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SUELO Y AGUA

SOIL AND WATER

ARTÍCULO ORIGINAL

Determination of basics mechanical properties in a tropical clay soil as a function of dry bulk density and moisture

Determinación de las Propiedades Mecánicas en un Suelo Arcilloso como Función de la Densidad y el Contenido de Humedad

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ABSTRACT. Specific information about physical-mechanical properties of soil is a support for simulation by computation techniques as Finite Element and Discrete Element methods to predict the soil behavior during soil tool interaction. Determination of basics mechanical properties needed for mathematical modeling of clay soils on the arable layer were carried out using triaxial compression and modified shear box test. Variations in shear strength, Yong's modulus, internal friction angle, soil-metal friction angle, cohesion and adhesion were determined at different experimental levels of gravimetric water content and soil dry bulk density. Multi-factorial regression analysis to estimate the corresponding values of above properties was performed resulting on statistical prediction equations for all basic mechanical properties under study.

Keywords: Tillage; Triaxial test; Elastic modulus; Shear test; Friction angle.

RESUMEN. La información detallada sobre las propiedades físico-mecánicas de los suelos constituye el soporte para la simulación mediante técnicas de cómputo como los métodos de Elemento Finito y de Elementos Discretos, los que están dirigidos a predecir la respuesta del suelo durante la interacción con las herramientas de labranza. La determinación de las propiedades mecánicas básicas incluidas en los modelos matemáticos que caracterizan la superficie de trabajo de los suelos cohesivos fue llevada a cabo mediante la ejecución de ensayos de compresión triaxiales y de corte directo modificado. La variación en los esfuerzos de corte, el módulo de Young, el ángulo de fricción interna, la fricción suelo-metal así como la cohesión y la adherencia fueron determinadas a diferentes niveles de humedad y densidad seca. Con el objetivo de estimar los valores de las propiedades mencionadas se realizó el análisis de regresión multifactorial obteniéndose las correspondientes ecuaciones estadísticas de predicción.

Palabras clave: Labranza; Ensayos triaxiales; Modulo de Elasticidad; Angulo de fricción.

INTRODUCTION

The optimum design of tillage tools and traffic systems aims at decreasing damages to soil structure. However, soil behavior under external load can change according to its physical and chemical properties, resulting on different design according of soil requirement. Specific content of water under action of stress, with certain amount of micro-cracks and linear pores, divides soil clods into small fragments, this relation is called index of soil physical quality and have a linearly and positively correlation with soil friability (Dexter y Birkas, 2004).

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In the area of simulation and geo-statistics several methods for predicting soil behavior in real-time by measuring draught on cutting tools were introduced with accuracy and advantage over traditional penetrometer methods (Adamchuk *et al.*, 2004; Saeys *et al.*, 2004; Mouazen y Ramon, 2006). On the other hand, soil simulation becomes a powerful tool for increasing the quality of tool design; however, the prognostics about the behavior of soil-soil and soil-tool interaction can be wrong with inaccurate selection of soil mechanical properties. Frictional, elasto-plastic, hypo-plastic and visco-plastic models require a group of soil parameters based on laboratory test as: elastic modulus, poison's ratio, soil density, internal friction and soil cohesion; correct values of all this properties define the real prognostic of soil deformation and draft demanding. Model of soil using finite element (Mootaz *et al.*, 2003; Abo-Elnor *et al.*, 2004; Huang *et al.*, 2004; Abbas *et al.,* 2006) and discrete element methods was developed in order to reproduce the laboratory and field experiment, this simulation showed well accuracy in term of force-displacement and general relationship between the soil mechanical properties and the physical soil condition. Predictive model developed basically for clay behavior is the well-known Cam Clay Model, A modified Clay Cam Model was introduced to improve this model; however, it is only suitable for clay with low cementation.

Mechanical properties behavior of Cuban soil related with soil moisture and bulk densities have been used to make numerical simulation related with soil compaction (Gonzalez Cueto *et al.,* 2009) getting a prognostic pressures over the soil by the effect of wheel inflation and weight. A methodology to obtain the parameters for a Finite Element model by mean of soil mechanical test in Ferralitic soil has been used obtaining accurate result with Duncan &Chan model (Herrera, 2010). Also the mechanical response in a Oxisol soil has been obtained using the elastic-plastic Dunker-Prager Model to reproduce the stress-strain curve (Herrera *et al.*, 2008).

