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Soil-Metal Sliding Resistance Forces of Some Trinidadian Soils at High Water Contents

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Abstract: *Soil-metal sliding resistance forces are influenced by factors such as soil physical properties, the geometrical characteristics of the tool and the speed between the two interacting surfaces. Soil-metal sliding resistance has a negative effect on the operation of earth-working machines. It results in increased downtime for cleaning tool surfaces, increased draft forces, and increased fuel consumption during the operation of the machinery thus leading to reduced operation efficiencies. This results in increased operational cost to the end user. Previous research exists on the subject area. However, there are few equipment that have been designed to adequately measure the dynamic forces that exist during this phenomenon. In this paper, soil-metal sliding resistance tests were performed by incorporating a soil-metal adapter tool (SMAT) to a Hounsfield tensometer. This permitted measurements of the dynamic forces on the SMAT as it moved on the soil surface. Data on the normal stress against shear stress at the soil-tool interface for some common soils in Trinidad were obtained. The measured shear stress at the soil-tool interface was separated into the components of adhesion constant and external friction angle. Soil penetration resistance measurements were also taken. Analysis of variance showed that the experimental factors such as soil type, water content and compaction effort had significant ($P < 0.001$) effect on adhesion constant and the external friction angle. Regression models were developed to predict the behaviour of the soil and the tool at the boundary surfaces. This information could be used in performing simulations at the soil-tool interface and thereby aid in improving designs of earth-working tools. Also the information could be used in improving soil management practices during tillage operations.*

Keywords: *Adhesion, Friction, Soil, Metal, Sliding, Resistance*

1. Introduction

Soil-metal sliding resistance can be described as the binding force that exists between the soil and solid (metal) area of contact (Ren et al., 2006). This phenomenon occurs when frictional forces and adhesive binding forces between the soil and the surfaces in contact are greater than the cohesive forces of the soil aggregate (Ren et al., 2001). Adhesion of soil on earth-working equipment and machinery results in downtime for cleaning, increased fuel consumption, draft of the machinery, loss of power of the machinery, and reduced efficiency and quality of work (Wang et al., 1998). Earth-working tools and machinery are constantly subjected to adhesion between soil particles and the surface of the tool during operations such as tilling, drilling, and excavating (Ramsahai et al., 2011).

Soil-metal sliding resistance is a factor which is normally considered when designing earth-working machinery and equipment (Shen and Kushwaha, 1998). It is a function variable in the fundamental earth moving equation (FEE) for draught requirements for earth-working equipment (Sahu and Raheman, 2006; Patel and Prajapati, 2011). Both physical properties of the soil and the tool influence adhesion (Sharifat and Kushwaha, 2000). Some of these soil properties include water content, void ratio, organic matter content, grain size distribution and clay content of the soil (Onwualu, 2010). Tool properties include the tool material characteristics, the geometry of the tool, surface roughness of the tool and the speed of operation (Ren et al., 2001). Fountaine (1954) when investigating the effects of normal loads on soil found that the soil-metal sliding resistance can be attributed entirely to the water film between the jointed surfaces of the soil-metal interface.

Adhesive forces are at maximum levels when the water content is between the plastic and liquid limits of the particular soil (Ramsahai et al., 2011). Khan et al., (2010) highlighted the effects of varying water content on soil adhesive property and showed that a particular soil would have its highest value of adhesion at water contents between 22% and 32%. This range also corresponds to the plastic limit of most soils in Trinidad (Roopnarine et al., 2012).

Satomi et al. (2012) identified that adhesive stress decreased as void ratio increased. Hence the bulk density and thus soil compaction will also influence adhesion. Sakharov et al. (1973) and Ramsahai et al. (2011) indicated that the value of adhesion is highest in clay soils. This is due to the fineness of the particles and the greater surface area developed at the soil-metal interface.

Soil-metal sliding resistance is a complex process and very difficult to measure. The process is a combination of adhesion and frictional forces (Soni and Salokhe, 2006). Authors such as Shrivastava et al. (1993) have proposed a simplified equation (Equation 1) to relate the phenomenon.

$$\tau = C\_\alpha + \sigma \tan(\delta) \qquad (1)$$

where τ is the sliding resistance stress and C_α is the stress due to adhesion, σ is the normal stress acting on the surface and δ is the external friction angle.

