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Methods for Quantifying Shrinkage in *Latossolos* (Ferralsols) and *Nitossolos* (Nitisols) in Southern Brazil

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ABSTRACT: Brown *Nitossolos* (Nitisols) and *Latossolos* (Ferralsols), according to the Brazilian System of Soil Classification (SiBCS), have a "caráter retrátil" as their distinctive property. Because this is a new topic, it is necessary to propose methods for evaluation. The objectives of this study were to evaluate methodologies for quantifying the shrinkage of soil using the Syringe Method and the Metallic Mercury Method, and to propose a new one, the "Ring with Sand Method". Soil samples from eight pedons were used, with six *Nitossolos* and *Latossolos* with shrinkage, a *Latossolo* without shrinkage, and a *Vertissolo* (Vertissol) with admittedly high shrinkage and expansion. The methods were effective in identifying the greater degree of shrinkage of the *Vertissolo*. However, the Ring with Sand Method was the only one to indicate significant differences between the *Vertissolo* and the *Latossolo* without shrinkage, and this method differentiated the shrinkable soils as to the intensity of the characteristic. The proposed method was effective and can serve as a standard to quantify shrinkage.

Keywords: clay soils, COLE index, shrinkage, Saran resin.

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INTRODUCTION

The "caráter retrátil" is a recent theme in Brazilian soil science. The expression "caráter retrátil" does not have a clear correspondence in the english language, but refers to shrinkage properties of soils after drying. The concept and its inclusion as a mandatory criterion in the definition of the taxonomic suborders of *Latossolo Bruno* (Ferralsols) and *Nitossolo Bruno* (Nitisols) was introduced in the proposal to update the second edition of the Brazilian Soil Classification System - SiBCS (Santos et al., 2012), and then inserted in the latest edition of the SiBCS (Santos et al., 2013). However, conceptualization and the criteria for identifying shrinkage are fragile, since they are based on qualitative and non-quantitative evaluations. It is therefore necessary to propose methodologies for evaluating the degree or intensity of this shrinkage in order to distinguish soils with shrinkage from non-shrinking soils.

The expansion and shrinkage properties of *Nitossolos* and *Latossolos Brunos*, as well as of some *Latossolos Vermelhos* (Ferralsols) derived from lava flows from the Serra Geral Formation in the extreme south of Brazil, are significant and were recognized as a peculiar property of these soils during the IX Soil Classification and Correlation Meeting held in 2008 (Almeida, 2008), in which more than 60 pedologists from various regions of Brazil participated. Lemos et al. (1973), during the Rio Grande do Sul Soil Recognition Survey, had already mentioned the presence of shrinkage in *Latossolos Brunos* of the Mapping Units of Vacaria and Durox, describing the presence of perpendicular slits in the face of the pedons when exposed to the sun.

The concept of "caráter retrátil", according to the SiBCS (Santos et al., 2013), stresses that it must be used only for *Latossolos* (Ferralsols) and *Nitossolos* (Nitisols), both *Brunos* and *Vermelhos*, clayey or very clayey, which exhibit sharp shrinkage of soil mass from drying of the aggregates after exposure of the pedons to the sun for a number of weeks, resulting in the formation of pronounced vertical cracks and large and very large prismatic structures. It is also suggested that, although kaolinite is generally identified as the predominant clay mineral in these soils, possible causes of shrinkage in these soils are due to the presence of 2:1-layer clay minerals with interlayered hydroxy-Al polymers (VHE or EHE), and also to the small size of the clay minerals in the clay fraction.

In Brazil, the main soils that show marked expansion and shrinkage properties are *Vertissolos* (Vertisols), although they are also frequently found in the B horizon of some *Chernossolos* (Chernozems), *Luvissolos* (Luvisols), and *Planossolos* (Planosols) with vertic properties. These properties are traditionally attributed to the predominance of expansive phyllosilicates, mainly of the smectite group (Coulombe et al., 1996; Taboada, 2004). However, Coulombe et al. (1996), in an extensive review on the subject, also indicate that other phyllosilicates, including kaolinites and 2:1 clay minerals with interlayered hydroxy-Al polymers, as well as other factors, can contribute to the expansion and shrinkage properties of *Vertissolos*, and the occurrence of shrinkage and expansion was also found in soils with predominance of kaolinite.

Several techniques have been proposed to evaluate the expansion and shrinkage properties of soils, but in Brazil, they are almost always related to the *Vertissolos*, mainly through determination of the Coefficient of Linear Extensibility (COLE), or COLE Index (Bardales, 2005), which can be measured by different methods. According to McKenzie et al. (2002), there is currently no universally accepted standard for evaluating soil shrinkage properties, and this is mainly due to the tendency of many authors to work with a restricted soil population in their research. Thus, it is difficult to define the best test and the boundaries between classes of soil shrinkage.

