Int. Agrophysics, 2007, 21, 1-5

INTERNATIONAL
Agrophysics
www.ipan.lublin.pl/int-agrophysics

Estimating trafficability of three Nigerian agricultural soils from shear strength-density-moisture relations**

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Received July 2, 2006; accepted January 12, 2007

Abstract. The dry density and shear strength of Iwo (Alfisols), Egbeda (Entisols) and Ondo (Ultisols) soil series in south-western Nigeria were measured at different compaction efforts and moisture contents. Results indicate that dry density and shear strength increased considerably with increase in compactive effort ($P < 0.05$). Maximum values of dry density were reached at predetermined critical moisture content for compacting the soils, while the strength decreased continuously with increasing moisture content. Superimposing the two curves of dry density and shear strength versus moisture content, respectively, gave the best compromise moisture content for trafficability of the soils. Regression equations were derived to relate the equilibrium moisture content for trafficability of the soils to soil components and dry density.

Keywords: compactive efforts, trafficability, moisture content, shear strength, dry density

INTRODUCTION

In Nigeria, the cost of farm machinery operation has been a major concern in the recent past (Igbeka, 1986). Apart from the high initial cost of farm tractor, the high fuel cost had led to substantial increase in the operational cost of agricultural mechanization. The draft force required by tractor in pulling given equipment through the soil is a function of shear strength of the soil. The higher the draft force, the higher the fuel consumption of the tractor. The shear strength of soil has been shown to decrease with moisture content and increase with the compaction of the soil (Panwar and Siemens, 1972).

The use of farm tractor on soil also leads to compaction of the soil which in turn leads to increase in dry density, penetration resistance and decrease hydraulic conductivity of the soil (Ohu *et al*., 1987). Compaction also affects crop yield, due to changes in the physical characteristics of the soils (Dawkins, 1983; Mckyes *et al*., 1979; Raghavan *et al*., 1978). While some crops can tolerate a little compaction, others have been shown to be very sensitive to compaction (Ohu and Folorunso, 1989). The dry density of soil at traffic (which is an index of compaction) increases with moisture content up to a maximum value at predetermined critical moisture content which is below the liquid limit of the soil, and thereafter decreases with moisture content (Ohu *et al*., 1987; Adekalu and Osunbitan, 2001). Farm tractors are better suited when the soil is not too wet, so that the soil can support the machinery and skidding of the wheels is avoided (Haraldsen and Sveistrup, 1994). Thus, farm operations are better performed below the critical moisture content, when the soil is relatively dry.

The objective of this study was to investigate the effect of applying different compactive efforts at varying moisture contents on the physical and strength characteristics of three prominent agricultural soils in south-western Nigeria, and to determine the best moisture content for trafficability of the soils.

MATERIALS AND METHODS

Description of the study area

The study area, south-western Nigeria (3 and 5°E; 6 and 9°N), has a mean annual rainfall of about 1000 and 2000 mm in the northern and southern parts respectively. The rainfall distribution is bimodal, with peaks in June and September.

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**This work was supported by the Commonwealth Scholarship Commission, UK.

The dry season extends from November to March of the following year. The average minimum and maximum air temperatures are 20 and 32°C, respectively. Parent materials in the northern part of the area are derived mainly from Precambrian basement complex rocks, occurring in a complex pattern. The most common rocks are granites, syenites, gneisses, schists, quartzites and amphibolites. The upland soils, (Alfisols) usually consist of a veneer of pedisediments over saprolites. The lower slope soils, formed from alluvium and colluvium, are Inceptisols or Entisols. Soils of the southern area are derived from sedimentary materials of Tertiary to Pleistocene age and are either Alfisols or Ultisols (Ashaye *et al.*, 1998). The vegetation in the northern part is wooded savanna, while lowland rain forest dominates the south and south-eastern areas.

