Effect of aggregate size and superficial horizon differentiation on the friability index of soils cultivated with sugar cane: a multivariate approach

Efecto del tamaño de los agregados y la diferenciación de horizontes superficiales en el índice de friabilidad de suelos cultivados en caña de azúcar: un enfoque multivariante

Edgar Alvaro Avila P.[1], Fabio Rodrigo Leiva[2], Enrique Darghan C.[3], and Raúl Madriñán M.[4]

ABSTRACT

Soil friability is a physical property that provides valuable information for minimizing energy consumption during soil tillage and for preparing the edaphic medium for plant development. Its quantitative determination is generally carried out with aggregates obtained from soil blocks taken at fixed depths of profiles without considering the superficial horizons of the soil. The objective of the this study was to determine the effect of aggregate size and superficial horizon differentiation on the friability index (FI) of some soils cultivated with sugar cane in the Geographic Valley of the Cauca River (Colombia), using univariate (CV_u) and multivariate (CV_m) coefficients of variation. The FI was evaluated using a compression test with four aggregate-size ranges taken from the Ap and A1 superficial horizons of 182 sampling sites located on 18 sugar cane farms. Of the five types of studied soils (Inceptisols, Mollisols, Vertisols, Alfisols and Ultisols), 7,280 aggregates were collected that were air dried and subsequently dried in a low-temperature oven before determining the tensile strength (TS), which was in turn used to calculate the FI using the coefficient of variation method. This study found that the FI varied with the aggregate size and the soil depth (first two horizons). Only three of the four size ranges initially selected were relevant. The CV_m proved to be very useful for the selection of a more relevant value from the confidence interval of the TS from the CV_u method for friability and established that the lower limit value (FI_i) of the TS CV_u was the FI value that was closest to the multivariate measurement.

Key words: soil quality, aggregates, tensile strength, compressive strength, coefficient of variation.

RESUMEN

La friabilidad del suelo es una propiedad física que proporciona valiosa información para minimizar el consumo de energía durante la labranza del suelo y adecuar el medio edáfico para el desarrollo de las plantas. Su determinación cuantitativa se realiza generalmente a partir de agregados obtenidos de bloques de suelo tomados a profundidades fijas en el perfil sin considerar los diferentes horizontes superficiales del suelo. El objetivo de esta investigación fue determinar el efecto del tamaño de los agregados y la diferenciación de los horizontes superficiales en el índice de friabilidad (IF) de algunos suelos bajo caña de azúcar en el Valle Geográfico del Río Cauca (Colombia), usando el coeficiente de variación univariante (CV_u) y multivariante (CV_m). El IF se evaluó mediante una prueba de compresión de cuatro rangos de tamaño de agregados tomados de los horizontes superficiales Ap y A1 de 182 sitios de muestreo, provenientes de 18 fincas dedicadas al cultivo de caña de azúcar. De los cinco tipos de suelos estudiados (Inceptisoles, Molisoles, Vertisoles, Alfisoles y Ultisoles), se colectaron 7.280 agregados que fueron secados al aire y posteriormente en horno a baja temperatura, previamente a la determinación de la RC, y a partir de esta, se calculó el IF usando el método del coeficiente de variación. El estudio encontró variación del IF con el tamaño de los agregados y con la profundidad del suelo (dos primeros horizontes); de cuatro rangos de tamaño inicialmente seleccionados, solo tres fueron relevantes. La utilización del CV_m resultó bastante útil en la selección de un valor más conveniente dentro del intervalo de confianza de la RC del método del CV_u para la friabilidad y permitió establecer que el valor del límite inferior (IF_i) del CV_u de la RC, fue el valor del IF más cercano a la medida multivariante.

Palabras clave: calidad del suelo, agregados, resistencia al rompimiento, resistencia a la compresión, coeficiente de variación.