The methodologies for determination of COLE have been modified over time. The classical methodology used for this purpose makes use of Saran resin ($COLE_{Saran}$), proposed by Brasher et al. (1966) and described by Tan (2005) and Donagema et al. (2011). The method basically consists of quantifying variation in the volume of a sample with preserved structure, which is maintained at moisture conditions at field capacity and related to the volume of the same sample after oven drying at 105 °C. The method is laborious, time-consuming, and currently little used in Brazil, mainly because saran resin, a synthetic product derived from petroleum, is no longer manufactured (Almeida et al., 2008). For Argentine *Vertissolos*, Taboada (2004) defined $COLE_{Saran}$ values lower than 0.03 as very low, and above 0.09 as very high. In the North American classification of soils (Soil Survey Staff, 2014), values of COLE for the *Vertissolos* order, determined according to the method of Schafer and Singer (1976), from 0.07 to 0.2 (Soil Survey Staff, 1999), are cited.

The COLE Index (modified) by Schafer and Singer (1976), called $COLE_{mod}$, is an alternative to the Saran Resin Method, where the shrinkage of a wet soil is measured linearly after drying. A stabilized soil paste is introduced into a syringe, which after pressing produces soil cylinders whose length is measured before and after drying the soil. This method is practical and relatively fast since in approximately 48 h the result is obtained. However, because soil with disturbed structure is used, this method may not adequately represent the actual shrinkage and expansion properties. The $COLE_{mod}$ values have good correlation with the Saran Resin Method, but the values obtained are generally higher than those (McKenzie et al., 2002).

The Metallic Mercury Method uses metallic mercury to evaluate the volume variations in dry and moist soil conditions, and mainly aims to determine the shrinkage limit (SL), which refers to the soil moisture condition below which soils would undergo practically no more appreciable volumetric shrinkage, mainly for use in civil works (ABNT, 1948). It therefore constitutes one of the limits of soil consistency. The degree of shrinkage (DS), resulting from the previous determination, allows evaluation of variation in volume between a wet sample and the sample dried at 105 °C (Donagema et al., 2011), and, thus, disturbed soil structure is used in this determination, as well as in obtaining the $COLE_{mod}$. One drawback of this method is that the use of mercury can have harmful effects on human health and the environment, as recently highlighted by the Minamata Convention on Mercury, which aims to establish restrictions in use (UNEP, 2013) in a text approved and signed by about 140 countries (Brasil, 2016). Currently, in Brazil, Ibama is the agency responsible for authorizing importation and control of production, commercialization, and use of metallic mercury, according to the National Environmental Policy, Law No. 6.938/1981, regulated by Decree No. 97.634/1989 (Ibama, 2016).

Considering the peculiar shrinkage and expansion properties of many *Latossolos* and *Nitossolos*, notably the *Brunos* and some *Vermelhos* modalities from the extreme south of Brazil, the lack of quantitative criteria to determine the shrinkage intensity of these soils and the need for better conceptualization of shrinkage, as established by the SiBCS, make it imperative to test methodologies that allow more precise evaluation of the shrinkage of the soils mentioned. Moreover, considering that the COLE determined through the use of Saran resin is considered quite accurate for quantification of the properties of soil shrinkage and expansion, but that production of that resin has been discontinued (Almeida et al., 2008), the development of alternative methodologies that consider the same principles, becomes necessary.

Our hypothesis is that obtaining the coefficient of linear extensibility (COLE) index of soils with shrinkage is a way of quantifying the shrinkage that occurs from drying. Thus, we evaluated methodologies for quantification of the shrinkage intensity of soils and also proposed a new and alternative method to the classic Saran Resin Method to determine the COLE index.

MATERIALS AND METHODS

For quantification of soil shrinkage intensity, eight pedons were selected for this study; six of them (NB_{PAI}, LB_{VAC}, LV_{CN}, NB_{PS}, NB_{CUR}, LB_{VAR}) are composed of *Latossolos* and *Nitossolos*, which exhibit the shrinkage trait identified in the field, and were collected in the states of

Santa Catarina (SC) and Rio Grande do Sul (RS), Brazil. Two other pedons were used for comparison of a *Latossolo* (LV_{CAS}) from the state of Paraná (PR), without shrinkage, and of a *Vertissolo* (VERT) from RS, admittedly with strong shrinkage and expansion properties. The classification of soils according to the SiBCS (Santos et al., 2013), their correspondence with the FAO (WRB, 2014), and their geographical locations are shown in table 1.

