Investigation into some soil strength parameters using a locally developed soil shearing equipment

B. O. Soyoye[1*], O. C. Ademosun[2]

(1. *Agricultural Engineering Department, School of Engineering and Engineering Technology, Federal University of Technology, P. M. B. 704 Akure Ondo State Nigeria;*
2. *Agricultural Engineering Department, School of Engineering and Engineering Technology, Federal University of Technology, P. M. B. 704 Akure Ondo State Nigeria*)

Abstract: A mechanical device was designed and fabricated for in situ measurement of soil strength parameters such as soil cohesion, soil adhesion, angle of soil internal friction, soil to metal friction angle, soil penetration resistance and soil bulk density. The equipment was tested on the field at soil depth interval of 10 cm ranging from the soil surface to the depth of 30 cm following the standard procedures for the measurement of these soil strength parameters at soil moisture contents of 16.71% and 20.15%. At soil moisture content of 16.71% dry basis, soil cohesion and soil adhesion were 5.313 and 6.968 kN/m^2 and 3.745 and 4.234 kN/m^2 at the soil surface and at soil depth of 30 cm respectively. At soil moisture content of 20.15%, soil cohesion and soil adhesion were 4.703 and 6.533 kN/m^2 and 2.961 and 4.181 kN/m^2 at the soil surface and at soil depth of 30 cm respectively. The comparison of soil cohesion and soil adhesion with soil bulk density gives a linear relationship at the same moisture content. The soil penetration resistance was found to have different values but followed the same trends or exhibit the same characteristics that is; the initial increment in the values of the penetration resistance at the first 15 cm depth and the values fall as the depth increases when tested under different soil conditions and time. The highest soil shearing stress was at the soil surface, while the least was recorded the depth of 30 cm, thereby showing that the shearing stress of soil decreases with depth and the strength of soil reduces with increase in soil moisture content. Also, the highest point of soil resistance to penetration was recorded at the soil depths of between 15 and 20 cm.

Keywords: soil strength parameters; soil cohesion, soil adhesion, soil penetration resistance

Citation: B. O. Soyoye, O. C. Ademosun. 2014. Investigation into some soil strength parameters using a locally developed soil shearing equipment. Agric Eng Int: CIGR Journal, 16(1): 12−20.

1 Introduction

Soil is a dynamic natural body composed of minerals, organic materials and living organisms occupying parts of the earth surface that support plant growth. Soils are classified in most cases based on the size of their particles which in turn affects their aeration and water drainage capacity. Soil strength is an important parameter that affects root growth and water movement, and controls nutrient and contaminant transportation below root zone. (Gee and Bauder, 1986). They are dynamic ecological systems providing plants with support, water, nutrients and supporting a large population of micro-organisms that recycle the materials of life (Michael and Donald, 1999).

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 machineries. The property is also important to specify the tilling machine to be used to change the soil structure at ploughing to improve agricultural production (Ohu et al., 1986). In civil engineering, inherent soil strength

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Received date: 2012-08-15 **Accepted date:** 2013-12-20.

* **Corresponding author: B. O. Soyoye,** Agricultural Engineering Department, School of Engineering and Engineering Technology, Federal University of Technology, P. M. B. 704 Akure Ondo State Nigeria. Email: soyoye2002@yahoo.com.

determines the compaction level for an optimum stability of road bases (earth works), influences the capacity for supporting civil structures, while in water resources engineering, it determines the choice of materials for earthdam and embankment construction (Ajayi et al., 2009). Soil strength plays very significant roles in ensuring better crop growth and soil quality. The soil strength parameters are part of the factors affecting the draught requirement of tillage implements (Ademosun, 1990). The soil physical conditions are estimated on the basis of the density of soil, particle size distribution, macro-aggregate size distribution and structural porosity (Medvedev, 1988). These properties determine the mobility of water and air through the soil, the extent to which agricultural equipment or machinery can work on the soil and resistance of soil to agricultural implements (Gill and Verdenberg, 1968).

Objectives of the research work:

The objective of this research is to develop an equipment suitable for the in-situ measurement of soil forces which could be used in the investigation into some soil strength parameters such as soil cohesion, soil adhesion, soil bulk density, soil internal friction angle, soil to metal friction angle and soil penetration resistance.

