Degree of compaction and compression strength of Nigerian Alfisol under tilled condition and different machinery traffic passes

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Abstract: Information on the effect of soil compaction on soil mechanical properties such as degree of compaction, compression and shear strength of tropical soils of Nigeria under different machinery traffic passes is very scarce. Field experiment was conducted in a tilled and compacted sandy clay loam (Alfisol) in Akure, Nigeria, under different machinery traffic passes to determine compaction effects on bulk density, compression strength, degree of compaction and the shear strength of soil. Four plots, A, B, C and D of area 20 m×50 m each were used for the field experiment. Treatment plot A was tilled with a tractor-mounted disc plough, and the remaining three plots: B, C and D were subjected to 5, 10 and 15 to and fro passes, respectively, using heavy duty Mercy Fergusson tractor model 4355 (3.82 Mg). The treatments were replicated three times in a randomized complete block design. Compacted plots progressively increased the bulk density from 1.63 g/cm^3 to 1.90 g/cm^3, but the highest bulk density was observed in plots under 15 traffic passes with the value of (1.90± 0.23) g/cm^3. The percentage of soil compaction varies from 90.5% to 97% at the 0-10 cm soil layer. The compression strength of soil increased from 31.00 kPa to 42.05 kPa and from 29.68 to 65.44 kPa at the 0-10 cm and 10-20 cm soil layers, respectively, which resulted in the increased shear strength from 15.79 kPa to 21.03 kPa and 14.8 kPa to 32.72 kPa at the 0-10 cm and 10-20 cm in plots under 5 and 15 traffic passes, respectively. Plot A (tilled soil) had the lowest bulk density, degree of compaction and compression strength with values (1.51±0.19) g/cm^3, 88.2%, and (12.15±0.37) kPa, respectively, and consequently the lowest shear strength of (6.02±1.23) kPa, which enhanced air movement and microbial activities in the soil. Soil under 15 traffic passes, especially at the 10-20 cm soil layer, may result in poor root penetration when cropped but can be very reliable and consistent when used for structural purposes.

Keywords: soil compaction, tillage, degree of compaction, compression strength, shear strength, farm machine, traffic passes, bulk density

DOI: 10.3965/j.ijabe.20120502.005

Citation: Fasinmirin J T, Joseph A A. Degree of compaction and compression strength of Nigerian Alfisol under tilled condition and different machinery traffic passes. Int J Agric & Biol Eng, 2012; 5(2): 34−41.

1 Introduction

The use of natural ecosystem for crop production results in significant changes in soil physical, chemical, and biological properties[1-4] and such changes may be caused by soil compaction, which reduces soil volume and consequently lowers soil productivity and environmental quality. Compaction at the farm level is mostly caused by the use of heavy duty machinery, pressure from wheels, trampling by animals, frequent use of chemical fertilizers and ploughing at the same depth for many years. Changes in soil water content as a result of soil compaction modifies soil moisture tension and diffusion of gases, the resistance to penetration, hydraulic conductivity, air permeability and other soil physical properties[5]. Other soil physical properties, altered by tillage operations using heavy duty machineries and farm animals, include aggregate stability, erodibility and erosion, and water infiltration and

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Received date: 2011-11-23 **Accepted date:** 2012-05-15

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drainage[6,7]. Compaction implies an increase in soil bulk density and soil strength, and decreases in air permeability and hydraulic conductivity[8]. A number of different methods have been used to characterize the state of compaction of soil layers. Dry bulk density and total porosity are the most frequently used parameters. However, these properties are limited when compaction between different machinery passes is to be compared. To overcome this problem, the actual-bulk density is expressed as a percentage of a reference compaction state of a given soil that is called 'degree of compaction' or 'relative compaction'[9,10]. Although penetration resistance is regarded as a useful measure of soil impedance to root growth[11], it is also limited. One of its drawbacks is its wide spatial variation because it is a point measurement rather than a bulk soil measurement[12].