This equation can be further rewritten as equation (2) developed by Chancellor (1994).

$$\tau = \mu\,(A\_N + \sigma) \qquad (2)$$

In this format the coefficient of friction is represented as μ and is equal to tan (δ). The term, A_N is the adhesion stress constant divided by friction. The equation argues that the combined effect of the adhesion (A_N) and normal stresses (σ) results in a total normal stress (Chancellor, 1994). This total normal stress when multiplied by the coefficient of friction gives the sliding resistance stress. Further the factors that affect the coefficient of friction ultimately affect the sliding resistance stress.

Limited tests on soil adhesion properties have been performed on local and regional soils of the Caribbean. Perusal of the literature revealed no information on the combined effects of water and compaction on soil-metal sliding resistance forces. One of the main reasons for this deficit could be the lack of specialised laboratory test equipment. Results from soil-metal sliding resistance experiments would be beneficial to the agricultural, mining and construction industries as such data would assist engineers and scientists to model the behaviour of soil under varying conditions. Such models would be useful in simulations and can be applied in the design analysis at the soil-tool interface, hence, improving the design of earth-working equipment and thereby optimising efficiencies during operations. This paper investigates the effect of varying water contents and compaction efforts on sliding resistance forces at the soil-metal interface of three local soils. A soil-metal adapter tool (SMAT) device was designed and fabricated. This device allowed the determination of coefficients of adhesion and friction of specific soil types with varying water contents of the soil.

2. Materials and Methods

Three local soils, Piarco sandy loam, Maracas clay loam and Talparo clay (Table 1) were used to represent some of the major soils in Trinidad. These soils are a representative of the three common soil textures common in Trinidad. Dehumidified soil samples were ground to pass through a 4.75 mm sieve. Particle size analysis (see Table 1) was carried out using the hydrometer method (Lambe, 1951). The organic matter content in the samples was measured using the method advocated by Walkley and Black (1934). The measurement of organic matter was done for completeness in determining the soil's physical properties. However, organic matter was not considered as a factor in these tests. The plastic limit test was carried out using the method described by Das (2012). The initial water contents of the soil were determined by the gravimetric method (Das, 2012). Water contents in the samples were then increased by adding the amount of water required for soil testing.

To determine the sliding resistance between the soil and a tool, a special device called the soil-metal adapter tool (SMAT) was designed, fabricated and used as a special attachment to the horizontal Hounsfield tensometer (see Figure 1(a) and (b)). The SMAT device is comprised two parts: one part is a moving blade whose surface roughness was 1.19 µm and the other is a fixed modified compaction mould (see Figure 2). The combined apparatus measured the sliding resistance forces between the metal blade and the soil surfaces. To measure soil penetration resistance on the soil surface, a hand pushed spring-type Proctor Penetrometer (ASTM, 1985) was used.

Before placing the soil samples in the Hounsfield tensometer, each sample was compacted in the compaction mould using the standard Proctor compaction method (Lambe, 1951). Three levels of compaction efforts (5, 15 and 25 Proctor blows) were applied each at four levels of water content (15%, 20%,

Table 1. Classification, organic matter, the particle size distribution (%) and plastic limit for the soils

Soil Series	Classification [a]	Organic Matter Content (%)	Sand (0.06-.002 mm)	Silt (.06 - .002 mm)	Clay (<0.002 mm)	Plastic Limit (%)
Piarco	Aquoxic Tropudults[1]	1.7[b]	64.9	17.0	18.1	20.29
Maracas	Orthoxic Tropudults[2]	4.7	44.7	24.7	30.6	23.37
Talparo	Aquentic Chromuderts[3]	2.7	25.4	28.3	46.3	27.13

[a] Classification according to Soil Taxonomy System (Soil Survey Staff,1999). Numbers in superscript are soil mineralogy given by Smith (1983) and represent (1) kaolinitic clay (2) clayey oxidic and (3) mixed clay mineralogy

[b] All values are means of three replicates

25% and 30%). The range of water content was chosen to represent those close to the plastic limit of all three soils. For each sample of soil tested, four normal loads of zero (0) kg, 1.0 kg, 2.0 kg and 3.0 kg mass were added incrementally. Two replicates were done for each test.

