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THE EFFECT OF TEXTURE ON STRENGTH OF SOUTHEASTERN COASTAL PLAIN SOILS[1]

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ABSTRACT

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The effect of texture on soil strength was analyzed for 17 soils, mainly from the Southeastern Coastal Plains. All samples were tested with a 5-mm, flat-tipped probe after equilibration at 100 kPa of soil—water tension. Both mechanical compression and water consolidation (compaction by wetting and drying) were used to compact the soils. Probe resistance of water-consolidated samples was significantly affected by texture. In fact, bulk density or probe resistance of soils compacted by methods of constant compactive force or constant methodology correlated well with texture for Coastal Plain soils.

A secondary effect of texture involved a significant, positive correlation of silt with probe resistance for sandy soils low in organic matter. Bulk densities at root-restricting conditions (2 MPa) compared well with bulk density values obtained by water consolidation and the Random Packing Model of Gupta and Larson, all of which were significantly correlated to texture.

INTRODUCTION

Many Ap and E horizons of soils in the Southeastern Coastal Plains of the United States tend to be sandy textured, weakly structured, low in organic matter and susceptible to drought. In addition to this, they have highly compacted layers which often limit root growth (Campbell et al., 1974). Cultural practices that decrease soil strength allow root exploration of an increased soil volume and thereby may increase yield (Barley et al., 1965; Taylor et al., 1966; Camp and Lund, 1968; Gerard et al., 1982; Box and Langdale, 1984; Ide et al., 1984; Peterson et al., 1984).

[1] A project report of research conducted jointly by the Agricultural Research Service and the Soil Conservation Service of the U.S. Department of Agriculture.

TABLE I

Soil classification data

Soil series	Soil ref. no.	Taxonomic classification	Location	Soil description	
Beatrice	2	Vertic Hapludult; clayey, montmorillonitic, thermic	Monroe Co., AL	Ap 0—8 cm;	10YR4/2 C; moderate fine granular structure; friable
Escambia	3	Plinthaquic Paleudult; coarse loamy, siliceous, thermic	Monroe Co., AL	Ap 0—22 cm;	10YR5/1 FSL; weak fine granular structure; very friable
Faceville	11	Typic Paleudult; clayey, kaolinitic, thermic	Peach Co., GA	Ap 0—20 cm;	10YR4/2 LFS; weak fine granular structure; very friable
Florala	9	Plinthaquic Paleudult; coarse loamy, siliceous, thermic	Covington Co., AL	A 0—20 cm;	10YR4/1 SL; weak fine granular structure; very friable
Lahaina[1]	15	Tropeptic Haplustox; clayey, kaolinitic, isohyperthermic	Oahu, HI	Ap SICL;	mixed composite sample; research plots; no pedon description
Lucy	1	Arenic Paleudult; loamy, siliceous, thermic	Clarke Co., AL	Al 0—13 cm;	2.5Y4/2 S; very weak fine granular structure; very friable
Lucy	12	Arenic Paleudult; loamy, siliceous, thermic	Mitchell Co., GA	Ap 0—23 cm;	10YR3/3 S; weak fine granular structure; very friable
Malbis	4	Plinthic Paleudult; fine loamy, siliceous, thermic	Conecuh Co., AL	Ap 0—15 cm:	10YR4/2 FSL; weak fine granular structure; friable
Norfolk	16	Typic Paleudult; fine loamy, siliceous, thermic	Florence Co., SC	Ap 0—23 cm;	10YR5/3 LFS; moderate medium granular structure; very friable
	20			E 23—33 cm;	10YR7/4 LFS; weak medium granular structure; firm
	21			Btl 33—97 cm;	10YR5/6 SCL; moderate medium sub-angular blocky structure; friable
Norfolk	17	Typic Paleudult; fine loamy, siliceous, thermic	Richland Co., SC	Ap 0—15 cm;	10YR4/3 LS; weak fine granular structure; very friable

TABLE I (cont.)