According to the ASTM standard, the unconfined compression strength (qu) is defined as the compression stress at which an unconfined cylindrical specimen of soil will fail in a simple compression test. In addition, in this test method, the unconfined compression strength is taken as the maximum load attained per unit area, or the load per unit area at 15% axial strain, whichever occurs first during the performance of a test[13]. Several parameters have been used to characterize the state of soil compaction, such as dry bulk density, total porosity and air-filled porosity[14]. However, these parameters vary between soils and have limited value when different conditions are compared such as 5, 10 and 15 traffic machinery passes and tilled conditions. This study will focus on the degree of compaction and compression strength of Nigerian Alfisol under tilled condition and machinery traffic passes.

2 Materials and methods

2.1 Site description

The research was conducted between the Federal University of Technology, Akure (FUTA) and step B (science and Technology Education Post-Basic) project site, Akure, located on latitude 7°10 N and longitude 5°05 E. The soil of the study area is a sandy clay loam soil according to USDA textural classification of soil[15]. Akure has a land area of about 2 303 km^2 and is situated in the western upland area within the humid region of Nigeria at latitude 7°16 N; longitude 5°13 N. The general elevation is 300-700 m. Local peaks rise to 1 000 m; other hill-like structures which are less prominent rise only a few hundred meters above the general elevations[16]. The pattern of rainfall is bimodal, the first peak occurring in June and July, and the second in September, with a little dry spell in August[17]. The mean annual rainfall ranges from 1 300 mm to 1 500 mm. More than half of humid zone of Nigeria is covered by Pre-Cambrian basement complex, principally composed of metamorphic and igneous materials[18]. The soils are light textured, fine sandy loam to fine sandy clay loam. The soil is moderately well supplied by organic matter and nutrients. Moisture holding capacity is moderately good. The soil of the environment is however subject to seasonal water logging for varying periods, but generally it becomes dry during the dry seasons which falls within November and March[16].

2.2 Field experiment

Field experiment was conducted to determine the effects of subsurface soil compaction under different machinery passes. There were four soil treatments plots: conventionally ploughed soil (CT) – Plot A, using a tractor-mounted disc plough, compacted with soil under 5 passes - Plot B, 10 passes – Plot C and 15 passes – Plot D, using heavy duty Mercy Fergusson tractor model 4355 (3.82 Mg). The treatments were replicated three times in a randomized complete block design. Soils sampling was carried out at six different locations per plot from tilled and compacted plots, making a total of 72 samples. Collected samples were used to determine the influence of traffic passes on some soil mechanical properties such as degree of compaction, compression strength and shear strength.

2.3 Measurements

2.3.1 Bulk density and degree of compaction

Samples were taken from soil core at 0-10 cm and 10-20 cm using ring cylinders (samplers) with height 10 cm and diameter 4.8 cm. The samplers were driven vertically into the soil enough to be filled with soil. The sampler and its contents were carefully removed to preserve the natural structure and packing of the soil as best as possible. The soil extending beyond each end of the sampler was trimmed to ensure soil is contained in exactly the volume of the cylinder. Thus, soil sample volume was established to be the same as the volume of the cylinder. The soil cores were wrapped in polyethylene, placed in wooden box and transported to the laboratory for analysis. The soil samples were transferred to a container, placed in an oven at 105℃, and dried to constant weight. The weight of soil was recorded and current bulk density was calculated using method described by Blake and Hartge[19].

$$Bulk\ Density\ (\rho) = \frac{weight\ of\ oven\ dreid\ soil}{volume\ of\ the\ soil} \tag{1}$$

The "degree of compaction" or "relative compaction" of the soil, DC, was defined as:

$$DC = \frac{BD}{BD_{ref}} \times 100\,\% \tag{2}$$

where, BD is the dry bulk density and BD_{ref} is the wet bulk density of the same soil in a reference state obtained at laboratory[14]. The degree of soil compaction is expressed in percentage.

