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SOIL FRIABILITY ASSESSMENT OF SOME AGRICULTURAL SOILS IN ROMANIA

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Abstract

Tensile strength is a dynamic property and is sensitive to soil structure because it is related to the presence of air-filled pores, the occurrence of micro-cracks and the strength of inter-granular bonds within and between micro-cracks. Moreover, the tensile strength of soil is much affected by the soil water content and processes which change pore characteristics and/or the cementation between structural units. A friability index has been proposed that is based on measurements of tensile strength of different sized aggregates. The main objectives of the present paper were to measure the mechanical properties (tensile strength and friability) of soil aggregates collected from three agricultural soils, and to explore the relationships between mechanical and basic physical properties of the investigated soils. Soils used in these investigations can be described as "friable" according to the classification used for friability index, F_1, values. Soil aggregates of the sandy soil from Grădiștea had the smallest values of tensile strength. The highest values of tensile strength were recorded in case of clayey soil, whereas the loamy soil had values between the sandy and clayey soils. Increasing organic matter content decreased the values of tensile strength for soil aggregates from all soils. High values of clay content in case of loamy and clayey soils increased the values of tensile strength. Increasing amount of clay in sandy soil has been shown to increase the tensile strength of this soil. This may be due to clay particles acting as cementing materials between large particles. Higher amounts of clay in sandy soils provide more opportunities for interparticle contact. Small size classes of aggregates presented higher values of tensile strength as compared with larger size classes of aggregates when the volume dependence method was used. In case of sandy and clayey soils were found underestimates and respectively overestimates of F_2 values. As for the loamy soil, the volume dependence method (F_2) gave similar values when compared to the coefficient of variation method (F_1). The coefficient of variation method is recommended as standard method for measuring soil friability.

Key words: *friability index, tensile strength, soil aggregates, aggregate size.*

INTRODUCTION

The term "tensile strength", *Y*, was defined by Dexter and Watts (2001) as the stress (force per unit area) required to breakdown the soil aggregates.

Tensile strength is an indicator which describes the minimum force required during seedbed preparation when large clods are fragmented without disturbing soil microstructure (Munkholm and Kay, 2002).

Tensile strength is a dynamic property (Kay and Dexter, 1992) and is sensitive to soil structure (Watts and Dexter, 1998) because it is related to the presence of air-filled pores, the occurrence of micro-cracks and the strength of inter-granular bonds within and between micro-cracks.

Moreover, the tensile strength of soil is much affected by the soil water content and processes which change pore characteristics and/or the cementation between structural units (Kay and Dexter, 1992).

A friability index has been proposed that is based on measurements of tensile strength of different sized aggregates (Utomo and Dexter, 1981b). Friability, *F*, is defined as 'the tendency of large clods or aggregates to breakdown and crumble under an applied stress into a certain size range of smaller fragments (aggregates)' (Utomo and Dexter, 1981b). This property is one of the objectives of tillage because a friable soil is much easier to till and large clods are relatively weak whereas the smaller aggregates are relatively strong and resistant to further breakdown (Dexter, 1997).

Theory

Determination of aggregate tensile strength, *Y*, has been widely applied to characterize the ease of aggregate fracture in tillage (Munkholm and Kay, 2002). As it is difficult to measure *Y* directly in a direct tension test (Dexter and Watts, 2001), most authors have used indirect tension tests to determine *Y*. For a spherical aggregate, *Y* can be determined from the equation (Dexter and Kroesbergen, 1985):

$$Y = q\frac{P}{D^2} \quad (1)$$

where: *q* is the proportionality constant, *P* is the applied compressive force at breakdown (N), and *D* is the effective diameter (m). The coefficient, *q*, depends on the relationship between the compressive and tensile stress in the centre of the aggregate and has been used ranging from 0.576 (Braunack et al., 1979) to 1.860 (Dexter, 1988b).

