Comissão 2.2 - Física do solo

IMPROVEMENT OF A TESTING APPARATUS FOR DYNAMOMETRY: PROCEDURES FOR PENETROMETRY AND INFLUENCE OF STRAIN RATE TO QUANTIFY THE TENSILE STRENGTH OF SOIL AGGREGATES[1]

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SUMMARY

Soil penetration resistance (PR) and the tensile strength of aggregates (TS) are commonly used to characterize the physical and structural conditions of agricultural soils. This study aimed to assess the functionality of a dynamometry apparatus by linear speed and position control automation of its mobile base to measure PR and TS. The proposed equipment was used for PR measurement in undisturbed samples of a clayey "Nitossolo Vermelho eutroférrico" (Kandiudalfic Eutrudox) under rubber trees sampled in two positions (within and between rows). These samples were also used to measure the volumetric soil water content and bulk density, and determine the soil resistance to penetration curve (SRPC). The TS was measured in a sandy loam "Latossolo Vermelho distrófico" (LVd) - Typic Haplustox - and in a very clayey "Nitossolo Vermelho distroférrico" (NVdf) - Typic Paleudalf - under different uses: LVd under "annual crops" and "native forest", NVdf under "annual crops" and "eucalyptus plantation" (> 30 years old). To measure TS, different strain rates were applied using two dynamometry testing devices: a reference machine (0.03 mm s^{-1}), which has been widely used in other studies, and the proposed equipment (1.55 mm s^{-1}). The determination coefficient values of the SRPC were high ($R^2 > 0.9$), regardless of the sampling position. Mean TS values in LVd and NVdf obtained with the proposed equipment did not differ

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(p > 0.05) from those of the reference testing apparatus, regardless of land use and soil type. Results indicate that PR and TS can be measured faster and accurately by the proposed procedure.

Index terms: soil compaction, soil physical quality, tensile stress, soil penetration resistance.

RESUMO: *MELHORAMENTO DE UMA MÁQUINA DE ENSAIO PARA DINAMOMETRIA: PROCEDIMENTOS PARA PENETROMETRIA E INFLUÊNCIA DA TAXA DE DEFORMAÇÃO NA QUANTIFICAÇÃO DA RESISTÊNCIA TÊNSIL DE AGREGADOS DE SOLO*

A resistência do solo à penetração (RP) e a resistência tênsil de agregados (RT) são comumente utilizadas para caracterizar a condição estrutural de solos agrícolas. O objetivo deste trabalho foi avaliar a funcionalidade de uma máquina de ensaio para dinamometria mediante a automatização do controle de posição e da velocidade linear de sua base móvel nas medições de RP e de RT. O equipamento proposto foi utilizado na determinação da RP em amostras indeformadas de um Nitossolo Vermelho eutroférrico argiloso sob cultivo de seringueira, considerando duas posições de amostragem (linha e entrelinha). Nessas amostras também foram determinados o teor de água e a densidade do solo, cujos dados foram utilizados para o ajuste da curva de resistência do solo à penetração (CRP). Os valores de RT foram medidos num Latossolo Vermelho distrófico de textura média (LVd) e num Nitossolo Vermelho distroférrico muito argiloso (NVdf) sob distintos sistemas de uso: LVd, sob culturas anuais e mata nativa, e NVdf, sob culturas anuais e mata com eucaliptos há mais de 30 anos. Quanto às determinações de RT, foram utilizadas duas máquinas de ensaio dinamométrico para aplicar distintas taxas de deformação: uma de referência (0,03 mm s^{-1}), já amplamente empregada em outros trabalhos, e o equipamento proposto (1,55 mm s^{-1}). A CRP apresentou elevado valor de coeficiente de determinação (R^2 > 0,9), independentemente da posição de amostragem. Os valores médios de RT do LVd e do NVdf obtidos com o equipamento proposto não diferiram (p > 0,05) daqueles da máquina de ensaio de referência, independentemente do sistema de uso e da classe textural do solo. Os resultados indicam que a RP e a RT podem ser determinadas mais rapidamente e com elevada acurácia utilizando o procedimento proposto.

Termos de indexação: compactação do solo, qualidade física do solo, estresse tênsil, resistência do solo à penetração.

INTRODUCTION

Soil penetration resistance (PR) is often used as soil quality indicator, to characterize compaction and mechanical limitations of root growth (Barber, 1994) as well as the effects of tillage (Busscher et al. 2000) and machinery traffic (Sharratt et al., 1998). Letey (1985) argues that PR is a soil physical property that influences plant growth directly and hence crop yield (Kirkegaard et al. 1995; Beutler et al., 2006). The PR is determined with penetrometers, i.e. an apparatus that measures the force required to penetrate the soil with a cylindrical rod, which usually has a cone-shaped tip with standard dimensions (Bradford, 1986; ASAE, 1999). Thus, the magnitude of PR is related to aspects of the cylindrical rod, such as basal diameter, length and angle of the cone, as well as soil physical properties, e.g., bulk density, shear strength, water content, and clay content (Bradford, 1986; Lowery & Morrison, 2002).

Penetrometers can be classified into: (i) dynamic devices, by which the rod is pushed into the soil through repeated impacts of a metal object with known mass (Schmid, 1966; Stolf, 1991), and (ii) static equipment, where the rod is inserted into the soil by hydraulic or electromechanical mechanisms (Bradford, 1986; Lowery & Morrison, 2002). Static penetrometers can maintain the penetration speed constant, which improves the accuracy of the results (Herrick & Jones, 2002) due to the reduction of systematic errors and, thus, of total variability in PR measurements. To facilitate operation, penetrometers can be coupled to different mechanical structures that make them more portable, to sensors that measure the rod penetration depth and soil water content (Vaz & Hopmans, 2001), and to computerized devices for data acquisition and storage (Bradford, 1986; Lowery & Morrison, 2002). But althouhg the use of these devices makes results more accurate, they increase costs and restrict the applicability.

PR measurements with penetrometers are quick and easy (Bengough & Mullins, 1990), but depend on soil water content and bulk density (Busscher, 1990), which limits their use and interpretation. On the other hand, mathematical equations provide an adequate description of a nonlinear relationship between PR and the cited variables (Busscher, 1990; Busscher et al., 1997), based on which soil resistance to penetration curves (SRPC) can be generated. These curves have been widely used to quantify the soil physical quality (Silva et al. 1994; Tormena et al., 1999, Imhoff et al. 2000; Leão et al., 2006) of undisturbed samples or directly in the field by measuring the PR of a set of soil samples with different water content and bulk density values. Thus, the SRPC includes the effect of different factors related to soil physical degradation, and possibly the establishment of critical values of soil water content and bulk density in which PR limits plant growth (Imhoff et al., 2000).