2.4 Unconfined compression strength (UCS)

The unconfined compression strength of soil samples was taken as the maximum load attained per unit area during the performance of a test. Soil samples were taken in each of the plots from the depth of 0-10 cm and 10-20 cm using another set of samplers same in diameter and height as the samplers used for the bulk density determination. The sampler was driven vertically into the soil surface enough to fill the sampler and its contents carefully removed to preserve the natural structure and packing of the soil as much as possible. The samples were taken to the geology laboratory and carefully extruded to determine its volumes and diameters. The unconfined compression strength (q_u) of the soil of each plot at the 0-10 cm and 10-20 cm soil layers was determined by uniaxial compression text using Consolidometer (Boart Longyear model) following the method described by Reichert et al.[14]. The results obtained were used to estimate the shear strength of the sandy clay soil under unconfined conditions. Soil samples were weighed by soil electronic weighing balance of 0.01 sensitivity.

Sampled soils were extruded from core sampler, ensuring the length to diameter ratio (L/d) is approximately 2:2.5 following the ASTM standard method. Exact diameter of the top and base of the soil specimen at three locations 120° apart was measured. The measurements were averaged and recorded as the diameter on the data sheet. Similar procedure was used in the estimation of length of specimen. The sample was weighed and the deformation (ΔL) corresponding to 15% strain (ε) was calculated which is given as:

$$\text{Strain } (\varepsilon) = \frac{\Delta L}{Lo} \tag{3}$$

where, the specimen was carefully placed in the compression device and centred on the bottom plate. Adjustment of the device was made so that the upper plate makes contact with the specimen, while the load and deformation dials were set at zero reading. Loading was done so that the device produces an axial strain at a rate of 0.5% to 2.0% per minute. The load and deformation dial readings were recorded at every 20 to 50 divisions on deformation dial. The load was applied until the load (load dial) decreased on the specimen significantly and remains constant for at least four deformation dial readings. The sketch depicting the sample failure was drawn sample removed from the compression device.

Analytical procedures used for the determination of the unconfined compression strength include: the conversion of the dial readings to the appropriate load and length units, computation of sample cross-sectional area (A_o), corrected area (A) strain e, and specimen stress (S_c). The stress values were plotted against the strain for the drawing of the compression curve. The undrained shear strength S_u was evaluated as follows:

$$S_u = \frac{q_u}{2} \tag{4}$$

3 Results and discussion

3.1 Bulk density

The results of BD and BD_{ref} of soil are presented in Tables 1 and 2. Results showed that the current bulk density varied among the different plots at the 0-10 cm and 10-20 cm soil layers. Mean BD was the highest in plot D. Machinery traffic on soil was responsible for the higher BD of soil and this observation must have been caused by the reduction in the soil total porosity most especially at the 0-10 cm soil layer. Roseberg and McCoy[21] found that CT increased total porosity of the soil but decreased effective pores overtime.

Table 1 Mean dry bulk densities (g/cm^3) of sampled soils under tilled condition and different compaction levels

Depth /cm	Dry bulk densities/g·cm^{-3}			
	Plot A (Tilled)	Plot B (5 Passes)	Plot C (10 Passes)	Plot D (15 Passes)
0-10	1.51(±1.42)	1.63(±1.57)	1.83(±0.55)	1.89(±1.12)
10-20	1.53(±0.95)	1.76(±3.24)	1.86(±1.32)	1.90(±0.23)

Table 2 Mean reference bulk densities (g/cm^3) of sampled soils under tilled condition and different compaction levels

Depth /cm	Reference bulk densities/g·cm^{-3}			
	Plot A (Tilled)	Plot B (5 Passes)	Plot C (10 Passes)	Plot D (15 Passes)
0-10	1.66(±1.15)	1.80(±0.43)	1.87(±0.59)	1.98(±0.11)
10-20	1.73(±1.62)	1.86(±0.19)	1.93(±1.28)	2.00(±0.75)