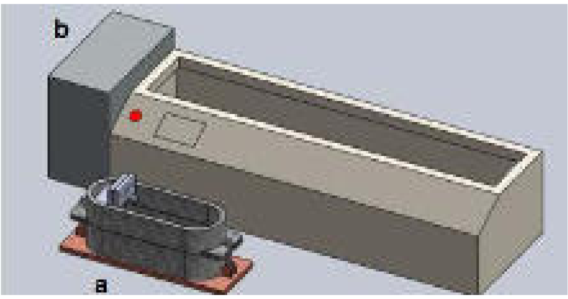

Figure 1: (a) Soil-Metal Adapter Tool (SMAT) and **(b)** Horizontal Hounsfield Tensometer

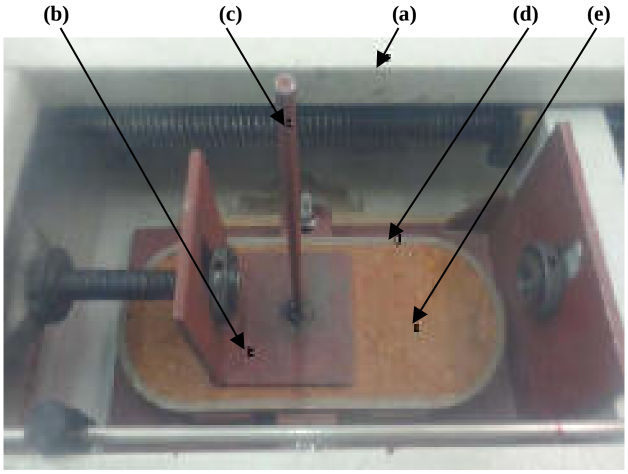

Figure 2. SMAT Tool Assembled in Tensometer and under Operation

(a) Horizintal Hounsfield Tensometer Cavity
(b) Moving Tool Place (Dimensions 70 mm (L) x 70 mm (W) x 90 mm (H))
(c) Extended Rod for Placement of Weights (Dimensions Φ 6 mm x 180 mm (H))
(d) Fixed compaction mould (Dimensions 350 mm (L) and Φ 100 mm for semi-circle)
(e) Compacted Soil

Before testing, the surfaces of the compacted samples were rolled forward and reversed twice with a miniature roller. Then the Proctor Penetrometer was placed on the surface of the soil. Two readings of penetration resistance were obtained. The surfaces of the soil samples were again rolled forward and reversed twice. The compaction mould was then placed and fixed on one end of the tensometer while the blade was attached to the opposite end and its bottom surface moved over the soil surface (see Figure 2). A constant speed of 20 mm/min was maintained for half hour on each test. 20 mm/ min was chosen as it is a sufficiently slow speed for easily obtaining measurements. For the first run, no normal load was added. Thereafter, loads were added in increments. Each time a new load was added the surfaces of the soil samples were rolled. This formed part of the preparation method.

The measured resistive forces occurred mainly at the interface of the soil and tool and were a combination of frictional forces and adhesion forces. In our investigations, we applied varying normal forces per unit area (σ) at the soil-tool interface and measured the corresponding resistive shear force (τ) per unit area. The approach as discussed by Koolen and Kuipers (1983) requires that plots of τ against σ be done. Hence, values of adhesion constant(C_{α}) and external frictional angle (δ) were graphically extrapolated.

This experimental investigation uses disturbed samples for measuring soil-metal sliding resistance forces. Though disturbed soils cannot fully replicate natural soil conditions they are suitable when seeking to simulate the tilled layer of soil (Moldenhauer, 1965) which is highly compactable. Woodburn and Kozachyn (1965) and Rose (1962) worked with disturbed and undisturbed samples and observed that the relative readings of the strength parameters of the soil they measured remained the same. Diaz-Zorita et al. (2002) showed that laboratory procedures using disturbed soils can be used to characterise soil conditions as found in the field, as long as only small stresses are applied to the soil during handling. In the present research, soil samples were not compressed after collection, but were gently fragmented and quickly air dried before sieving through 5 mm openings in order to minimise the disruption of the aggregates in the laboratory. It was therefore expected that results in this research will not be significantly affected by soil structure condition.

3. Results and Discussion

Table 2 shows the values of the maximum sliding resistance stress (τ_{max}), the adhesion (C_{α}) constant, external frictional angle (δ) and penetration resistance (P) for three soil types at varying water contents and compaction levels. The highest τ_{max} value for any soil occurred at 20% water content and this was similar to values of δ. The highest values for τ_{max} were observed for Maracas clay loam soil. The values for δ ranged between 15.7^{o} to 71.9^{o}. Maracas clay loam also had the highest value of δ. The lowest δ value occurred at 30% water content for each soil, with Talparo clay having the lowest value. For Talparo clay, after 20% water content there was a greater decrease in the value of the external friction angle. Seemingly, this can be attributed to the higher % clay content of the soil and the onset of the plastic limit. This supports the work done by Sakharov et al., (1973) who showed that after the 20% water content as soils approached the liquid limit, soils decreased in frictional resistance and acted more as a lubricator to implements.