Soil series	Soil	Taxonomic classification	Location	Soil description	
Norfolk	18			E 15—36 cm;	10YR5/6 LS; weak fine granular structure; very friable
	19			Btl 36—76 cm;	7.5YR5/8 SCL; moderate medium sub-angular blocky structure; firm
Norfolk	13	Typic Paleudult; fine loamy, siliceous, thermic	Lee Co., GA	Ap 0—25 cm;	2.5YR4/2 LS; weak fine granular structure; very friable
Oktibbeha		Vertic Hapludalf; very fine; montmorillonitic, thermic	Conecuh Co., AL	A 0—8 cm;	10YR3/2 SCL; moderate medium sub-angular blocky structure; firm
Orangeburg	10	Typic Paleudult; fine loamy, siliceous, thermic	Peach Co., GA	Ap 0—20 cm;	10YR4/2 LFS; weak fine granular structure; very friable
Red bay	8	Rhodic Paleudult; fine loamy, siliceous, thermic	Covington Co., AL	Ap 0—28 cm;	7.5YR3/2 LS; weak fine granular structure; very friable
Shubuta variant	7	Typic Paleudult; clayey, kaolinitic, thermic	Henry Co., AL	Ap 0—10 cm;	5YR5/6 FSL; massive; firm
Shubuta variant	6	Typic Hapludult; clayey, kaolinitic, thermic	Henry Co., AL	All 0—8 cm;	10YR3/2 SCL; weak fine granular structure; friable
Tifton	14	Plinthic Paleudult; fine, siliceous, thermic	Tift Co., GA	Apcn 0—25 cm;	10YR4/2 FSL; weak fine granular structure; very friable

[1] This soil sample is from Hawaii. All other soils used in this study are from the Southeastern Coastal Plains.

Penetrometer resistance or a similar measurement that emulates soil strength or soil resistance to root growth is often correlated with bulk density and water content (Mirreh and Ketcheson, 1972; Vorhees et al., 1975). However, in single grained or massive soils such as these, texture might also be related to strength. Hints of this come from textural relationships with both water content and bulk density (Gupta and Larson, 1979; Byrd and Cassel, 1980; Stitt et al., 1982).

Therefore, it is the purpose of this paper to look at the correlations between soil texture and strength, and to compare both with bulk density.

METHODS AND MATERIALS

Soils for this study were chosen to represent the textures and organic matter contents of the Southeastern Coastal Plains. These emphasize the sandy-textured, weakly-structured plow layers of the Paleudults of the area, underlain by root restricting dense layers. Other soils were included in the study to provide a range in soil texture.

Samples were collected at 17 locations: 9 in Alabama; 5 in Georgia; 2 in South Carolina; 1 in Hawaii. At each site, a loose, moist sample of the soil, weighing approximately 7 kg, was collected for laboratory analysis. Soils were taxonomically documented by the Soil Conservation Service and are listed by series in Table I. The table also includes a reference number that is used to identify the soil throughout the text.

Characterization data for each soil are listed in Table II. All the soils, except Nos. 2, 5, 6 and 15, are Paleudults, with high sand content, low silt, clay and organic carbon contents, and with vermiculite and kaolinite clay mineralogy. Soils numbered 2, 5, 6 and 15 generally contain more clay and organic carbon and less sand and have kaolinite and smectite clay mineralogy.

Soil samples used in this study were crushed by hand and passed through a sieve with 2-mm openings to remove roots, leaves and pebbles. Water was added by sprinkling and mixing, if necessary, to bring each sample to approximately 10—30 kPa soil—water tension. The moist soil was thoroughly mixed by rolling on a polyethylene sheet before removal of subsamples for analysis.

Consolidation

Individual sets of soil samples were compacted by mechanical force and by water consolidation. Mechanically-compacted samples were weighed and compressed into a known volume to give a desired targeted oven-dry bulk density. Targeted bulk densities were at intervals of approximately 0.05 mg m^{-3} within a range that was determined by the ease of compaction. To do this, each moist sample was poured loosely into a fixed-volume, cylindrical containment-assembly and consolidated to a known volume

TABLE II

Soil characterization data (numerical values are percentages)