Utomo and Dexter (1981b) proposed the scale factor between aggregate size and the aggregate tensile strength as an index of friability, *k*:

$$\log_e Y = -k \cdot \log_e V + B \quad (2)$$

where: *V* (m^3) is the aggregate volume, and *B* (kPa) is the predicted log strength of $1m^3$ of soil. The intercept *B* can be written as:

$$B = \log_e\{Y_0 V_0^k \Gamma(1+k)\} \quad (3)$$

where: Y_0 and V_0 are the strength and volume respectively of the basic soil elements, which comprise the bulk aggregates, and Γ is the tabulated Gamma function.

Three methods for quantifying friability were described by Watts and Dexter (1998) and Dexter and Watts (2001), and are based on the statistical theory of brittle fracture. Briefly, this theory can be described by the "weakest link" concept: the strength of the total solid is determined by the local strength of the weakest volume element, in the same way as the strength of a chain is determined by its weakest link (Dexter and Watts, 2001). The methods for quantifying friability are as follows:

1. The first method is based upon the coefficient of variation of the tensile strength and is derived from Dexter and Watts (2001, Eq. 14). Only one size class of soil aggregates is needed for calculation of friability index using this method. The index F_1, is given by:

$$F_1 = \frac{\sigma_Y}{\bar{Y}} \pm \frac{\sigma_Y}{\bar{Y}\sqrt{2x}} \quad (4)$$

where: σ_Y is the standard deviation of measured values of tensile strength, $\bar{Y}$ is the mean of the tensile strength measurements and *x* is the number of replicates. The second term is the standard error of the coefficient of variation or friability.

2. The volume dependence method is based on Dexter and Watts (2001, Eq. 18), and leads to:

$$F_2 = \frac{1}{\beta} \quad (5)$$

where: β is obtained from the slope of a plot of

$$log_e Y_V = -\frac{1}{\beta} log_e V + E \quad (6)$$

where: Y_V is the tensile strength of volume *V*, and *E* is the intercept, the value of which is given in Dexter and Watts (2001, Eq. 18). Because the aggregate strength is size dependent, for this method at least 3 – 4 size classes of aggregates are needed for calculation of F_2.

Chan et al. (1999) found that for an Australian clayey soil:

$$F_1 \approx 2F_2 \quad (7)$$

Dexter and Watts (2001) recommended the first method as the standard method for measuring soil friability because it is easy to calculate and because it requires fewer measurements than the second method.

The main objectives of the present paper were to measure the mechanical properties (tensile strength and friability) of soil aggregates collected from three agricultural soils, and to explore the relationships between mechanical and basic physical properties of the investigated soils.

MATERIALS AND METHODS

Sample collection and preparation

For soil tensile strength measurements samples were collected from the field. Two sampling points were located in Giurgiu county (Grădiștea, Brăniștari) and one point in Teleorman county (Drăgănești-Vlașca) so that three different textured soils were covered, namely: sandy soil, loamy soil and clayey soil. At the time of sampling the plots had been cropped with winter wheat and alfalfa. The soils were characterized using standard methods and the results are given in Table 1.

Soil aggregates from the plough layer were collected from two depth intervals (5-10 cm and 15-20 cm), and soil aggregates from the subsoil were collected from the 35-40 cm depth interval.

Table 1. Physical characterization of the soil profiles

Location	Depth (cm)	Clay content (%)	Organic matter (%)	Bulk density (Mg m^{-3})	Texture class
Grădiştea	5-10	11.7	1.55	1.46	sandy loam
	15-20	11.2	1.22	1.46	
	35-40	8.3	0.49	1.39	
Brăniştari	5-10	28.5	2.71	1.48	clayey loam
	15-20	30.1	2.37	1.46	
	35-40	31.2	1.88	1.45	
Drăgăneşti - Vlaşca	5-10	36.5	6.39	1.20	clay
	15-20	39.0	5.10	1.40	
	35-40	44.4	3.53	1.41	

To obtain aggregates of the desired size range, a set of two sieves was used. The soil mass was carefully passed through these sieves and the remained aggregates on each sieve were placed in airtight containers in order to avoid any further mechanical disturbance of the aggregates. After completing this operation three size classes of aggregates were obtained: aggregates of diameter larger than 2 cm, between 1-2 cm, and smaller than 1 cm.

