Proctor cone penetrometer for *in-situ* soil strength studies in Nigeria

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Abstract: Investigations of *in-situ* or laboratory soil strength properties, particularly the resistance of soil to penetration, usually referred to as cone index (CI) are often required in soil tillage and traction studies. This helps in the analysis of the interactions of both tillage tools and tractive elements with the soil. However, penetrometer, the instrument used for measuring this important parameter (CI), is not readily available in Nigeria. Following the recommendations in ASAE standards, a functional proctor cone penetrometer for soft soils has been developed and calibrated. The major parts include the handle, made of half-inch galvanized pipe, constructed in such a way that it can be screwed on and off the pressure shaft conveniently, the graduated pressure and penetration shafts made of stainless steel; the spring loaded pressure chamber, and a cone probe. The penetrometer was calibrated by applying known forces on the handle while noting corresponding penetrations and displacements on the graduated pressure shaft. A performance test was carried out on a clayey loam soil to compare the readings obtained from the developed penetrometer and an imported one. The major difference between the two is that while one is very expensive and scarce to come by, the other is produced locally with locally sourced materials and technology. The cost of the imported one is ten times more than that of the local one. The mean CI obtained for twenty-four random samples on the soil surface for the test area at 18 cm depth was found to be 1.4358 MPa for the local, and 1.5096 MPa for the imported. Regression analysis of the two sets of values of CI for the local and the foreign showed a strong correlation ($R^2 = 0.779$, $P<0.05$). This implies that the locally produced proctor penetrometer is reliable for measurements of CI at 0 – 18 cm soil depth for soft soils.

Keywords: cone index, soil tillage, traction studies, soil mechanical properties
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1 Background of the study

1.1 Soil mechanics and soil tillage research

The study of soil mechanics is broad and involves many basic physical and engineering concepts such as mechanics of material, dynamics, kinematics and fluid mechanics. These basic concepts help in understanding the mechanical nature of soils and their behaviour under applied forces and variable conditions which are requisite knowledge in soil tillage studies. Some basic theories of soil mechanics include description and classification of soil, effective stress, shear strength, consolidation, lateral earth pressure, bearing capacity, slope stability, and permeability. Furthermore, foundations, embankments, retaining walls, earthworks and underground openings; these theories from soil mechanics are very useful in

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tackling practical problems in Agricultural Engineering, Geotechnical and Geophysical Engineering as well as Engineering Geology.

In agricultural soil mechanics, the most relevant soil properties are the reactions of soil to applied forces[1]. These properties are often called strength properties which for a given soil can change with time under the influence of climate, soil management and plant growth. The strength properties of any given soil and their changes with time can be determined through the measurement of soil shear strength and penetration resistance whose values depend to a great extent on bulk density and moisture content. Soil penetration resistance is related to the pressure required to form a spherical cavity in the soil, large enough to accommodate the cone of the penetrometer, allowing for the friction resistance between the cones and its surrounding soil[2]. Several experiments have been performed specifically to study soil mechanics, such as the use of penetrometers, which are rods that measure the force required to penetrate to various depths in the soil. Measurements of some of the soil properties such as permeability, compressibility, strength and etcetera, sometimes can be difficult, time consuming and expensive to obtain. In certain engineering projects, due to budget, site and other constraints, engineers and technologists are unable to carry out detailed and more costly site investigations[3]. Index properties and soil classifications provide engineers and technologists the qualitative measurements of the soil properties. It has been noted that specialized area of soil tillage dynamics research is taking a new positive dimension in Nigeria as researchers now develop soil bin facilities for model studies of soil engaging implements and tractive devices[4]. This has become necessary in view of global trends, emerging technologies and ideas for curriculum modification of agricultural engineering programmes to produce better, more competent, and self-reliant graduates[4-8]. It has also been reported that the intensity of mechanization of farming operations in Nigeria is still very low[9] and that the volume of tractors and implements in Nigeria is not commensurate with the work done by the machines on Nigerian farms due to frequent breakdown and lack of spare parts[10]. These problems have been traced to lack of relevant data for the appropriate design of agricultural machines and implements and unsuitability of some imported machinery. It is hoped therefore that more research in the special area of soil tillage/traction and related topics, like this one, would help to address some of these problems.