Introduction

Friability is synonymous with quality for the physical condition of a soil and indicates the structural state (Macks *et al.*, 1996; Watts and Dexter, 1998). This physical property provides valuable information for making the soil a physically suitable medium for the development of roots and for

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[1] Faculty of Agricultural Engineering, Universidad del Tolima. Ibague (Colombia). eaavila@ut.edu.co
[2] Department of Rural Development, Faculty of Agricultural Sciences, Universidad Nacional de Colombia. Bogota (Colombia)
[3] Department of Agronomy, Faculty of Agricultural Sciences, Universidad Nacional de Colombia. Bogota (Colombia)
[4] Faculty of Agricultural Sciences, Universidad Nacional de Colombia. Palmira (Colombia)

minimizing the energy required during farming of the soil (Munkholm, 2011).

Friability has been defined as a tendency of a unconfined soil mass to break down into a particular range of small-sized aggregates under an applied stress (Dexter and Watts, 2001); therefore, a friable soil is characterized by an ease of fragmenting large aggregates, which have little value to sowing, and resistance to fragmentation seen in small-sized aggregates of undesired small elements. In order to estimate the friability, qualitative, semi-quantitative and quantitative methods are used (Munkholm, 2011); of these, the quantitative method based on the tensile strength (TS) of aggregates proposed by Dexter and Watts (2001) is one of the more common ones. TS, described as the force necessary to cause failures or ruptures in a soil mass (Dexter and Watts, 2001), is probably the most useful measurement of the individual strength of aggregates due to the ease with which it is carried out with simple tests and diverse aggregate sizes (Dexter and Kroesbergen, 1985).

The coefficient of variation is widely used to measure the relative variation of a random variable in its measurement or to evaluate and compare the performance of analytical techniques (Rencher, 2002). In the case of determining friability, the method proposed by Watts and Dexter (1998) for determining the friability index (FI) of soils using the CV_u of the TS has been recommended as a standard method due to its reliability and ease of calculation (Dexter and Watts, 2001). However, when the friability index is determined in the same soil with different aggregate sizes, the friability can be calculated using a multivariate approach, which possesses desirable properties from the statistical point of view (Rencher, 2002). The CV_m only requires the calculation of the mean vector and a covariance matrix of the TS. In biometry, genetics and edaphology, multiple characteristics are usually measured in individuals or in experiment units of various population, resulting in difficulty in evaluating the relative variability of each population. Clearly, calculating the CV_u of each characteristic is not sufficient because the structure of the correlation between the measurements is not taken into account, associated in this particular case with the different aggregate sizes. The CV_m can be obtained by Eq. 1.

$$CV_m = [(\bar{y}^T S \bar{y}) / (\bar{y}^T \bar{y})^2]^{1/2} \quad (1)$$

where, $\bar{y}^T$ represents the transpose (T) of the sample mean vector of the TS and $\bar{y}$ represents the variance-covariance matrix of the samples, which in this case had a 10 × 10 dimension due to the 10 repetitions obtained for the TS of each sample and in each horizon (Albert and Zhang, 2010).

Friability and, therefore, TS depend on the soil structure and particularly on the fissures of the soil structure (Dexter, 2004). Dexter (1988a) discussed a hierarchy in the soil structure, the stable micro-aggregate part that is grouped into aggregates and their lumps. As an aggregate gets bigger, it is weaker than its constituents because they contain larger-sized fissures; therefore, the TS also depends on the aggregate size. The majority of research that estimates soil friability using the TS only evaluates one range of aggregate size, which is generally between 12.5 and 19.0 mm (Imhoff *et al*., 2002; Tormena *et al*., 2008; Guimarães *et al*., 2009; Seben *et al*., 2013). According to Imhoff *et al*. (2002), this aggregate-size range is easier to manually separate and measure and predominates in the soil after farming operations. Furthermore, studies have reported on aggregate-size ranges between 13.2 and 19.0 mm (Watts and Dexter, 1998) and between 2 and 4 mm (Rahimi *et al*., 2000). Other studies have used more than one aggregate-size range; Chan (1989), for example, used four ranges between 2.8 and 12.7 mm, Munkholm *et al*. (2002a, 2002b) also used four ranges but between 2 and 16 mm and Macks *et al*. (1996) used eleven ranges between 1.4 and 50.0 mm.