Soil ref. no.	USDA texture	Sand					Silt		Clay	Organic carbon
		VC[1]	C[2]	M[3]	F[4]	VF[5]	CSi	FSi		
1	S	0.3	5.2	31.6	45.7	3.9	3.0	7.8	2.5	1.37
2	C	0.7	0.7	1.2	3.3	8.6	10.9	27.6	47.0	5.04
3	FSL	0.7	4.0	20.7	21.3	17.0	17.4	15.2	3.7	1.22
4	FSL	1.6	4.9	16.2	24.0	14.5	11.8	16.6	10.4	1.31
5	SCL	2.9	6.1	13.7	15.6	6.8	8.0	14.8	32.1	2.65
6	SCL	1.2	5.9	7.4	22.3	13.3	12.3	15.4	22.2	5.17
7	FSL	2.5	8.7	22.9	32.9	8.6	1.9	5.7	16.8	0.93
8	LS	0.8	7.1	26.1	33.7	12.8	2.9	8.5	8.1	0.54
9	SL	0.5	9.7	23.3	28.7	10.6	7.5	12.0	7.7	2.82
10	LFS	1.9	6.2	13.5	41.5	18.9	4.2	7.3	6.5	0.80
11	LFS	0.9	5.2	12.3	34.1	26.7	5.8	8.1	6.9	0.66
12	S	1.8	9.0	27.9	38.5	12.4	3.2	4.0	3.2	0.60
13	LS	2.6	10.7	20.4	29.9	15.4	6.8	9.7	4.5	0.77
14	FSL	2.8	7.4	17.8	36.7	16.0	4.2	4.1	11.0	0.66
15	SICL	0.1	0.7	2.1	6.2	10.4	15.2	31.2	34.1	1.98
16	LFS	0.3	1.2	2.5	41.5	33.2	10.8	7.7	2.8	0.53
17	LS	3.8	18.6	31.9	22.7	8.6	5.5	5.7	3.2	0.46
18	LS	4.6	18.2	27.2	20.2	8.4	5.8	9.2	6.4	0.16
19	SCL	7.2	17.2	19.3	13.0	5.3	3.9	4.9	29.2	0.19
20	LFS	0.3	1.1	2.1	37.9	31.8	10.8	13.6	2.4	0.26
21	SCL	0.1	0.8	1.4	25.3	24.1	9.8	7.7	30.8	0.29

[1] Very coarse.
[2] Coarse.
[3] Medium.
[4] Fine.
[5] Very fine.

in a hydraulic press. The containment-assembly consisted of 76-mm diameter aluminum sleeves held in place during compaction by a section of plastic pipe that was split on one side. In vertical order, sleeves were arranged with a 13-mm sleeve on top, followed by a 25-mm sleeve and another 13-mm sleeve. After the soil was pressed to a fixed volume, the two 13-mm sleeves were removed and the soil was trimmed to produce a test sample that was 76 mm in diameter and 25 mm thick.

The compressed samples were further moistened by placing them on a coarse, wet sand bed. The water level in the sand was maintained about 13 mm below the sand surface. Samples were allowed to reach near saturation, then placed on standard ceramic pressure-plates. Samples were then brought to equilibrium at 100 kPa soil—water tension.

After probing (described later), the test samples were oven-dried and the actual bulk density determined. Final bulk density was usually slightly different from the target, probably due to the non-uniformity in onedirectional mechanical compaction. Differences between targeted and actual values averaged 0.026 mg m^{-3} (σ=0.015) or 1.5% (σ=0.9%). Therefore, cores were assumed to be uniform.

Samples compacted by water-consolidation were used to simulate field conditions, where soil is wetting and drying by intermittent rain and compacted by gravitational forces. These samples were analyzed as a separate set. The water-consolidation technique used an assembly of 76-mm diameter sleeves placed on a wet ceramic pressure-plate which was in place in a moisture extraction chamber. Moist soil was poured loosely into the sleeve assembly. The amount of soil was visually estimated to give a resultant consolidated sample that was 50—80 mm thick. Water was then poured into the open extractor chamber until it covered the plate by 1—2 mm. Samples were allowed to slowly wet and consolidate. The water level was raised slowly (about 25 mm h^{-1}) until the samples were submerged in water. The water level was then slowly lowered, and the samples further consolidated. Samples were allowed to drain overnight. Samples were then equilibrated at a tension of 100 kPa. Water was added and removed very slowly to prevent washing of fine soil particles in the sample matrix.

When the consolidated samples were at equilibrium, the outer sleeves were removed and the section that was 13—38 mm above the plate was trimmed, used in probe resistance measurements and then oven-dried and weighed to determine water-consolidated bulk density (WCBD).

The water-consolidation technique was developed because it is simple, uses constant compactive force (gravity) and constant water tensions, and roughly approximates natural field-consolidation of Coastal Plain soils.