Table 2. Values of the measured parameters for the three soils

Soil type	Water content (%)	Soil compaction Levels											
		5 Proctor blows				15 Proctor blows				25 Proctor blows			
		*τ_{max} (kPa)	**C_α (kPa)	$^{+}\delta$ (°)	$^{++}$P MPa	τ_{max} (kPa)	C_α (kPa)	δ (°)	P MPa	τ_{max} (kPa)	C_α (kPa)	δ (°)	P (MPa)
Piarco Sandy loam	15	7.90	1.99	60.7	5.33	4.03	0.91	43.4	8.50	3.41	0.43	42.2	9.00
	20	9.31	2.18	65.2	0.98	4.60	1.30	45.0	0.95	4.40	0.59	48.9	1.70
	25	6.20	2.40	49.1	0.23	4.60	1.80	39.8	0.30	4.10	1.70	35.3	0.33
	30	6.00	2.80	43.9	0.25	5.20	2.50	39.2	0.10	3.60	2.20	22.0	0.10
Maracas clay loam	15	7.60	1.66	60.9	10.2	6.50	1.40	57.2	11.6	6.24	0.84	58.5	14.2
	20	12.1	2.00	71.9	4.70	7.51	1.69	60.5	4.80	6.80	1.10	59.9	8.60
	25	8.62	2.90	60.2	1.60	6.13	1.80	52.8	3.00	6.35	1.60	55.1	3.30
	30	10.6	5.70	56.6	1.02	8.74	4.50	52.3	1.20	7.08	3.10	50.4	1.41
Talparo Clay	15	3.83	0.22	47.6	19.3	3.50	0.22	44.8	22.6	6.24	4.70	25.6	23.3
	20	5.43	0.97	53.3	6.10	5.32	1.80	47.1	9.00	7.22	3.50	48.6	12.5
	25	4.22	1.98	34.1	3.45	5.17	3.14	31.7	6.60	7.80	6.25	25.0	5.88
	30	5.91	4.16	27.7	1.20	7.47	5.70	28.1	3.10	8.55	7.62	15.7	3.40

* τ_{max} is maximum sliding resistance; **C_α is Adhesion constant; $^{+}\delta$ is the external friction angle, and $^{++}$ P is the Penetrometer Resistance.

Values of C_α increased exponentially with increasing water contents for all soils ranging from 0.22 kPa at 15% water content to 7.62 kPa for 30% water content, with Talparo clay having the highest value at 30% water content followed by Maracas soil and Piarco sandy loam in that order. Soils with substantial clay content tend to bond closer together. Hence there is greater attraction by clay soil particles to metal, resulting in the increase in the adhesion constant. This infers that higher clay content in soils increases the adhesion of the soil. This supports the work by Sakharov et al. (1973). Generally, penetration resistance decreased with increasing water contents varying from 0.1 MPa to 23.25 MPa with the highest value again for Talparo clay soil at 15% water content. It was observed that soils with high C_α values had corresponding low P values and vice versa.

For Maracas clay loam and Piarco sandy loam soils, the penetration resistance increased while sliding resistance, external friction and adhesion decreased with increasing compaction levels. This can be attributed to the increase in cohesive bonding between particles when compaction was increased. This showed that the more compact the soil is, the less likely it offers frictional resistance at the soil-metal interface when a tool moves over the surface. This concurs with the work of Satomi et al. (2012) who mentioned that an increase in void ratio resulted in a decrease in adhesive stresses. However, the more compact the soil, the higher the penetration resistance. Hence earth-working tools spend more energy in penetrating these highly compacted soils than on overcoming the frictional resistance offered by the soil on the tool as it moves through the soil. For Talparo clay soils, the penetration resistance, sliding resistance and adhesion increased with increasing compaction while external friction decreased.

Table 3 summarises the mean values of τ_{max}, C_α, δ and P for different experimental factors. Generally the mean values for the adhesion constant (C_α) showed an increase with increasing clay, water contents and compaction efforts. The mean values for Penetration resistance (P) generally increased with increasing clay and compaction efforts, and decreased with increasing water contents. Hence there was similarity between C_α and P with respect to clay content and compaction effort while the reverse was the case for water content. Mean external friction also increased with water content from 15% to 20% and thereafter decreased as water content increased to 30%. Its values generally decreased with increasing compaction effort. The mean values for maximum sliding resistance (τ_{max}) and the external friction angle varied in a similar manner to the experimental factors. Hence the external friction angle may be the dominant component in the sliding resistance equation (i.e., Equation (1)).