TS and friability are affected by other physical, chemical, and mineralogical properties of the soil (Macks *et al*., 1996; Munkholm *et al*., 2002, 2012), properties that maintain a close relationship with the soil genesis and the soil horizons (Kempen *et al*., 2011). Often, when taking samples for a friability study, one or various fixed soil depths are used, but sometimes samples are taken from the horizon differentiation in which the properties maintain a certain homogeneity.

The objective of this study was to determine the effect of the aggregate size and the superficial horizon differentiation on the friability index of some soils cultivated with sugar cane in the Geographic Valley of the Cauca River (Colombia), using the multivariate coefficient of variation.

Materials and methods

Description of the sample-site locations

This study was carried out on 18 farms dedicated to sugar cane cultivation, with similar mechanical management practices for the soil, located in the central and southern regions of the Valle del Cauca Department and the northern region of the Cauca Department (Colombia). The boundary coordinates of this area were: 3°3'1" and 4°4'59" N latitude and 76°14'12.5" and 76°30'43.2" W longitude. Following the Köppen climate classification, the study area corresponded to a tropical wet savanna (Awi).

Distribution of the observation sites and soil types

A soil taxonomic unit was placed on each of the farms, with which five observation sites were selected that were approximately 100 m apart. In each sampling point, a 50 x 50 x 50 cm opening was made and the first and second horizons were delineated (Ap and A1, respectively). The weighted average thickness of Ap varied between 7.4 and 19.4 cm and, for A1, it varied between 7.2 and 24.4 cm. A soil block was taken from each horizon (approximately 30 cm long x 18 cm wide x 12 cm thick); however, in those sites where the horizons were thinner, the thickness of the collected blocks were adjusted to 7 cm. The soils were taxonomically classified as Inceptisol, Mollisol, Vertisol, Alfisol and Ultisol (Soil Survey Staff, 2010) and characterized as presenting organic carbon contents that varied between 8.61 and 34.01 g kg^{-1}, clay contents that varied between 240 and 674 g kg^{-1}, lime contents that varied between 263 and 545 g kg^{-1}, and sand contents that varied between 36 and 336 g kg^{-1}.

Aggregate separation

In total, 182 soil blocks were collected, 91 from the Ap horizon and 91 from the A1 horizon. In the laboratory, the soil blocks had their aggregates separated along their natural weakness plains. Afterwards, the aggregates were dried in a greenhouse for 5 d at an average daily temperature of 29°C. Subsequently, the samples were sieved with a set of sieves (1, 2, 4.7, 9.5, 12.5, 19, 25, 37.5 and 50 mm), where it was found that four aggregate-size ranges predominated: 2.0 to 4.7 mm, 4.8 to 9.5 mm, 9.6 to 18.9 mm and 19.0 to 35.7 mm. The aggregate sizes over 19 mm were in agreement with the report from Macks *et al.* (1996), who used an aggregate-size range of up to 50 mm. From each size range, 10 aggregates were selected and, in accordance with the suggestions of Guimarães *et al.* (2009), dried in an oven at a constant temperature of 40°C for 48 h. The remaining moisture of the aggregates after the drying was 3.3% (2.0-4.7 mm), 3.4% (4.8-9.5 mm), 3.8% (9.6-18.9 mm) and 4.1% (19.0-35.7 mm).