Taken in consideration the necessity of the right parameters of soil to implement the numerical model the objective of this study is to obtain the behavior of the basic mechanical properties needed for numerical simulation of soil-soil, and soil-metal interfaces as a function of dry bulk density and water content in a cohesive tropical soil.

METHODS

Soil physical properties

Soil specimens were collected in four diagonal points at three different depths: 15; 30 and 50 cm, from sugar cane fields located at the central region of Cuban Island. Texture and physical properties showed in Table 1 were obtained by combination of soil sieve and hydrometer test (Archer y Marks, 1985). Attended to high content of expansive clay the soil was classified as a Vertisol according to the international classification based on the soil taxonomy.

TABLE 1. Physical properties of soil by layers

Depth, cm	Gs	PL	LL	PI	Sand	Silt	Clay
15	2,61	18,6	63,5	44,9	7	27	66
30	2,64	28,6	78,9	50,3	6	29	66
50	2,62	17,2	67,9	50,7	8	29	63

Pl, LL and PI are the plastic limit in %t, liquid limit and plastic index, respectively. Gs is a specific weight, all parameters without unit are in %.

Modified direct shear box test

Direct shear box modification was used to obtain the soil-metal adhesion and soil-metal friction coefficient. Soil samples were remolded and prepared for direct shear test using standard apparatus (Figure 1a), seven specimens of soil were molded with four replicas, using experimental combination of gravimetric water content measured as a percentage of dry weight at 15, 20, 25, 30 and 35% and soil bulk density at 1,0; 1,2 and 1,4 g/cm^3.

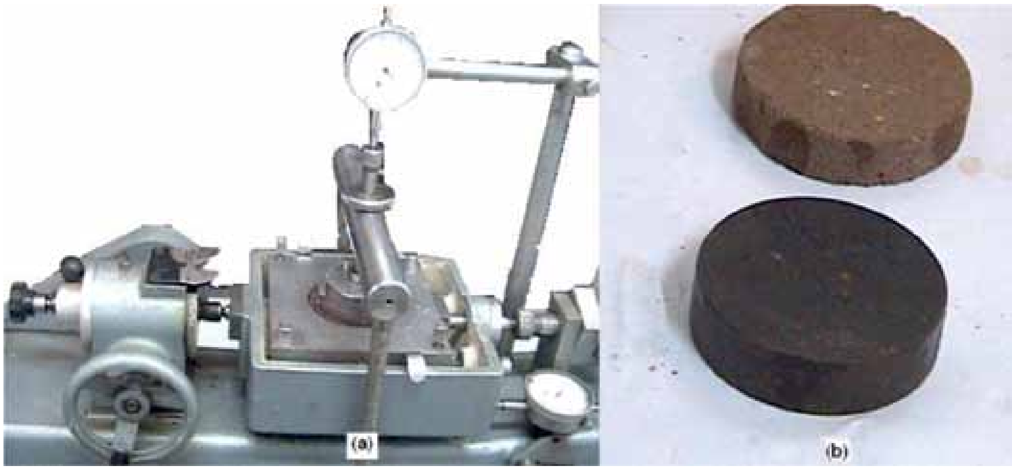


FIGURE 1. Direct shear box apparatus (a), cylindrical soil sample and dick metal (b).

The dimensions of the cylindrical soil samples were 70 mm diameter and 16 mm height (Figure 1b). Normal pressures at 35, 50, 75 and 100 kPa on the upper box were applied for testing four similar samples of the same combination, constant velocity of 1 mm/min was used to slide the bottom of the shear box, data of relative displacement versus shear forces were collected during the sliding time. The strength coefficients were calculated according to Mohr-Coulomb criterion of soil failure.

Standard triaxial compression test

The mechanical properties related to soil-soil interaction were obtained by standard triaxial undrained unconsolidated compression test. Internal friction angle, cohesion and Young's modulus of soil were determined by testing eleven specimens each one with four replicas. Soil cylindrical samples with 50 mm diameter and 100 mm height were obtained by mixed, remolded and conformed the soil collected (Figure 2a). In order to get four different principal stress combinations ($\sigma_1 - \sigma_3$) the axial pressure of water was changed at 36, 50, 75 and 100 kPa. The principal axial stress was supplied pressing on top of the soil cylinder (Figure 2b), at constant velocity of 1 mm/min.