2 Main body

2.1 Measurement of soil densities

Dry bulk density is determined by the value of weight (mass) of dry matter in a soil sample that occupies a core of known volume. The core sampling method usually determines bulk density (Abu-Hamdeh and Al-Jalil, 1999). Pressing the core sampler into the soil usually avoids the vibration that causes fracturing, but soil may be displaced in front of the core due to compression if the static loading rate exceeds the rate at which soil can enter into the core sampler (Blake and Hartge, 1986; Rogers and Carter, 1987). Hammering, compared with hydraulically pressing the core sampler into the soil, appears to cause more distortion within the soil core, which increases variability (Stone, 1991). The bulk density is the mass of soil element per unit volume (Blake and Hartge, 1986). Soil compaction can result in an increase in the bulk density of the soil, decreased porosity and/or increase in penetration resistance (Raghavan et al., 1990). This results in an increase in soil strength and hence the draft force requirement to alleviate compaction. Soil bulk density can be quantified by Core method, Excavation method, Clod method, Radiation method, either of these four methods (Blake, 1965; Blake and Hartge, 1986).

2.2 Measurement of soil penetration resistance

The most common way to assess soil penetration resistance is by using a soil penetrometer, which characterizes the force needed to drive a cone of specific size into the soil (Bradford, 1986). The soil cone penetrometer (ASAE Standards, 2002) has been traditionally used to assess the soil strength within a soil profile. The cone penetrometer measures the force required to insert a cone tip into the soil. Cone index is calculated by dividing this insertion force by the base area of the cone. Cone index is an empirical measurement of soil state and measures the net effect of several soil properties.

2.3 Measurement of soil shear strength

Several methods are available for measuring soil strength properties. These include the vane shear test, the direct shear test, the triaxial compression and unconfined compression test (Sallberg, 1965; Mckyes, 1985). The soil strength results obtained depending not only on the soil conditions but also on the test method employed. This work is like this because of the variation in soil penetration requirements as well as the steps in testing of the soil specimen.

Soil shear strength is made up of a cohesive component as well as a frictional component (Mckyes, 1985). Empirically the soil shear strength is usually defined by the Mohr-Coulomb Equation (1) as cited in Mckyes (1985) and Davies (1985).

$$\tau = c + \sigma \tan \phi \qquad (1)$$

where, τ = soil strength, kN/m^2; c = soil cohesion, kN/m^2; and ϕ = Soil friction angle.

3 Materials and methods

3.1 Equipment conception

The soil strength measuring equipment is a machine designed for the in-situ measurement of soil strength parameters. In order for this machine to effectively carry out these operations, it requires some functional components.

The machine has a steel metal hollow pipe that has all other working components attached to it as shown in Figure 1a and Figure 1b. The steel metal pipe was made hollowed to reduce its weight. At the base of the steel metal pipe was the shearing plate which was of two types: one was a circular steel metal plate and the other a circular steel metal plate with grousers (blades) inside the plate to grip the soil as shown in Figure 2. At the outer side of the steel metal pipe were two frictionless bearings. One of the bearings was positioned very close to the top side of the steel pipe, this helps in the application of the normal loads on the shear plate. At the centre of the steel pipe was a hook which helps in the application of shearing stress needed to shear the soil at the shear plates through a pulley mechanism. Beneath this mechanism was the second frictionless bearing, which provided supports for the steel pipe during the experiments or measuring processes. Connected to the upper bearing was a metal plate (cap) which received the normal force before sending it to the shear plate. On the metal plate (cap) was a screw adjuster and between which there was a spring loaded gauge that measured the normal force applied on the cap. At the same time another spring gauge was between the hook and pulley mechanism to measure the shear force applied.