Methodology

Two samples each of the soils were collected from the top 15 cm of the soil profile from uncultivated locations in south-western Nigeria that have been left fallowed for three years, air-dried and clods reduced to smaller fractions to pass through a No. 10 sieve, with an apparent opening size of 2 mm. Each soil sample was then mixed to obtain a homogenous sample and particle size analyses were obtained using the modified hydrometer method (Lambe, 1951). The soil textures whose initial moisture contents varied from 2 to 3% were each brought up to six moisture levels (8, 12, 16, 18, 20, and 22%) dry mass basis. The Atterberg limits (plastic and liquid limits) were also determined following the procedure described by Lambe (1951).

The soils were subjected to 5, 15 and 25 blows of a standard proctor hammer in cylindrical moulds, 102 mm in diameter and 116 mm in height, at each moisture content (Lambe, 1951). Five blows correspond to the normal conditions of the field, 15 blows correspond to the weight of a medium-sized tractor, and 25 blows to the weight of a heavy tractor (Raghavan and Ohu, 1985). The dry density of the soils at the different moisture contents was determined at each compaction level. The dry density measurements were repeated four times for each soil at every moisture content and compactive effort.

The shear strength was determined by a tri-axial test. The test was unconsolidated and undrained. A weighed, compacted specimen, 38 mm in diameter and 78 mm in height, was enclosed in a condom membrane to prevent the specimen from absorbing water. This was then placed on the base pedestal of the tri-axial cell. Applied water pressure supplied a minor principal stress on the sides of the specimen while a major principal stress was continuously applied vertically until the specimen failed. It was removed and reweighed and its moisture content determined. This process was repeated two more times for each soil sample using varying minor principal stress. The results were used to plot Mohr circles to obtain shear strength parameters. The process was repeated for different levels of moisture contents and dry density (initial dry densities for the different compactive efforts).

RESULTS AND DISCUSSION

The results of the grain size analysis and consistency limits of the soils tested are presented in Table 1. Organic matter content of the Iwo, Egbeda and Ondo soil series were 1.56, 1.61, and 2.5% of organic carbon, respectively.

It can be seen from the particle size analysis that the Egbeda series has relatively larger specific surface than the other two soils based on the total percentage of silt and clay particles in the three soils. The plasticity index of the Egbeda series is higher than that of the other two soils because of the higher silt and clay contents and the lower sand in Egbeda. Similar increase in plasticity index with increase in clay content were observed by Ekwue *et al.* (2002) and Mapfumo and Chanasyk (1998).

From the results of compaction test, the dry density versus moisture content relationships for the three soils is as shown in Fig. 1a, b, and c. The plotted point is the average of four replicates at each moisture content with a maximum standard deviation of 2%. These plotted values were found to increase with increase in compactive effort. The maximum densities of Ondo at 5, 15 and 25 proctor hammer blow compaction were found to be 1.62, 1.73, and 1.84 g cm^{-3}, respectively; at a critical moisture content of 14.5, 13.8 and 13%, and the maximum densities of Egbeda at these compactions blows were 1.53, 1.68 and 1.81 g cm^{-3} at critical

Table 1. Particle size distribution, consistency limits and initial organic matter content of the soils

Soils	Liquid limit	Plastic limit	Organic matter content	Particle size distribution (%)			Granulometric group	Taxonomy
		(%)		Sand	Silt	Clay		
Ondo	18.8	13.2	2.50	74.5	6.7	18.8	Sandy loam	Ultisols
Egbeda	20.6	13.8	1.61	73.7	4.3	22.0	Sandy clay loam	Entisols
Iwo	15.8	11.5	1.56	80.4	4.7	14.9	Loamy sand	Alfisols

moisture content of 15.2, 14.2, and 13.8%, while those for Iwo at the same treatments were 1.68, 1.82, and 1.95 g cm^{-3} at critical moisture content of 13.4, 12.8, and 12.6%, respectively. The higher maximum density of Iwo at all compaction levels, with a lower critical moisture level, is not unexpected because Iwo has a higher percentage of sand particles than the other two soils. This shows that Iwo is more susceptible to compaction, and since the plasticity index of Iwo was found to be less than that of the other two soils, the lower critical moisture for the proctor hammer compaction of Iwo is adequate. Similar observations were obtained by Ohu *et al*., (1987) and Ekwue *et al*., (2002).