In the laboratory, the soil aggregates were allowed to air dry at room temperature.

After air-drying the aggregates, an additional sieving of the aggregates smaller than 1 cm in diameter was performed so that two more size classes of aggregates were obtained, namely: aggregates of diameter between 0.5-1 cm, and between 0.25-0.5 cm. These two size classes of aggregates together with aggregates of diameter larger than 2 cm and between 1 and 2 cm, were then used for determination of the friability index (F_2) using the second method. In total, four classes of aggregate sizes were obtained and subsequently subjected to the crushing tests.

Indirect tension tests for measurement of soil tensile strength

For the size classes of aggregates larger than 1 cm a loading frame was used. The loading frame consists of two parallel plates between which the aggregates are crushed by raising the lower plate with the help of a handle. The force acting across the soil sample is measured by a load ring.

The force which is applied to the aggregates is measured by a load-ring of 0-1 kN range placed between the upper plate and the cross beam of the loading frame. In this work, 40 replicate aggregates were measured for each size class, depth and soil texture.

For the size classes of aggregates smaller than 1 cm a digital balance was inserted into the loading frame and acted as a load sensor. The force P (N) applied to the aggregate is the product of the balance output in kg, and g = 9.807 m s^{-1}, which is the acceleration of gravity (Dexter and Watts, 2001).

Before crushing the aggregates, the size of each aggregate was measured by using callipers and then calculated as described below. To provide a standard sample orientation, the aggregates were then placed with the flattest side downwards on the lower plate as suggested by Dexter and Watts (2001) so that the aggregates would be crushed across their shortest axis.

When the load was applied to the aggregate, the force measured increased up to the point of breakdown and a vertical crack appeared into the aggregate when a rapid drop in force was recorded. The peak force, P (N), at breakdown was recorded and then used in calculating the aggregate tensile strength (Y) using Eq. (1) with q = 0.576 and D was calculated from Eq. (8) from below.

Measurement of aggregate size

Aggregate diameter (D) had to be estimated before the aggregates were crushed. For the size classes of aggregates larger than 1 cm, the diameter was estimated from "*Method 2*" described by Dexter and Watts (2001):

$$D = \frac{D_x + D_y + D_z}{3} \tag{8}$$

where: D_x, D_y and D_z represent the longest, intermediate and smallest diameters respectively of each aggregate. Also the mass (M) of individual aggregates and the mean mass ($\overline{M}$) of the aggregates in the population were recorded.

To determine the friability index F_1, a single size class of aggregates was used, which was the size class of aggregates with diameter between 1 and 2 cm.

For determining the friability index F_2, four size classes of aggregates were used, namely: aggregates of diameter larger than 2 cm, between 1-2 cm, 0.5-1 cm, and 0.25-0.5 cm.

In order to obtain the friability index F_2, it was necessary to calculate firstly the effective density and the effective volume of each aggregate.

For each aggregate that was measured from each size class of aggregates, the effective density (ρ_e) was calculated using Dexter and Watts (2001, Eq. 27, *"Method 4"*):

$$\rho_e = \frac{6 \cdot M}{\pi \cdot D_1^3} \tag{9}$$

where: M is the aggregate mass (kg) and D_1 is aggregate size (m) calculated using Eq. (10) described above and then corrected to the mass weight of each aggregate separately from the following equation:

$$D_1 = D \cdot \left(\frac{M}{\overline{M}} \right)^{1/3} \tag{10}$$

where the terms D, M and $\overline{M}$ are as described above.

Then, for each depth at the three locations, the mean effective density ($\overline{\rho_e}$) was calculated.

