk density were both significant with respect to depth (Pro), soil site (S) and moisture (w). There was no significance in the interaction or combined effect Pro*S. Table 4 shows the least significant difference analysis, where it clarifies the effects of the independent variables on the dependent variables studied. The mean shear strength and dry bulk density as function of moisture presented statistically significant differences, pointing out the variation that caused the moisture in both parameters. The mean dry bulk densities with respect to moisture content of the upper and lower Proctor cylinder surfaces exhibited significant difference, the highest value recorded corresponded to the subsurface. Both surfaces mean shear strengths were not significant difference, with greater value for the bottom surface, possibly caused by the higher compacting value.

CONCLUSIONS

The shear strength increased with increasing dry bulk density, indicating that the reduction in pore volume caused soil resistance. The 100 kPa mean maximum shear strength, lied between 6.5 and 7.3% soil water contents and 1.77 g·cm⁻³ bulk density. The dry bulk density showed a maximum of 1.84 g·cm⁻³ at optimum moisture between 9 and 10% with 84.24 kPa shear strength. According to the regression equations obtained the utmost shear strength of 120.49 kPa was reached for site A, at 600 mm depth, with 7.24% water content. The regression equations show that the 120.49 kPa maximum shear strength at 7.24% optimal

Table 3. Shear strenght (τ) and bulk density (ρ$_S$) ANOVA adjusted for depth, two surfaces and moisture at two sites (San Jacinto, Sector Costo Arriba y Jusepin) of savanna soil of Monagas state, Venezuela.

Source of variation	GL	Suma de cuadrados	Cuadrados medios	F	P
Shear strenght (τ)					
Surface (Su)	1	67	67.4	0.53	0.4682
Depth (Pro)	1	27004	27003.9	211.28	0.0000
Soil (S)	1	17597	17596.8	137.68	0.0000
Wetness (w)	15	543759	36250.6	283.62	0.0000
Error	493	63012	127.8		
Average	36,327				
VC	31,12				
Dry density (ρ$_S$)					
Surface (Su)	1	0.24878	0.24878	54.95	0.0000
Depth (Pro)	1	0.15122	0.15122	33.40	0.0000
Soil (S)	1	0.92974	0.92974	205.37	0.0000
Wetness (w)	16	8.78196	0.58546	129.32	0.0000
Error	493	2.23185	0.00453		
Average	1.6722				
VC	4.02				

water content happened in the 600 cm depth textured silt loam soil. According to the regression equations obtained the lowest shear strength of 42.12 kPa was reached for site B, at 300 mm depth, with 6.67% water content. Superimposing the two curves of shear strength and dry density with moisture content gave the equilibrium moisture content, between 7 and 8%, approaching the soils with the least shear strength and minimum compaction on the soils.

The shear strength and dry bulk density optimal values happened at different soil water content, meaning that the soil compaction influenced the soil resistance depending on soil wetness. Although soil strength increased as compaction increased in the soil compaction-water characteristic curve, the optimal soil shear strength took place before the optimal compaction occurred. The effect of moistness weakening the shear strength was greater than the effect of dry bulk density strengthening shear strength. The results of this study support the argument that the resistance of the compacted soil is a function of water content.

A good preventative management practice is to avoid having equipment travel on working the soil at the wrong moisture content that increases the probability of soil compaction. Soil moisture content is the dominant property affecting soil strength during field traffic. As the moisture content increases, the strength of an unsaturated soil drops. Thus, the same stress compacts a soil more when it is moist than when it is dry. Saturated soil does not technically compact without the water draining out from the soil; however, wet soil is in a very weak state and may smear. Higher moisture content decreases the strength of the soil and increases the stress transmitted deeper into the soil. So, to prevent these situations, it is necessary to manage this soil in the friable state, or that the water content is not close the soil field capacity or over.

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Table 4. Shear strength (τ) (kPa) and bulk density (ρ_S) (g·cm^{-3}) averages for two depths (Pro), two surface measurements (Su), two soils (S) A and B (A: San Jacinto, Sector Costo Arriba y B: Jusepin, Monagas, State, Venezuela) and soil wetness (w).

Independent Variables	Dependent variables			
	Shear strength		Dry density	
	Average	Group	Average	Group
Depth (Pro)				
0-30	28,148	B	1,6915	A
30-60	44,505	A	1,6528	B
Surface (Su)				
Top (1)	35,956	A	1,6498	B
Bottom (2)	36,696	A	1,6946	A
Soil (S)				
(A)	43,762	A	1,6182	B
(B)	28,891	B	1,7262	A
Water content (w)				
5	68,54	C	1,6246	H
6	83,69	B	1,6988	EFG
7	100,30	A	1,7711	BCD
9	84,24	B	1,8360	A
10	33,88	DE	1,8002	AB
11	29,47	E	1,7780	BC

Least significant difference (LSD). Paired comparisons ($p \leq 0.01$). Different letters indicate statistically different means

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