FIGURE 2. Triaxial compression test; cylindrical sample (a), water pressure recipient (b) and pressure system control (c).

Mohr-Coulomb criterion of conical failure surface was used in order to determine the soil shear strength. This criterion establishes a direct relationship of shear stress at failure τ_f with soil cohesion c, normal stress σ_v and internal friction angle φ. Maximum stress at failure ($\sigma_1 - \sigma_3$) obtained at four confined pressures was plotted on tension-shear plane and a straight line was drawn. Based on data from triaxial compression test for each experimental combination, Young's Modulus was adopted as the slope of the linear section of the stress strain curve.

RESULTS AND DISCUSSION

3.1. Shear Strength

The average of stress-strain values at four different content of water, testing with constant density of 1,2 g/cm^3 (Figure 3), shows the variation of soil failure patter. The maximum stress was reached at minimum content of water showing a typical curve of fragile materials, cementation process forms a strong inter-granular bonds as a result of high content of clay and pressures, other studies on clay soil shows that the values of shear strength depends also on the mineralogical properties of clay (Dolinar, 2010).Large plastic deformation at lower level of moisture become undefined the failure shear point. For all contents of water, the soil under study showed high values of failure in comparison with loam and sandy soils (McKyes y Maswaure, 1997). Studies carried out in Ferrasol soil with 32% of clay (Suarez *et al.*, 2008) report values of shear strength around 20% less on the failure point, however the pattern of behavior was the same at different contents of water.

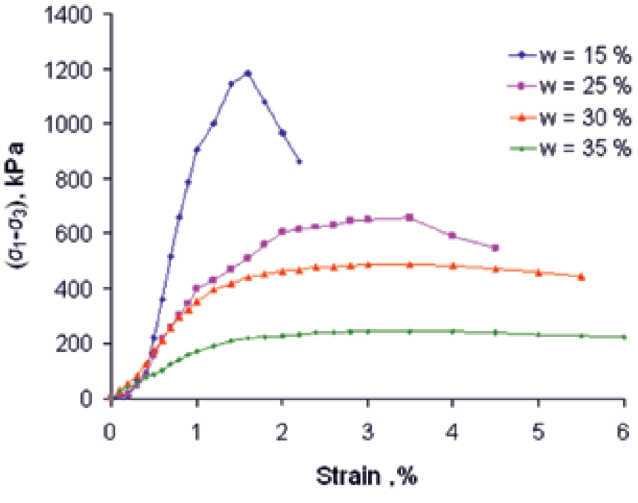


FIGURE 3. Stress-strain relationship for clay soil at 1.2 g cm^{-3} dry bulk density.

The result of soil shear strength calculated at 50 kPa axial pressure from triaxial test, show an important increment when decrease in soil moisture for all levels of dry bulk densities under studies (Figure 4), however non linear relation was found almost between water content and shear strength, The curve is clearly divided in two sections: over 20% the void spaces are filling by water and the soil strength depend mainly of pore water pressure while the other section is characterized by high values according to the strong clay cementation process.