The samples collected in SC corresponded exactly to the sites where the soils were identified and analyzed in the VIII National Meeting of Correlation and Classification of Soils of Santa Catarina (Almeida et al., 2008) for pedons identified as NB_{PAI}, LV_{CN}, NB_{PS}, NB_{CUR}, and LB_{VAR}. The LB_{VAC} samples were collected at the site described by Curcio et al. (2000), the LV_{CAS} by Guidin et al. (2006), and the VERT by Reinert et al. (2007).

In all pedons, soil samples with disturbed structure were collected and preserved from horizons A and B, except for VERT, where they were collected only from horizon A. Soil collection occurred when the soil had moisture near or below field capacity. The samples with disturbed structure were used to obtain the coefficient of linear extensibility index (Schafer and Singer, 1976) and the degree of shrinkage (Donagema et al., 2011), both with eight replicates in the laboratory. Since the object of this study is the shrinkage in soils, that is brought about by shrinkage of the soil mass and the formation of pronounced vertical slits and large and very large structures through drying of the soil in the field, soil with undisturbed structure was collected in volumetric rings with dimensions of 10 × 10 cm (785 cm^3) in order to better represent the characteristic, using five replications per horizon. With these samples, the soil shrinkage index was obtained through a new method proposed by this study called the Ring with Sand Method.

Syringe Method

Described by Schafer and Singer (1976) to obtain the coefficient of linear extensibility (COLE), hereinafter called $COLE_{mod}$. The method consists of moistening a soil sample and homogenizing it with a spatula until it forms a uniform paste, which is left to stand for 24 h and then introduced into a plastic syringe with a 1 cm diameter opening at its end. The plunger is pressed, thereby constructing soil cylinders of 3 to 6 cm lengths, which are placed on a glass surface. Then, with the aid of a caliper, the length of the cylinder of the moist sample (Lm) is measured, and, after drying, the length of cylinder of the dry sample (Ld) is measured. For this study, the cylinders were dried in a greenhouse with forced air circulation for 48 h at the temperatures of 35, 60, and 105 °C, with length being measured immediately after drying (Ld) at the respective temperatures. The samples that fragmented after drying were discarded and were not considered. The $COLE_{mod}$ was then determined by the following formula:

$$COLEmod = (Lm - Ld)/Ld$$

in which *Lm* is the moist sample length (mm) and *Ld* is the dry sample length (mm).

Table 1. Classification and location of soils studied

Pedon	SiBCS[1]	WRB[2]	Municipality/State	Geographical coordinate
NB_{PAI}	*Nitossolo Bruno Distrófico*	Umbric Nitisols	Painel/SC	27° 53’ 41.8” S; 50° 07’ 45” W
LB_{VAC}	*Latossolo Bruno Distroférrico*	Ferritic Ferralsols	Vacaria/RS	28° 30’ 47.40” S; 50° 53’ 36.90” W
LV_{CN}	*Latossolo Vermelho Distroférrico*	Ferritic Ferralsols	Campos Novos/SC	27° 22’ 21.76” S; 51° 15’ 44.89” W
NB_{PS}	*Nitossolo Bruno Distrófico*	Umbric Nitisols	Ponte Serrada/SC	26° 51’ 22.9” S; 52° 02’ 32.71” W
NB_{CUR}	*Nitossolo Bruno Distroférrico*	Ferritic Nitisols	Curitibanos/SC	27° 22’ 12” S; 50° 34’ 46.0” W
LB_{VAR}	*Latossolo Bruno Distrófico*	Xantic Ferralsols	Vargeão/SC	26° 51’ 13.3” S; 52º 05’ 56” W
LV_{CAS}	*Latossolo Vermelho Distroférrico*	Ferritic Ferralsols	Cascavel/PR	24° 59’ 45.16” S; 53° 17’ 44.61” W
VERT	*Vertissolo Ebânico*	Haplic Vertisol	Santana do Livramento/RS	30° 43’ 15.46” S; 55° 47’ 37.85” W

[1] SiBCS (Santos et al., 2013); [2] WRB (2014).

Metallic Mercury Method

Described by Donagema et al. (2011), the shrinkage limit (SL) and the shrinkage degree (SD) of the soil are determined. The method, in short, consists of moistening and making a uniform paste with the soil sample, which previously passed through a 0.42 mm mesh sieve. This sample is then put into a metal container of known volume (metal capsule), which is placed in an air circulation oven at 105 °C for 24 h. After the container is removed from the oven, the volume of the dry soil pellet is determined. To obtain this volume, a glass vat of 5 cm diameter and 2.5 cm height completely filled with metallic mercury is placed inside a porcelain capsule. The dry soil pellet is dipped into the vessel and, with the aid of a glass plate, the mercury is leveled with the edge of the vessel. This results in the displacement of a volume of mercury into the porcelain capsule corresponding to the volume of the dry soil pellet; the volume of mercury displaced is measured and the SL, expressed as a percentage, is calculated by the following formula:

$$SL = [(\frac{a}{b} \text{ x } pa) - (1)/c] \times 100$$

in which a is the volume of the dried tablet in m^3, pa is the water density in Mg m^{-3} at the temperature of the essay, b is the mass of the dry pellet in Mg, and c is the density of the sample particles in Mg m^{-3}.