Determination of the friability index

The FI was initially determined from the TS of each aggregate by the CV_u method proposed by Dexter and Watts (2001). For the measurement of the TS, 10 aggregates were used for each size range, for a total of 3,640 aggregates per horizon. Each aggregate was subjected to unconfined compression in loading equipment for CBR tests (Soiltest - CF410) at two speeds, consisting of two parallel plates, between which the aggregates were compressed. In each of the tests, the inferior plate had a constant rate of deformation of 0.07 mm s^{-1} (Watts and Dexter, 1998). The TS was calculated with the Eq. 2 described by Utomo and Dexter (1981); Dexter and Kroesbergen (1985) and Dexter and Watts (2001).

$$TS = 0.576\ (P/D_e^2) \tag{2}$$

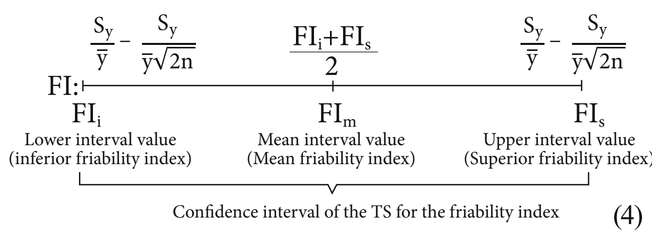
Where, TS (kPa) is the TS, P (N) the peak strength value registered at the moment of aggregate failure and D_e (mm) the effective diameter of the aggregates. The 0.576 value corresponded to a constant proportionality.

With the TS of each aggregate, the FI was determined with the CV_u method proposed by Dexter and Watts (2001) (Eq. 3).

$$(FI_i; FI_s) = \left(\frac{S_y}{\bar{y}} - \frac{S_y}{\bar{y}\sqrt{2n}}; \frac{S_y}{\bar{y}} + \frac{S_y}{\bar{y}\sqrt{2n}}\right) \tag{3}$$

which relates the standard deviation of the measured TS values (S_y) and the mean of the measured TS values ($\bar{y}$) for size samples = 10. In this equation, (FI_i; FI_S) represents the lower and upper limits of the friability index.

This method is based on the confidence interval of the CV_u of the TS measurements (Eq. 4).



(4)

In many studies that have determined the FI using the CV_u method, the value normally employed corresponded to the mean of the TS confidence interval, that is to say, the mean friability index (FI_m).

Statistical analysis

The analysis of the data involved descriptive and inferential components. The statistical descriptive was associated with the mean FI and the TS per horizon (Ap and A1) and per aggregate-size range (2.0 to 4.7 mm, 4.8 to 9.5 mm, 9.6 to 18.9 mm and 19.0 to 35.7 mm). Furthermore, using the univariate friability (for each range of aggregate size), the FI was determined based on the CV_m method (Albert and Zhang, 2010) from the variance-covariance matrix of the measured TS of all of the aggregate sizes separated by horizon. In addition, the marginal and set means of the horizons and the aggregate sizes were determined. For the inferential approach, the lineal friability model was used with a profile analysis (Statistical Analysis System, v. 9.3), which, with a sequential contrast hypothesis (Khattree and Naik, 1999), resulted in more information than the hypothesis normally associated with the equality of FI means. At the start, a profile test for parallelism was used for each aggregate-size range and, afterwards, coincidence and horizontality tests were used. The profile analysis was carried out to justify joining the smaller aggregate-size ranges (2.0 to 4.7 mm and 4.8 to 9.5 mm).

Results and discussion

Table 1 shows the means of the FI_m based on the CV_u per horizon and per aggregate-size range. The results demonstrated that the aggregate sizes at or below 9.5 mm presented very similar FI_m values in each of the two horizons, while the aggregate sizes over 9.5 mm had a higher friability, both in Ap and A1. As a result, the FI_m value in the Ap horizon was progressively higher (between 0.05 and 0.06, respectively) with the increase in the aggregate size, while in the A1, this increase was approximately between 0.04 and 0.07. In general, the profiles of the FI_m demonstrated a certain parallelism and the friability values of the first horizon were higher than those that followed (Tab. 1 and Fig. 1); the latter agrees with the results of Watts and Dexter (1998) in clay and sandy loam soils in the United Kingdom, in which the aggregates of the superficial horizon were more friable, attributed to the additional confinement tensions of overloading and to the lower influence from the penetration of roots into the aggregates of the deeper horizons.