The tensile strength of soil aggregates (TS) has also been considered an important indicator of soil structural quality. The TS is the force per unit area required to rupture a particular soil aggregate (Dexter & Watts, 2001). It is influenced by factors such as water content and wetting-drying cycles (Utomo & Dexter, 1981; Kay & Dexter, 1992), clay content and mineralogy (Bartoli et al., 1992; Imhoff et al., 2002), dispersible clay content (Shanmuganathan & Oades, 1982), soil organic matter (Causarano, 1993; Perfect et al., 1995; Imhoff et al., 2002), cementing materials, such as silica and poorly crystalline aluminosilicates (Kay & Dexter, 1992; Kay & Angers, 1999), and chemical composition and concentration of soil solution (Rahimi et al., 2000). Thus, TS is a soil structure property sensitive to effects of land use and management systems (Watts & Dexter, 1997; Schjønning & Munkholm, 2004; Canqui-Blanco et al., 2005; Tormena et al., 2008).

The TS measurements can be obtained in direct and indirect tests (Dexter & Kroesbergen, 1985). Direct tests consist of the application of forces of equal magnitude and opposite directions to either end of a soil aggregate to break it into two parts. In the indirect tests, a compressive force is applied along the polar diameter of a soil aggregate by two flat parallel plates, one fixed and the other mobile. The linear displacement of the mobile plate provides successive increases of the internal tensile stress of the soil aggregate. Theoretically, the maximum value of this tensile stress occurs in the central vertical plane of the soil aggregate. Thus, a crack appears in the center of the soil aggregate, breaking it into smaller units (and larger TS) when the internal tensile stress exceeds the tensile strength of soil aggregates (forces of equal magnitude, perpendicular to each other). The TS is often determined by the indirect method, using mobile plates with extremely low linear displacement speed, which is an arduous and time-consuming procedure.

There must be a steady increment of the internal tensile stress on soil aggregates (Dexter & Kroesbergen, 1985; Dexter & Watts, 2001) in TS measurements. For this purpose, in indirect tests, the displacement rate of the mobile plate must be kept constant during the compression of individual soil aggregates. In this context, Dexter & Kroesbergen (1985) recommended to increase the load until soil aggregate failure occurs in about 100 s. However, this is quite uncertain since the shape and dimensions of soil aggregates of a given sample set are not identical. Dexter & Watts (2001) reported that different loading rates on soil aggregate may affect TS results. These authors recommended a constant strain rate of 0.07 mm s^{-1}, and suggested the possibility of using different values. Currently, many studies have been conducted at a constant strain rate of individual soil aggregates of 0.03 mm s^{-1}, as indicated by Imhoff et al. (2002). Therefore, more detailed studies are needed to clarify the effects of different loading (or strain) rates in TS measurements.

The purposes of this study were to: (i) evaluate the functionality of a low-cost and portable dynamometry testing apparatus for measuring PR under laboratory conditions; (ii) model the PR data, obtained at a constant cone penetration rate of 1.55 mm s^{-1}, using the equation proposed by Busscher (1990) and compare the fitted model coefficients to those obtained in other studies; and (iii) assess the feasibility of the proposed equipment to measure tensile strength of soil aggregates at a constant strain rate of 1.55 mm s^{-1}, to test the hypothesis that TS results did not differ from those obtained at a constant strain rate of 0.03 mm s^{-1} with the reference testing apparatus (control). The confirmation of this hypothesis would mean that TS can be measured faster and accurately by the proposed procedure.

MATERIAL AND METHODS

Dynamometry testing apparatus

The proposed equipment is originally marketed as a manual testing apparatus for dynamometry (Lutron FS-1001™). It has a mobile base (Figure 1e), which is driven by a crank. In this study, however, this base was driven by an electric BOSCH™ motor - CEP 12 V (with two speed options). This motor was preferred because of its easy availability and low weight and size, appropriate for a portable, lightweight equipment. During preliminary tests, the original structure of this motor was modified, by isolating the internal electrical circuit from its case, to ensure safe operation.

After installing the electric motor, the manual machine was automated by an electronic module that was developed to control the motor's direction and rotation speed as well as the mobile base displacement to reduce (or even eliminate) user interference in measurements of the proposed equipment. The electronic module is basically composed of transistors and power relays, with the following characteristics:

Power supply - the electric motor and automatic control module are operated at low voltage (12 Volts DC power supply). Alternatively, this module can

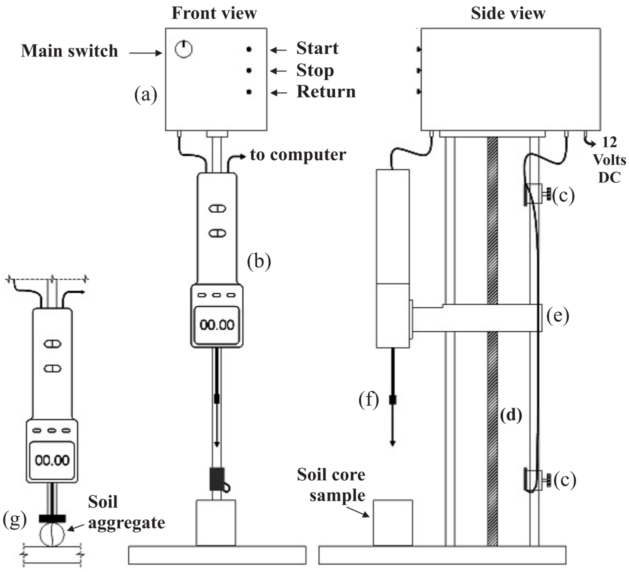

Figure 1. Construction details of the dynamometry testing apparatus (proposed equipment): (a) electric motor case - automatic control module and command keys, (b) electronic dynamometer – 20 kgf capacity, (c) sensors - limit switches, (d) lead screw with a metric thread pitch of 2 mm, (e) mobile base, (f) cylindrical rod with a cone-shaped tip used in penetrometry studies and (g) cylindrical rod with a flat plate to measure tensile strength of soil aggregates.

provide the dynamometer with stabilized voltage of 9 Volts DC (Figure 1b);

Command keys (Figure 1a) - the "START", "RETURN", and "STOP" keys correspond to the commands used to control displacement of the mobile base, which contains the dynamometer. Thus, when the user briefly presses a specific key, the previously selected command will be activated and keep running. The "START" command initiates the dynamometer's vertical downward motion. Optionally, this motion is instantly reversed when the "RETURN" command is activated by the user. Considering the rotation speed options of the electric motor, the mobile base speed varies between 1.55 and 2.00 mm s^{-1} for the descent and ascent, respectively, and its motion can be manually interrupted by the "STOP" command;

Process control aided by position sensors (Figure 1c) - these sensors (limit switches) have functions similar to those of the "RETURN" and "STOP" commands, making it possible to automatically reverse the downward motion when the bottom sensor is activated by the mobile base, or to stop the upward motion when the upper sensor is triggered. Thus, the maximum displacement of the mobile base is determined by adjusting the position of the limit switches according to the height of the soil sample used for testing;

Memory function - if the "STOP" command is activated, the same direction of movement of the mobile base used immediately before the interruption of the process will be resumed when the user restarts the equipment.