The SD, expressed as a percentage, is then obtained by the following formula:

$$SD = \frac{a - b}{a} \times 100$$

in which a is the initial volume of the pellet (cm^3) and b Is the final pellet volume (cm^3).

Only the SD data will be discussed and presented.

Ring with Sand Method

Aiming to test a new manner of quantification of soil shrinkage, whose principle would be similar to the classical Saran Resin Method (Brasher et al., 1966; Tan, 1996; Donagema et al., 2011), using soil samples with undisturbed structure, a new methodology was developed based on quantification of soil volume variation. The initial volume corresponds to the soil at field capacity, and the final volume is obtained after oven drying at 105 °C for 48 h. Variation in volume is obtained after drying the soil, filling the volume of the void of the volumetric ring with fine sand (from 0.425 to 0.053 particle diameter), which, in preliminary tests, proved to penetrate the fissures resulting from shrinkage of the soils, filling them. It should be noted that sand was chosen instead of liquids because a solid does not cause the soil mass to expand. The method in this study is called the Ring with Sand Method and will serve as the basis for obtaining a soil shrinkage index, hereinafter referred to as $COLE_{sand}$.

The method consists of collecting undisturbed soil samples in pedons without anthropic use, which can be carried out in ravine cuts. Initially the pedon is exposed with the aid of a shovel, starting from the top, until the lower limit of the B horizon. After that, the soil is collected from the middle portion of each horizon (A and B), beginning with A, in 0.10 × 0.10 m metal rings (Figure 1). In the laboratory, the volumetric rings containing the soil samples are placed in basins and then water is added until the soil level comes very close to the upper edge of the ring, for complete saturation for 48 h. After saturation, the samples are transferred to a tension table (Reinert and Reichert, 2006) and subjected to a tension equivalent to 1.00 m of water column for approximately three days, aiming to achieve a humidity condition close to field capacity and uniformity of this condition for all samples. The rings are then removed from the tension table, and excess soil that surpassed the upper and lower limits of the ring is cut, thus making the soil volume uniform to correspond exactly to the volume of the ring. The "ring + soil" assembly is placed in an oven at 105 °C for 48 h. After drying, the assembly is cooled in a desiccator and the rings are sealed in their lower base with masking tape and placed on a vibrating sieve. At low and constant vibration (600 vpm), in order to promote accommodation of the sand particles in the soil cracks, the ring volume (with the shrunken soil mass) is filled to the upper edge with fine sand previously placed in a 100 mL burette, which will serve to measure the volume of sand used. The time for filling the ring with the sand varies among the soils; however, on average, it is approximately 10 min. It is suggested that the procedure be performed slowly and with necessary care so that the sand is level with the upper edge of the ring (Figure 2). If the sand overflows during leveling, it should be returned to the burette. The $COLE_{sand}$, equivalent to the COLE determined from the use of the Saran resin, is obtained by the following formula:

$$COLEsand = \left|\frac{(vsu)}{(vss)}\right|^{\frac{1}{3}} - 1$$

in which *vsu* is the volume of moist soil (corresponding to the volumetric ring volume) at field capacity, and *vss* is the volume of the soil dried at 105 °C, obtained by the difference between the volume of the ring (m^3) and the volume of fine sand (m^3) used to fill the ring after drying at 105 °C.

Statistical analyses

Correlation analysis

All variables used to evaluate soil shrinkage were initially subjected to normality analysis using the Shapiro-Wilk test. After checking the normality of the shrinkage data, they were correlated to each other using the Pearson linear correlation test (r).

Grouping analysis

Aiming to statistically group the soils and their pedogenic horizons according to the $COLE_{sand}$, and to define limits between the shrinkage intensities, we used univariate

Figure 1. Soil samples with undisturbed structure.

Figure 2. Volumetric rings with soil mass shrunk and after filling with sand (Ring with Sand Method).

statistics with a mixed model in the "PROC GLIMMIX" procedure of the SAS 9.2 program (Schabenberger, 2007). Soil horizons were considered as a fixed effect and the profiles as a random effect. The mean values of shrinkage were compared by the least significant difference test (LSD).