To obtain the effective aggregate volume (V), firstly the effective diameter (D_2) for each aggregate separately was calculated, using from Dexter and Watts (2001, Eq. 29, *"Method 5"*):

$$D_2 = \left[\frac{6 \cdot M}{\pi \cdot \overline{\rho_e}} \right]^{1/3} \tag{11}$$

where the terms in this equation are as described above, and secondly, the effective aggregate volume (V) was calculated using $V = \pi \cdot D_2^3 / 6$, which is the same as:

$$V = \frac{M}{\overline{\rho}} \tag{12}$$

For each aggregate size class, the mean aggregate volume ($\overline{V}$) for each depth at each of the three locations was calculated.

Quantification of soil friability

The methods for quantifying friability, F, which were used in this paper, were described in the Introduction section.

Statistical analysis of the soil mechanical properties was done by using the OriginLab software.

RESULTS AND DISCUSSIONS

Aggregate tensile strength and friability index, F_1

The values of tensile strength of aggregates 1-2 cm in diameter and of friability index F_1 are summarized in Table 2. According to the soil friability classification used by Imhoff et al. (2002), the soils used in these investigations may be classified as "friable". Out of 9 obtained values, 1 was "very friable" and 8 were "friable". High values of friability (F_1) indicate that the larger clods have lower values of tensile strength than smaller aggregates and can be more easily crushed into small strong fragments. This is of particular interest when tillage operations are performed in the field because one of the aims of tillage is to produce a suitable aggregate-size distribution for an optimum seedbed with a few passes of tillage implements (Imhoff et al., 2002).

Table 2. Mean values of tensile strength and friability index, F_1

Location	Depth (cm)	Tensile strength Y (kPa)	Tensile strength ± s.d. (kPa)	Friability index F_1
Grădiștea	5-10	50.07	25.13	0.504
	15-20	121.04	59.16	0.498
	35-40	160.86	80.68	0.490
Brăniștari	5-10	75.39	21.54	0.285
	15-20	206.65	67.31	0.326
	35-40	252.54	91.63	0.363
Drăgănești - Vlașca	5-10	156.77	35.41	0.226
	15-20	238.15	58.61	0.247
	35-40	281.03	72.09	0.257

From mean aggregate tensile strength ($\overline{Y}$) for each of the three soil textures and for the sampling depths (Figure 1) it can be seen that the aggregates collected from sandy soil were weakest, followed by the aggregates from loamy and clayey soils respectively.

Analysis of variance showed that there are statistically significant differences between the soil profiles at the 95% confidence level (F-

Ratio = 96.86; P-Value = 1.79745E-13) when the depth was taken as factor of influence.

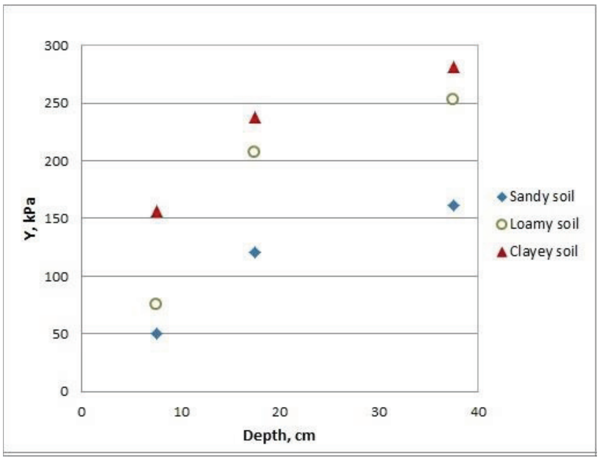


Figure 1. Variation of the tensile strength with depth

A similar trend of the soil tensile strength values was obtained by Vizitiu et al. (2010) for Polish soils. Also the average values of the tensile strength were higher in the deeper layers of the soil profiles when compared to the topsoil layers.