To check the capacity of the electric motor to supply the requirements of the equipment, the maximum axial force transmitted through the lead screw (Figure 1d), which moves the mobile base and the dynamometer, was calculated. According to Budynas & Nisbett (2007), equation (1) estimates the torque required to move a given load by a metric-thread lead screw (similar to the one in this study):

$$T = \frac{F\,dm}{2}\left(\frac{L + \pi\, f\, dm \sec\alpha}{\pi\, dm - f\, L \sec\alpha}\right) + \frac{F\, fc\, dc}{2} \qquad (1)$$

where T is motor torque (Nm); F is the maximum axial force (kN) generated by the lead screw/motor the lead screw thread assembly; dm is the mean lead screw diameter (mm); L the axial displacement (mm) resulting from one rotation of the lead screw; f the friction coefficient on the surface of the lead screw thread; α the flank angle of the thread (º); fc is the thrust collar friction coefficient; and dc the mean thrust collar friction diameter (mm).

Then, equation (1) can be rearranged to express the maximum force applied against a body:

$$F = 2T\left[dm\left(\frac{L + \pi\, f\, dm \sec\alpha}{\pi\, dm - f\, L \sec\alpha}\right) + fc\, dc\right]^{-1} \qquad (2)$$

Soil penetration resistance

The proposed equipment was used for measuring the PR of a "Nitossolo Vermelho eutroférrico" (Embrapa, 2006) - Kandiudalfic Eutrudox (Soil Survey Staff, 2010) - of clayey texture (480 g kg^{-1} clay, 300 g kg^{-1} sand) under rubber trees at the "Luiz de Queiroz" College of Agriculture, São Paulo State - Brazil. The experimental plot consisted of a 14 x 30 m area within the stand. Sixty-six undisturbed soil samples were randomly collected from within and between tree rows in the center of the 0–10 cm layer using volumetric rings (diameter and height 5 cm). In the laboratory, each sample was adjusted to the ring volume, and a nylon screen was fixed at the ring bottom. Immediately afterwards, the samples were saturated (by capillarity) with deionized water for 48 h. Then, the top of each sample was covered with paper and air-dried (slowly, with free drainage) to obtain different levels of water contents between samples. As the samples dried, groups with three replicates per sampling position were selected, and then each sample was coated with PVC film and stored under refrigeration (5 °C for 30 d) to allow internal water redistribution.

Before initiating the tests, the samples were individually weighed (precision 0.01 g). Subsequently, a cylindrical steel rod was coupled to the dynamometer and its cone-shaped tip (60 º angle and 0.4 cm basal diameter) was vertically inserted to a 4.5 cm depth from the upper surface of each soil sample, at a constant rate of 1.55 mm s^{-1}. The cone penetration depth was controlled by adjusted limit switches. When the steel cone was completely inserted into the soil sample, the measured force (kgf) data was transferred to the computer using a program supplied by the dynamometer manufacturer (communication protocol RS-232). The data acquisition frequency was 1 Hz, resulting in 29 measurements per soil sample. Later, in a spreadsheet, each force measurement was related to its depth in the sample, calculated by multiplying the steel rod displacement rate by the elapsed time. Excluding the force measurements at the borders, equivalent to 0.95 cm (top and bottom, respectively), a layer of 3.1 cm of each soil sample was used for PR determination. The average force value obtained in each sample was converted to pressure:

$$PR = \frac{Fg}{A\,10^6} \qquad (3)$$

where PR is expressed in MPa, F is the measured force (kgf), g the acceleration due to gravity (m s^{-2}) and A the basal area of the cone (m^2).

At the end of the trial, the gravimetric soil water content was determined by the ratio between the masses of water and dry soil, and soil bulk density (BD) was obtained by the core method (Blake & Hartge, 1986). The volumetric soil water content (θ) was obtained from the product of gravimetric soil water content and BD.

Tensile strength of soil aggregates

Two devices were used to evaluate the effect of compression speed on TS measurements: the proposed equipment and a reference testing apparatus (Imhoff et al., 2002), already used in other studies. For this purpose, soil blocks (undisturbed samples) were collected at a depth of 0–20 cm from two soils: a "Latossolo Vermelho distrófico" (LVd) (Embrapa, 2006) - Typic Haplortox (Soil Survey Staff, 2010) - with sandy loam texture, under "native forest" and "annual crops", from the Experimental Farm of the State University of Maringá (UEM), Paraná State - Brazil, and a "Nitossolo Vermelho distroférrico" (NVdf) (Embrapa, 2006) - Typic Paleudalf (Soil Survey Staff, 2010) - with very clayey texture, under "eucalyptus plantation" (> 30 y.o.) and "annual crops", from the experimental area of the Technical Center of Irrigation of the UEM (Table 1).

One undisturbed soil block (width, length and height 0.20 x 0.20 x 0.10 m, respectively) was randomly collected per experimental plot. These blocks were covered with PVC film, stored in coolers and transported to the laboratory. Afterwards, the blocks were manually broken up into their natural aggregates by applying minimal force required to separate them at their points of weakness. The individual soil aggregate diameter was classified with two sieves, through meshes of 19.0 and 12.7 mm (Imhoff et al., 2002). For final drying and homogenization of the water content, these aggregates were air-dried for 36 h, then oven-dried at 60 ºC for 24 h, and finally stored in paper bags until the tensile strength test. Altogether, 400 soil aggregates were used, with 50 replicates per treatment.

Table 1. Characterization of particle size distribution(1) and organic carbon content(2) at 0–20 cm soil depth used to evaluate the aggregate tensile strength

Land use	Clay	Silt	Sand	OC
	g kg^{-1}			g dm^{-3}
"Latossolo Vermelho distrófico" (Typic Haplortox)				
Native Forest	190	20	790	11,3
Annual crops	200	30	770	7,9
"Nitossolo Vermelho distroférrico" (Typic Paleudalf)				
Eucalyptus plantation (> 30 y.o.)	735	90	175	23,6
Annual crops	735	90	175	14,7

(1) Clay, < 2 µm; silt, 2–50 µm; sand, 50–2000 µm (Gee & Or, 2002). (2) Organic carbon (OC), according to Embrapa (1997).