TABLE 1. FI_m means per horizon and aggregate-size range for soils cultivated with sugar cane (Colombia).

Horizon size range	Ap	A1
2.0 to 4.7 mm	0.451	0.383
4.8 to 9.5 mm	0.454	0.386
9.6 to 18.9 mm	0.503	0.450
19.0 to 35.7 mm	0.565	0.496

Figure 1 shows that the highest FI_m value in both horizons was from the 9.5 mm aggregate-size range, which coincided with the results of Dexter and Watts (2001), who found that strength and, therefore, friability depended on the aggregate size, with the bigger aggregates being weaker due to the fact that they contained bigger fissures. Due to these fissures, the large aggregates of a sample commonly have a porosity that is higher than those of the small aggregates (Dexter, 1988b). According to Schjønning *et al.* (2011), in general, the FI of the natural aggregates of well-managed soils is higher as the aggregate size increases.

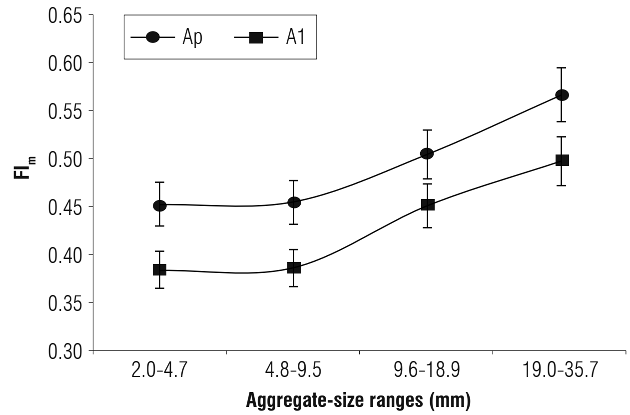


FIGURE 1. Distribution of the FI_m per horizon for the different aggregate-size ranges (confidence interval 95%) for soils cultivated with sugar cane (Colombia).

Figure 2 shows that the TS of the studied soils had an inverse relationship with the FI; the smaller aggregates (2.0-9.5 mm) registered the higher TS values of between 77.4 and 92 kPa, while the larger sizes (19.0-35.7) had a TS that was lower, with values between 31.07 and 33.35 kPa. In general, a decrease was observed for the TS when the sized increased for the aggregates in both horizons, Ap and A1, and a tendency to present similar TS values in the larger-sized aggregates in the two horizons.

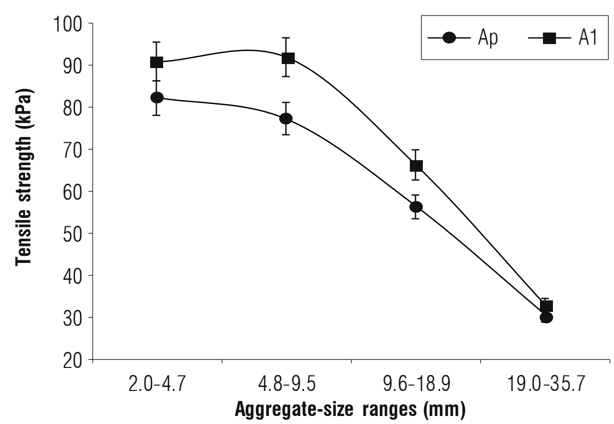


FIGURE 2. Distribution of the TS per horizon for the different aggregate-size ranges (confidence interval 95%) for soils cultivated with sugar cane (Colombia).

Figure 3 presents the inferior and superior quartiles, the measurement and the interquartilic range of the mean of the FIm for each aggregate-size range in each horizon. As a result, for all of the considered sizes at a large volume of the utilized aggregates, only apparently atypical observations were collected, which were not considered extreme. It was sufficiently clear that there was similarity of the interquartilic range in all of the compared groups, which was relevant to the requirement for homoscedasticity of the FI per treatment (horizon and aggregate-size range). This same figure supports the descriptive idea that the aggregate-size range partitioning did not present differences in the smaller aggregates (2.0 to 4.7 and 4.8 to 9.5 mm).