The influence of organic matter and clay content on the tensile strength values was assessed through simple analysis using linear regressions. In Figures 2 and 3 are shown the variation in tensile strength as a function of organic matter and clay content. The regression lines which are drawn in Figure 2 can be described by the following equations:

- for sandy soil:

$$Y = 213.58 - 94.81\ OM \qquad r^2 = 0.70$$
$$(\pm 27.74)\ (\pm 23.54) \qquad p = 0.005$$

- for loamy soil:

$$Y = 605.18 - 184.05\ OM \qquad r^2 = 0.78$$
$$(\pm 86.76)\ (\pm 36.95) \qquad p = 0.002$$

- for clayey soil:

$$Y = 427.89 - 40.47\ OM \qquad r^2 = 0.83$$
$$(\pm 35.42)\ (\pm 6.88) \qquad p = 0.0006$$

The three investigated soils showed a statistically significant decrease of the tensile strength as a function of organic matter content, the most obvious decrease being recorded for clayey soil. Some researchers found a positive correlation between tensile strength and organic matter (Bartoli et al., 1992; Imhoff et al., 2002), whereas others found no correlation (Watts and Dexter, 1998) or negative correlation (Guérif, 1990; Watts and Dexter, 1997).

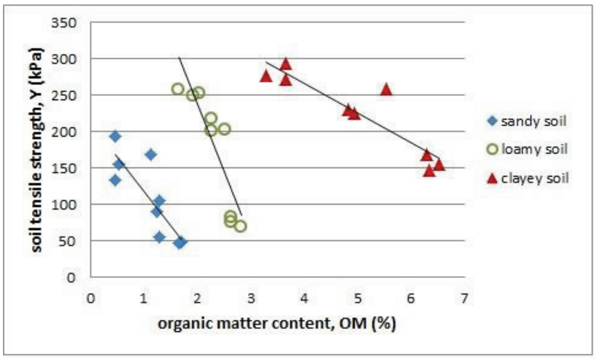


Figure 2. Effect of organic matter on tensile strength

The tensile strength of air-dry soil aggregates is shown in Figure 3 to be highly correlated with the clay content (Guérif, 1990) in the case of loamy and clayey soils and less correlated for the sandy soil. The regression lines are given by the following equations:

- for sandy soil:

$$Y = 297.16 - 17.95\ C \qquad r^2 = 0.32$$
$$(\pm 103.47)\ (\pm 9.84) \qquad p = 0.111$$

- for loamy soil:

$$Y = -1125.60 + 43.51\ C \qquad r^2 = 0.64$$
$$(\pm 369.63)\ (\pm 12.32) \qquad p = 0.0096$$

- for clayey soil:

$$Y = -320.87 + 13.67\ C \qquad r^2 = 0.75$$
$$(\pm 120.87)\ (\pm 3.01) \qquad p = 0.0027$$

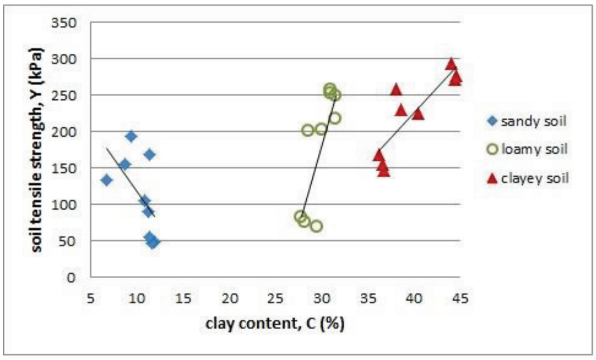


Figure 3. Effect of clay content on tensile strength

Increasing amount of clay in sandy soil has determined an increase of the soil tensile strength values (Figure 3). This may be due to clay particles acting as cementing materials between large particles, high amounts of clay providing more opportunities for interparticle contact and also adsorb more water, causing higher tensions in soil water at a specific water content (Kemper et al., 1987). Dispersion of cementing materials (e.g. clay) can cause migration of those to lower energy positions, and the greatest effect on tensile strength is recorded when the bonding occurs at contact points within or at the ends of microcracks (Kay and Dexter, 1992).

Friability index, F_2

In Table 3 are presented the values of friability index, F_2, and Figure 4 a, b and c show some examples of the volume dependence of the tensile strength.

As expected from the work of Dexter and Watts (2001), the values of friability index, F_2, obtained using Eqs. (5) and (6) from the volume dependence method described in the introduction section, are smaller than the values of friability index, F_1, obtained using Eq. (4) from the coefficient of variation method.