Each soil aggregate was previously weighed and then subjected to an indirect tension test. In both testing apparatuses, the soil aggregates were individually placed in the most stable position between two parallel flat plates: one lower plate fixed to the machine base, and an upper mobile plate coupled to a load cell with 20 kgf capacity. In the proposed equipment, the force required to break each soil aggregate was measured with the dynamometer operating in "peak and hold" mode, where the maximum force exerted is frozen immediately before breaking up the soil aggregate. In the reference testing apparatus, a computer was used for data acquisition and selection of the maximum force required to break each soil aggregate. This machine is described in more detail by Imhoff et al. (2002). It basically consists of an electromechanical linear actuator (designed for high-precision positioning) that moves a load cell (type "S", 20 kgf capacity) at a constant strain rate of 0.03 mm s^{-1}. All measurements of maximum force (kgf) were recorded and used in TS calculations. For approximately every 1/3 of the total number of samples (per treatment) used in the test, the soil aggregates were weighed on a digital analytical balance and subsequently oven-dried at 105 ºC for 48 h for mean residual water content determination. The TS was calculated as described by Kroesbergen & Dexter (1985):

$$TS = \frac{0{,}576(P)}{D^2\,10^3} \qquad (4)$$

where TS is expressed in kPa, 0.576 is the proportionality constant, P the applied force at tensile failure (N) and D the effective diameter of each soil aggregate (m).

The effective diameter of each soil aggregate was calculated by the equation (Dexter & Kroesbergen, 1985):

$$D = D_m\left(\frac{M}{M_0}\right)^{0,333} \quad (5)$$

where D_m is the mean diameter of soil aggregates (m), defined as the arithmetic mean of the sieve mesh sizes used to select them, M is the dry mass of an individual soil aggregate (g) and M_o the mean dry mass of soil aggregates per treatment (g).

Statistical analysis

The PR, θ and BD data, from within and between rows, were used in nonlinear model fitting to estimate the soil resistance to penetration curve (SRPC), by the equation (Busscher, 1990):

$$PR = a\theta^b BD^c \quad (6)$$

where PR is expressed in MPa, θ is the volumetric soil water content (m^3 m^{-3}), BD is expressed in Mg m^{-3}, *a*, *b* and *c* are the coefficients of the fitted model.

The Kolmogorov-Smirnov test was used to assess normality of distribution of residuals from the nonlinear regression analyses to generate the SRPC.

The tensile strength of soil aggregate was measured in an experiment conducted in a completely randomized design in a 2 x 2 x 2 factorial scheme, consisting of two soil types (sandy loam and very clayey texture), two land uses (forest and annual crops) and two apparatuses, a reference testing apparatus (Imhoff et al., 2002) and the proposed equipment. Analyses of variance for independent samples were performed to detect differences between treatments, in which the Kolmogorov-Smirnov test was applied to assess residual distribution normality.

In order to quantify the proposed equipment's performance, graphs and linear regression analyses were also used. Additionally, robust statistical techniques were used for the quantification of experimental errors (Zacharias et al., 1996; Mesquita et al., 2002), i.e. techniques that do not require normal data distribution, except for equations (13) and (14) (Table 2). These two equations require estimates of the dependent variable, and thus the Kolmogorov-Smirnov test was applied to assess whether the residuals of the linear regressions were normally

Table 2. Additional statistical indexes used to evaluate the performance of the proposed equipment

Description	Equation(1)	Number
Agreement index (Legates & McCabe, 1999):	$d = 1 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(\lvert P_i - \bar{O}\rvert + \lvert O_i - \bar{O}\rvert)^2}$	(7)
Deviation ratio (Loague & Green, 1991):	$DR = \frac{\sum_{i=1}^{N}(O_i - \bar{O})^2}{\sum_{i=1}^{N}(P_i - \bar{O})^2}$	(8)
Efficiency coefficient (Legates & McCabe, 1999):	$EF = 1 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i - \bar{O})^2}$	(9)
Mean absolute error (Willmott et al., 1985):	$MAE = N^{-1}\sum_{i=1}^{N}\lvert O_i - P_i\rvert$	(10)
Maximum error (Loague & Green, 1991):	$ME = \max(\lvert O_i - P_i\rvert)_{i=1}^{N}$	(11)
Square root of the normalized quadratic mean error (Loague & Green, 1991):	$RMSE = \left[N^{-1}\sum_{i=1}^{N}(O_i - P_i)^2\right]^{0,5}\left(\frac{100}{\bar{O}}\right)$	(12)
Unsystematic (RMSEu) and systematic (RMSEs) components of the normalized total error (Legates & McCabe, 1999):	$RMSEu = \left[N^{-1}\sum_{i=1}^{N}(\hat{P}_i - P_i)^2\right]^{0,5}\left(\frac{100}{\bar{O}}\right)$	(13)
	$RMSEs = \left[N^{-1}\sum_{i=1}^{N}(\hat{P}_i - O_i)^2\right]^{0,5}\left(\frac{100}{\bar{O}}\right)$	(14)
Coefficient of residual mass (Loague & Green, 1991):	$CRM = \frac{\sum_{i=1}^{N}O_i - \sum_{i=1}^{N}P_i}{\sum_{i=1}^{N}O_i}$	(15)

*: $\bar{O} = N^{-1}\sum_{i=1}^{N}O_i$; O_i e P_i corresponds to the soil mechanical strength data; $\hat{P}_i$ is estimate of the dependent variable (Willmott et al., 1985), which is calculated from the intercept (a) and slope (b) of a least-squares regression, $\hat{P}_i = a + bO_i$; N is number of experimental observations.

distributed or not, to allow the determination of systematic and unsystematic experimental errors.

Considering the statistical indexes in table 2, of the PR study, O_i are the measured data using the proposed equipment and P_i the predicted data from the nonlinear model (Busscher, 1990). In the TS study, O_i are the measured data using the reference testing apparatus, and P_i the data measured obtained with the proposed equipment.

RESULTS AND DISCUSSION

Constructive aspects of the proposed equipment

Considering the motor nominal torque (6.5 Nm, according to the manufacturer's specifications) and other aspects of the proposed equipment, such as dm (14.7 mm), L (2.0 mm), dc (15.0 mm), f and fc (0.15) and α (30º), the maximum force the lead screw (Figure 1d) can exert during the downward movement of the mobile base, calculated by eq. (2), is approximately 2.38 kN (243 kgf). For this study, the force required is ≤ 20 kgf and represents up to 8.2 % of the maximum load generated by the lead screw/motor assembly, i.e., the dynamometer displacement rate will probably not vary significantly during PR and TS measurements. This was verified in preliminary cone penetration tests (basal diameter of 0.4 cm) in undisturbed soil samples (diameter and height 5 cm). For each sample, the cone penetration force (average value at 0–4.5 cm depth) was calculated. Also, in order to obtain values under no-load conditions, the test was conducted without a sample. The resulting data set of cone penetration force values varied between 0 and 20 kgf, which confirmed that the motor used in the proposed equipment maintained a constant displacement rate of the mobile base. By relating cone area and range of measured force, it is clear that the proposed equipment covers the range of values commonly found in evaluations of soil penetration resistance, including critical values for plant growth (Taylor et al., 1966; Ehlers et al., 1983; Tormena et al., 1998). Alternatively, the equipment can also be used for TS measurements by replacing the rod with a cone-shaped tip (Figure 1f) by one with a flat metal plate (Figure 1g) (Imhoff et al., 2002).

