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INDEX OF SOIL PHYSICAL QUALITY OF HARDSETTING SOILS ON THE BRAZILIAN COAST[1]

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SUMMARY

Many soils have a hard-setting behavior, also known as cohesive or "coesos". In such soils, the penetration resistance increases markedly when dry and decreases considerably when moist, creating serious limitations for plant emergence and growth. To evaluate the level of structure degradation in hard-setting soils with different texture classes and to create an index for assessing soil hardness levels in hard-setting soils, six soil representative profiles were selected in the field in various regions of Brazil. The following indices were tested: *S*, which measures soil physical quality, and *H*, which analyzes the degree of hardness and the effective stress in the soil during drying. Both indices were calculated using previously described functions based on data from the water-retention curves for the soils. The hard-setting values identified in different soils of the Brazilian Coastal Tablelands have distinct compaction (hardness) levels and can be satisfactorily measured by the *H* index. The *S* index was adequate for evaluating the structural characteristics of the hard-setting soils, classifying them as suitable or poor for cultivation, but only when the moisture level of the soil was near the inflection point. The *H* index showed that increases in density in hard-setting soils result from increases in effective stress and not from the soil texture. Values for Bd > 1.48 kg dm^{-3} classify the soil as hard-setting, and the structural organization is considered "poor".

Index terms: *S* index, coastal tablelands, soil consistency, hardened horizons.

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RESUMO: *ÍNDICE DA QUALIDADE FÍSICA EM SOLOS COESOS NA FAIXA COSTEIRA DO BRASIL*

Muitos solos exibem o comportamento coeso, o qual caracteriza solos que, quando secos, apresentam incremento acentuado de resistência à penetração e sensível redução dessa resistência, quando úmidos, oferecendo sérias limitações à emergência e ao crescimento das plantas. Com os objetivos de avaliar o nível de degradação da estrutura em solos coesos com diferentes classes texturais e estabelecer um índice para determinar o grau de dureza dos solos que apresentam o caráter coeso, foram selecionados seis perfis de solos previamente identificados no campo e localizados em diferentes regiões do país. Testaram-se os índices: S*, que determina a qualidade física do solo; e o* H*, que avalia o grau de dureza e o estresse efetivo sofrido pelo solo durante o secamento. Ambos os índices foram definidos por meio de funções preestabelecidas, utilizando dados da curva de retenção de água no solo. Os resultados comprovaram que o caráter coeso identificado em diferentes solos, na faixa de Tabuleiros Costeiros do Brasil, evidenciou níveis distintos de adensamento (dureza) e pode ser quantificado satisfatoriamente pelo índice* H*. A utilização do índice* S *foi adequada para avaliar as condições estruturais dos solos com caráter coeso, classificando-se como bons ou ruins para o cultivo, mas somente quando o solo estava na umidade correspondente ao ponto de inflexão. O índice* H *comprovou que o aumento da densidade do solo nos solos coesos é proveniente do aumento do estresse efetivo e não da textura do solo. Valores de Ds > 1,48 kg dm*$^{-3}$ *permitem o enquadramento do solo como coeso, em razão da organização estrutural ser considerada "ruim".*

Termos de indexação: índice S*, tabuleiros costeiros, consistência do solo, horizontes endurecidos.*

INTRODUCTION

Brazilian cohesive soils are soils with compacted subsurface pedogenic horizons, which are highly resistant to penetration with tools and hard to extremely hard when dry. However, when wet, the cohesion disappears and the soil becomes friable (Embrapa, 2013). Cohesive soils are structurally very unstable, and generally dense with a typical behavior of degraded soils (Jacomine, 1996).

These soils occur in a geomorphological unit known as the Coastal Tablelands (CTs) in Brazil and are attributed to the sedimentary deposits from the Tertiary era that created the Barreiras Formation. Despite the extensive area occupied by the Coastal Tablelands (CTs) along the Brazilian coast (10,000,000 ha in the Northeast region alone) and their agricultural and economic importance, the identification of cohesive soils is still mainly based on qualitative analysis of the morphological properties of the soil, as described by Embrapa (2013), which makes the identification of Brazilian cohesive soils arbitrary and largely dependent on experience. Giarola et al. (2001) demonstrated the similarity between the physical and morphological properties of cohevise soils in Brazil and hard-setting soils in Australia. Advances in the study of Australian hard-setting soils allowed the use of quantitative indices to identify hard-setting soils in that country based on the curve of soil penetration resistance (Becher et al., 1997), the soil organic matter content and the tensile strength of air-dried aggregates (Mullins, 1997). The cohesive soils are called hard-setting for better reading.