Table 3. Values of friability index, F_2

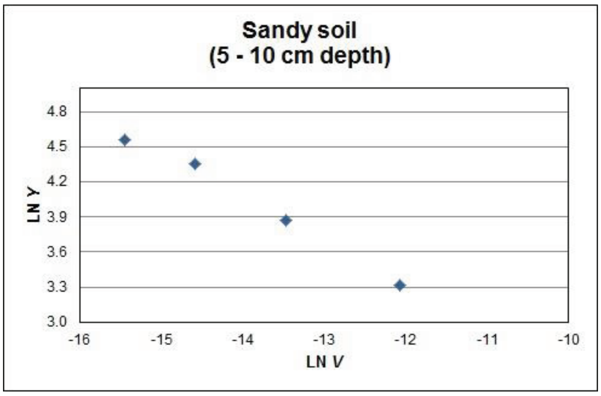
Location	Depth (cm)	Friability index F_2	Ratio between F_1/F_2
Grădiștea	5-10	0.314	1.60
	15-20	0.217	2.29
	35-40	0.202	2.43
Brăniștari	5-10	0.370	0.77
	15-20	0.289	1.13
	35-40	0.291	1.25
Drăgănești - Vlașca	5-10	0.335	0.68
	15-20	0.286	0.86
	35-40	0.381	0.68

Measurement of the tensile strength of soil aggregates as functions of volume is based on the assumption that small aggregates are fragments of larger aggregates (Watts and Dexter, 1998).

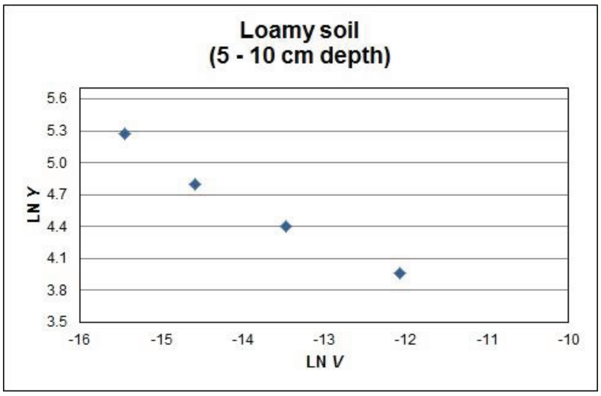
It is desirable that the material of the smaller aggregates, which initially comprised the larger clods, has a relatively greater strength than that of the larger clods, otherwise, the soil mass could break down into individual mineral particles or dust (Utomo and Dexter, 1981).

Statistical analysis of the friability (F_2) results showed that F_2 was not correlated with organic matter content and clay content.

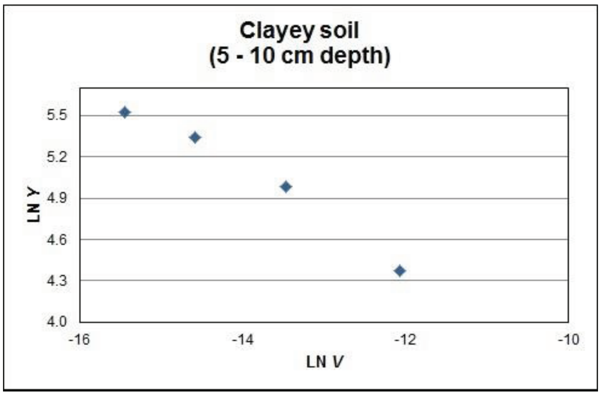
One possible explanation could be that soil aggregates of different size may have been formed by different mechanisms (Dexter, 1988b), may be of different ages, and may have weathered differently (Watts and Dexter, 1998), and these can affect the subsequent strength behavior of the aggregates.



a) sandy soil



b) loamy soil



c) clayey soil

Figure 4. Plots of aggregate tensile strength as a function of volume for the topsoil layer of: a) sandy soil; b) loamy soil; c) clayey soil

Amongst the main factors which can affect friability index, F_2, is the water content. Utomo and Dexter (1981) found maximum friability at around the soil plastic limit when assessed the friability using the volume dependence method. Similar results were reported by Shanmuganathan and Oades (1982), Munkholm and Kay (2002) and Munkholm et al. (2002).