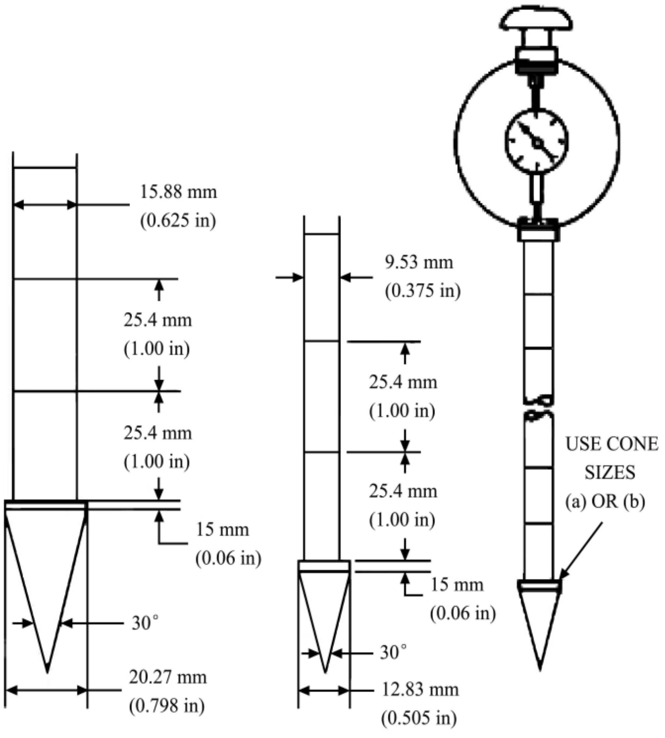
1.2 Statement of the problem

Agricultural soil tillage in sub Saharan Africa, particularly Nigeria as a developing country is more of art or culture rather than science. This has continually resulted in subsistent/family level rather than commercial, profit oriented farming. Part of the problem is that there is lack of requisite agricultural field operation and general practice record and data bank Instruments and equipment for soil tillage research are not only uncommon but rarely available; where some are, usually heavy and or expensive to procure, operate and maintain[11]. Penetrometer which is one of the vital instruments in Agricultural soil tillage research and teaching is not readily available in Nigeria. Despite the fact that penetrometer technology has far advanced from the manual types to the digital and real-time data logging types, many agricultural engineers or agricultural engineering students have never seen a penetrometer once neither know how to use it practically. At best, it is just mentioned in passing during soil mechanics or soil-machine interaction lectures in the higher institutions. This is why the idea to develop and calibrate a proctor type penetrometer, which is sourced completely locally, was conceived in this work.

2 Penetrometer

2.1 Developments in penetrometer technology

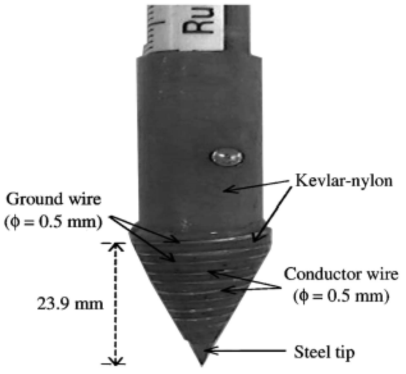
The history of the penetrometer dates back to 1846 when a French engineer, Alexandre Collin, developed a 1 mm diameter needle shaped penetrometer to estimate the cohesion of different clay types[12]. The Waterways Experiment Station[13] later developed a circular cone penetrometer with an apex angle of 30-deg and base area of 1.61 cm^2 that was mounted on a graduated shaft of 0.95 cm diameter and 91.4 cm long. Historical perspectives on the cone penetrometer design (sizes and shape) and operation procedures are described in the literature[12,14]. Cone Penetrometer can therefore be defined as a device which measures the force required to insert a cone into the soil. It is an easy and quick tool to measure relative soil strength. Soil cone penetrometers have numerous applications in Agriculture and off-road traffic studies that include *in-situ* soil in layered soils, compaction assessment, predicting trafficability and bearing capacity for foundations[14] and simulation of root growth[15]. In developing their modified soil cone penetrometer, which was called soil impedometer, Tollner E W, et al.[15] used polymer and water as cone lubricating agents. The American Society of Agricultural and Biological Engineering (ASABE) has established standards for a 30-deg circular stainless steel cone penetrometer and procedure for using and reporting data obtained with the soil cone penetrometer[16,17]. The standard[16] recommended two cone basic types: 20.27 mm diameter cone base with 15.88 diameter shaft for soft soils; and 12.83 mm diameter cone base with 9.53 mm diameter shaft for hard soils (Figure 1). The penetrometer should be inserted at a uniform rate of 30 mm/s, either normally with the unit mounted on a tractor truck or a trailer.