Similarly, mean BD_{ref} values at both 0-10 cm and 10-20 cm soil layers were the highest and lowest in plot D and CT, respectively. In a related study, Al-Ghazal[22] reported that BD increased significantly with an increase in compaction depending on the number of passes of tractor wheel. The BD under 15 passes of machinery was 20.1% and 13.8% higher than those under tilled condition and 5 passes of machinery, respectively. Cassel et al.[23] reported an increase in soil bulk density for tracked inter-row areas of a controlled traffic area. Also, Lowery and Schuler[24] showed that values of bulk density of soil increased with increasing level of compaction by 8 and 10 tons of farm machinery. Lowest bulk density was recorded in tilled plots and this must have been due to soil pulverization and break down of aggregates into smaller fragments.

3.2 Degree of compaction

The result of the degree of compaction (DC) of sampled soils is presented in Table 3. Though, high DC values were obtained in plots B (90%) and C (94.62%) at 0 – 10 cm and 10 – 20 cm depth, respectively, when compared with tilled plots (plot A) but highest degrees of compaction, 97% and 96.37% were recorded in compacted plots under 15 traffic passes of machinery (plot D). Different degree of soil compaction could result from the management of the soil, such as different machinery traffic passes[25].

Table 3 Mean degree of compaction (%) of sampled soils under tilled condition and different compaction levels

Depth /cm	Degree of compaction/%			
	Plot A (Tilled)	Plot B (5 Passes)	Plot C (10 Passes)	Plot D (15 Passes)
0-10	88.2(±2.18)	90.5(±4.28)	95.9(±0.10)	97.0(±6.21)
10-20	88.43(±1.76)	94.62(±5.43)	95.0(±2.18)	96.37(±0.38)

The lowest degree of compaction of tilled soil might have been caused by the relatively low strength and increased air permeability of soil. Soil parameters that are adversely affected by compaction of soil particles are those that control the content and transmission of water, air, heat and nutrients[26]. It was noticed that a high degree of compaction reduced the soil porosity and aeration, and increase bulk density and soil penetration resistance, which impedes root development of crops. Soane et al.[27] reported unfavorable changes in soil bulk density, porosity and penetration resistance. This constraint results in restricted root growth that may affect whole plant growth and grain yield. Adverse effects of compacted soil horizons on plant root growth and concomitant poor plant growth and yields have been recognized for many years[28].