The analysis of variance shows that the main effects of soil type, water content and compaction effort as well as the interaction effects were all significant for the measured parameters. The water content was the most important factor followed by soil type and compaction effort. As shown in Table 4, soil type had a greater influence on external friction angle than water content. In addition, the most significant interaction between the three experimental factors was that between soil type and compaction effort. The main and interaction effects of these experimental factors are discussed below.

3.1 Soil Type and Water Content

The interaction between soil type and water content (see Figure 3(a)) showed that at low water contents, the values of adhesion for the soils were similar but varied immensely on increasing water content to 30%. At low water contents there were small variations in external friction angle among soil types (see Figure 3(b)). However, as soil types approached 20% water content, the values of the external friction angle converged. As

Table 3. Mean[a] values of adhesion, external friction angle, sliding resistance and penetration resistance for the three soils

Factor level	Adhesion Constant, C_α (kPa)	External Friction Angle, δ (°)	Max. Sliding Resistance, τ_{max} (kPa)	Penetration Resistance, P (MPa)
Soil type				
Piarco Sandy Loam	1.74a	44.56a	5.26a	2.29a
Maracas Clay Loam	2.35b	58.01b	7.86b	5.47b
Talparo Clay	3.35c	35.78c	5.88c	9.69c
LSD (p = 0.001)	0.10	1.65	0.27	0.50
Water Content (%)				
15	1.37a	49.0a	5.46a	13.77a
20	1.68b	55.6b	6.96b	5.48b
25	2.62c	42.56c	5.9c	2.74c
30	4.24d	37.3d	7.01d	1.28d
LSD (p = 0.001)	0.12	2.02	0.33	0.62
Compaction effort				
5 Proctor blows	2.41a	52.6c	7.30a	4.51a
15 Proctor blows	2.22b	45.1b	5.72b	5.98b
25 Proctor blows	2.80c	40.6a	5.97bc	6.97c
LSD (p = 0.001)	0.10	1.65	0.27	0.50

[a] Mean values for each factor were obtained by averaging the measured values over the levels of the other two experimental factors. Number of experimental factors was 72 representing a factorial experiment with three soil types, four water contents, three compaction levels and two replications. Values followed by different letters in each column were significantly different at the 0.1% level

Table 4. 'F' values in the analysis of variance for the measured parameters.

Sources of variation	Degrees of freedom	Adhesion constant	External friction angle	Penetration resistance
Soil type	2	845.9	524.6	625.2
Water content	3	1605.1	197.3	1059.6
Compaction effort	2	113.1	153.6	69.9
Soil type x water content	6	149.7	12.3	79.4
Soil type x compaction effort eff	4	895.6	18.6	9.0
Water content x compaction effort	6	25.5	8.3	9.0

* Not significant at 1% level

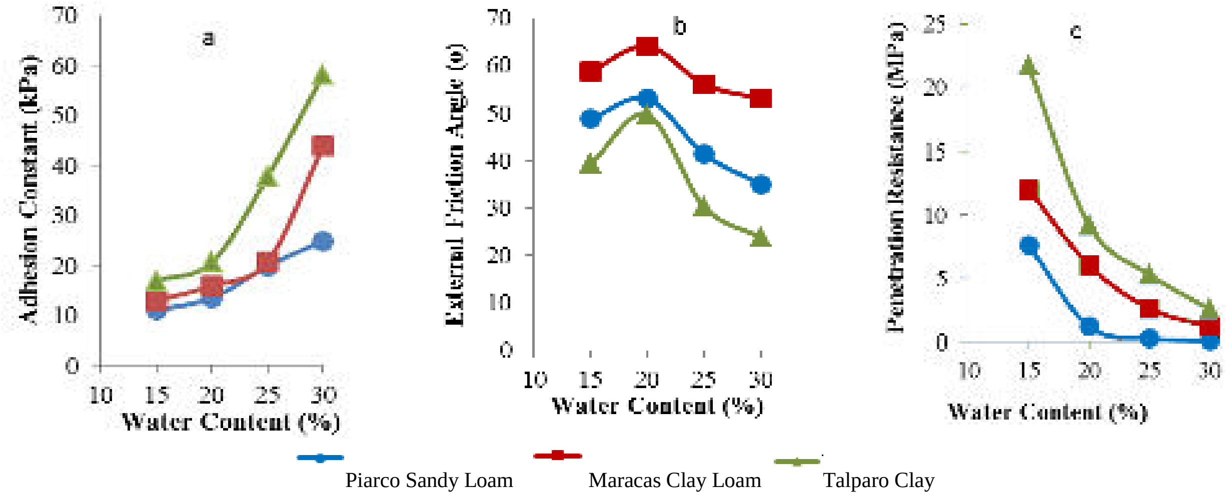

Figure 3. Effect of Interaction between water content and soil type on (a) adhesion (b) external friction angle (c) penetration resistance

the water content increased beyond the 20 % water content, there were large variations in the external frictional angle value among the soil types. Hence high water contents especially greater than 20% decreased the external friction angle for all soils.