RESULTS AND DISCUSSION

Analyses that measured soil shrinkage resulted in different values for the same soil (Table 2), as expected, since: i) the procedures used differed among the methods, as well as the calculations to obtain the results; ii) the Metallic Mercury and Syringe methods use soil samples with disturbed structure, such as a wet soil paste, whereas in the Ring with Sand Method, samples with undisturbed structure are used; and iii) the values obtained with the Syringe Method refer to linear shrinkage, while the other two refer to volumetric shrinkage. Therefore, these factors should be weighed in interpretation of the results.

Soil shrinkage, in all the methods tested and at different drying temperatures to obtain $COLE_{mod}$, was higher in the VERT (Table 2). This shows that all the methods were effective in identifying the property of greater shrinkage and greater expansion of this soil in relation to the others studied. For the different soils, however, the only method that indicated large differences in values between highly shrinking and non-shrinkable soil was the "Ring with Sand Method", which generated the $COLE_{sand}$. This method differentiated very high values of $COLE_{sand}$ indexes for VERT and extremely low ones for non-shrinkable soil (LV_{CAS}) (Table 2). For the other *Latossolos* and *Nitossolos* with shrinkage, the values were intermediate (Table 2). But there were significant numerical differences between the extremes (0.06 to 0.12 = 100 % variation), indicating that the method discriminated the pedons/horizons as to shrinkage intensity.

Table 2. Shrinkage of soils obtained by the Syringe Method - $COLE_{mod}$ (Schafer and Singer, 1976), Metallic Mercury Method - DS (Donagema et al., 2011), and Ring with Sand Method - $COLE_{sand}$

Pedon/horizon	Shrinkage index[1]				
	$COLE_{mod}$[2]			DS (%)	$COLE_{sand}$[3]
	35 °C	60 °C	105 °C	105 °C	105 °C
NB_{PAI}[4]/A	0.18	0.20	0.24	25	0.12
NB_{PAI}/B	0.16	0.19	0.21	29	0.10
LB_{VAC}/A	0.16	0.23	0.24	21	0.11
LB_{VAC}/B	0.15	0.18	0.24	29	0.08
LV_{CN}/A	0.15	0.16	0.24	25	0.06
LV_{CN}/B	0.18	0.19	0.20	28	0.07
NB_{PS}/A	0.16	0.20	0.20	27	0.08
NB_{PS}/B	0.20	0.22	0.23	22	0.12
NB_{CUR}/A	0.10	0.22	0.25	27	0.10
NB_{CUR}/B	0.09	0.19	0.21	28	0.08
LB_{VAR}/A	0.11	0.13	0.15	21	0.06
LB_{VAR}/B	0.15	0.16	0.16	20	0.08
LV_{CAS}/A	0.11	0.14	0.16	12	0.02
LV_{CAS}/B	0.10	0.14	0.15	2	0.03
VERT	0.22	0.25	0.27	38	0.17
Standard deviation	0.04	0.04	0.04	0.08	0.03

[1] $COLE_{mod}$: modified coefficient of linear extensibility obtained at three soil drying temperatures; DS: degree of shrinkage; $COLE_{sand}$: coefficient of linear extensibility obtained by the Ring with Sand Method. [2] Values of $COLE_{mod}$ and SD: average of eight replicates. [3] $COLE_{sand}$ values: average of five replicates. [4] NB_{PAI}: *Nitossolo Bruno*, located in Painel/SC; LB_{VAC}: *Latossolo Bruno*, located in Vacaria/RS; LV_{CN}: *Latossolo Vermelho*, located in Campos Novos/SC; NB_{PS}: *Nitossolo Bruno*, located in Ponte Serrada/SC; NB_{CUR}: *Nitossolo Bruno*, located in Cutitibanos/SC; LB_{VAR}: *Latossolo Bruno*, located in Vargeão/SC; LV_{CAS}: *Latossolo Vermelho*, located in Cascavel/PR; and VERT: *Vertissolo*, located in Santana do Livramento/RS.

For DS, the differences in the extremes of values between shrinking and non-shrinking soils were high (2 to 38 %), but less expressive when considering only the group of shrinkable *Nitossolos* and *Latossolos*, whose values varied from 20 to 29 % (45 % variation between the extremes), thus not allowing more detailed definition of the differences in the intensities of shrinkage between these soils. For non-shrinking soil (LV_{CAS}), DS values were lower than for the other soils, but with large numerical discrepancy between the A and B horizons, a fact not observed in $COLE_{sand}$ and $COLE_{mod}$ values for the same situation (Table 2).