The "START", "STOP", and "RETURN" keys allow a user-friendly (automatic or manual) control of the vertical mobile base and dynamometer movement, and also for an immediate shutdown of the equipment in emergencies. Sensors, called limit switches, control the mobile base displacement and can also be adjusted to vertical distances, ranging from 0 to 30 cm, above the machine base surface. This setting is important in PR measurements because with just a tap of the "START" key, it is possible to automatically and accurately penetrate to a desired depth from the top of each soil sample with the cone-shaped rod tip. Also, in TS measurements, a satisfactory control over the compressive force on soil aggregates is possible. For example, for each soil aggregate, the user should first briefly press the "START" key, and once sample tensile failure has occurred, immediately tap the "RETURN" key. The use of manual control to determine the tensile strength of soil aggregates is necessary due to varied diameters in samples, i.e. in this case, the limit switch sensors were used only as a safety precaution by limiting the mobile base displacement to a lowest position (≈ 0.5 cm above the machine base surface) and highest position (≈ 1 cm above the soil aggregate) to avoid damage to the proposed equipment.

Soil Resistance to Penetration

The proposed equipment was used to measure soil penetration resistance in undisturbed samples of a "Nitossolo Vermelho eutroférrico" (NVef), at a constant cone penetration rate of 1.55 mm s^{-1}. However, it should also be emphasized that the range of penetration rates recommended for penetrometer operations is wide. This fact can be explained by the complex interactions between cone speed and penetration force, where a small increase in the cone penetration rate can cause positive, negative, or zero influence on soil penetration resistance measurements. This is due, e.g. to changes in soil water potential generated by cone penetration, as well as its dissipation rate, and also dilatancy properties of a particular soil (Bradford, 1986). In this context, Lowery & Morrison (2002) argue that constant cone penetration rates of less than 8.3 mm s^{-1} are common under laboratory conditions, and satisfactory in the field (Lowery, 1986; Larney et al., 1989). Since the vertical displacement rate of the cone reached only 18.7 % of the maximum value suggested by Lowery and Morrison (2002), and in view of other characteristics, such as cone tip and sampling ring geometry, which were similar to those in other studies (Tormena et al., 1999; Imhoff et al. 2001; Serafim et al., 2008), it is possible to affirm that the obtained PR results are representative of soil structural conditions of the evaluated samples.

The variability degree of soil physical properties (Table 3) can be analyzed from the coefficient of variation (CV), based on the classification proposed by Warrick & Nielsen (1980), with the limits CV < 12 %, 12 ≤ CV < 52 %, and CV ≥ 52 %, for soil properties with low, medium, and high variability, respectively. In both sample positions, variability for BD and θ was classified as low and medium, respectively, according to Warrick & Nielsen (1980) and other authors (Silva et al., 1994; Tormena et al., 1999; Silva et al., 2008). Therefore, the high coefficient of variation values in PR were justified by measurements performed under a wide range of θ and BD conditions.

Considering BD, the similarity of maximum and minimum values within and between rows, respectively, is noteworthy (Table 3). For θ values, the range within was higher than between rows. These results can be explained by the effect of machinery traffic on the experimental area, which resulted in different degrees of soil compaction. Compaction alters the original soil structure due to the rearrangement of aggregates in the matrix and causes air expulsion, reducing the total pore space (Gupta & Allmaras, 1987) by the transformation of larger diameter pores to smaller ones (Dexter, 2004; Zhang et al., 2006). This causes an increment of BD (Gupta et al., 1989; Hill, 1990, Hakansson & Voorhees, 1998) and raises capillary forces that influence water retention (Zhang et al., 2006), resulting in a narrower range of θ and BD in-between crop rows.

In general, PR should not be interpreted separately, i.e. without considering other physical properties, such as BD and θ (Busscher, 1990), although in the literature there are indications that PR evaluations can be carried out under an arbitrary θ condition, as equivalent to field capacity (Henderson, 1989; Arshad et al., 1996). Therefore, in this study, for a better assessment of the efficiency of the proposed equipment in differentiating the soil compaction degree between treatments, soil resistance to penetration curves (SRPC) were generated, defined by a nonlinear relationship between PR, BD and θ (Table 4). Initially, the normal distribution of SRPC residuals was confirmed by applying the Kolmogorov-Smirnov test.

The fitted model explained 92 and 93 % of PR variability within and between rows, respectively. The fitting coefficients *a*, *b*, and *c* of the nonlinear regression were highly significant (Table 4) with similar magnitudes as in other studies (Leão et al., 2006; Silva et al., 2008). These coefficients showed that PR varied positively with BD and negatively with θ, in agreement with results obtained by several authors (Taylor et al., 1966; Tormena et al., 1999; Silva et al., 2008) and confirmed the expected influence on PR by these physical properties (Busscher, 1990). The increase in PR with decreasing θ is due to an increase in effective stress (Snyder & Miller, 1985), which is positively intensified by BD due to the increased cohesion and friction forces between soil

Table 3. Statistical indexes[(1)] for the soil physical attributes[(2)] determined in undisturbed samples of a "Nitossolo Vermelho eutroférrico" (or Kandiudalfic Eutrudox) from different sampling positions under rubber trees. N = 33

Soil attribute	Value		Mean	SD	CV
	Minimum	Maximum			
		In crop rows			
PR	0.395	3.331	1.371	0.781	56.9
BD	1.173	1.478	1.317	0.073	5.5
θ	0.199	0.472	0.354	0.067	18.8
		In-between crop rows			
PR	1.100	6.596	2.784	1.345	48.3
BD	1.454	1.632	1.546	0.048	3.1
θ	0.252	0.420	0.348	0.041	11.8

[(1)] SD, standard deviation; CV, coefficient of variation (%). [(2)] PR, soil penetration resistance (MPa); BD, soil bulk density (Mg m^{-3}); θ, soil water content (m^3 m^{-3}).