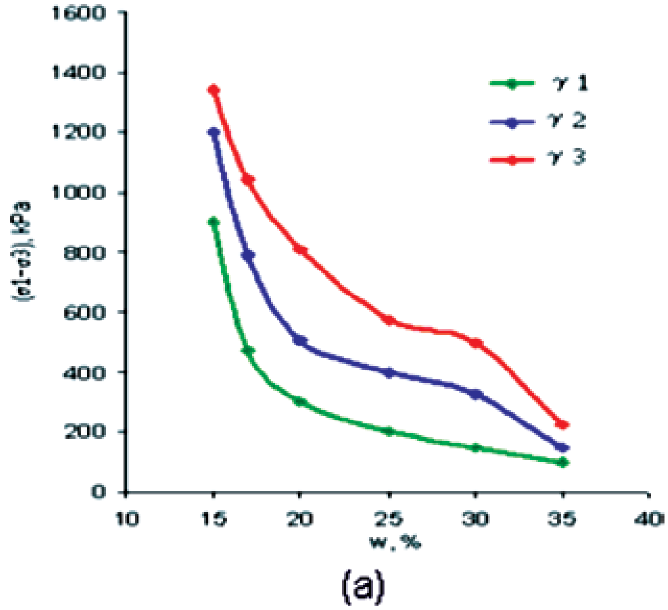


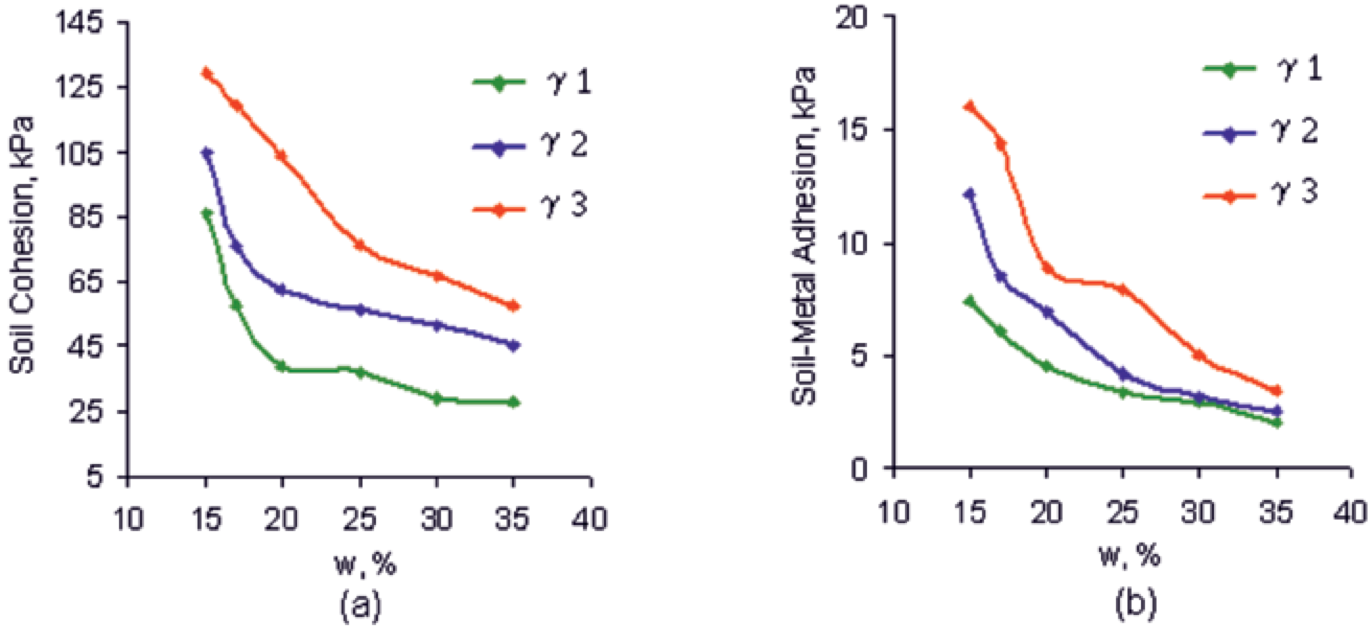
FIGURE 4. Variation of shear stress versus content of water at different soil densities.

Compacted soil shows more linearity with respect of change in moisture; nonetheless between 25 to 30% of water content remain the tendency to form a constant interval. At maximum value of water content the stress for all densities reach the minimum points for the current experiment, possible explained by the dissolution of intergranular bonds reducing internal tension and making possible slide soil layers over water films.

Soil cohesion

Soil natural cohesion, obtained by triaxial compression test as function of dry bulk density and moisture exhibit a strong dependence with both factors (Figure 5a); the increment on dry bulk density reduce the void ratio, making possible the strong connection between grain of soil, on the other hand shape irregularities contribute to reinforce the union, the abundant clay and silt particles cover the void spaces into the soil joining the element in contact.

For samples lower than 20% of water content cohesion experiment a rapidly increment, above this value decrease with low ratio, also tending to be constant almost for bulk densities at 1,0 and 1,2 g/cm^3, similar patterns of behavior were obtained by McKyes in clay soils (Zhang *et al.*, 1986; McKyes *et al.*, 1994). The property of clay to hold on the metal surface at different condition obtained by modified direct shear box test follow the same pattern of soil cohesion (Figure 5b), however the effect of water on this case is different, slide process is aid by water films on the metal surface making a lubricant function.