The values of the $COLE_{mod}$ had high amplitude of variation between the extremes (0.09-0.27), considering the variations in the three temperatures, but, the differences in the shrinkage index of the shrinkable *Latossolos* and *Nitossolos*, compared to the non-shrinking soil (LV_{CAS}) were generally very low, so it is not possible to discriminate them with certainly. Several soils of the shrinking group, for example, have $COLE_{mod}$ values equal to or lower than the ones of the non-shrinking soil (LV_{CAS}) (Table 2). A similar fact occurred when comparing the values of the $COLE_{mod}$ of the VERT with the shrinkable *Latossolos* and *Nitossolos*, where we observe, for example, differences in index value from 0.22 in the VERT to 0.20 in the NB_{PS} (Horizon B) at 35 °C, from 0.25 in the VERT to 0.23 LB_{VAC} (Horizon A) at 60 °C, and from 0.27 in the VERT to just 0.25 in the NB_{CUR} (Horizon A).

The results thus demonstrate that the $COLE_{mod}$ method was not effective in distinguishing differences between shrinking and non-shrinking soils, since it not only did not allow detection of significant variations in quantification of shrinkage among soils with shrinking characteristics (also including in this comparison the VERT), but also could not detect sensitive differences between the soils with shrinkage and the ones with non-shrinking characteristics.

The values of $COLE_{sand}$ showed significant correlation ($p<0.01$) with DS and with the $COLE_{mod}$ at the different soil drying temperatures (Table 3). There was also a significant correlation of the DS with the $COLE_{mod}$ (Table 3). Although these significant correlations occurred, it should be noted that the CG and $COLE_{mod}$, as discussed previously, did not allow adequate discrimination of the non-shrinking soil from the shrinking ones, or among the shrinkable soils as to the intensity of shrinkage.

Considering that the use of the proposed "Ring with Sand Method" to obtain soil shrinkage indexes ($COLE_{sand}$) recognized the VERT as the soil with the highest shrinking property and the LV_{CAS} soil as the one with the lowest (Table 2), and because it discriminated the soils of the shrinking group in terms of their shrinkage intensities, it becomes acceptable and secure in evaluation of the shrinking property. In addition, this method has advantages compared to the established methods of Metallic Mercury, Syringe, and Saran resin.

Some advantages of the proposed method, when compared to the Saran resin method, are that it is also possible to measure the retraction volume of the internal fissures that may occur in the soils after drying, and the absence of the resin wrap in the clod, because the wrap could generate some resistance to expansion when the clod is saturated (Dinka

Table 3. Pearson correlation between the degree of shrinkage (DS), modified coefficient of linear extensibility ($COLE_{mod}$), and coefficient of linear extensibility obtained by the "Ring with Sand Method" ($COLE_{sand}$)

	DS (%)	$COLE_{mod}$ 35 °C	$COLE_{mod}$ 60 °C	$COLE_{mod}$ 105 °C
DS (%)	-	0.53*	0.66**	0.72**
$COLE_{sand}$	0.73**	0.72**	0.88**	0.76**

Test H0: |r| = zero, when *: significant ($0.01<p<0.05$) and **: significant ($p<0.01$). $COLE_{mod}$: for three soil drying temperatures, method proposed by Schafer and Singer (1976). DS: obtained by the Metallic Mercury Method (Donagema et al., 2011).

and Lascano, 2012), as well as to shrinkage during sample drying. The soil sample with undisturbed structure in the volumetric ring during drying does not undergo any resistance to shrinkage, although this may occur during saturation through lateral resistance of the ring walls. Other advantages are the absence of chemical reagents, lower cost after the preparation of the rings, and agility in obtaining results.

It should be noted, however, that the two methods (Saran resin and the proposed "Ring with Sand") have similar principles, since both work with soil samples with undisturbed structure, evaluate shrinkage in volume in samples practically under the same moisture conditions (at field capacity and after drying at 105 °C) and calculation of the COLE values can be obtained through the same formula. Although the $COLE_{Saran}$ method was not used for comparison in this study, the value of $COLE_{sand}$ obtained by the Ring with Sand Method for the VERT, used in the comparison, was within the normal parameters for *Vertissolos* with predominance of smectites cited by several authors in diverse environments of the world (Coulombe et al., 1996; Taboada, 2004).

From the values of $COLE_{sand}$, cluster analysis was performed by error estimation (Table 4), obtaining a division of the soils into groups of shrinkage intensity. The groups were divided by the proximity of values of $COLE_{sand}$, in which the letter A indicates soils with the greatest shrinkage intensities, and the letters H and I, the smallest. In group A was the soil VERT. Soils NB_{PS} (horizon B), NB_{PAI} (horizon A), and LB_{VAC} (horizon A) were in group B, representing soils with the greatest shrinkage. Groups H and I coincided with the A and B horizons of the LV_{CAS} soil, and were consistent with the lowest shrinkage observed among the soils studied. Group C gathered the soils NB_{CUR} (horizon A) and NB_{PAI} (horizon B). The other soils with their horizons had intermediate shrinkage values, and were grouped between the C and the G.