Generally, the critical moisture contents at 25 blows are lower than those of lower compaction levels. This implies that heavy tractors can only be used over a limited range of moisture content, apart from compacting the soils more than lighter ones. The results of shear strength versus moisture content relationship are shown in Fig. 2a, b, and c. The plotted points are the average of four replicates at each moisture content with a maximum standard deviation of 3%. The figures show that the shear strength decreased with increasing water content. The decrease was rapid at the lower water content and gradual at the higher water content. The relationship is close to being exponential. Earl (1997)

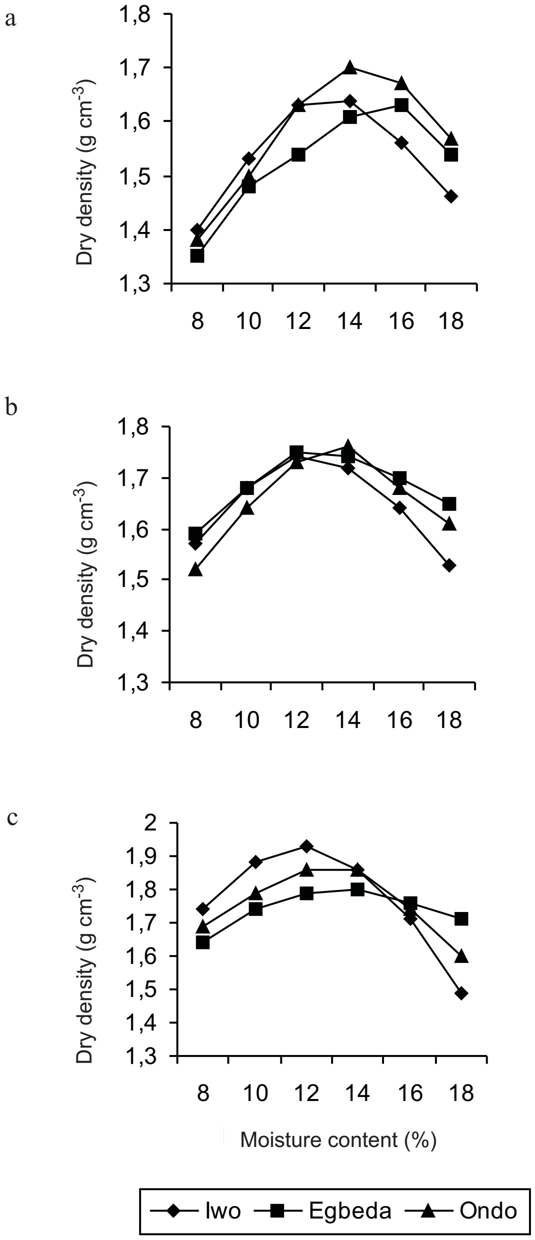

Fig. 1. Moisture content versus dry density at: a) 5, b) 15, and c) 25 blows.