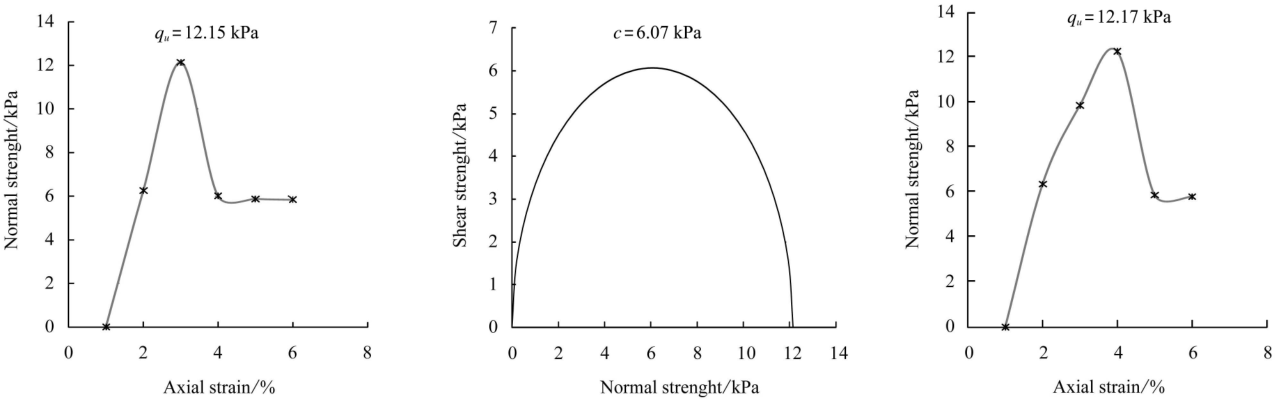
3.3 Unconfined compression strength

The influences of tillage and compaction on compression strength (q_u) and compression curve of sampled soil are shown in Table 4, and Figures 1 and 2. Plot A (tilled soil) has the lowest compression strength of (12.15±0.27) kPa and (12.27±1.50) kPa at the 0 – 10 cm and 10 – 20 cm soil layer, respectively. Plots under 5 traffic passes of machinery recorded q_u value of (31.57±1.09) and (29.68±2.81) kPa at the 0 – 10 cm and 10 – 20 cm soil layers, respectively. These observed values indicated that 5 traffic passes of machinery resulted to more than 100% increase in the compression strength of soil over tilled soils, while 15 traffic passes could lead to as much as 246.1% and 433.3% increase in soil compression strength at the 0 – 10 cm and 10 – 20 cm soil layer, respectively.

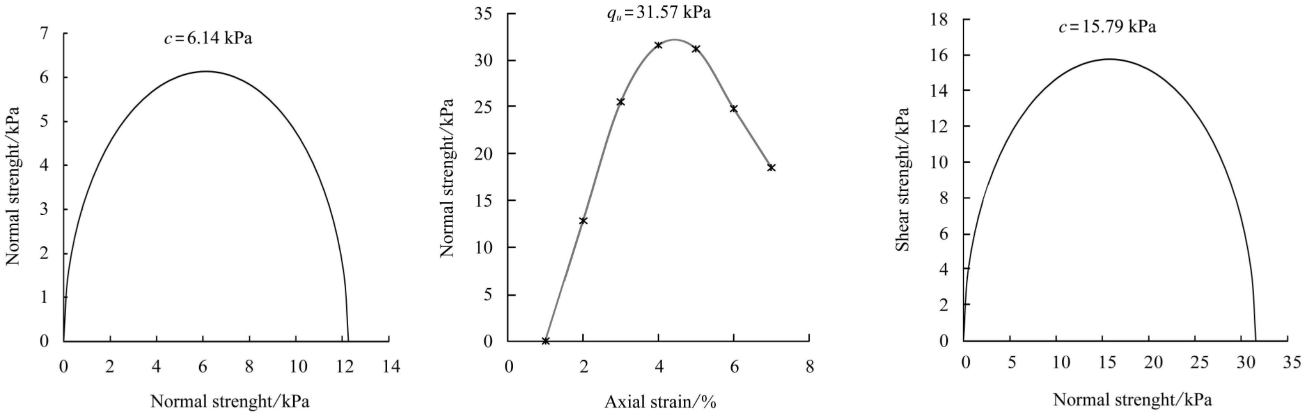
Table 4 Mean maximum compression strength (q_u) of sampled soils under tilled condition and different compaction levels

Depth /cm	q_u/kPa			
	Plot A (Tilled)	Plot B (5 Passes)	Plot C (10 Passes)	Plot D (15 Passes)
0 – 10	12.15^a (±7.43)	31.57^b(±1.06)	18.68^a (±2.64)	42.05^c(±5.28)
10 – 20	12.27^a (±3.59)	29.68^b (±9.45)	31.26^b (±0.54)	65.44^c (±10.12)

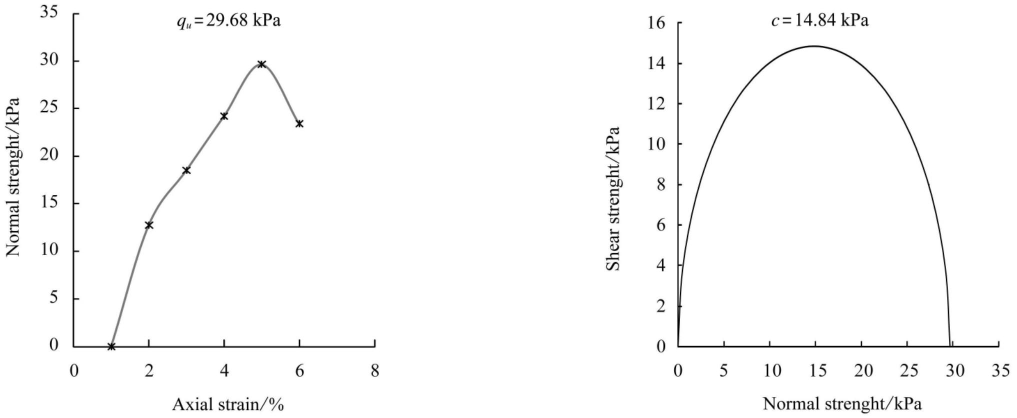
Note: Means of same letter in same row are homogenous at p = 0.05 (Tukey HSD test).