In Figure 3(c), at low water contents, there was considerable variation in penetration resistance among soils, but with an increase in water content, the penetration resistance for all soil types converged. Hence at high water contents, penetration resistance among soils did not vary considerably when compared to soils at low water contents. This agrees with the work by Ekwue et al. (2014) that at water contents of soils below their optimum water contents (OMC), penetration resistance varied widely but at water levels greater that the OMC, there were little variation among the penetration resistance of soils. The penetration resistance thus had the opposite effect to that of adhesion constant.

3.2 Soil Type and Compaction Effort

The interaction of soil type and compaction effort on adhesion constant is depicted in Figure 4. It shows that at the low compaction effort of 5 Proctor blows, the values of adhesion for the three soils were close to each other while at the 25 Proctor blows, the difference in the values for the three soils widened. Hence soils that are loose or not heavily compacted will have little variation in their adhesion constant. However, as the compaction effort increases, the variation in adhesion constant increases among soils; and soils with high clay content having the greatest values. Compacted clay particles have a higher attraction than sand or silt particles. Hence they bind better to metals and therefore stick to metal surfaces easier than other soil particles thus offering a higher adhesion constant than other soils. This agrees with the work reported by Khan et al. (2010).

3.3 Derivation of Regression Equations relating measured soil parameters to experimental factors

For each measured soil parameter, the experimental factors were used to generate linear multiple regression equations that could be used for prediction. The multiple regression equations are of the form:

$$Y = a + b\,(M) + c\,(Ct) + d\,(Pc) \tag{3}$$

Where: Y is the measured parameters of adhesion constant, external friction angle and penetration resistance; M is the water content (%); Ct is clay content (%); Pc is compaction effort and a, b, c, and d are empirically derived coefficients (see Table 5). The signs of the experimental factors obtained confirm how the factors affected the measured parameters.

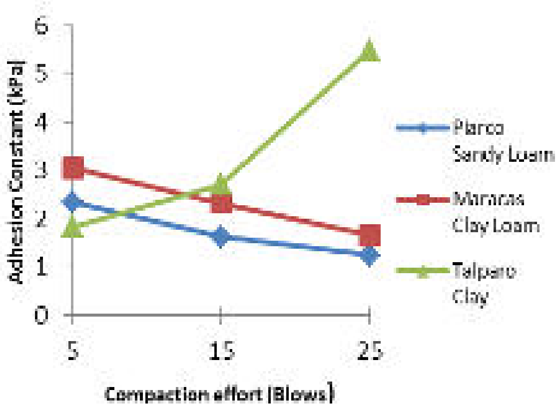

Figure 4. Effect of Interaction between compaction effort and soil type on adhesion

Table 5. Values of coefficients in multiple regression Equation (3) relating the measured parameters to experimental factors

Experimental Factors:	Adhesion Constant (kPa)	External Friction Angle (^{o})	Penetration Resistance (MPa)
Total Intercept	-3644.00	85.20	14.2
Clay content, %	57.34	-0.36	0.26
Water content, %	191.40	-0.96	-0.80
Compaction effort, kPa	-	-0.02	0.003*
Number of observations	72	72	72
Multiple correlation coefficient	0.714	0.520	0.877

*Not significant at 1% level

4. Conclusion

Water content and soil type had the greatest influence on the soil-metal sliding resistance forces while compaction effort had the least influence. At 20% water content, all soil types showed a substantial increase in frictional resistance. This, however, decreased thereafter as the soil behaved more as a lubricant. Water content affects the adhesion constant with appreciable increase after 20% water content. These findings therefore suggest that an effective soil management practice would be to till soils below 20% water content. This ensures that the sliding resistance forces for soil-metal during these operations are kept to a minimum. The study also show that the effect of soil type on soil-metal sliding resistance will be highest at the highest water contents. At low water contents, soils of diverse texture exhibit similar sliding resistance.

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