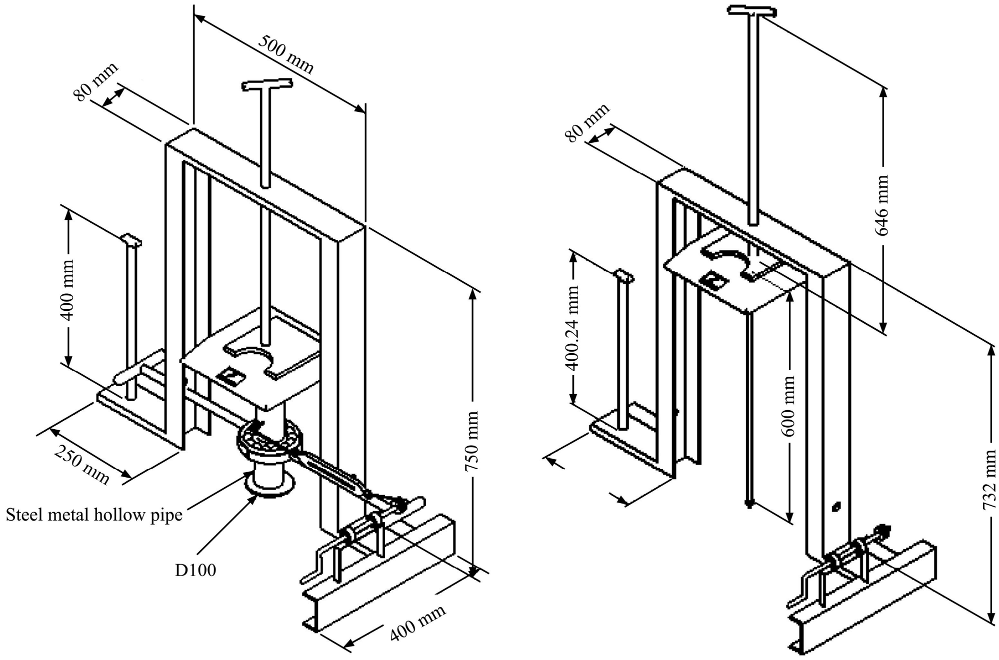


Figure 1a Conceptual drawing of the shear stress measuring equipment

Figure 1b Assembled equipment during field testing

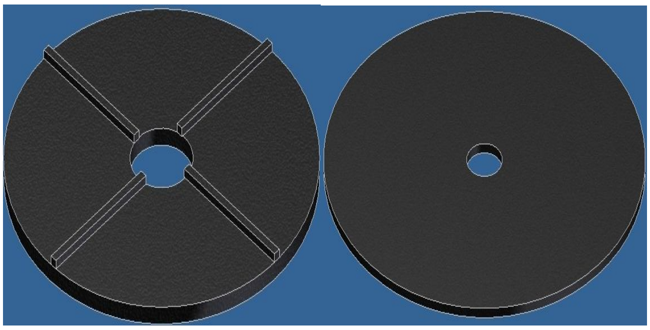


Figure 2 Shearing plates

The penetrometer has a cone shaped end which penetrated the soil at the application of the normal force through the screw adjuster and the force applied was measured in the spring gauge attached between the screw adjuster and the penetrometer. The whole mechanism (machine) was housed in a frame which gave it the maximum rigidity needed during the operation Figure 1a and Figure 1b.

3.2 Machine testing

The machine was tested on the Agricultural Engineering Departmental Research farm of the Federal University of Technology Akure. Akure is an area of about 15,500 km^2, situated within the western upland area and also has a population of about 3,440,000 and also located within the humid region of Nigeria at latitude 7.16^{0}N; longitude 5.13^{0}E. The area has a general elevation of between 300 and 700 meters above sea level. Soil sample was collected on the research farm for moisture content determination soil textural analysis. After the soil collection, the machine was then coupled on the soil for the soil tests. The machine was assembled; different amounts of loads were applied on the machine which was recorded at the top loaded compression spring gauge on the machine. At the same time the corresponding loads at shearing were recorded at the side loaded tension spring gauge provided at the side of the machine. These procedures were carried out repeatedly for the soil at the surface, 10, 20 and 30 cm deep. For each of the tests, the normal load and its corresponding shear load were noted and recorded.

3.3 Determination of soil moisture content

The gravimetric with oven drying method described by Gardner (1986) was used in the determination of moisture content. A soil auger was used to sample the soil at different depths. The samples were enclosed in sampling cans immediately to minimize evaporation from the sample. Sampling was done at 10 up to 30 cm depth. This was done to cover the entire depth range encountered in normal tillage operations. The soil samples were weighed on a digital scale in the laboratory and oven dried at 105ºC for a period of 24 hours. The samples were then reweighed and the weight of each marked. The moisture content was calculated using Equation (2).

$$w = \frac{W_w - W_d}{W_d} \times 100\% \qquad (2)$$

where, w is soil moisture content, %; W_w is weight of wet soil, kg; W_d is weight of dry soil, kg.