With the purpose of creating effective and easily measured quantitative indices, Dexter (2004a,b) proposed two for identifying hard-setting soils. The first index, *S*, evaluates the physical quality of soils and is determined from the slope of the soil water retention curve at the inflection point. The second index is called the hard-setting or *H,* index, and is based on the rate of change of the effective stress with water content θ at the inflection point θi. According to Dexter (2004a), the value of the *S* index indicates the size classes into which soil porosity most commonly fits. A value of 0.035 is used as the threshold between degraded and non-degraded soils and, consequently, between hard-setting and non-hard-setting soils. The *H* index shows that a soil with a high degree of hard-setting behavior at a given moisture level and at inflection point θi, will also have a hard-setting behavior at higher moisture levels.

According to Lima et al. (2005a), the various hard-setting soils along the Brazilian coast have the same physical limitations, but to different extents. Thus, this study confirmed the hypothesis that the hardness of the hard-setting soils of the Brazilian Coastal Tablelands can be quantified using the *S* and/or *H* indices. The aim of this study was to analyze the level of structural degradation in hard-setting soils with different textural classes and to determine which index best measures the hardness of hard-setting soils in various regions of the country.

MATERIAL AND METHODS

Locations of the study areas

Six soil profiles were collected in several areas of the Coastal Tablelands (CTs) in Brazil, located between the States of Rio de Janeiro (RJ) and Ceará (CE), distributed as follows: Profile 1 - Located in an area under secondary forest in Camocim (CE); Profile 2 - Area under native forest in the municipality of Parazinho (CE); Profile 3 - Embrapa - Experimental Station CNPAT under a cashew orchard in Pacajus (CE); Profile 4 - Forest reserve of the Bahian Corporation for Agricultural Development (Empresa Baiana de Desenvolvimento Agrícola - EBDA) with evergreen rainforest in Cruz das Almas (BA); Profile 5 - Experimental area of the Aracruz corporation under an *Eucalyptus* forest in Aracruz (ES); and Profile 6 - Area under abandoned perennial pasture in the municipality of Campos dos Goytacazes (RJ) (Figure 1).

The study soils were described using 1.5 × 1.5 × 2.0 m trenches. Morphological analysis and determination of horizons with hard-setting properties were based on the standards and definitions of Lemos & Santos (1996), paying particular attention to the degree of consistency and type of structure, as defined by Jacomine (1996) and Embrapa (1999). The data are shown in table 1. This step allowed the proper

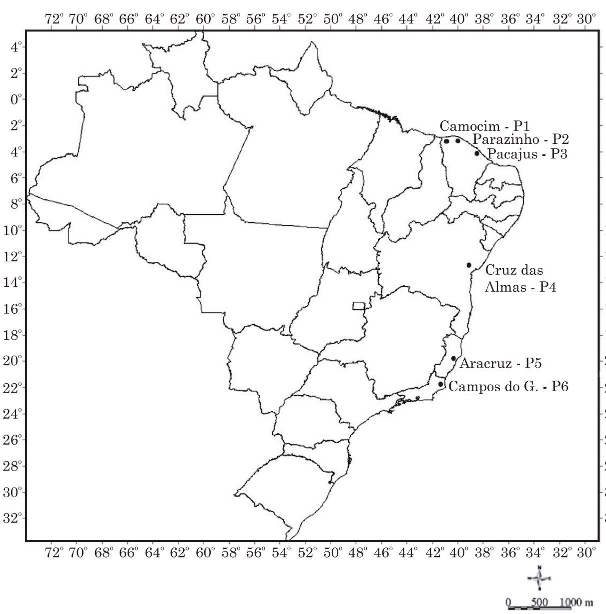

Figure 1. Location of the counties on the Coastal Tablelands in Brazil where the studied hard-setting soils were selected.

localization of the hard-setting soils as well as their taxonomic classification based on the Brazilian System for Soil Classification (Embrapa, 2013), as follows:

Profile 1 - Camocim (CE): Plinthic Dystrophic Cohesive Abruptic Yellow Argisol

Profile 2 - Parazinho (CE): Plinthic Dystrophic Cohesive Abruptic Red-Yellow Argisol

Profile 3 - Pacajus (CE): Dystrophic Cohesive Sandy Gray Argisol

Profile 4 - Cruz das Almas (BA): Argisolic Dystrophic Cohesive Yellow Latosol

Profile 5 - Aracruz (ES): Dystrophic Cohesive Typic Yellow Argisol

Profile 6 - Campos dos Goytacazes (RJ): Dystrophic Cohesive Typic Yellow Argisol.