In these investigations, we looked also for a correlation between F_1 and F_2, and the results are shown in Figure 5. The regression line in Figure 5 show a small linear correlation between F_1 and F_2, and the equation of regression is as follows:

$$F_1 = 0.67 - 1.115\, F_2 \qquad r^2 = 0.45$$
$$(\pm 0.076)\ (\pm 0.251) \qquad p = 0.0002$$

When the results for each soil profile were compared separately, these have shown different trends. Whereas for the sandy and clayey soils were found underestimates and respectively overestimates of F_2 values, for the other loamy soil the volume dependence method (F_2) gave similar values when compared to the coefficient of variation method (F_1). The ratio F_1/F_2 is as follows: 2.11 for the sandy soil, 1.05 for the loamy soil and respectively 0.74 for the clayey soil.

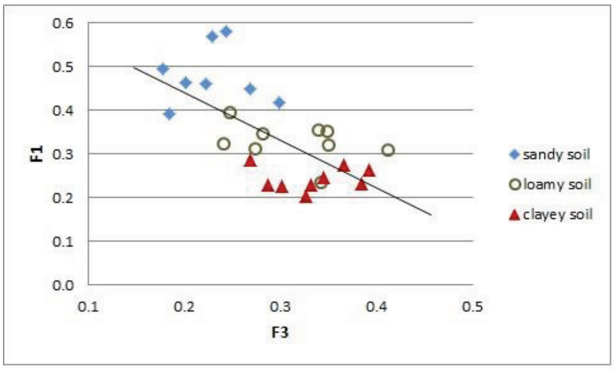


Figure 5. Plot of friability indices (F_1 and F_3) as measured by two different methods.

Dexter and Watts (2001) suggested that at least two factors contribute to the finding that F_1 is always larger than F_2. The first factor which they mention is that some variability of the force, *P*, for sample breakdown, is due to differences in the shape of individual soil aggregates.

The second factor mentioned by Dexter and Watts (2001) is that, for natural aggregates, some of the flaws or micro-cracks are not very small when compared with the sample size, and this negates one of the main assumptions of the weakest link theory of soil strength.

Therefore, it was recommended (Watts and Dexter, 1998; Dexter and Watts, 2001) that the coefficient of variation method can be used as a standard method for describing soil friability (F_1) because it is easy to calculate, because it can be related to the principal parameter, $1/\alpha$, of brittle fracture theory, and because it requires fewer measurements than the second method (F_2).

CONCLUSIONS

Soils used in these investigations can be described as "friable" according to the classification used for F_1 values.

Soil aggregates of the sandy soil from Grădiştea had the smallest values of tensile strength. The highest values of tensile strength were recorded in case of clayey soil, whereas the loamy soil had values between the sandy and clayey soils.

Increasing organic matter content decreased the values of tensile strength for soil aggregates from all soils.

High values of clay content in case of loamy and clayey soils increased the values of tensile strength.

Increasing amount of clay in sandy soil has been shown to increase the tensile strength of this soil. This may be due to clay particles acting as cementing materials between large particles. Higher amounts of clay in sandy soils provide more opportunities for interparticle contact.

Small size classes of aggregates presented higher values of tensile strength as compared with larger size classes of aggregates when the volume dependence method was used.

In case of sandy and clayey soils were found underestimates and respectively overestimates of F_2 values. As for the loamy soil, the volume dependence method (F_2) gave similar values when compared to the coefficient of variation method (F_1).

The coefficient of variation method (F_1) is recommended as standard method for measuring soil friability.

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REFERENCES

Bartoli F., Burtin G. and Guérif J., 1992. Influence of organic matter on aggregation in Oxisols rich in gibbsite or in goethite. II. Clay dispersion, aggregate strength and water stability. Geoderma 54, p. 259-274.