3.4 Determination of soil cohesion and angle of soil internal friction

Four tests were conducted for the determination of soil cohesion and angle of internal friction. These were done at various soil depths; soil surface, 10, 20 and 30 cm. The results generated and their equivalent linear trends and R^2 values are as displayed in Figure 3.

The data obtained were analyzed using Microsoft excel to determine the values of soil cohesion and angle of internal friction. The line graph equations obtained were used in both cases;

$$y = mx + c \qquad (3)$$

where, m = slope of the graph and c = the intercept.

The coulomb equation (Arora, 1988) states;

$$\tau = C + \sigma \tan \phi \qquad (4)$$

where, τ = shear stress, kN/m^2; σ = normal stress, kN/m^2; C = soil cohesion (intercept), kN/m^2; and $\tan \phi$ = tangent of the angle of internal friction (slope).

Comparing the two Equations (3) and (4);

Soil cohesion is the intercept on the linear graph and $\tan \phi$ is the slope of the linear graph.

$$C = c \qquad (5)$$

$$\tan \phi = m$$

$$\phi^0 = \tan^{-1} m \qquad (6)$$

3.5 Determination of soil adhesion and angle of soil to metal friction

The same tests and procedures carried out for cohesion and angle of internal friction were repeated for the determination of adhesion and angle of soil to metal friction. The results generated and their equivalent linear trends and R^2 values are as displayed in Figure 3. Applying the coulomb equation (Arora, 1988);

$$\tau = C_a + \sigma \tan\theta \qquad (7)$$

where, τ = shear stress, kN/m^2; C_a = soil adhesion, kN/m^2; σ = normal stress, kN/m^2 and θ = angle of soil to metal friction, degree.

For each of the tests conducted a line graph equation of the form of Equation (3) was developed and compared with Equation (7), the following conclusion were made;

The intercept at the graph is the same as the soil adhesion and the slope of the graph represents tanθ in the coulomb's equation.

$$C_a = c \qquad (8)$$

$$\tan\theta = m$$

$$m = \tan^{-1}\theta \qquad (9)$$

3.6 Determination of soil bulk density

The regression equation relating soil strength parameters to both soil bulk density and soil moisture content in sandy loamy soil described by Korayem et al (1996) was used in the determination of soil bulk density;

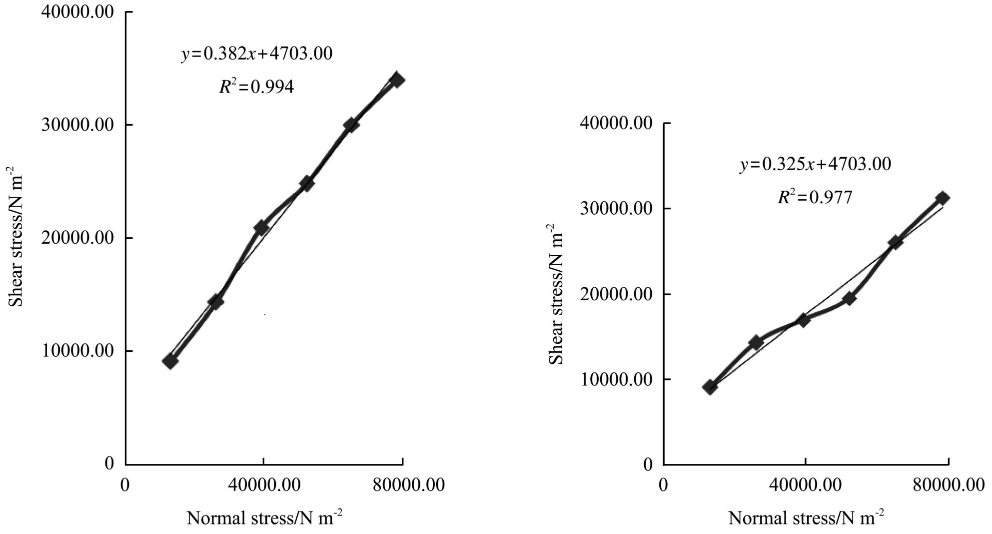
$$C = 0.0865 \times \rho^{2.53} \times M^{-0.0277} \qquad (10)$$

$$\tan Ø = 0.761 - 0.0122M \qquad (11)$$

where, ρ = Soil bulk density, g/cm³, C = Soil cohesion, kN/m^2; M = Soil moisture content, % (d.b.); and Ø = Internal friction angle of soil, degree.