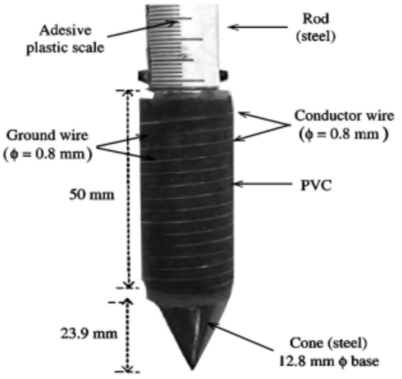
(a) (b)

Figure 1 ASAE standard cone penetrometer

The data obtained from cone penetration tests are reported as cone index, defined as, force of insertion per unit cone base area. Recent advances in the equipment design have been reported for multiple-probe cone penetration resistance reading and real-time cone penetration measurement[18,19]. The interpretation of cone penetrometer data, however, has not progressed well mainly due to the influences of soil factors and soil material heterogeneity in space and time. Figure 2 shows a combined CI and soil moisture probe for simultaneous measurement of the two parameters, which is an improvement on the separate measurement probe methods.



a. Coiled cone TDR



b. Coal rod TDR[2]

Figure 2 Combined CI and soil moisture probe[2]

2.2 Types of penetrometer

There are two general types of hand-held penetrometers: Static and Dynamic penetrometers. Both measure soil resistance to vertical penetration of a probe or cone. The distinction between the two lies in how force is applied to the cone. Static penetrometers subject to a constant hydraulic, mechanical, or electric power (via truck, tractor, or other motorized source) record data deep into the soil profile using digital data acquisition. These mechanical penetrometers work well to document compaction profiles due to the constant penetration rate, but are expensive and often limited to road-accessible site.

2.2.1 Static cone penetrometer

These measures the force required to push a metal cone through the soil at a constant velocity. The force is usually measured by a load cell or strain guage (e.g. proving ring) coupled with an analog dial or pressure transducer for readout[20]. The force is commonly expressed in kilopascals (kPa), an index of soil strength referred to as the cone index[16], or as kg/cm^2 or psi. As the operator pushes down on the penetrometer, the note keeper records cone index values for each depth increment to evaluate the degree, depth and thickness of compacted layers. Cone indices depend on cone properties (angle and size) and soil properties e.g. bulk density, texture, and soil moisture[17,20]. A static cone penetrometer with a 30° cone has been recommended by the American Society of Agricultural Engineers (ASAE), as the standard measuring device for characterizing the penetration resistance of soils[16]. While this configuration may work in a wide variety of soils, it is not critical that all instruments adhere to these standards, since results are generally related to one another at a particular time and space.

2.2.2 Dynamic cone penetrometer

These apply a known amount of kinetic energy to the cone, which causes the penetrometer to move a distance through the soil[20]. Dynamic penetrometers do not rely on constant penetration velocity, as most dynamic penetrometers use a slide hammer of fixed mass and drop height to apply consistent energy with each blow. Either the number of blows required to penetrate a specified depth, or the depth of penetration per blow are measured, or results can be calculated as a cone index. The weight of the hammer, slide distance, and cone angle influence the energy delivered and can be adjusted to local conditions (e.g. soft vs hard soils). Measurements are taken by placing the cone on the soil surface with the shaft upright. To minimize variability in starting depth, the cone is pressed into the soil until the soil is level with the base of the cone. The slide hammer is raised until it touches the coller and is released. The depth of penetration is recorded for each blow until a maximum or desired depth is reached. Penetrometers driven to depths greater than approximately 30 cm may be difficult to remove from the soil. Soil resistance for each depth interval is calculated using standard equations that account for differences in hammer drop distance, weight, and cone size.