Through the grouping of data, $COLE_{sand}$ values were organized by creating numerical limits of shrinkage intensity for soils, namely: highly shrinking, shrinking, low shrinking, and non-shrinking (Table 5). With the limits obtained, it was possible to organize the seven soils and their horizons (with the exception of the VERT), classifying them statistically

Table 4. Division of shrinkage intensity groups ($COLE_{sand}$), through cluster analysis by error estimation

Observation	Pedon/horizon	$COLE_{sand}$ [1]	Group
1	VERT[2]	0.1770	A[3]
2	NB_{PS}/B	0.1220	B
3	NB_{PAI}/A	0.1186	B
4	LB_{VAC}/A	0.1140	B
5	NB_{CUR}/A	0.1050	C
6	NB_{PAI}/B	0.0980	C
7	LB_{VAC}/B	0.0848	D
8	NB_{CUR}/B	0.0780	DE
9	LB_{VAR}/B	0.0775	DEF
10	NB_{PS}/A	0.0752	EF
11	LV_{CN}/B	0.0684	FG
12	LB_{VAR}/A	0.0650	GH
13	LV_{CN}/A	0.0582	H
14	LV_{CAS}/B	0.0303	I
15	LV_{CAS}/A	0.0187	J

[1] $COLE_{sand}$: coefficient of linear extensibility obtained by the Ring with Sand Method. [2] VERT: *Vertissolo Ebânico* located in Santana do Livramento RS; NB_{PAI}: *Nitossolo Bruno*, located in Painel/SC; LB_{VAC}: *Latossolo Bruno*, located in Vacaria/RS; LV_{CN}: *Latossolo Vermelho*, located in Campos Novos/SC; NB_{PS}: *Nitossolo Bruno*, located in Ponte Serrada/SC; NB_{CUR}: *Nitossolo Bruno*, located in Cutitibanos/SC; LB_{VAR}: *Latossolo Bruno*, located in Vargeão/SC; LV_{CAS}: *Latossolo Vermelho*, in Cascavel/PR; and VERT: *Vertissolo*, located in Santana do Livramento/RS. [3] Equal letters indicate that there was no statistical difference at 5 % probability of error (p<0.05).

Table 5. Intervals of $COLE_{sand}$ indexes and the shrinkage intensities of shrinkable soils, through cluster analysis by the error estimate

Intervals of the $COLE_{sand}$[(1)] indexes	Shrinking intensity	Pedon/horizon[(2)]
>0.105	Highly shirinking	NB_{PAI}/A, LB_{VAC}/A, NB_{PS}/B
0.085 to 0.105	Shirinking	NB_{PAI}/B, NB_{CUR}/A
0.05 to 0.085	Low shirinking	LB_{VAC}/B, LV_{CN}/A, LV_{CN}/B, NB_{PS}/A, NB_{CUR}/B, LB_{VAR}/A, LB_{VAR}/B
< 0.05	Non-shirinking	LV_{CAS}/A, LV_{CAS}/B

[(1)] $COLE_{sand}$: coefficient of linear extensibility obtained by the Ring with Sand Method. [(2)] NB_{PAI}: *Nitossolo Bruno*, located in Painel/SC; LB_{VAC}: *Latossolo Bruno*, located in Vacaria/RS; NB_{PS}: *Nitossolo Bruno*, located in Ponte Serrada/SC; LV_{CN}: *Latossolo Vermelho*, located in Campos Novos/SC; NB_{CUR}: *Nitossolo Bruno*, located in Cutitibanos/SC; LB_{VAR}: *Latossolo Bruno*, located in Vargeão/SC; LV_{CAS}: *Latossolo Vermelho*, in Cascavel/PR.

in regard to shrinkage intensities. Based on this evaluation, we can conclude that the NB_{PAI} (horizon A), LB_{VAC} (horizon A), and NB_{PS} (horizon B) soils were classified as highly shrinking. The LV_{CAS} A and B horizons were classified as non-shrinking, as shrinkage was not verified in field observations.

The analysis of groups did not lead to a distinction of soils in accordance with A and B horizons, which indicates that several factors besides mineralogy and organic matter content may be involved in soil shrinkage processes.