Braunack M.V., Hewitt J.S. and Dexter A.R., 1979. Brittle fracture of soil aggregates and the compaction of aggregate beds. J. Soil Sci. 30, p. 653-667.

Chan K.Y., Dexter A.R. and McKenzie D.C., 1999. Categories of soil structure based on mechanical behaviour and their evaluation using additions of lime and gypsum on a sodic soil. Aust. J. Soil Res. 37, p. 903-911.

Dexter A.R., 1975. Uniaxial compression of ideal brittle tilths. J. Terramechanics 12, p. 3-14.

Dexter A.R., 1985. Shapes of aggregates from tilled layers of some Dutch and Australian soils. Geoderma 35: p. 91-107.

Dexter A.R., 1988a. Strength of soil aggregates and of aggregate beds. Catena Supplement 11, p. 35-52.

Dexter A.R., 1988b. Advances in characterization of soil structure. Soil Till. Res. 11, p. 199-238.

Dexter A.R., 1997. Physical properties of tilled soils. Soil Till. Res. 43, p. 41-63.

Dexter A.R. and Kroesbergen B., 1985. Methodology for determination of tensile strength of soil aggregates. J. Agric. Eng. Res. 31, p. 139-147.

Dexter A.R. and Chan K.Y., 1991. Soil mechanical properties as influenced by exchangeable cations. J. Soil Sci. 42, p. 219-226.

Dexter A. R. and Watts C.W., 2001. Tensile Strength and Friability. In: Smith, K. A. and Mullins, C. E. (Eds.), Soil and Environmental Analysis. Physical Methods. 2nd edition. Marcel Dekker Inc., New York, p. 401-430.

Guérif J., 1990. Factors Influencing Compaction-Induced Increases in Soil Strength. Soil Till. Res. 16, p. 167-178.

Imhoff S., da Silva A.P. and Dexter A.R., 2002. Factors Contributing to the Tensile Strength and Friability of Oxisols. Soil Sci. Soc. Am. J. 66, p. 1656-1661.

Kay B.D. and Dexter A.R., 1992. The influence of Dispersible Clay and Wetting/Drying Cycles on the Tensile Strength of a Red-Brown Earth. Aust. J. Soil Res. 30, p. 297-310.

Kemper W.D., Rosenau R.C. and Dexter A.R., 1987. Cohesion development in disrupted soils as affected by clay and organic matter content and temperature. Soil Sci. Soc. Am. J. 51, p. 860-867.

Munkholm L.J. and Kay B.D., 2002. Effect of Water Regime on Aggregate-tensile Strength, Rupture Energy, and Friability. Soil Sci. Soc. Am. J. 66, p. 702-709.

Munkholm L.J., Schjønning P., Debosz K., Jensen H.E. and Christensen B.T., 2002. Aggregate strength and mechanical behaviour of a sandy loam soil under long-term fertilization treatments. Eur. J. Soil Sci. 53, p. 129-137.

Shanmuganathan R.T. and Oades J.M., 1982. Effect of Dispersible Clay on the Physical Properties of the B Horizon of a Red-brown Earth. Aust. J. Soil Res. 20, p. 315-324.

Utomo W.H. and Dexter A.R., 1981. Soil friability. J. Soil Sci. 32, p. 203-213.

Vizitiu O.P., Czyż E.A. and Dexter A.R., 2010. Soil physical quality - theory and applications for arable soils. 166 pp. Ed. SITECH, Craiova, ISBN 978-606-11-0844-2.

Watts C.W. and Dexter A.R., 1997. The influence of organic matter in reducing the destabilization of soil by simulated tillage. Soil Till. Res. 42, p. 253-275.

Watts C.W. and Dexter A.R., 1998. Soil friability: theory, measurement and the effects of management and organic carbon content. European J. Soil Sci. 49, p. 73-84.

Watts C.W., Dexter A.R. and Longstaff D.J., 1996. An assessment of the vulnerability of soil structure to destabilisation during tillage. Part II. Field trials. Soil Till. Res. 37, p. 175-190.