The hard-setting horizons studied were divided into two texture classes based on their particle size distribution (Table 2), which was measured using the pipette method, as described by Gee & Or (2002). Soil organic matter (OM) was evaluated by titration (Raij & Valadares, 1979).

Soil physical quality index

The hard-setting index, *H*, was calculated using the method proposed by Dexter (2004a,b,c). The curve was created using 11 pressure levels, four of which were equilibrated using soil cores (2.4 × 4 cm) in a tension table (-1, -2, -4, -8 kPa), as described by Tormena et al. (1998). The others (-25, -50, -100, -200, -400, -800, -1500 kPa) were performed on aggregates (clods) with a diameter of approximately 4 mm, using pressure chambers with porous plates (Klute, 1986).

For all horizons, volumetric rings were removed in a laboratory under controlled humidity using the method proposed by Lima et al. (2005b).

Data were fitted by an equation of van Genuchten (1980):

$$\theta = (\theta s - \theta r)\,[1 + (\alpha h)^n]^{-m} + \theta r \qquad (1)$$

where θs represents the saturation moisture, θr is the residual humidity at a tension of -1500 kPa, h is the applied pressure, and α and n are the model parameters. Using the restriction $m = 1 - 1/n$ proposed

Table 1. Field descriptions of Brazilian hard-setting soils

Location	Hardsetting horizon[1]	Sample depth	Soil structure	Soil consistence	
			Dry	Dry	Moist
		m			
P1 - Camocim (CE)	Bt	0.52	massive (apedal)	extremely hard	friable
P2 - Aracruz (ES)	Bt	0.39	massive (apedal); block formation tendency	hard	friable
P3 - Campos dos Goytacazes (RJ)	Bt	0.60	massive (apedal); block formation tendency	hard	friable
P4- Pacajus (CE)	Bt	0.97	massive (apedal); block formation tendency	extremely hard	friable / firm
P5 - Parazinho (CE)	AB	0.41	massive (apedal)	extremely and very hard	very friable
P6 - Cruz das Almas (BA)	AB	0.21	massive (apedal); block formation tendency	hard	very friable

[1] Bt: horizon with alluvial clay accumulation, AB: transition horizons.

Table 2. Chemical properties and particle size distribution of hard-setting soils

Location	OM(1)	Bd(2)	Clay	Silt	Sand	Textural class
	g kg^{-1}	kg dm^{-3}		g kg^{-1}		
P1 - Camocim (CE)	2.20	1.62	400	70	530	Sandy clay
P2 - Aracruz (ES)	7.33	1.57	410	50	540	Sandy clay
P3 - Campos dos Goytacazes (RJ)	5.97	1.53	510	40	450	Sandy clay
P4 - Pacajus (CE)	3.48	1.71	270	50	680	Sandy clay loam
P5 - Parazinho (CE)	4.26	1.60	250	50	700	Sandy clay loam
P6 - Cruz das Almas (BA)	11.12	1.53	300	50	650	Sandy clay loam

(1) OM: organic matter. (2) Bd: soil bulk density. Clay < 0.002 mm, Silt 0.002-0.05 mm, and Sand 0.05-2.00 mm.

by Mualem (1986), m was calculated. In this study, h is expressed in kPa and θ in g g^{-1}.

The derivative of equation 1 can be expressed as follows:

$$\frac{d\theta}{d\,ln(h)} = -mn(\theta s - \theta r)\alpha^n h^n \left[1 + (\alpha h)^n\right]^{-m-1} \quad (2)$$

Thus, the model for the water pressure in the soil at the inflection point was:

$$hi = \frac{1}{\alpha} \times \left[\frac{1}{m}\right]^{\frac{1}{n}} \quad (3)$$

The soil physical quality index, S, representing the curve slope at the inflection point, was obtained by substituting equation 3 into equation 2, resulting in:

$$S = \left(-n \times (\theta s - \theta r) \times \left(1 + \frac{1}{m}\right)^{-(1+m)}\right) \quad (4)$$