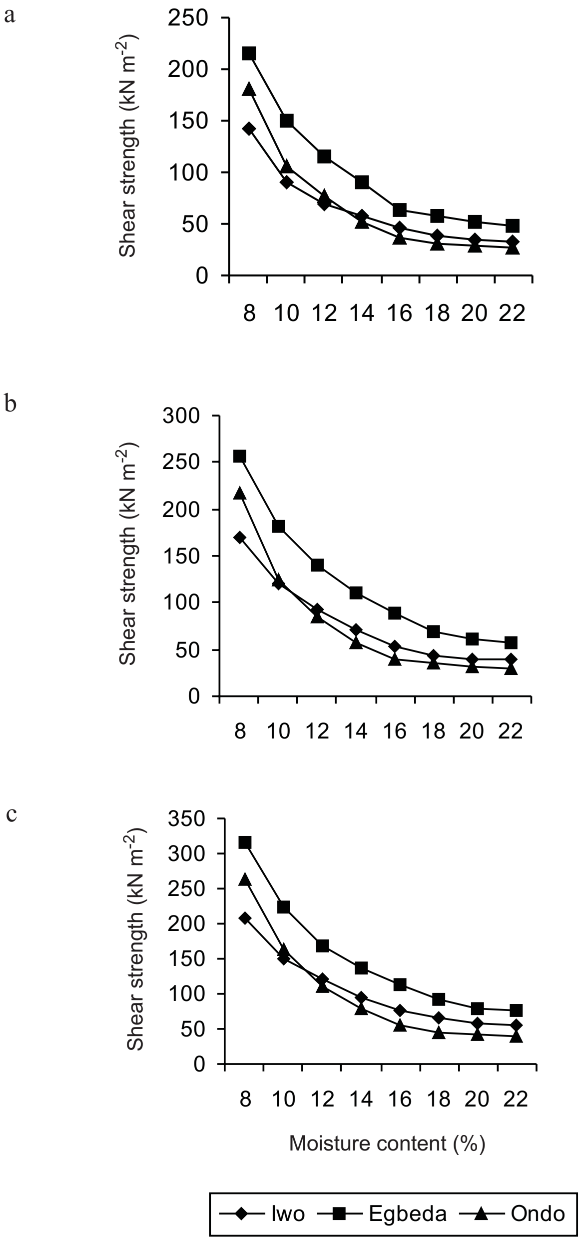

Fig. 2. Moisture content versus shear strength at: a) 5 , b) 15, and c) 25 blows.

obtained a similar exponential relationship between moisture content and penetration resistance. The equations relating moisture to shear strength derived for the three soils (Iwo, Egbeda and Ondo, respectively) at the minimum dry density are as follows:

$$S = 458\exp^{-0.18m} \tag{1}$$

$$S = 713\exp^{-0.26m} \tag{2}$$

$$S = 445\exp^{-0.23m} \tag{3}$$

where: S – the shear strength (kN m^{-2}) , m – the moisture content (%).

As the compaction levels increased, the shear strength of the soils increased. Panwar and Siemens (1972) observed similar behaviours in shear strength and energy of soil failure in relation to density and moisture content. Unlike in the compaction test, Iwo soils – with the highest sand content and least colloidal contents – have the least shear strength compared to the other two soils for all compactive efforts, while Egbeda series – with the highest clay contents has the highest shear strength. This is because the shear strength, like dry density, is related to soil components. The shear strength of Egbeda series was considerably higher than those observed for the other two soils at all compaction levels ($P< 0.01$). The difference between the shear strength of the soils was more pronounced with increasing level of compaction for all moisture levels ($P<0.05$). The shear strength of Ondo was lower than that of Iwo at low moisture levels (< 12%) and became higher afterwards. This might have been due to higher organic content of Ondo series. The influence of organic matter on soil strength properties is pronounced in soils with low clay content (Ekwue and Stone, 1995).

According to Simalenga and Have (1994), a soil is trafficable if:

a) it has significant compressive strength to withstand the weight of the machinery,

b) it has sufficient shear strength to meet the traction requirement with acceptable wheel slip and soil damage and,

c) a suitable soil tilth can be produced.

Conditions (a) and (b) are mutually related and they define the upper limit of the soil moisture, and (c) defines the lower limit of the soil moisture. Condition (a) is generally satisfied when the soil moisture is below the liquid limit, and condition (b) when it is below the plastic limit. This is because the compressive strength of sandy soil is usually more than that of clay soil even though the shear strength may be less. Condition (c) is satisfied when the shear strength is not too large to cause a drag resistance greater than the pulling force of the tractor. Referring to Fig. 2a for five blows of the proctor hammer, which corresponds to the normal compaction obtained in the field, and assuming a Massey Ferguson 165S tractor (commonly used in Nigeria) with a drawbar power of 40 hp and field-travel speed of 8 km h^{-1}, carrying a two-row mouldboard/disc plough equipment with a width of 1.5 m, penetrating to a depth of 10 cm, a limit of shear strength of 90 kN m^{-2} is obtained. This gives a moisture range of 6.0 to 11.5, 8.5 to 13.8 and 7.5 to 13.2% for Iwo, Egbeda and Ondo soil series, respectively, for the trafficability of the soils. The lower values of the moisture range of Iwo and Ondo series were obtained by a logarithmic extension of the curves using the derived equations. The lower limit values of the moisture range are similar to those suggested by Earl (1997) and Mapfumo and Chanasyk (1998) using penetrometer readings. The Ondo series with the highest colloidal content has the highest moisture range, while the Iwo series with the highest sand content has the lowest moisture range. This is quite expected because soils with low organic matter content exhibit low cohesion, which results in low drag resistance; while soils with high colloidal content have high consistency limit, which makes them resistant to smearing and sinkage under loading.