Table 4. Fitting parameters of the soil resistance to penetration curve ($PR = a\theta^b BD^c$) for different sampling positions under rubber trees. PR: soil penetration resistance; θ: soil water content; BD: soil bulk density. N = 33

Parameter	Estimate	Standard deviation	t[(1)]	Pr > | t |[(2)]
		In crop rows		
a	0.0297	0.0079	3.744	< 0.0008
b	-2.2334	0.1272	-17.563	$< 2.0\ 10^{-16}$
c	4.8374	0.5442	8.890	$6.58\ 10^{-10}$
		In-between crop rows		
a	0.0046	0.0020	2.282	0.0297
b	-3.6649	0.1889	-19.398	$< 2.0\ 10^{16}$
c	5.5394	0.7228	7.664	$1.51\ 10^{-8}$

[(1)] Student's *t*-test value. [(2)] p-value of *t*-statistic.

particles (Vepraskas, 1984). This confirms the structural differences observed between the soil samples due to machinery traffic within the experimental area.

Generally, PR values of ≥ 2 MPa have been considered critical to plant growth (Taylor et al., 1966; Ehlers et al., 1983; Silva et al., 1994), except for some crops with growth restrictions at lower PR values (Bengough & Mullins, 1990). Notably, the occurrence of critical PR values depends on soil conditions in terms of θ and BD. Thus, θ variation governs BD values where PR allows soil root penetration. For NVef, these data were used in nonlinear model fitting to estimate distinct θ ranges that are less restrictive to plant growth (Figure 2). It can be observed that BD had a great impact on PR = 2 MPa values, whose magnitude also depended on soil drying. Thus, in the crop rows, where the lowest BD values indicate decreased cohesion and friction forces between soil particles (Vepraskas, 1984), there will be less physical constraints for plant growth with more soil drying than in-between crop rows. Due to this wide variability in BD values, in which PR = 2 MPa, these results agree with findings by Letey (1985) that this physical property influences plant growth indirectly, and should therefore not be used alone to evaluate the effect of management practices on physical soil quality.

Although the determination coefficient values of the SRPC were satisfactory ($R^2 \geq 92$ %) in both treatments, the interpretation of this index is limited, in view of its insensitivity to the size difference between a reference value (control) and a value obtained by

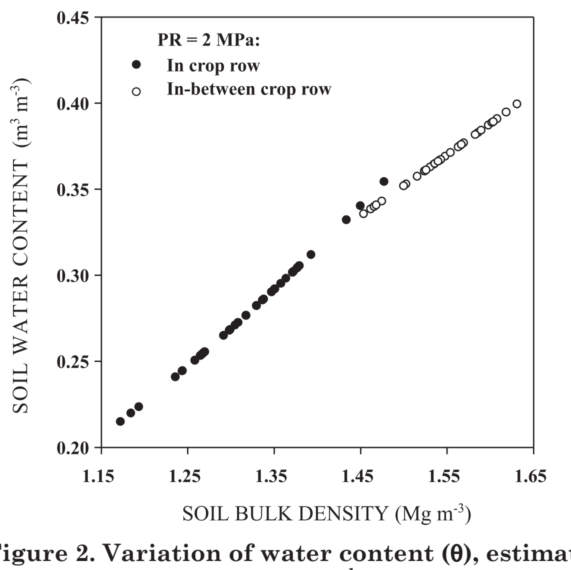

Figure 2. Variation of water content (θ), estimated using the equation $PR = a\theta^b BD^c$ (Busscher, 1990), for the soil bulk density (BD) levels where soil penetration resistance (PR) is equal to 2 MPa at different sampling positions of a "Nitossolo Vermelho eutroférrico" (or Kandiudalfic Eutrudox) under rubber trees. N = 33

other methods (Willmott & Wicks, 1980; Legates & McCabe, 1999), as with SRPC equations proposed by Busscher (1990). Given the possible fragility of R^2 to generate more detailed conclusions about effects of the cone penetration rate on experimental results of the proposed equipment, graphic displays (Figures 3a,b) and other statistical indexes (Table 5) were used, which together serve to evaluate the quality of different settings of the equation of Busscher (1990) to estimate PR. This equation was chosen since it is widely used in other studies (Silva et al., 1994; Imhoff et al., 2000; Leão et al., 2006; Silva et al., 2008) and obtained excellent results. As mentioned, it is expected that a cone penetration rate of 1.55 mm s^{-1} should produce PR values that are representative of soil structural conditions as a function of BD and θ. Thus, if the adjustment degree between the observed and predicted (modeled) PR data is adequate, the statistical indexes should provide a close relationship to: R^2 = d = DR = EF = 1 and ME = MAE = RMSE = RMSEu = RMSEs = CRM = 0 (see Table 1 for abbreviations). The Kolmogorov-Smirnov test showed that linear regression residues between the observed and predicted PR data were normally distributed, which allowed determinations of RMSEu and RMSEs.

In both sampling positions, considering PR variation only as a function of θ, the R^2 values of the fitted model were lower than those of the d index (Table 5), indicating that part of the PR data variability is probably due to other factors. This was confirmed by fitting the PR model in relation to θ and BD, resulting in higher and closer R^2 and d values. The d index, which reflects the homogeneity of dispersion of the experimental data in relation to the 1:1 line (Figures 3a,b), showed satisfactory accuracy of PR measurements (d > 0.90) for both adjustments to the equation proposed by Busscher (1990). Moreover, although PR measurement accuracy had been acceptable, the total variability proportion of the observed (measured) data explained by the predicted was quite close to the ideal condition (DR = 1) only when the effects of θ and BD were included in the SRPC. Similarly, EF values indicated that the most efficient model was PR (θ, BD), suggesting that their predicted PR data averages are more consistent and closer to those obtained by the observed PR data, although EF values above 0.7 are also considered statistically adequate.

The other statistical indexes complement the evaluation of θ and BD effects on PR. The absolute magnitudes of ME, MAE, CRM, RMSE, RMSEu, and RMSEs indexes decreased from PR(θ) towards PR(θ, BD), in other words, the PR predictions were improved by reduction of the experimental error, especially systematic errors (CRM and RMSEs). This confirms that θ and BD were the main factors influencing the PR values in both sampling positions, since there was no variation in soil composition used in this study. These results agree with arguments of several authors on the influence of these physical properties on PR