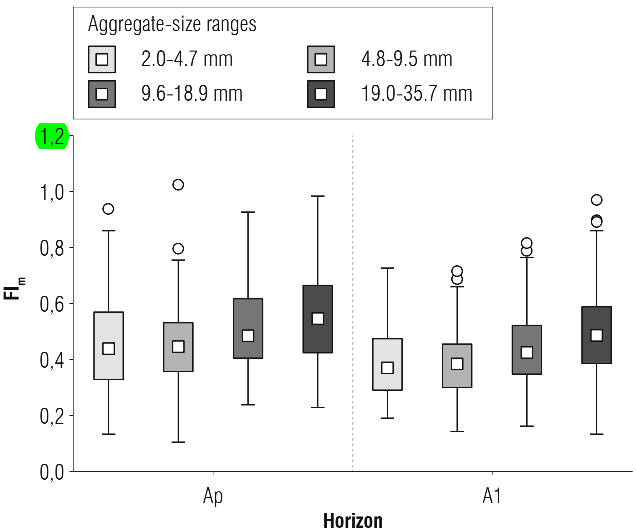


FIGURE 3. Box-plot of the mean friability index (FI_m) per horizon for the different aggregate-size ranges for soils cultivated with sugar cane (Colombia).

The use of four aggregate-size ranges and two horizons allowed for the construction of a unique mean for the multivariate friability per horizon, also based on the TS of the soil. The multivariate measurement took the covariance of the TS per aggregate size and per horizon into account, as well as the correlations that could have existed in the measurements associated with the aggregate size.

In order to justify the separation by horizon, a profile analysis was carried out with the help of SAS (Statistical Analysis System, v. 9.3). The profile analysis also allowed for the evaluation of the FI behavior in the four studied size ranges with a multivariate approach.

In this study, it was found that the multivariate friability measurement by horizon and by aggregate size presented a value very close to the FI_i of the confidence interval of the CV_u method (Tabs. 2 and 3); this suggests that the univariate evaluation probably overestimated the FI, considering that the FI_m is usually used in the determination of friability (Imhoff *et al.*, 2002; Dexter, 2004; Tormena *et al.*, 2008; Guimarães *et al.*, 2009). In this sense and to avoid a possible overestimation of the friability, this study calculated the profile analysis with the lower limit of the confidence interval (FI_i) as developed by Dexter and Watts (2001).

Figure 4 presents the distribution of the FI taken from the lower limit of the confidence interval (FI_i) proposed by Dexter and Watts (2001). These values were similar to the multivariate values of Tabs. 2 and 3. The profiles of Fig. 4 are equal to those of Fig. 1, but were transferred with respect

TABLE 2. Lower (FI_i), mean (FI_m) and upper (FI_S) measurements of the multivariate and univariate friability, separated by horizon for soils cultivated with sugar cane (Colombia).

Approach \ Horizon	Ap	A1
Multivariate	0.380	0.308
Univariate, lower limit of the TS confidence interval (FI_i)	0.395	0.347
Univariate, mean value of the TS confidence interval (FI_m)	0.505	0.447
Univariate, upper limit of the TS confidence interval (FI_S)	0.625	0.545

TS, tensile strength.