Substituting equation 3 into equation 1 provides the water content at the inflection point, which is also the optimal water content for cultivation:

$$\theta i = (\theta s - \theta r) \times \left[1 + \frac{1}{m}\right]^{-m} + \theta r \quad (5)$$

Using the above equations, the H index can be calculated as follows:

$$H = \left[\frac{hi}{\theta s}\right] \times \left[1 + \frac{\theta i}{S}\right] \quad (6)$$

The suffix i represents the inflection point of the curve. The above equations were previously described by Dexter (2004a,b). The significant difference between the above parameters was tested using the t-test, coefficient of variance and the standard error of three replications in the SAS software package, version 8.2. The S and H values used in this study are expressed in kPa, and soil moisture in gravimetric bases (g g^{-1}).

The effective diameter (D) of the empty pores at a given pressure (h) was calculated using the capillary equation of Vomocil (1965):

$$D = -\frac{4\sigma\, cos\gamma}{\rho g h} = -\frac{C}{h} \quad (7)$$

where σ (kg s^{-2}) is the surface tension of the water, γ the contact angle between the pore walls and the water in degrees, ρ is the water density (kg m^{-3}), g the acceleration due to gravity (m s^{-2}), and C the constant of $(4\sigma cos\gamma)/(\rho g)$.

RESULTS AND DISCUSSION

Table 3 shows the average and standard error of the parameters θr, θs, α and n determined (Equation 1) by fitting the water retention curve for hard-setting soils, divided into two groups based on the soil texture class (Table 2). In this way, differences between the degrees of compaction for each horizon could be analyzed.

The moisture content at the saturation point θs in sandy clay textures soils was not significantly different between horizons in profiles P1 and P5, unlike P6, which had a higher θs value (0.24 g g^{-1}; Table 3). For the hard-setting soils with medium texture (sandy clay loam, P3 and P2), θs was not significantly different, and the highest θs value was found for P4 (0.22 g g^{-1}). The higher θs values in the P6 and P4 profiles may be due to the larger amount of total clay found in these horizons compared to the other horizons from the same texture group.

Residual moisture θr was not significantly different ($p<0.001$) between hard-setting horizons with clayey texture (sandy clay). The opposite was found in the hard-setting soils with medium texture: the highest θr value (0.11 g g^{-1}) was found in P4 and the lowest (0.06 g g^{-1}) in P3 (Table 2), consistent with the different hard-setting degrees in these horizons.

The α values behaved similarly to θs in both texture classes. For parameter n, which determines the shape of the retention curve, there were no statistical differences between the various hard-setting horizons studied here, regardless of the texture class. These results show that the differences between the retention curves for these horizons are induced by the parameters θs, α and θr (Table 3).

Parameter α is correlated with the inverse of the air-entry pressure, which is the pressure at which air enters the soil during drying. Under these conditions, high α values indicate a rapid change in water content, and low α values indicate a slight change in water content as the pressures become more negative, which generally occurs in soils with fine texture and in unstructured soils (Hodnett & Tomasella, 2002).

The observation of higher values for α in the P4 and P6 hard-setting soils (0.2015 and 0.2602 kPa) indicates that the two horizons have a particularly stable structure that is likely associated with higher levels of organic material and clay, and that structure is consistent with their tendency to form blocks in the field. That is, the sudden change in water content indicates that pores with effective diameters between 0.15 and 0.03 mm were emptied by the application of pressure at low levels (-2 to -10 kPa). The other hard-setting soils (P1, P2, P3 and P5) required higher pressure (> -10 kPa) to clear pores with similar diameters (Figure 2a,b).

Although water retention differed between the sandy clay hard-setting soils at low pressures (Figure 2a) when higher pressures were applied, the curves intersected between -20 and -90 kPa, and a significant difference was not observed after this point. Therefore, it can be inferred that water retention and the extent of particle compaction vary between hard-setting soils with sandy and clayey textures, as the behavior of the curve is determined by the structure type under moist conditions (Ψ > -20) and by the soil texture when dry. That is, even the horizons that tend to form clumps when moist have the same physical restrictions as other hard-setting soils in the same texture class at low water content.

The hard-setting soils with a sandy clay loam texture behave differently, and distinct retention levels were observed under both low and high pressure levels (Figure 2b), which are mainly governed by higher or lower compaction of the particles and distribution of the porous space and, to a lesser extent, the colloidal fraction of the soil.