2.2.3 Drop cone penetrometer

These are considered a type of dynamic penetrometer. It is used to estimate surface soil strength. It has been used to estimate compaction effects associated with cattle grazing and military vehicles[20]. The drop cone used in the aforementioned studies was constructed based on design information provided by Godwin R J, et al.[21] and advice from Dr. Paul Ayers. The drop-cone technique is rapid and precise, allowing many samples to be obtained in a short period of time. It is inexpensive, easy to use, rapid and highly repeatable. The disadvantage of this penetrometer is that, only surface soil resistance is measured and nothing can be inferred about the underlying soil profile.

2.3 Soil behavior modeling by cone penetration

Soil behavior under cone penetration involves a combination of cutting, compression, shear or plastic failures, or any combination of these[22]. Various approaches[15,23-25] have been considered to study the soil responses in cone penetration including (1) bearing capacity theory; (2) cavity expansion theory; (3) steady state deformation; (4) finite element (FE) analysis; and (5) laboratory experimental methods. Most of these approaches used analytical methods whereby a shape of soil failure surface was assumed and then limit equilibrium of forces over the soil-tool system was solved. Analytical approaches have limitations to explain soil dynamic responses in cone penetration, in particular in layered and heterogeneous soil conditions because of the difficulty in pre-defining the soil failure shape and complexity of force equilibrium analysis[26]. Tollner E W, et al.[15] have conducted experiments in plastic chambers to study soil responses to cone penetration from lubricated and non-lubricated cone penetrometers using

X-ray computer tomography (CT). With the availability of powerful machines with high computational speeds and FE codes that contain advanced material models, the FE method can be implemented in solving the soil cone penetration problem[27-30]. In modeling cone penetration using the finite element method, availability of soil constitutive models that account for soil behaviors that occur in cone penetration and meshing techniques for the soil and cone contact problems have to be selected and developed for the simulation to be successful.

2.4 Current uses of penetrometers and applications of cone index measurements

Penetrometers are used for the following: to determine the resistance to penetration, Cone Index (CI) or bearing capacity of soils; to determine soil strength; to identify compacted soil conditions; to predict the depth of the compacted layer for precision tillage. Some of the practical applications include: general soil research, basic advise for foundations, checking artificial compaction of soil, research of the growing circumstances (to be expected) of plants in the soil, tracking compacted layers in the soil. Further more, the cone penetrometer has been modified for precision tillage by incorporating GPS and improving data acquisition[18,31]. Raper R L, et al.[18] developed a tractor mounted multiple–probe–soil-cone-penetrometer (MPSCP) that has five probes and the capability of rapidly obtaining high-density cone index readings. The device still offers an easy and economical method of soil compaction evaluation. Cone index has also a good relationship with the fundamental soil strength properties (cohesion and angle of friction)[24]. Research also showed that soil penetration resistance is a good indicator of root impedance[32]. Precision farming has further promoted the use of the cone penetrometer in evaluating the potential of real-time soil compaction measurement systems.