The range of bulk density for a given soil was very narrow (less than 0.05 mg m^{-3} variation) for water-consolidated samples, indicating the repeatability of the method.

Probing

Soil strength measurements were made with a 5-mm diameter, flat-tipped, stainless-steel probe which was attached to a strain-gage load cell. The complete assembly was moved vertically by a reversible electric motor. The motor was geared to operate at a constant loading rate of 0.28 mm s^{-1}. The maximum depth of soil penetration was 7 mm and the maximum time of penetration was 25 s.

Probe resistance was recorded on an $X—Y$ plotter as a continuous function of depth. Values of probe resistance used in data analyses were taken from the charts at about a 5-mm depth where resistance had reached equilibrium. Strength (kPa) was calculated by dividing total resistance by the cross-sectional area of the probe. Three measurements were made on both the top and bottom of the test sample, and the average was used in analysis. Some test samples fractured and were excluded. These could be identified visually and detected in the probe recorder tracings.

A difference in probe resistance was observed between the top and bottom of the same test sample. These experiments indicate that the direction of water flow during pressure-plate extraction contributed to the effect. It is not related to mechanical compaction. It was suspected that silt particles in some soils may have been deposited in void cavities, preferentially on the bottom side (direction of water flow), and this contributed to a higher level of probe resistance for the top. For this reason, probe measurements were made on both sides and the average was used in data analysis.

Analyses

Analyses of particle size distribution, organic carbon, clay mineralogy, pH and 1.5 MPa gravimetric water content were performed by the National Soil Survey Laboratory (Lincoln, Nebraska) of the Soil Conservation Service according to published methods (Black, 1965). Proctor maximum dry density testing was performed by the Soil Mechanics Laboratory (Lincoln, Nebraska) of the Soil Conservation Service using Standard ASTM-698, Method A (American Society for Testing Materials, 1958). Simulated estimates of bulk densities were computed using the Random Model (Gupta and Larson, 1979). Statistical analysis and computation of regression equations were performed by data analysis based on standard statistical methods.

RESULTS AND DISCUSSION

Mechanically compacted samples

Probe resistances for 426 samples of the 17 soils are shown in Fig. 1 after they were mechanically compacted to varying bulk densities and

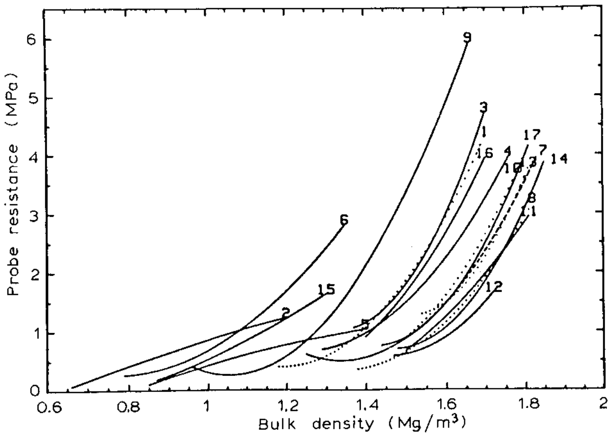

Fig. 1. Probe resistance as a function of bulk density at soil—water tension = 100 kPa for the A horizon of the soils. The numbers associated with each line are the soil reference numbers.

equilibrated at 100 kPa soil—water tension. The curves plotted are the result of least square fits. The P_r^2 value for individual soils ranges from 0.90 to 0.99, except for soil Nos. 11 and 12 for which the P_r^2 values are 0.78 and 0.81, respectively. All curves are statistically significant to at least the 0.01 level.

Generally, the curves in Fig. 1 fit into two groups. Soil Nos. 2, 5, 6 and 15, with sandy-clay loam, silty-clay loam or clay textures, have a low range of bulk densities and probe resistances. The sandy-textured soils have a larger range of bulk densities and a broader range of probe resistances. The curves of the sandy soils are roughly parallel to each other. However, there is no easily recognized relationship between the curves and soil texture. For example, soil Nos. 1 and 12 have a sand texture. At a bulk density of 1.60 mg m^{-3}, soil No. 1 has a probe resistance of approximately 3.0 MPa. Soil No. 12 at the same bulk density has a probe resistance of approximately 1.0 MPa. Furthermore, there is no common bulk density value at which probe resistances of all soils can be compared since some compact more readily than others. Therefore, the soils are compared at two bulk densities (1.2 and 1.65 mg m^{-3}).