The distribution of the pore classes in the hard-setting soils with sandy clay texture and sandy clay

Table 3. Mean and standard error of the adjustment parameters of the van Genuchten equation for hard-setting soils with sandy clay and sand clay loam texture (n = 3)

Area	θs	θr	α	n
	g g^{-1}		kPa	
		Sandy clay		
P1 - Camocim (CE)	0.19 ± 0.001 b	0.13 ± 0.001 a	0.0811 ± 0.006 b	1.832 ± 0.044 a
P2 - Aracruz (ES)	0.20 ± 0.001 b	0.14 ± 0.003 a	0.0637 ± 0.011 b	2.385 ± 0.158 a
P3 - Campos dos Goytacazes (RJ)	0.24 ± 0.011 a	0.14 ± 0.019 a	0.2015 ± 0.051 a	1.941 ± 0.276 a
		Sandy clay loam		
P4 - Pacajus (CE)	0.15 ± 0.002 b	0.09 ± 0.001 b	0.0569 ±0.012 b	2.286 ± 0.114 a
P5 - Parazinho (CE)	0.15 ± 0.005 b	0.06 ± 0.002 c	0.0782 ± 0.015 b	1.948 ± 0.197 a
P6 - Cruz das Almas (BA)	0.22 ± 0.013 a	0.11 ± 0.003 a	0.2602 ± 0.047 a	1.877 ± 0.095 a

Means followed by the same letter in the columns do not differ significantly (p<0.001).

Table 4. Mean and standard error of Index *S*, optimal water potential for tillage (*hi*), optimal soil water content for tillage (θi) and hardsetting index (*H*) for the hard-setting soils studied (n=3)

Area	Index *S*	*hi*	θi	Index *H*
		kPa	g g^{-1}	
		Sandy clay		
P1 - Camocim (CE)	0.021 ± 0.001 cD	-19 ± 1.546 aA	0.16 ± 0.001 cC	891 ± 101.778 aA
P2 - Aracruz (ES)	0.027 ± 0.001 bCD	-21 ± 2.684 aA	0.17 ± 0.001 bCB	768 ± 089.731 aBA
P3 - Campos dos Goytacazes (RJ)	0.033 ± 0.002 aCB	-09 ± 1.456 bB	0.20 ± 0.003 aA	266 ± 058.270 bC
		Sandy clay loam		
P 4 - Pacajus (CE)	0.028 ± 0.002 bCB	-24 ± 3.551 aA	0.12 ± 0.001 bD	877 ± 84.911 aA
P5 - Parazinho (CE)	0.034 ± 0.003 baB	-20 ± 1.384 aA	0.12 ± 0.004 bD	580 ± 03.021 bB
P6 - Cruz das Almas (BA)	0.041 ± 0.002 aA	-06 ± 0.872 bB	0.18 ± 0.007 aB	149 ± 31.536 cC

Different lowercase letters, in columns, differ significantly between texture classes of horizons (p<0.001). Uppercase letters compare all horizons, regardless of the texture class. *S*: index of soil physical quality, *hi*: soil water potential at the inflection point; θi: optimum soil water content for tillage; *H*: hard-setting index.

loam texture (Figure 3), demonstrates the different compaction levels in the hard-setting soils as a function of texture class. The differences between macro- and micropore behavior in the sandy clay hard-setting soils showed were clear, but similarly within pore classes. However, the differences between pore classes were not as apparent in the sandy clay loam texture soils, and significant differences were observed within a single pore class. These differences may severely hamper the identification of hard-setting soil behavior in the field.

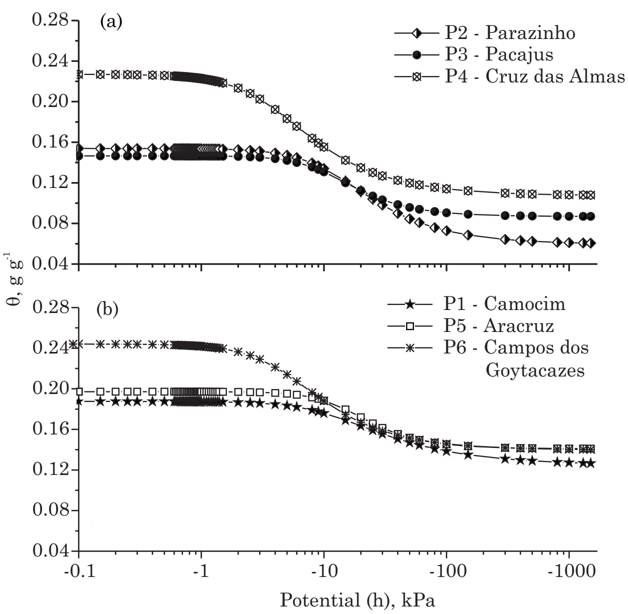

Figure 2. Water retention curve for hard-setting soils with sandy clay (a) and sandy clay loam (b) textures, at different locations of the Coastal Tablelands in Brazil.