a. Tilled condition b. Tilled condition c. 5 traffic passes

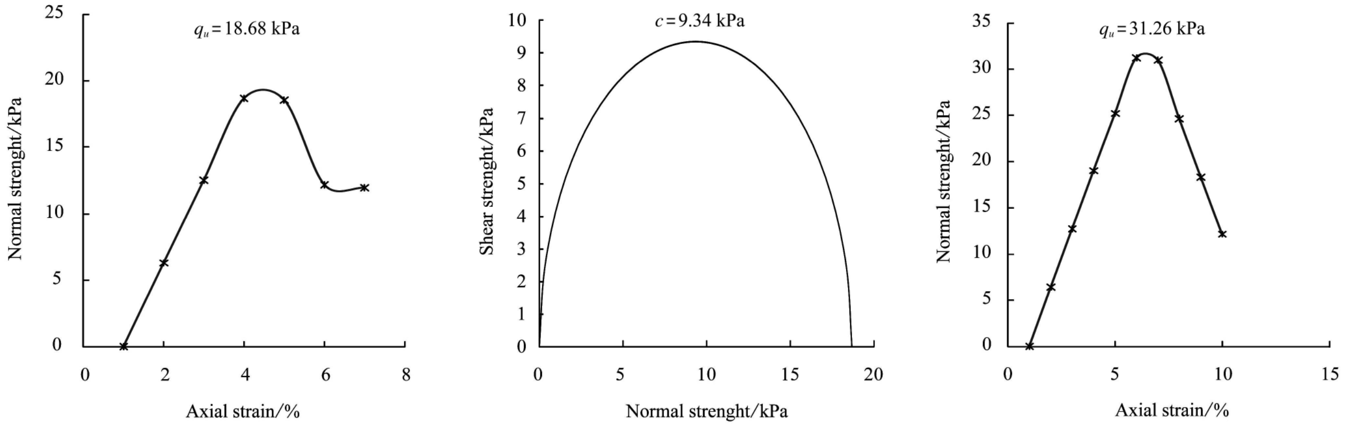


d. 5 traffic passes e. 10 traffic passes f. 10 traffic passes

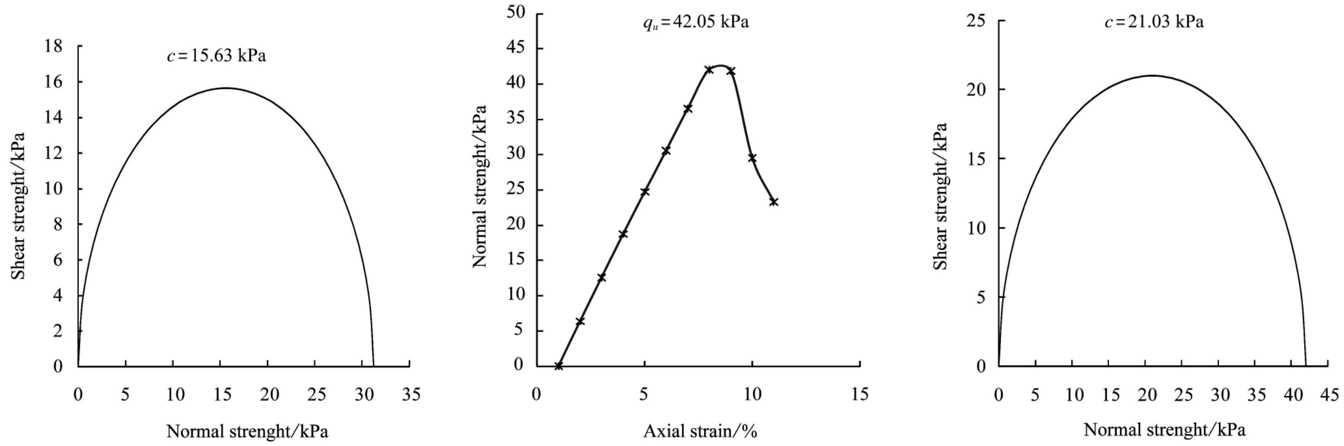


g. 15 traffic passes at the 0 - 10 cm soil layer and shear strength of soils under h. 15 traffic passes at the 0 - 10 cm soil layer

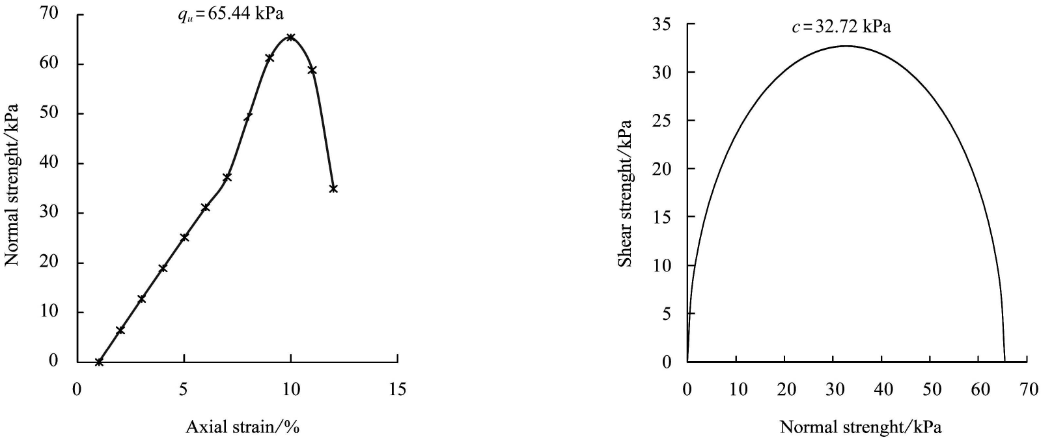
Figure 1 Mean compression strength of soil under (a) tilled condition, (c) 5 traffic passes, (e) 10 traffic passes, and (g) 15 traffic passes at the 0 – 10 cm soil layer and shear strength of soils under (b) tilled condition, (d) 5 traffic passes, (f) 10 traffic passes, and (h) 15 traffic passes at the 0 – 10 cm soil layer



a. Tilled condition b. Tilled condition c. 5 traffic passes



d. 5 traffic passes e. 10 traffic passes f. 10 traffic passes



g. 15 traffic passes at the 10 - 20 cm soil layer and shear strength of soils under h. 15 traffic passes at the 10 - 20 cm soil layer

Figure 2 Mean compression strength of soil under (a) tilled condition, (c) 5 traffic passes, (e) 10 traffic passes, and (g) 15 traffic passes at the 10 – 20 cm soil layer and shear strength of soils under (b) tilled condition, (d) 5 traffic passes, (f) 10 traffic passes, and (h) 15 traffic passes at the 10 – 20 cm soil layer

Alakukku[29] observed that the first pass of a wheel causes most compaction. Damage from wheels under high axle loads increases on wet soil because its strength is reduced[30]. The q_u of the tilled plots was sufficient to support crop growth and development in the soil, and enhance grain yield as a result of increased soil micro-porosity and reduced bulk density when compared to the compacted plots where soil bulk density ranged between 1.8 and 2.0 g/cm^3, which was reported to be on the high side for crop growth and development[31].