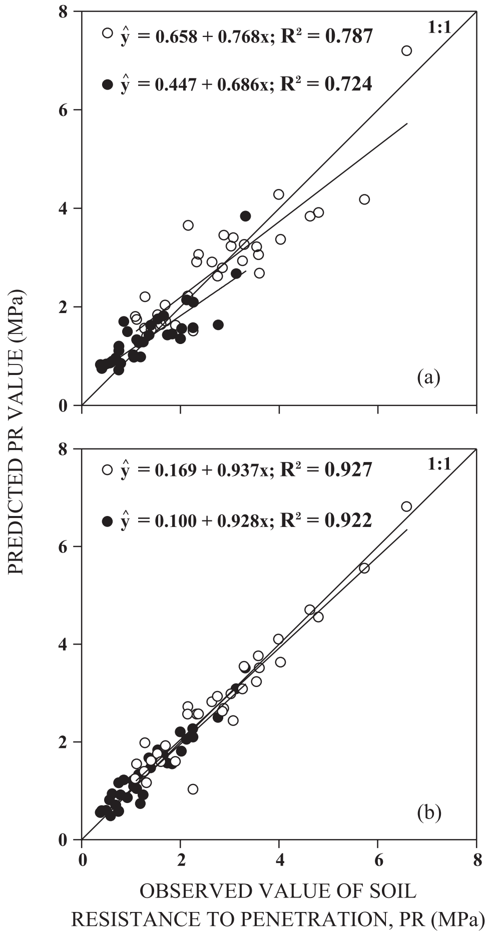

Figure 3. Linear regressions between observed data of soil penetration resistance (PR), measured by the proposed equipment, and predicted PR data from the models PR = $a\theta^b$ (graph a) and PR = $a\theta^b BD^c$ (graph b) for different sampling positions under rubber trees: in crop row (●) and in-between rows (○). θ: soil water content; BD: soil bulk density. N = 33

(Camp & Lund, 1968; Campbell & O'Sullivan, 1991; Pabin et al., 1998). Thus, it can be stated that the proposed equipment was both sensitive to changes in soil moisture and structural conditions. Therefore, it can be inferred that PR measurements at a constant cone penetration rate of 1.55 mm s^{-1} produce reliable results and are suitable for soil compaction quantification.

Aggregate tensile strength

Given the lack of pre-established values related to the speed at which a soil aggregate is compressed until tensile failure, the chosen treatments in this study included different soil particle size distributions and different land uses in order to obtain a wide variation of soil structural conditions and physical properties that affect the tensile strength of soil aggregates (TS), such as clay and organic carbon contents (Dexter & Watts, 2001; Imhoff et al., 2002). This was important to enable the identification of possible TS value ranges that would be more sensitively detected by testing apparatuses according to the displacement speed of the mobile device used in soil aggregate compression. The water content averages of "Latossolo Vermelho distrófico" (LVd) at aggregate tensile failure were 0.003 and 0.002 kg kg^{-1} in soils under "native forest" and "annual crop", respectively. On the other hand, for "Nitossolo Vermelho distroférrico" (NVdf), the water content averages were 0.049 and 0.028 kg kg^{-1} in soils under "eucalyptus plantation" and "annual crop", respectively. These differences in soil water content of similar soil types are most likely related to higher levels of organic carbon content in soils under "native forest" or "eucalyptus plantation" (Table 1). However, these experimental conditions were maintained during TS measurements to allow a performance comparison of the proposed equipment with the reference testing apparatus.

Table 5. Statistical indexes[1] to compare the observed data of soil penetration resistance (PR), measured by the proposed equipment and the predicted PR data from the models PR = $a\theta^b$ and PR = $a\theta^b BD^c$ for different sampling positions under rubber trees. θ: soil water content; BD: soil bulk density. N = 33

Sampling position	Statistical index									
	R^2	d	DR	EF	MAE	ME	CRM	RMSE	RMSEu	RMSEs
					PR = $a\theta^b$					
In crop row	0.724	0.909	1.540	0.722	0.316	1.162	-0.011	29.58	23.73	17.67
In-between rows	0.787	0.936	1.335	0.787	0.474	1.578	-0.004	21.97	18.99	11.05
					PR = $a\theta^b BD^c$					
In crop row	0.922	0.980	1.072	0.922	0.180	0.485	0.002	15.63	15.09	4.06
In-between rows	0.927	0.981	1.056	0.927	0.271	1.258	0.002	12.85	12.49	3.00

[1] R^2, determination coefficient; d, agreement index; DR, deviation ratio; EF, efficiency coefficient; MAE, mean absolute error; ME, maximum error; RMSE, square root of the normalized quadratic mean error; RMSEu, unsystematic component of the normalized total error; RMSEs, systematic component of the normalized total error; CRM, coefficient of residual mass. MAE and ME have the same unit as the respective soil property; RMSE, RMSEu and RMSEs in percentage units. The other statistical indexes are dimensionless.

Considering both soil types, the difference between the minimum and maximum values showed similar results of the testing apparatuses, i.e. there was lower amplitude of TS values in LVd than of NVdf (Table 6). These results also indicate great variability in the experimental data, which has been reported to be related to the soil aggregate shape (Imhoff et al., 2002), which ranged from spherical to prismatic in this study. The values of coefficient of variation (CV) of TS data were similar between testing apparatuses, where the CV values were observed to be closest to the LVd land uses in comparison to NVdf. These observations reflect the equality degree between the performance of the two testing apparatuses. In general, the higher CV values for soils under "native forests" or "eucalyptus plantations" may be due to the higher number of wetting-drying cycles, which can improve the soil microstructure and generate heterogeneous areas of low-resistant within soil aggregates (Kay & Dexter, 1992) and increase the shape variability, as observed in the TS measurements. Moreover, changes in soil aggregate structure caused by machinery traffic are consistent with the lower TS variability observed in soils under "annual crops" (Tormena et al., 2008).

The difference between the mean and median TS values was more pronounced for some treatments (Table 6). This indicates that not all experimental observations were symmetrically distributed around these statistical indexes, which probably requires prior data transformation so that results can be analyzed and interpreted correctly (Mesquita et al., 2002). The Kolmogorov-Smirnov test was applied to verify normal residual distribution of variance analysis, where the need for logarithmic data transformation to stabilize the treatment variances and tailor them to parametric statistical tests was confirmed (McIntyre & Tanner, 1959; Logsdon & Jaynes, 1996; Mesquita et al., 2002).

Variance analysis indicated that TS measurements were not influenced by the testing apparatus ($F = 0.23$, $p > 0.63$) and statistical interactions involving this factor were not significant ($p > 0.05$) (Table 7). This shows that the strain rate of 1.55 mm s^{-1}, used for soil aggregate tensile failure, does not produce different

Table 6. Statistical indexes[1] of aggregate tensile strength for the factors soil type[2], land use and testing apparatus[3]. N = 50

Soil type	Land use	Value		Median	Mean	SD	CV
		Minimum	Maximum				
		kPa					%
		Reference testing apparatus (control)					
LVd	Native forest	22.06	145.56	49.57	52.90	24.08	45.52
LVd	Annual crops	18.44	93,36	54.58	55.09	21.01	38.14
NVdf	Eucalyptus plantation (> 30 y.o.)	24.00	308.03	97.92	117.88	70.09	59.46
NVdf	Annual crops	58.16	407.27	185.24	195.18	78.17	40.05
		Proposed equipment					
LVd	Native forest	21.44	99.47	45.87	48.29	16.37	33.91
LVd	Annual crops	18.37	118.10	54.30	53.02	21.55	40.64
NVdf	Eucalyptus plantation (> 30 y.o.)	11.61	561.56	141.59	157.02	104.00	66.23
NVdf	Annual crops	70.36	361.91	166.32	183.56	71.64	39.03

[1] SD, standard-deviation; CV, coefficient of variation (%). [2] LVd, "Latossolo Vermelho distrófico" (Embrapa, 2006) or Typic Haplortox (Soil Survey Staff, 2010); NVdf, "Nitossolo Vermelho distroférrico" (Embrapa, 2006) or Typic Paleudalf (Soil Survey Staff, 2010). [3] Strain rates of 0.03 and 1.55 mm s^{-1} were used in the reference testing apparatus and proposed equipment, respectively.