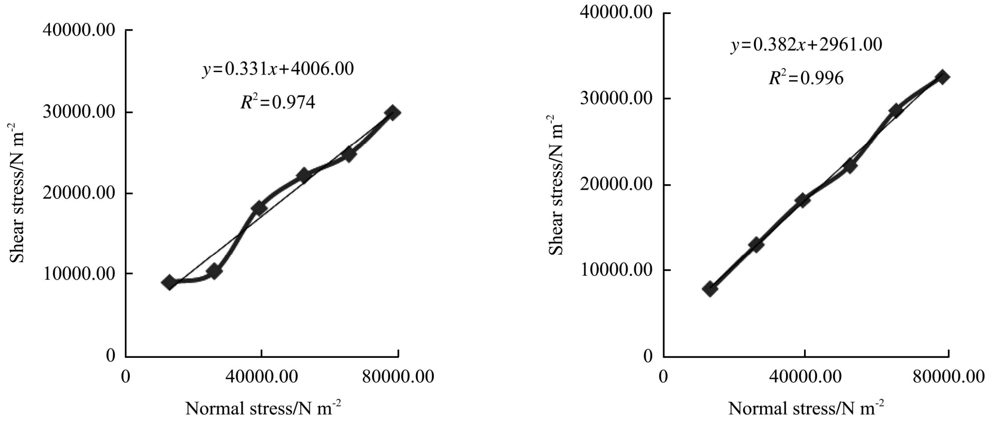
3.7 Method of data analysis

Data collected were subjected to appropriate statistical analysis such as analysis of variance (ANOVA) and Duncan Multiple Range Test using Statistical Package for Social Sciences (SPSS) and Microsoft Excel software packages.



a. Soil cohesion at the soil surface

b. Soil cohesion at the depth of 10 cm



c. Soil cohesion at the depth of 20 cm

d. Soil cohesion at the depth of 30 cm

Figure 3 Variation of shear stress with normal stress at soil moisture

4 Results and discussion

Variations of shear stresses with the normal stresses, the linear equivalents and coefficient of determination (R^2) values of the tests are presented in the Figure 3. Linear variations were observed between the shear stresses and the normal stresses with R^2 values ranging from 0.96 to 0.99 for all the tests at soil moisture content of 20.15% and 16.71% dry basis respectively.

The results of soil cohesion, soil adhesion, soil bulk density, soil to metal friction angle and soil internal friction angle are shown in Tables 1 and 2. At soil moisture contents of 20.15% and 16.71% dry basis, the highest values were obtained for soil cohesion, soil adhesion and soil bulk density at the soil surface while the least values were recorded at the soil depth of 30 cm (Tables 1 and 2). The statistical analysis of the soil strength parameters are presented in Tables 3 and 6. At soil moisture content of 20.15% dry basis, the mean values of soil cohesion, soil adhesion, soil bulk density, soil to metal friction angle and soil internal friction angle were 3.90 kN/m^2, 5.47 kN/m^2, 1.51 g/cm^3, 28.75° and 20.48°, respectively (Table 3). The result of the analysis of variance in Tables 4 and 5 revealed a significant difference (p<0.05) between the soil cohesion, soil adhesion, soil bulk density soil to metal friction angle and soil internal friction angle at different soil depths. At soil moisture content of 16.71% dry base the mean values of soil cohesion, soil adhesion, soil bulk density, soil to metal friction angle and soil internal friction angle were 4.44 kN/m^2, 6.13 kN/m^2, 1.59 g/cm^3, 33.30° and 18.32° respectively (Table 6). In the soil strength parameters tested, the strength was highest at the soil surface and decrease as the soil depth increases (Figures 4, 5 and 6). It is clear from the result as given in Tables 1 and 2 that increasing moisture content decreased soil cohesion, soil adhesion and soil bulk density. The statistical analysis clarified the relationship between the soil strength parameters at different soil moisture content and soil depths (Tables 1, 2, 3 and 6; and Figures 4, 5 and 6). It was observed that soil cohesion, soil adhesion and soil bulk density were inversely proportional to both the soil moisture content and soil depth.