Significant differences between micropores and macropores were observed in the hard-setting soils with sandy clay loam texture (Figure 3b), which may seriously impair the identification of this trait in the field, as the difference between pore classes in P2 was only 13 %, whereas the variation in the other horizons was higher than 40 %, independent of the texture.

Figure 4 shows the derivative of equation 1 relative to the log of the pore radius, i.e., the changes in the shape of the pore-size distribution curve in all studied hard-setting soils. The peak of the derivative, corresponding to the value of the S index, was highest in the soils P4 and P6. The value for S, corresponding to the part of the curve where the pore volume increases greatly as the radius decreases, represents the point on the curve where most changes occur during compaction (Startsev & McNabb, 2001), i.e., the higher this value, the less physical damage to the structure. Using the critical value of S = 0.035 suggested by Dexter (2004c), as the limit between soils with "suitable" and "poor" physical quality, the hard-setting soils of the profiles P4 and P6, with $S > 0.035$, had the best structural condition. We emphasize that the value of the S index can be used as a complementary parameter to morphological descriptions in the field (Table 1), as well as used to determine the hardness of the hard-setting soil.

Figure 4 shows that all soils with "poor" physical quality have derivative peaks at the same pore size, thereby indicating that the physical structures of these horizons are homogeneous, despite differences in the compaction degree: the lower the derivative

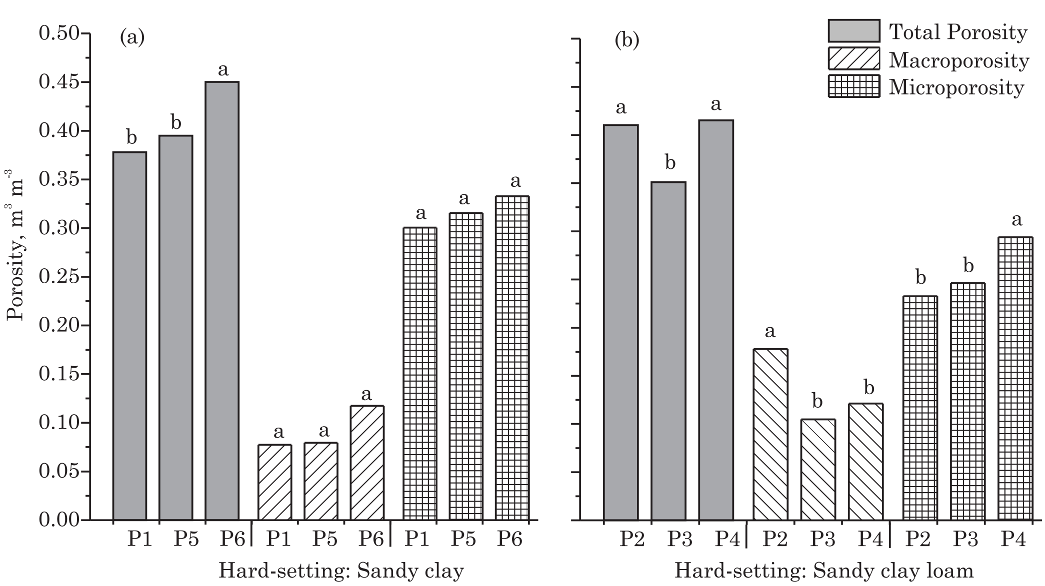

Figure 3. Macroporosity, microporosity and total porosity of hard-setting soils with sandy clay (a) and sandy clay loam (b) textures. Means followed by the same letter do not differ significantly from one another (p=0.05). P1: Camocim (CE), P2: Parazinho (CE), P3: Pacajus (CE), P4: Cruz das Almas (BA), P5: Aracruz (ES), and P6: Campos dos Goytacazes (RJ).

peak or S value, the greater the soil compaction (Startsev & McNabb, 2001).