The observed higher mean q_u in plot B (5 passes) at the 0 – 10 cm soil depth (31.26 kPa) over the q_u at the 10 – 20 cm soil depth (29.68 kPa) might have resulted from the combined effects of hardpan formation of soil aggregates and the degree of compaction at the soil superficial layer (0 – 10 cm) by machinery traffic. Soils of coastal plain often form hardpans extending from the surface to the transitional E horizon, thus restricting root growth and reducing yields[32,33]. Soil compression strength value of over 60 kPa and above could result in poor root growth, stunted growth and reduced grain productivity. Medvedev and Cybulko[34] reported a permissible soil compression pressure of within 30 – 60 kPa when the soil water content is above the optimum soil crumbling (0.26 – 0.28 kg/kg). The soil compression strength of plots under 15 traffic passes (65.44 kPa) was above the permissible limit for effective root development.

However, soil compression strength at the 0 – 10 cm soil layer is correlated significantly with the 10 – 20 cm soil layer (r = 0.617*) at the p = 0.05 level. The mean difference between all treatment plots at the 0 – 10 cm soil layer is significant at the p = 0.05 level, except the means between tilled soils and soils compacted under 10 traffic passes of machinery (Table 5).

Table 5 Comparisons of mean compression strength of tilled and compacted soils

Soil depth /cm	Treatments		Mean difference
0 – 10	A	B	-19.39*
		C	-4.86^{ns}
		D	-29.83*
	B	C	14.53*
		D	-10.43*
	C	D	-24.96*
10 – 20	A	B	16.96*
		C	-18.93*
		D	-52.85*
	B	C	-1.97^{ns}
		D	-35.89*
	C	D	-33.91*

Note: * - The mean difference is significant at the 0.05 level; ns–not significant; A – tilled soil B – 5 traffic passes C – 10 traffic passes D – 15 traffic passes.

Similarly, the mean difference between treatment plots at the 10 – 20 cm layer is significant at the p = 0.05, except between soils compacted under 5 and 10 traffic passes of machinery (Tukey test at p = 0.05). Mean maximum and minimum soil shear strengths at the 0 – 10 cm soil depth are (21.03±7.29) and (6.07±3.75) kPa in plots under 15 traffic passes and tilled soil, respectively (Table 6). Similarly, the mean soil shear strength of plots under 15 traffic passes at the 10 – 20 cm soil layer was (32.72±8.24). The shear strength of soil under 15 traffic passes was 109.34% over soils under 10 traffic passes at depth 10 – 20 cm, while the shear strength of soil under 5 traffic passes was 69.06% over the shear strength of soils under 10 traffic passes.

Table 6 Mean shear strength of sampled soils under tilled condition and different compaction levels

Depth /cm	Shear strength/kPa			
	Plot A (Tilled)	Plot B (5 Passes)	Plot C (10 Passes)	Plot D (15 Passes)
0 – 10	6.07(±3.75)	15.79(±1.21)	9.34(±6.28)	21.03(±7.29)
10 – 20	6.14(±2.37)	14.8(±1.89)	15.63(±1.53)	32.72(±8.24)

4 Conclusions

Plot A (tilled soil) has the lowest bulk density of (1.51 g/cm^3) but increased from 1.63 g/cm^3 in plot B (5 passes) to 1.90 g/cm^3 in plot D (15 passes), which implies, the more compaction of the soil is, the greater the bulk density and the same effect was recorded for the degree of compaction. Compacted Plot B (5 passes), C (10 passes) as the higher degree of compaction and plot D has the highest. Also, plot D has the highest compression strength (maximum load attained per unit area) which resulted to the highest shear strength when compared to the remaining compacted plots (B and C under 5 and 10 traffic machinery passes, respectively) and plot A (tilled soil) that have the lowest bulk density, degree of compaction and compression strength which resulted to the lowest shear strength. An increase in soil compaction resulted in increase in compression and shear strength of the soil which restricts crop development and reduced soil productivity.

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