Table 1 Soil characteristics at 16.71% moisture content

Depth /cm	Soil cohesion /kN m^{-2}	Soil adhesion /kN m^{-2}	Soil internal friction angle (ϕ)	Soil to metal friction angle (θ)	Soil bulk density /g cm^{-3}
0	5.313	6.968	18.32	33.31	1.714
10.00	4.703	6.794	18.00	34.76	1.634
20.00	4.006	6.533	18.32	31.55	1.533
30.00	3.745	4.234	18.62	33.58	1.493

Table 2 Soil characteristics at 20.15% moisture content

Depth /cm	Soil cohesion /kN m^{-2}	Soil adhesion /kN m^{-2}	Soil internal friction angle (ϕ)	Soil to metal friction angle (θ)	Soil bulk density /g cm^{-3}
0	4.703	6.533	20.91	29.12	1.631
10.00	4.094	6.120	19.19	24.23	1.546
20.00	3.841	5.052	20.91	27.34	1.506
30.00	2.961	4.181	20.91	34.29	1.359

Table 3 Mean values for the soil strength parameters at soil moisture content of 20.15% dry basis

Groups	Sum	Average	Variance
Soil cohesion/kN m^{-2}	15.599	3.89975	0.522549
Soil adhesion/kN m^{-2}	21.886	5.4715	1.129568
Soil internal friction angle	81.92	20.48	0.7396
Soil to metal friction angle	114.98	28.745	17.74897
Soil bulk density/g cm^{-3}	18.66	4.665	0.124357

Table 4 Analysis of variance for the soil strength parameters at soil moisture content of 20.15%

Source of variation	SS	DF	MS	F	P-value	F crit
Between groups	2067.237	5	413.447	13.271	1.64E-05	2.773
Within groups	560.795	18	31.155			
Total	2628.032	23				

Table 5 Analysis of variance for the soil strength parameters at soil moisture content of 16.71%

Source of variation	SS	DF	MS	F	P-value	F crit
Between groups	2508.727	5	501.746	17.634	2.23E-06	2.773
Within groups	512.154	18	28.453			
Total	3020.881	23				

Table 6 Mean values for the soil strength parameters at soil moisture content of 16.71%

Groups	Sum	Average	Variance
Soil cohesion/kN m^{-2}	17.767	4.44175	0.500889
Soil adhesion/kN m^{-2}	24.529	6.13225	1.633448
Soil internal friction angle	73.26	18.315	0.0641
Soil to metal friction angle	133.2	33.3	1.757533
Soil bulk density/g cm^{-3}	19.689	4.92225	0.095357

The results of this study indicated that the measured soil strength parameters at different depths were significantly different. The field experiments showed that the strength of the tested soil dropped significantly as the depth increased. Also, increase in moisture content reduced the values of the soil cohesion, soil adhesion and soil bulk density. These results are in agreement with Panwar and Seimens; (1972); who established that soil cohesion in sandy clay loam soil decrease with increasing soil moisture content. Korayem et al (1996) also observed that soil cohesion increased with increasing the initial bulk density and decreased with increasing soil moisture content in sandy loam soil.

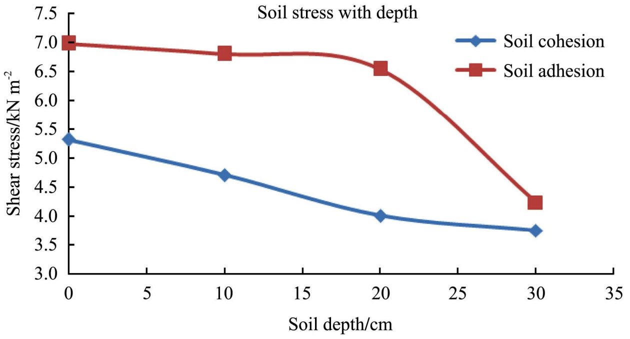


Figure 4 Variation of soil cohesion and adhesion with soil depth at moisture content of 16.71%