In Brazil, the main soils for which the processes of expansion/shrinkage are normally studied are the *Vertissolos*. They have limit values already set in the literature and established through the Saran Resin method. As already mentioned, this method is currently little used, since the resin is quite toxic and is no longer marketed. Another disadvantage is that the procedure is quite time consuming. Because of that and introduction of shrinkage as obligatory for classification of *Latossolos* and *Nitossolos*, it becomes pertinent to introduce a method for evaluating the intensity of shrinkage that can be related to existing ones; however, with features that allow it to distinguish this property from others and that is easy to use.

In a study involving *Vertissolos* of Argentina, Taboada (2004) proposed COLE indexes to evaluate the degrees of shrinkage using the Saran Resin methodology. The authors classified the soils in four degrees of shrinkage, according to the COLE values obtained, as low (COLE <0.03), moderate (COLE from 0.03 to 0.06), high (COLE from 0.06 to 0.09), and very high (COLE >0.09). COLE values were calculated by the ratio of volume and displaced liquid, in undisturbed wet and dry samples, through the formula: $COLE = [(v\ ⅓atm/v\ dried)^{⅓}] - 1$, in which *v ⅓atm* is the volume of the sample subjected to a tension of ⅓ atmosphere, and *v dried* is the dry soil volume at 105 °C.

According to the classification proposed by Taboada (2004), COLE values above 0.03 are already considered a moderate degree of shrinkage. In the USA soil classification system, for indication of the vertic subgroups, a COLE value greater than 0.06 (Soil Survey Staff, 2014) is proposed, and in the conceptualization of *Vertissolos* contained in the 2nd complete edition of Soil Taxonomy (Soil Survey Staff, 1999) values of COLE between 0.07 and 0.20 are cited as the common interval. In all cases, the suggested methodology for COLE determination involves the use of samples with undisturbed structure in the laboratory or measurements of linear displacement in the field.

It should be noted that the A and B horizons of the LV_{CAS} (Table 6) were considered low using the Taboada (2004) classification, which highlights the viability of the method, since this soil does not exhibit shrinkage. Very high values were randomly found in the A and B horizons, so that the occurrence of shrinkage cannot be associated with external factors of action in any way.

The new methodology, tested in the present study, proved capable of efficiently evaluating shrinkage in *Nitossolos* and *Latossolos*, and, thus, it can be applied in a practical way for quantification of these soils, since the intervals were also established.

Table 6. Soil shrinkage intensities, using the classification obtained for *Vertissolos* with the Saran Resin Method (Taboada, 2004) as: low (COLE <0.03), moderate (COLE from 0.03 to 0.06), high (COLE from 0.06 to 0.09), and very high (COLE >0.09)

Pedon/horizon[1]	$COLE_{sand}$[2]	Shrinkage intensity
NB_{PAI}/A	0.12	Very high
NB_{PAI}/B	0.10	Very high
LB_{VAC}/A	0.11	Very high
LB_{VAC}/B	0.08	High
LV_{CN}/A	0.06	Moderate
LV_{CN}/B	0.07	High
NB_{PS}/A	0.08	High
NB_{PS}/B	0.12	Very high
NB_{CUR}/A	0.10	Very high
NB_{CUR}/B	0.08	High
LB_{VAR}/A	0.06	Moderate
LB_{VAR}/B	0.08	High
LV_{CAS}/A	0.02	Low
LV_{CAS}/B	0.03	Low

[1] NB_{PAI}: *Nitossolo Bruno*, located in Painel/SC; LB_{VAC}: *Latossolo Bruno*, located in Vacaria/RS; NB_{PS}: *Nitossolo Bruno*, located in Ponte Serrada/SC; LV_{CN}: *Latossolo Vermelho*, located in Campos Novos/SC; NB_{CUR}: *Nitossolo Bruno*, located in Cutitibanos/SC; LB_{VAR}: *Latossolo Bruno*, located in Vargeão/SC; LV_{CAS}: *Latossolo Vermelho*, in Cascavel/PR. [2] $COLE_{sand}$: coefficient of linear extensibility obtained by the Ring with Sand Method.

CONCLUSIONS

The quantification of shrinkable soils in southern Brazil can be determined by a simple, fast, and efficient methodology that is based on obtaining the variation of soil volume between the soil with moisture at field capacity and the dry soil. The method, called the Ring with Sand Method, proved to be feasible for quantification of soil shrinkage, serving as an alternative to the classical Saran Resin method.

The Metallic Mercury Method and the Syringe Method were not effective in discriminating soil shrinkage. Thus, they are not recommended for use in evaluation of the shrinking property in soils of the South of Brazil.

With practical application of the Ring with Sand Method, the coefficient of linear extensibility ($COLE_{sand}$) of the evaluated soil is obtained. According to the intensity of shrinkage (higher or lower $COLE_{sand}$) of shrinkable soils, soils can be classified as highly shrinking, shrinking, low shrinking, and non-shrinking.

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