The main constraints of the cone penetrometer as a tool in precision tillage could be the influence of its readings by soil factors, mainly soil moisture and bulk density, and the difficulty in data interpretation especially in layered soils characterized by varying soil moisture contents and soil strength profiles. Researchers[17,33] have recommended that (1) Measurement of soil cone penetration should be taken under wet soil conditions; (2) Depth to peak (maximum) cone index or critical cone index value (2 MPa) characterizes the hardpan layers; (3) Compacted layers or hardpan location as predicted from cone index-depth data is generally not affected by soil moisture content variations and (4) Tillage depth should be set 3 cm below the predicted depth of the layer. Detection of the hardpan is done by evaluating the cone index vs. depth profile. Interpretation of soil cone index-depth data is difficult due to layering, compactibility of soils, soil conditions and soil-tool interactions[12,22,23,34-36]. Gill WR[22] and Mulqueen J, et al.[35] showed that formation of a soil wedge in front of the cone could erroneously increase the soil penetration resistance. ASAE 1999b[17] recommends soil cone penetrometer measurements be taken at soil moisture content near field capacity to minimize the effect of varying soil moisture on the cone index data. The difficulty to discern single soil moisture content in layered soils, spatio-temporal soil moisture variability and appropriate sampling time could make cone index sampling at soil moisture near field capacity very difficult. In precision tillage, accurate soil hardpan detection is important because errors of a few centimeters could cause variations in precision tillage depth recommendations. Real-time soil strength sensing methods are intended to detect hardpan at soil moisture conditions similar to the tillage operation, which often is expected under dry soil moisture conditions for maximum performance[37,38]. Appropriate evaluation of real-time soil strength sensing methods with the cone index measurement in predicting soil hardpan would require study of the influences of soil moisture and layering on soil cone penetration resistance.

3 Design considerations and material selection

3.1 The overview of the proctor-type penetrometer

Proctor-type penetrometer is a device that is used to determine the strength of the soil in terms of its resistance to penetration. It is commonly used in characterization of the soil by off-road mobility experts and scientists. It consists of a removable 30° hardened steel cone with 22 mm diameter base and sectional area of 3.8 cm^2

mounted on a 22 mm long 12.6 mm penetrating shaft, connected to a 32 mm diameter and 278 mm long pipe (pressure shaft), enclosing a 253 mm mean diameter, 3.3 mm diameter of the wire and 243 mm long compression spring, with a connecting nut. This nut equally connects a 210 mm long and 12.6 diameter pressure shaft. The handle is a 305 mm long and 21.5 mm diameter pipe which is connected to the pressure shaft. This tool is designed to allow a maximum force of 2 000 kPa (in line with ASAE recommendations for soft soils, considering possible *in-situ* soil strength values and the fact that it is a hand tool) and can be operated in a vertical position. The design is limited by the fact that resistance increases with increasing depth due to increase in contact area with the cone. The 3D prototype design was accomplished with ProE Wildfire version 4.0 (Figure 3).

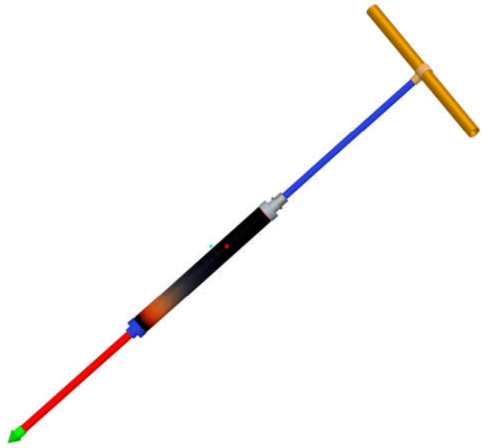


Figure 3 3D ProE design of proctor-type penetrometer

3.2 Description of component parts and their functions (Figure 4a-j)

Cone probe (a): As the name implies, it is cone-shaped, made of hardened steel with a cone angle of 30^o, 22 mm diameter base, 42 mm long, base height of 27 mm and 10.7 mm threaded bore for the attachment of the penetrating shaft. It is the point of contact to the soil during penetration.

Penetrating shaft (b): This is made of 240 mm long and 12.6 mm diameter, calibrated stainless steel rod with both ends threaded 10 mm externally, for the attachment of the cone probe and the pressure chamber pipe, with the aid of connecting nut. It is used to determine the depth of penetration on the soil.

Connecting nuts (c & d): This is a 23 mm long mild steel with a larger outer diameter of 30 mm, for the attachment of the pressure chamber, and a small external diameter of 20 mm. It is two in number. One with an internal bore of 13 mm for free movement of the pressure shaft and the other with a threaded bore of 12.5 mm for the attachment of the penetrating shaft. Both help in the connection of the pressure chamber to the pressure and the penetrating shafts.