(a)

(b)

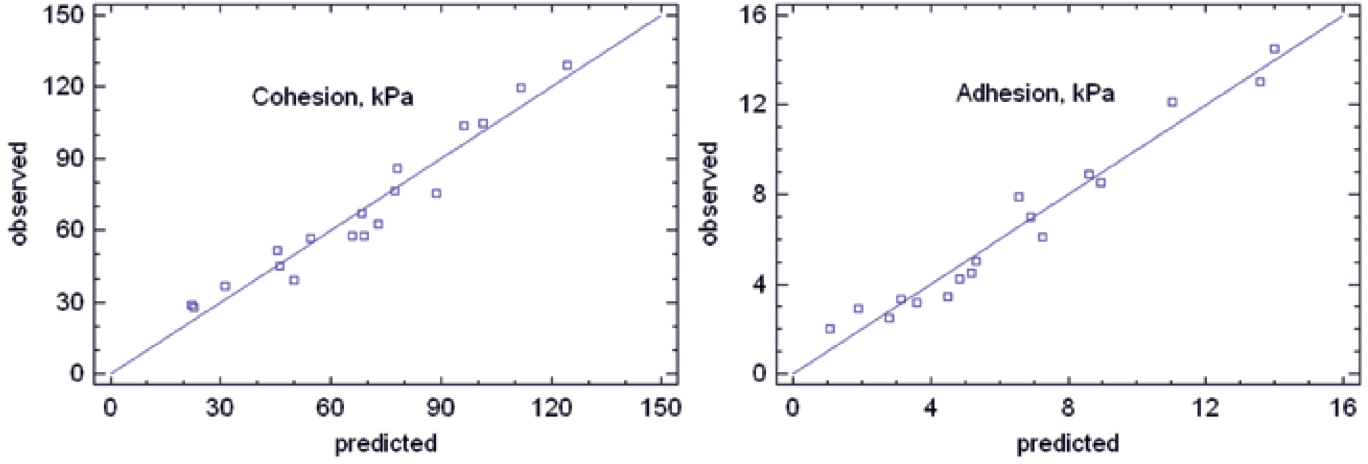
FIGURE 5. Variation in soil-soil cohesion (a) and soil-metal cohesion (b) versus water content.

However, cohesion in compacted soil (γ_3 = 1,4 g/cm^3) showed more dependence on water content in the interval of 20 to 35%. The soil-metal cohesion tended to be independent of dry bulk density for values of water content over 30%, this behavior results from the lubrication process on the metal surface by the fluid of water. The statistical equations result from multiple regression analysis to predict the cohesion and soil adhesion are written as:

$$c_{s\text{-}s} = 10{,}1 + 11{,}4\,\gamma + 0{,}1\,w^2 - 12{,}3\,w \qquad R^2 = 93{,}7\% \tag{1}$$

$$c_{s\text{-}m} = -13{,}6 + 8{,}5\,\gamma + 0.4\,w \qquad R^2 = 94{,}5\% \tag{2}$$

Where ($c_{s\text{-}s}$) is soil cohesion and ($c_{s\text{-}m}$) soil-metal adhesion measured in kPa, (γ) dry bulk density and (w) water content. The figure 6a and 6b show the prediction values using above equations with mean absolute error of 5,6 kPa for soil cohesion and 0,85 kPa for soil adhesion.



(a)

(b)

FIGURE 6. Observed versus predicted of cohesion (a) and adhesion (b).

Elastic Modulus

Strong relation with water content and also with bulk density was found in elastic modulus, values obtained from studies carried out on three kinds of soil (Kezdi, 1980), showed the same pattern, though the results obtained there were quite lower; that difference is attributed to the quality of Vertisol to form hard structure during consolidation with constant pressure.

Soil elasticity have substantial changes on different physical condition. For all bulk density the Young's Modulus (E) show the same pattern of behavior, sank gradually after reaching 25% of water content and rising rapidly under dry condition (Figure 7).The state of plastic deformation is reaches by loose soil at average of 40 MPa with respect to compacted soil for all range of water content, remarking the influence of bulk density. Statistical relationship was found as expression of the predictable behavior of Elastic Modulus:

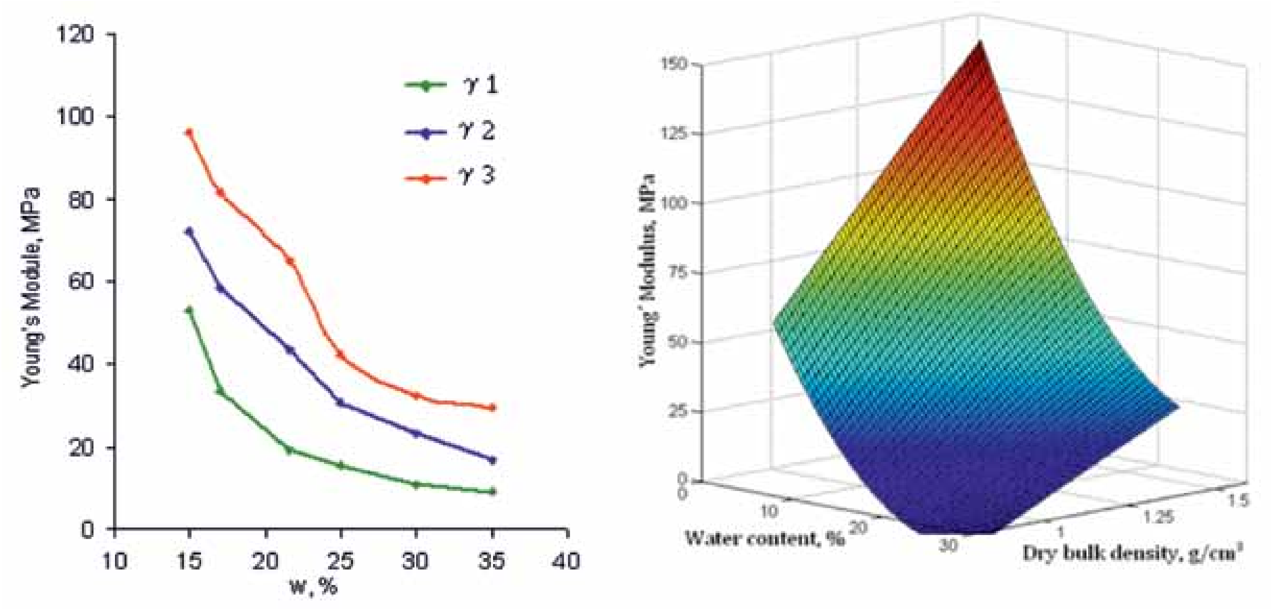


FIGURE 7. Variation of Elastic Modulus versus water content.

$$E = 82{,}1 + 89{,}8\,\gamma + 0{,}1\,w^2 - 10{,}2\,w \qquad R^2 = 95{,}5\% \qquad (3)$$

Where (E) is Young´s Modulus measured in MPa.

Graph of observed versus predicted values is represented in the Figure 8, the mean absolute error of Young's Modulus from prediction equation is 3,1 MPa.

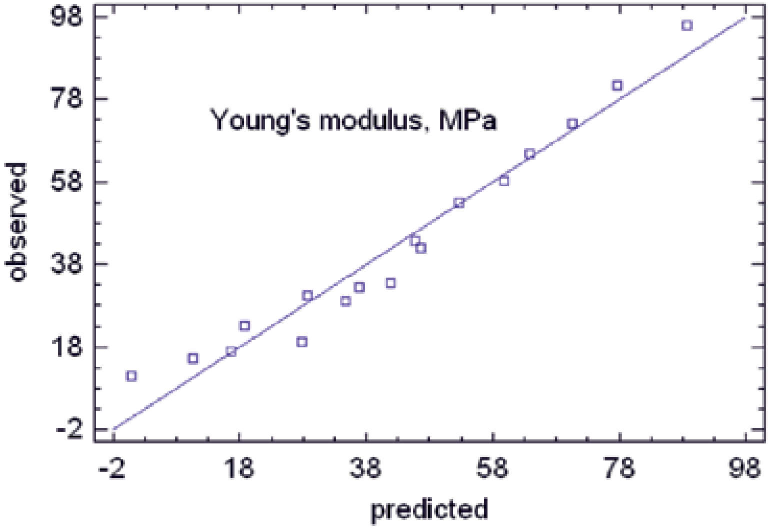


FIGURE 8. Observed versus predicted values of Young's modulus.

Soil friction

Soil friction angle on the soil-soil interface (Figure 9a) tends to reach maximum values at low content of water; this behavior is most evident on soil-metal interface (Figure 9b) consequence of layer of water stored on the metal surface providing lubrication during sliding. The same result was found in fine-grained soil (Yao y D.Zeng., 1988). However, some authors found no relation between soil and bulk density (McKyes *et al*., 1994; Mouazen *et al*., 2002); that behavior was observed only for soil-metal friction (Figure 10b). Different results can be attributed of particular soil quality and the range of water content that were used for each investigation.