Superimposing the curves of shear strength versus moisture content and those of the dry density versus moisture content gave the equilibrium moisture content of approaching the soils with the least shear strength and compaction (Table 2). Though these trafficability ranges and equilibrium moisture content values were obtained using disturbed samples in the laboratory, they could be useful guides for identifying the moisture range for least draft and compaction on the field. While this does not eliminate field trials, they could reduce the numbers of experimental runs. The Egbeda series with the highest clay content also has the highest equilibrium moisture content, while Iwo series with the highest sand content has the lowest equilibrium moisture content. This is possibly due to the interactive effect of the soil component and organic matter on compaction, sinkage and cohesion properties of the soil. Strong interaction between soil type and organic matter content on compaction and compressibility of soils have been reported by Ekwue and Stone (1994) and Stone and Ekwue (1995), respectively. The lower dry densities at the higher moisture contents are not desirable due to skidding of farm machinery unless the soils are supported by animal wastes or other conditioners. The date of attainment of the moisture content given in Table 2 after a rainfall event can

Table 2. Equilibrium moisture content* (%) of the shear strength and dry density of the soils

Soil type	Compaction level			
	Number of blows			Average
	5	15	25	
Egbeda	12.2	11.9	11.4	11.8
Ondo	10.9	10.4	10.0	10.4
Iwo	9.9	9.5	9.1	9.5

*Data are average of four replicates and two samples.

easily be obtained using a pre-calibrated hand penetrometer pushed to a depth of 15 cm, as Nath and Johnson (1980) have shown that the first 15 cm soil layer largely determine whether the soil is trafficable or not. It can also be obtained using any of the existing soil moisture prediction models that has been calibrated for the area under study. Table 3 shows the results of the regression analysis of the equilibrium moisture content on the individual soil components and dry density. Dry density and clay content was positively correlated with equilibrium moisture content while sand content was negatively correlated. Based on these a multiple regression equation derived relating the significant component is as follows:

$$MC = 13.66 - 2.35\gamma + 0.20\,Cy - 1.69\,C \quad r = 0.85 \quad (4)$$

where: MC – the equilibrium moisture content (%); γ – the dry density (g cm^{-3}); Cy – the clay content (%); and C – the organic matter content (%).

Table 3. Regression of equilibrium moisture content on soil components and dry density

Soil components and dry density	Equilibrium moisture content (%)		
	a	b	r
Sand (%)	16.03	-7.15	0.41
Silt (%)	14.82	- 0.81	0.43
Clay (%)	7.22	0.18	0.87
Organic matter (%)	13.84	-1.72	0.73
Dry density (g cm^{-3})	16.30	-3.71	0.82

a – intercept, b – slope, r – correlation coefficient.

CONCLUSIONS

1. The higher compaction levels increased the dry density and shear strength. While shear strength decreased with increasing moisture content of the soils for all compaction levels, the dry density increased with increasing moisture content up to a maximum level and thereafter decreased with increasing moisture content.

2. Superimposing the two curves of shear strength and dry density with moisture content gave the equilibrium moisture content of approaching the soils with the least shear strength and minimum compaction on the soils. The moisture range for trafficability of soil increased with the colloidal content of the soil while the equilibrium moisture content increased with the clay content.

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