Pressure chamber (e): This is a hollow pipe with both ends threaded 10 mm externally for the attachments of the penetrating and pressure shafts by the connection nuts. It is made of mild steel and is used to house the spring.

Pressure shaft (f): This is like the penetrating shaft made of a calibrated stainless steel of 320 mm long and 25.6 mm diameter. It is the point of attachment to the handle. It also contains a knob that helps to determine the displacement on the shaft. It also compresses the spring when pressure is applied on the handle.

Knob (g): This is a fibre material of 20 mm long, with an external and internal diameter of 25 mm and 12.7 mm respectively at one end, and an external diameter of 19 mm, with thickness of 3 mm and 16 mm bore at the other end. It is used to determine the displacement on the pressure shaft.

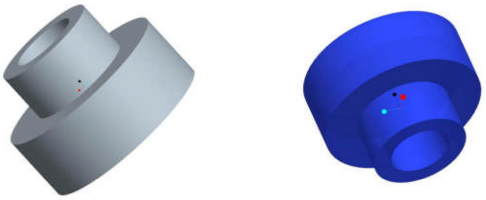
Handle (h): This is a metal pipe of 305 mm long, 21.5 and 17.5 mm external and internal diameters respectively. It is made of high carbon steel and is attached to the pressure shaft. It is the point of application of pressure.

Handle coupling (i): This is made with two short pieces of metal pipe joined normally to each other; with one end threaded to be screwed on to upper end of pressure shaft and the second to hold the handle at the center passing through it.

Spring (j): This is made of 243 mm long and 25.3 mm mean diameter, with 8 mm pitch, 3.3 mm diameter of the wire, and a spring index of 7.77.

The photographs of the completed locally produced proctor type penetrometer as compared to the imported one are shown in Figures 5 and 6 respectively.

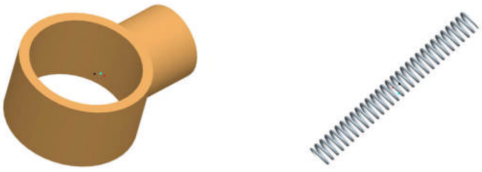
a. Cone probe b. Penetrating shaft



c. Connecting nuts d. Connecting nuts

e. Pressure chamber f. Pressure shaft

g. Knob h. Handle



i. Handle coupling j. Spring

Figure 4 a-j 3D ProE design of components

Figure 5 Locally produced proctor-type penetrometer

Figure 6 Imported proctor-type penetrometer

The cost estimates for the locally produced penetrometer is presented in Table 1. The total cost was five thousand, three hundred and fifty naira only (which is equivalent to thirty-five US Dollars as at the time of this study); and it was found out through the quotation given by an importer that it would cost well above ten times this amount, to import a similar penetrometer.

Table 1 Cost estimations (in Nigerian currency-Naira) for the locally produced penetrometer

S/n	Component	Amount (₦)
1	Penetrating shaft	500
2	Pressure shaft	500
3	Pressure chamber	1 200
4	Spring	850
5	Handle pipe	200
6	Bolt	30
7	Machining some parts at Energy Centre UNN	1 500
8	welding	570
	TOTAL (approx. USD 35)	5 350

4 Calibration, comparative field evaluation and results

The penetrometers were calibrated by applying known forces on the handles and taking corresponding displacements on the pressure shaft, and the results were used to obtain prediction equations. The imported penetrometer (whose operation manuals and other information are not available) has clearly shown lines of calibrations but no unit indicated. Through regression analysis of corresponding readings from both the imported and the locally produced penetrometer, a prediction/conversion equation was developed for each, and the results obtained for both are in the unit of pressure (Pa or MPa). The field test was carried out on a clayey loam soil towards the end of rainy season when the soil moisture content was relatively very low. The area of land used for the *in-situ* test was divided into four plots and each plot was divided into blocks A, B and C as a field lay out to facilitate record taking. The test was performed for twelve randomly selected sample points each day for two days. The effects of soil moisture and land slope were considered constant since the land is almost flat and there was no significant change in soil moisture content during the time of the test. Average CI values at 18 cm depth obtained from the comparative field tests of both penetrometers for a total of twenty-four samples for the two days are presented in Tables 2 and 3. The depth of 18 cm was selected for analysis based on common average ploughing depth which is 18 cm in most parts of Nigeria. Regression analysis and 2-tailed Pearson correlation were carried out on the two sets of data using SPSS version 16 and Microsoft Excel and the results which showed positive relationship with R^2=0.779 (P<0.05) are presented in Tables 4 and 5, and Figure 7. The average values of *in-situ* CI at 18 cm depth for both instruments were computed; and results showed that for the local it was 1.4358 MPa , while that of imported was 1.5096 MPa.