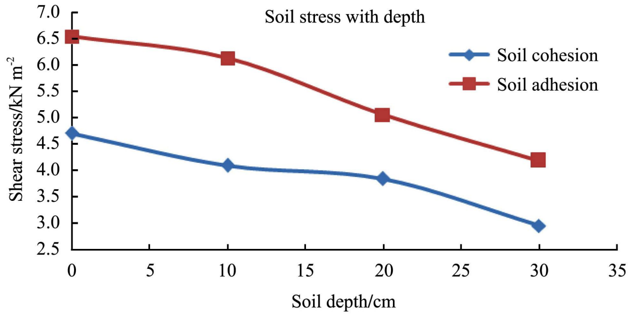


Figure 5 Variation of soil cohesion and adhesion with soil depth at moisture content of 20.15%

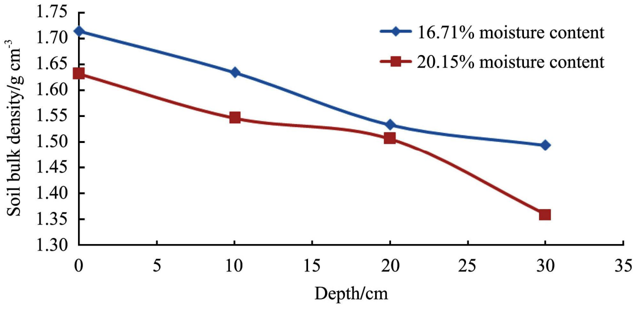


Figure 6 Variation of soil bulk density with depth at moisture content of 16.71% and 20.15% (d.b.)

The following findings are in agreement with the results recorded in Tables 1 and 2; Fountain (1954) demonstrated that water film plays a dominant role in soil adhesion. He reported that the soil adhesion is very strong when the water is very thin and vice versa. In the same trend, Chancellor (1994) and Cong et al. (1990) found that the soil adhesion was the highest when the soil moisture content was between the plastic limit and liquid limit and an increase in soil water tension elevated the soil adhesion. Dexter (1988) and Horn and Baumgartl (2002) reported that soil strength, especially in sandy soils, is often at first approximated by bulk density and water content, but decreases with decreasing bulk density and increasing water content as a result of changes in proportions between water-filled and air-filled pores. Baumgartl and Horn (1991) observed an increase in soil shear strength with increasing soil bulk density and attributed it to a higher number of contact points between the single particles per volume. Soil bulk density was the greatest at the soil surface and reduces down the soil depths, as shown in Figure 6. This agrees with the findings of Ehlers et al. (1983) that compared no-tillage with other conservation or more conventional tillage systems and found that soil bulk density was greater in no-tillage in the first 5 to 10 cm of soil. Furthermore, increasing soil bulk density increased the above mentioned soil strength parameters at the same soil moisture content as shown in Figures 7 and 8. These results are in conformity with those of Stafford and Tanner (1971) who reported that soil adhesion increased with increasing soil bulk density.

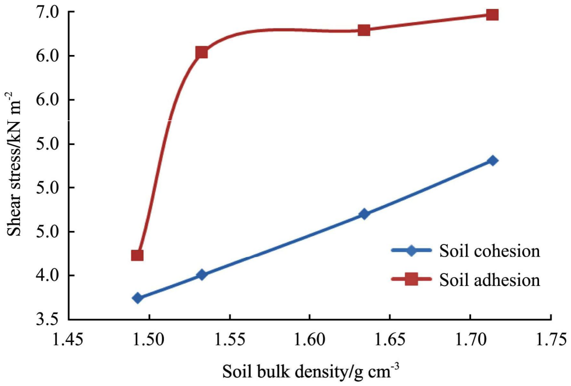


Figure 7 Variation of soil cohesion and adhesion with soil bulk density at moisture content of 16.71%

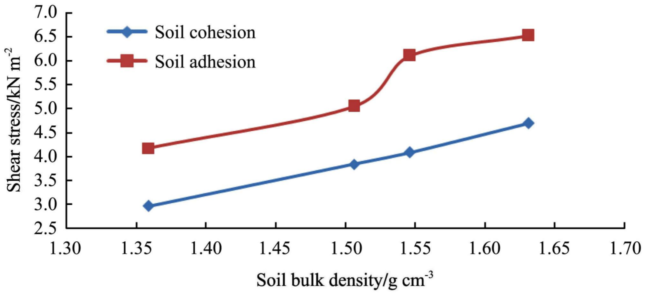


Figure 8 Variation of soil cohesion and adhesion with soil bulk density at moisture content of 20.15%