Figure 4 also shows that the greater the S value, the smaller is the interval between the diameters of the maximum pore volume. With a decrease in the S value, regardless of the texture class, there was an increase in the maximum pore diameter, and the pores were emptied more gradually. Startsev & McNabb (2001) reported that many of the changes in the shape of the water-retention curve and the pore-size distributions occur at pressures greater than the field capacity (-10 kPa) of non-compacted soils, and as compaction increases, the pressures decrease.

The data shown in figure 5 show that a comparison of the values of the S index with bulk density using the limit of 0.035 yields a bulk density

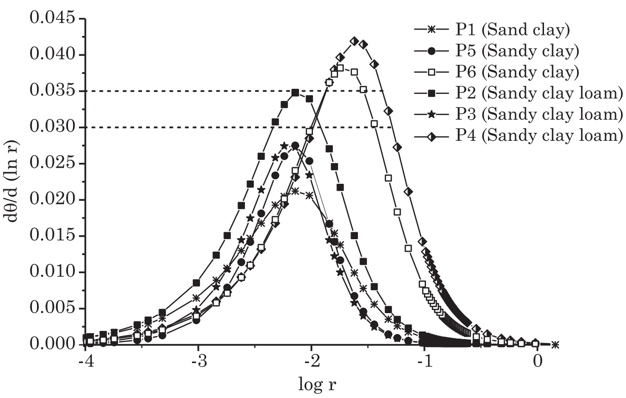

Figure 4. Pore size distribution determined by the derivative equation of the soil water retention curve (Equation 2) in function to the logarithm of the pore radius of hard-setting soils with sandy clay and sandy clay loam textures.

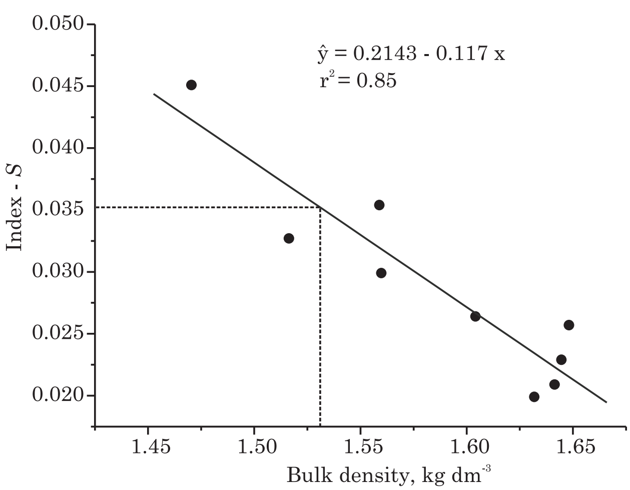

Figure 5. Index S values related to soil bulk density of hard-setting soils with sandy clay and sandy clay loam textures. The dashed line shows the S = 0.035 and the corresponding value of bulk density.

limit of 1.53 kg dm^{-3}, i.e., hard-setting soils with soil densities equal to or greater than the density limit require special attention for the particular type of limitation caused by hard-setting and the degree of physical damage.

The averages and standard errors for S, hi, θi and H are shown in table 4. The values of the optimal cultivation pressure, hi, differed based on the amount of compaction in the hard-setting soils, indicating the pressure at which the peak of the derivative is maximized. The lowest pressures were observed for the soils from profiles P3 and P6; the other soils did not significantly differ from each other ($p<0.001$), exhibiting values below the field capacity (-10 kPa). Parameter θi represents the optimal moisture for cultivation at pressure (hi). These values varied more than those of hi in clay-textured horizons (Table 4).

The regression in figure 6 illustrates the negative linear correlation between the S and H indices. This relationship can be used to estimate a critical value or limit of the H index, which differentiates between hard-setting soils with "suitable" or "poor" structural organization based on the critical value of the S index, and the critical value for H is 292. The H index measures the effective stress in the hard-setting soils at the moisture level found at the inflection point, θi. This stress is mainly due to the pockets of water that remain between the particles when the soil dries. The water pockets pull the particles together as a result of two phenomena: the negative pore pressure caused by the water bridges and the surface tension of the water forming the bridges (Dexter, 2004b).