Table 2 Average values of CI at 18 cm depth for first day field tests

Plots	Local/MPa	Imported/MPa
Plot 1		
A	1.58	1.65
B	1.66	1.86
C	1.58	1.74
Plot 2		
A	1.74	1.86
B	1.19	1.02
C	1.47	1.75
Plot 3		
A	1.30	1.39
B	1.71	1.97
C	1.90	2.00
Plot 4		
A	1.35	1.71
B	1.40	1.19
C	0.77	0.85

Table 3 Average values of CI at 18 cm depth for second day field tests

Plots	Local/MPa	Imported/MPa
Plot 1		
A	1.57	1.95
B	1.49	1.37
C	1.44	1.46
Plot 2		
A	1.69	1.88
B	1.43	1.21
C	1.49	1.48
Plot 3		
A	1.40	1.56
B	1.38	1.36
C	0.85	0.61
Plot 4		
A	1.40	1.26
B	1.27	1.42
C	1.40	1.68

Table 4 Correlations

		VAR00001	VAR00002
VAR00001	Pearson Correlation	1	.883**
	Sig. (2-tailed)		0
	N	24	24
VAR00002	Pearson Correlation	.883**	1
	Sig. (2-tailed)	0	
	N	24	24

Note: **. Correlation is significant at the 0.01 level (2-tailed).

Table 5 Model summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	0.883a	0.779	0.769	0.12152	0.779	77.764	1	22	0

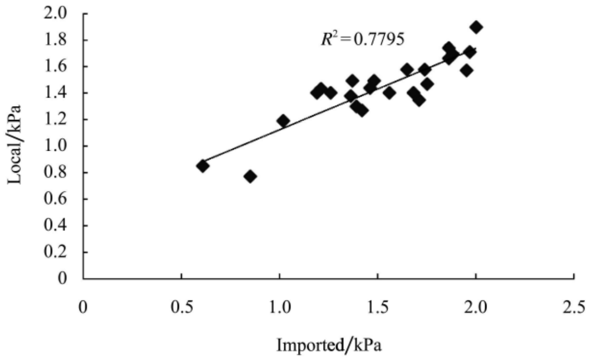


Figure 7 Regression plot of the readings of imported verses local penetrometer

5 Conclusions

The study of soil mechanics is broad and involves many basic physical and engineering concepts such as mechanics of material, dynamics, kinematics and fluid mechanics. These basic concepts help in understanding the mechanical nature of soils and their behavior under applied forces and variable conditions which are requisite knowledge in soil tillage and traction studies. In agricultural soil mechanics, the most relevant soil properties are the reactions of soil to applied forces. These properties are often called strength properties which for a given soil can change with time under the influence of climate, soil management and plant growth. The strength properties of any given soil and their change with time can be determined through the measurement of soil shear strength and penetration resistance whose values depend to a great extent on bulk density and moisture content. Soil penetration resistance is related to the pressure required to form a spherical cavity in the soil, large enough to accommodate the cone of the penetrometer, allowing for the friction resistance between the cones and its surrounding soil. This study in addition to presenting an overview of the instrument called cone penetrometer, its applications and current developments; has demonstrated the possibility of local design and manufacture of proctor-type cone penetrometer which can give comparable and appreciable precision as the imported one. The price has also been proved to be much more economical (more than ten times cheaper), while making the instrument readily available to researchers and teachers in the area of soil tillage and traction studies. The study can also serve as a guide to other researchers and students in developing countries in similar situation like Nigeria, who are involved in soil tillage and traction studies, to develop a proctor cone penetrometer from locally available resources.

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