The mean test values of soil penetration resistance are shown in Table 7. The results showed a mean penetration resistance value of 198.25 kN/m^2 on cleared soil tested in the morning period (9.00 GMT), while the penetration resistance was 235.85 kN/m^2 at sun-set (18.00 GMT) the same day. However, the soil had a mean penetration resistance of 358.89 kN/m^2 after a period of

3 days. Finally, the soil has a mean value of 444.36 kN/m^2 after the soil had been worked upon and got compacted. Analysis of variance in Table 8 showed a significant difference (p<0.05) between the soil penetration resistance and soil depth. The soil penetration resistance increased almost linearly to the depth of between 15 and 20 cm before decrease in penetration resistance with increase in soil depth was observed (Figure 9). The initial increase in soil penetration resistance can be attributed to the level soil compaction at the soil surface, the low moisture content level at the soil surface due to continuous moisture loss (evaporation) at the soil superficial layer and overburdened pressure on the soil. While the decrease in soil penetration resistance experience can be attributed to the formation of sediments down the soil profile and the increase in the water stored in the soil bodies.

Table 7 Mean values for soil penetration resistance

Groups	Count	Sum	Average/N m^{-2}	Variance
Depth	7	140	20	116.666667
Before sun rise	7	1387756.09	198250.87	4249776994
At sun set	7	1650951.22	235850.174	1.0493E+10
Compacted soil	7	3110487.81	444355.401	1.1889E+10
Exposed soil	7	2512235.77	358890.824	5642280493

Table 8 Analysis of variance for soil penetration resistance

Source of variation	SS	DF	MS	F	P-value	F crit
Between groups	8.05E+11	4	2.0119E+11	31.1697183	2.71E-10	2.689628
Within groups	1.94E+11	30	6454762758			
Total	9.98E+11	34				

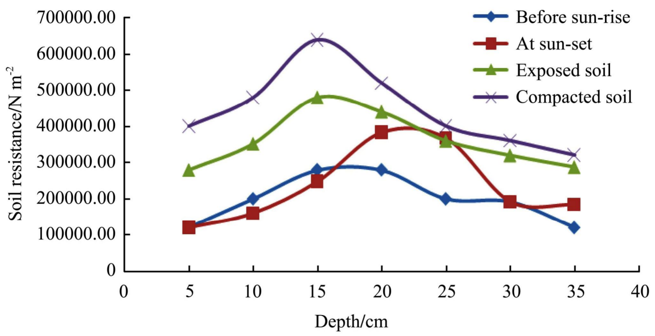


Figure 9 Soil penetration resistance with depth at different soil conditions

These results agree with the previous findings of Cassel et al. (1978) and they observed increase in cone index with depth on three different tillage treatments for a Norfolk sandy loam. Ehlers et al., (1983); Radclifee et al., (1989); Hammel, (1989) and Hill, (1990) reported that greater penetration resistance was found under no-tillage, especially in the upper 10 cm. Upadhyaya et al., (1995) plotted penetration force against depth and their results revealed an increase of soil penetration resistance with depth. They suggested that the resistance reaches a maximum and then dropped off slightly or in some cases remained constant. Campbell and O'Sullivan, (1991); Franzen et al., (1994); Ayers and Perumpral, (1982) and Ohu et al., (1988) reported that soil moisture content had been found to affect the soil penetration resistance significantly. They recorded that the soil strength as indicated by the soil penetration resistance, increased with depth. The resistance was increasing gradually up to a certain depth and started decreasing gradually as the depth increases.

5 Conclusions

The soil strength measuring equipment was designed and fabricated for the in situ measurement of soil strength parameters. The highest shear stress was at the soil surface while the least was recorded the depth of 30 cm thereby showing that the shear stress of soil decreases with increase in depth. There is linear relationship between the soil shear stress and the soil bulk density for soil cohesion. The soil penetration resistance was found to be at the peak between the depth of 15 and 20 cm in the sandy loamy soil tested. The least soil internal friction angle was at the depth of 10 cm for both soil moisture status (16.71% and 20.15%) dry basis. The soil to metal friction angle was minimum at the soil surface at the moisture content of 16.71% dry bases and at the depth of 10 cm at soil moisture content of 20.15% dry basis.

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