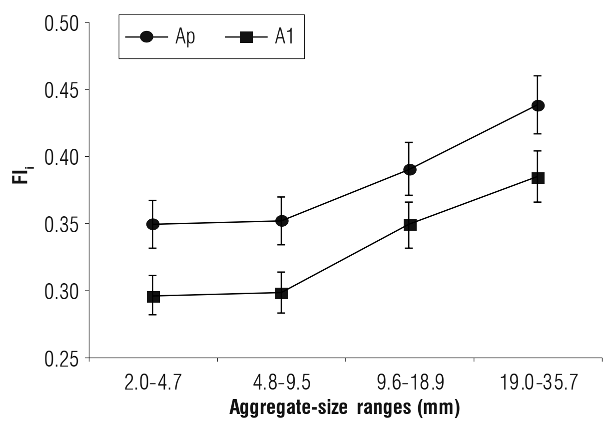


FIGURE 4. Distribution of the FI_i for each horizon in the different aggregate-size ranges (confidence interval 95%) for soils cultivated with sugar cane (Colombia).

TABLE 3. Lower (FI_i), mean (FI_m) and upper (FI_S) measurements of the multivariate and univariate friability, separated by aggregate size in each horizon for soils cultivated with sugar cane (Colombia).

Aggregate size (mm)	Univariate measurement						Multivariate measurement	
	Ap			A1			Ap	A1
	FI_i	FI_m	FI_S	FI_i	FI_m	FI_S		
2.0-9.5	0.38	0.48	0.60	0.32	0.42	0.51	0.40	0.32
9.6-18.9	0.39	0.50	0.62	0.35	0.45	0.55	0.54	0.44
19.0-35.7	0.44	0.56	0.69	0.39	0.50	0.61	0.40	0.38

to the y-axis using a value corresponding to the standard error of the CV_u, taking into account that, in this case, the friability measurements corresponded to the FI_i.

The Profile Analysis for the four aggregate-size ranges allowed for parallel contrast hypothesis (null hypothesis: non-parallelism), horizontality and coincidence tests. In the case of parallelism, a Wilks lambda statistical test (Λ) presented significance at P = 0.9233 (P>5%), which confirmed the parallelism of both profiles (Fig. 4), which in practical terms meant that the differences in the FI_i for each aggregate-size range were constant. Furthermore, it confirmed the hypothesis of coincidence (P<1%), indicating that the differences in the FI_i in each horizon were constant (around 0.05), but not null, that is to say that each horizon was differentiated in the FI_i measurement. Finally, the hypothesis of horizontality (P<1%) was rejected, which indicates that the FI_i means of the four aggregate-size ranges could not be considered equal within the same horizon.

The two larger aggregate sizes presented high friability (Fig. 4), similar to the findings of Fig. 1, demonstrating that, starting at the aggregate sizes greater than 9.5 mm, the FI_i values were progressively higher. This behavior was associated with the soils with moderate to high friability and that had a high TS in the small aggregates and a low TS in the large aggregates (Macks *et al*., 1996).

Given the similarity of the values obtained for the FI_i of the two smaller aggregate-size ranges (2.0 to 4.7 mm and 4.8 to 9.5 mm), a horizontality profile analysis was carried out on them, which presented a P>0.05, confirming their horizontality. This allowed for the statistical grouping of the FI_i of these size ranges into only one group, based on the mean of the two measurements separated by horizon. This suggests the use of only 3 of the four initial ranges for the determination of the friability of the studied soils: 2.0 to 9.5 mm, 9.6 to 18.9 mm and 19.0 to 35.7 mm.

Conclusions

The multivariate analysis showed that the lower value of the confidence interval of the tensile strength used in the univariate coefficient of variation method proposed by Dexter and Watts (2001) was the value that best represented the friability index value of the studied soils.

With the significant volume of soil samples used in this study, a higher FI_i value was seen with an increase in the aggregate size in the soils of different typology but the same cultivation.

Only three of the initial four aggregate-size ranges that were separated by their predominance in the soil proved to be relevant because the two ranges of the smaller aggregate sizes presented closeness to the FI_i value.

There were differences in the friability of the soils due to depth. The friability of the Ap horizon was higher than the friability seen in the A1 horizon. As a result, this study confirmed the need to consider the limits of the superficial horizons of a soil when carrying out field sampling for the purpose of evaluating friability so that the friability can be determined for each superficial horizon.

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