Table 7. Variance analysis of tensile strength of soil aggregates values obtained with the reference testing apparatus (control) and the proposed equipment for different soil types and land uses

Source of variation	Degree of freedom	Mean square	F	p > F
Soil type	1	114.349	524.950	< 0.0001
Land use	1	6.024	27.650	< 0.0001
Testing apparatus	1	0.050	0.230	0.6329
Soil type x Land use	1	3.749	17.210	< 0.0001
Soil type x Testing apparatus	1	0.561	2.570	0.1095
Land use x Testing apparatus	1	0.488	2.240	0.1355
Soil type x Land use x Testing apparatus	1	0.657	3.010	0.0833

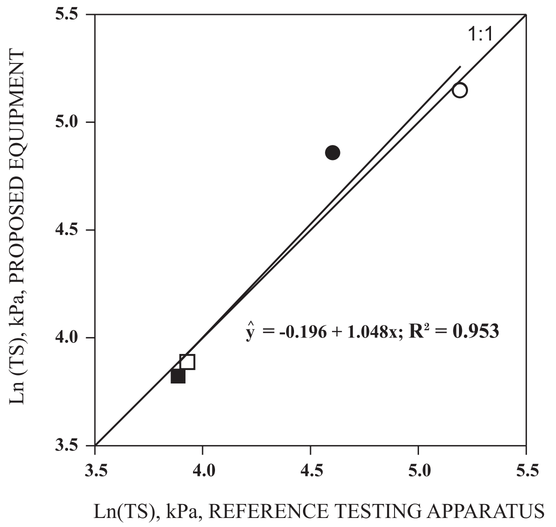

Figure 4. Linear regression for the mean data of aggregate tensile strength (TS) obtained with the proposed equipment and reference testing apparatus using strain rates of 1.55 and 0.03 mm s^{-1}, respectively, in soil-type and land-use combinations as follows: ■, "Latossolo Vermelho distrófico" (LVd) under "native forest"; □, LVd under "annual crops"; (●), "Nitossolo Vermelho distroférrico" (NVdf) under "eucalyptus plantation" (> 30 y.o.); (○), NVdf under "annual crops".

TS results from those obtained at a strain rate of 0.03 mm s^{-1} by the reference testing apparatus. Consequently, it is possible to measure TS using only the proposed equipment.

Figure 4 shows the linear regression analysis between mean TS values of the evaluated treatments obtained with both the proposed equipment and reference testing apparatus. It can be observed that the experimental plots generally adhere very closely to the 1:1 line, which confirms the similarity of mean TS values between testing apparatuses found in variance analysis (Table 7). The statistical indexes (Table 8), which do not depend on the data distribution pattern, enabled further evaluation of strain rate effect on TS measurement depending on testing apparatus. In this study, if the strain rates used to break soil aggregates provide satisfactory TS results, the expected adjustment degree between the testing apparatuses under evaluation should be closest to the relation: R^2 = d = DR = EF = 1 and ME = MAE = RMSE = RMSEu = RMSEs = CRM = 0. The results of the Kolmogorov-Smirnov test showed that linear regression residuals between the mean TS data obtained by both testing apparatuses were normally distributed, which allowed determinations of RMSEu and RMSEs.

The precision (R^2) and accuracy (d) statistical indexes were highly consistent with each other (Table 8), with values approaching the unit (ideal condition). The DR value indicates similar behaviour between the testing apparatuses in data dispersion around their respective means. This fact was confirmed by the high EF value (0.94), which shows that mean TS values from the treatments evaluated were consistent between the testing apparatuses. Moreover, MAE and ME indexes showed that the error magnitude, related to the treatment set evaluated, remained statistically acceptable. Notably, RMSE, RMSEu and RMSEs, i.e. the total, random and systematic errors, respectively, showed very low percentage values. The magnitude of RMSEu was similar to that of RMSE, while RMSEs represented less than 1 % of the mean TS value in the treatment set evaluated, a fact confirmed by the CRM value (practically zero). These results confirm the predominance of random over systematic errors in the comparison of TS data between testing apparatuses. Therefore, considering strain rates used for soil aggregate tensile failure, one can say that there is no range of TS values that is more accurately detected by one of the testing apparatuses evaluated. Thus, this research provides an important contribution to methodological advances in soil physics because of the possibility of carrying out faster analyses without affecting the accuracy of TS measurements, which facilitates routine laboratory determinations and widens the use of TS as a soil structural quality indicator.

Table 8. Statistical indexes[(1)] to verify the adjustment degree between mean data (in natural log scale) of tensile strength of soil aggregates obtained with the proposed equipment and reference testing apparatus using strain rates of 1.55 and 0.03 mm s^{-1}, respectively, in different soil-type and land-use combinations

R^2	d	DR	EF	MAE	ME	CRM	RMSE	RMSEu	RMSEs
0.953	0.986	0.859	0.940	0.102	0.248	-0.005	3.01	2.90	0.77

[(1)] R^2, coefficient of determination; d, agreement index; DR, deviation ratio; EF, coefficient of efficiency; MAE, mean absolute error; ME, maximum error; RMSE, Square root of the normalized quadratic mean error; RMSEu, square root of normalized random mean error; RMSEs, square root of normalized systematic mean error; CRM, coefficient of residual mass. MAE and ME have the same unit of the respective soil property; RMSE, RMSEu and RMSEs have percentage units. The other statistical indexes are dimensionless.

CONCLUSIONS

1. The proposed equipment was found to be suitable for soil penetration resistence (PR) measurements under laboratory conditions, and the soil penetration resistance curves allowed a satisfactory identification of differences in soil structure due to sampling position.

2. No significant difference was found between the tensile strength of soil aggregates (TS) measurements obtained under constant strain rates of 0.03 and 1.55 mm s^{-1}.

3. Accurate PR and TS measurements can be performed using the proposed equipment.

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