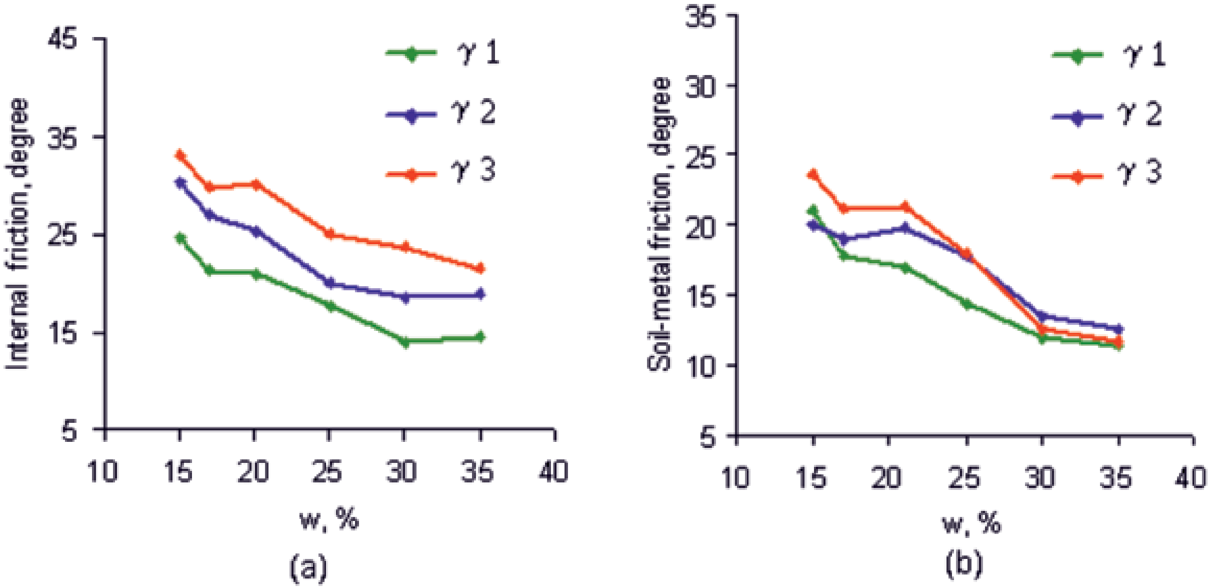


FIGURE 9. Variation of internal friction (a) and soil-metal (b) versus water content.

Bulk density on soil-metal interface have some slight fluctuation in the range of 1,2 degree for all contents of water, no significant statistical influence was observed and this effect was excluded to the model. Relationships for prediction of soil friction angles were written as:

$$f_{s\text{-}m} = -23{,}6 + 12{,}9\ln(w) \qquad R^2 = 91{,}7\% \qquad (4)$$

$$f\ s\text{-}s = 22{,}1 + 0{,}5\ w - 37{,}5\ \gamma + 16{,}4\ \gamma^2 \qquad R^2 = 96{,}5\% \tag{5}$$

Where ($f_{s\text{-}m}$) is soil metal friction and ($f_{s\text{-}s}$) soil internal friction measured in degree, (γ) dry bulk density and (w) water content.

CONCLUSION

A set of prognostic equations is proposed, able to calculate the predictive values of elastic modulus, cohesion, adhesion, internal friction and soil-metal friction as a function of dry bulk density and gravimetric water content.

The stress-strain curve shows the transition between fragile into plastic behavior testing by triaxial unconsolidated compression test at different water content. Shear strength determined at 50 kPa axial pressure show the quality to forming a hard structure, when water content is higher than 20% reaching maximum point under dry condition.

Soil cohesion and soil adhesion have a strong dependence with water content, showing the same pattern for different levels densities, cohesion values on soil-metal interface during sliding time decrease at least 70% to respect of soil-soil cohesion, for values up to 25% of water content soil adhesion for loose and medium soil become similar.

The Elastic modulus increase under dry condition up to 100 MPa, predominated by the influence of water content, bulk density play a secondary roll. Similarly internal friction angle is affected by the water content and weak connection was found between soil-metal friction angle and bulk density.

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