The average H values found in Brazilian hard-setting soils with sandy clay loam and sandy clay textures were 535 and 642, respectively (Table 4), which are much higher than the average H values

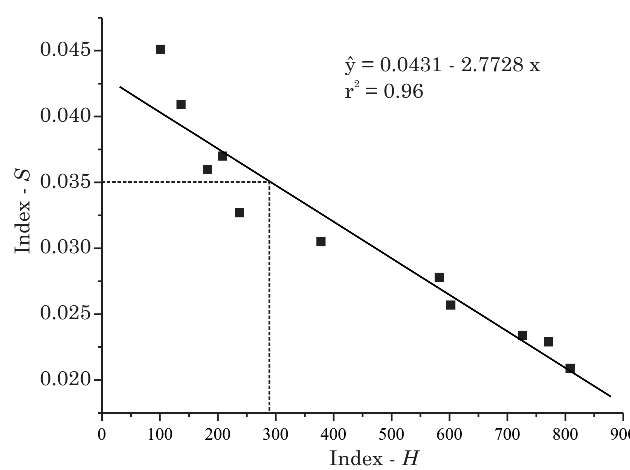

Figure 6. Illustration of negative linear dependence between the indexes S and H. The dashed line shows the S value of 0.035 and the corresponding H value.

found in Australian hard-setting soils, which were between 150 and 200 for the same texture classes, respectively (Dexter, 2004b), demonstrating the limitations of the observed similarities between the physical behavior of the two soils (Giarola et al., 2001).

The *H* index indicates a high degree of hard-setting behavior for a given moisture content at the inflection point, θi, and this high value is also found at higher moisture levels, unlike the *S* index, which reaches its maximum value only at the point of minimum curvature. It is therefore estimated, that at the point where the soil ceases to be friable and becomes hard, the *H* index quantifies the degree of hardness or degree of physical damage between the hard-setting soils more accurately, because the effective stress increases linearly with increasing soil penetration resistance (Giarola et al., 2003).

Under conditions of low moisture, when pores are filled with water and pressure is high, the curve of the derivative ($d\theta/d(\ln r)$) decreases, and the *S* value is not significantly different between soils (Figure 4).

The data in figure 7 show the effects of the various levels of compaction (measured via bulk density) of the soils on the *H* index, which rapidly increases as bulk density increases, regardless of the texture class. Thus, a function was developed that allows the estimation of the dependence of *H* on bulk density, Bd: $H = -4106.42 + 2968.45$ Bd (Figure 7). This demonstrates that increases in hard-setting bulk density are driven by an increase in effective stress, not by soil texture, and that horizons with Bd > 1.48 kg dm^{-3} have sufficiently high effective stresses to classify them as hard-setting with poor structural organization.

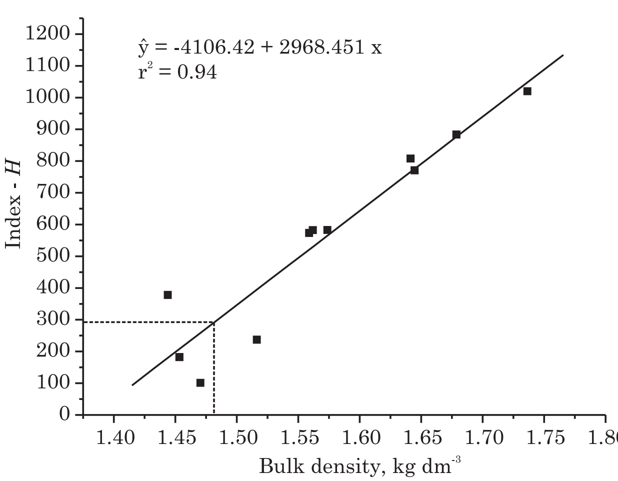

Figure 7. Index *H* values in function of the soil bulk density for hard-setting soils with sandy clay and sandy clay loam textures. The dashed line shows the value *H* = 292 and the corresponding value of bulk density.

CONCLUSIONS

1. These results support the hypothesis that hard-setting soils of the Brazilian Coastal Tablelands have varying levels of compaction (hardness) and that soil hardness can be satisfactorily quantified by the *H* index.

2. The soil physical quality index *S*, adequately evaluated the structural conditions of the hard-setting soils, classifying them as suitable or poor for cultivation, but only when the moisture level of each soil was at the inflection point.

3. The soil profiles collected in Campos dos Goytacazes and Cruz das Almas, despite having been identified as hard-setting under field conditions, have good physical and structural conditions for cultivation due to their low degree of hardness compared to the other studied soils.

4. The *H* index showed that increased bulk density in the hard-setting soils arises from increased effective stress and is not a result of soil texture. Values of Bd > 1.48 kg dm^{-3} indicate that soils are hard-setting because their structural organization is considered "poor".

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