In the initial evaluation of particle size, probe resistance relationships consisted of the comparison of correlation coefficients for individual particle size fractions with probe resistance, bulk density, and gravimetric water content. The *r*-values for these comparisons are shown in Table III. Particle size fractions used in the calculations consist of the conventional USDA sizes with organic carbon included as a fraction.

Probe resistance values at a bulk density of 1.65 mg m^{-3} were obtained from the curves of Fig. 1 and compared with particle size fractions of the

TABLE III

Correlation coefficients between particle size classes and probe resistance and bulk densities for the A horizons of the soils used in the study

Particle size clase	Probe resistance (X 100 kPa)			Bulk density (mg m^{-3})				
	At water-consolidated bulk density	At bulk density 1.20[1]	At bulk density 1.65[2]	Water consolidated	Critical rooting[3]	Proctor	Gupta	
							Minimum	Random
A horizon of 17 soils								
VC	0.10	−0.03	0.55*	0.27	0.53*	0.40	0.31	0.38
C	0.21	−0.44	−0.17	0.39	0.37	0.48*	0.46	0.47
M	0.23	−0.84*	−0.03	0.47	0.46	0.61**	0.61**	0.58*
F	0.43	−0.62	−0.08	0.66**	0.50	0.68**	0.75**	0.62**
VF	0.61**	0.77	−0.10	0.49*	0.14	0.29	0.33	0.31
CSi	0.05	0.84*	0.37	−0.39	−0.65**	−0.56*	−0.57*	−0.49*
FSi	−0.45	0.58	0.50	−0.71**	−0.68**	−0.76**	−0.79**	−0.71**
Clay	−0.73**	0.60	−0.15	−0.82**	−0.54*	−0.78**	−0.84**	−0.77**
Tot. silt	−0.28	0.69	0.46	−0.63*	−0.71**	−0.73**	−0.76**	−0.67**
Tot. sand	0.57	−0.67	−0.36	0.80**	0.70**	0.83**	0.87**	0.79**
Org. C	−0.70**	0.76*	0.88*	−0.91**	−0.88**	−0.92**	−0.96**	−0.98**

[1] Soils 2, 3, 5, 6, 9 and 15 only.
[2] Soils 2, 5, 6 and 25 excluded.
[3] Soils 2 and 5 excluded.

13 sandy-textured soils. For this comparison, organic carbon had the highest (most significant) correlation with probe resistance (r = 0.88). A similar positive and significant correlation was obtained with the samples compared at a bulk density of 1.2 mg m^{-3}. It is unusual to have a direct relationship between organic matter and probe resistance since organic matter traditionally reduces bulk density. The relationship may be due, at least in part, to the type of packing and the low bulk density of the organic matter. When soils with a higher organic matter content are pressed to the same bulk density as those with a lower organic matter, the mineral fraction is pressed into a smaller volume. The samples with a denser packing of the mineral fraction (and higher organic matter contents) would have a higher probe resistance. This was partially verified for the 1.65 mg m^{-3} case by re-calculating the bulk density with organic matter (1.724 × organic carbon) weighing 2.65 mg m^{-3} rather than the estimated 1.0 mg m^{-3}. The correlation coefficient was reduced to 0.75, but it was still positive and significant. Nevertheless, soils here are compacted into a specific volume (and not by a specific force, which will be shown later), and probe resistance is not related to mineral fractions of the soil.

In an effort to circumvent the effect of organic matter described above, correlation coefficients (relating probe resistance to particle size classes) were calculated using data from the 9 soils that contained less than 1.0% organic carbon, as shown in Table IV. In this comparison, there was no significant correlation between organic matter and probe resistance. However, silt was significantly correlated (r = 0.70) to probe resistance. This suggests that at low levels of organic matter, increasing silt content (2—11%) resulted in increased probe resistance.

TABLE IV

Silt content and probe resistance for samples with less than 1% organic matter

Sample No.	Silt (%)	Probe resistance (MPa)	
		At 1.65 mg m^{-3}	At WCBD
12	7.2	1.17	0.59
7	7.6	1.89	0.61
14	8.3	1.41	0.70
	11.2	1.94	1.02
	11.4	1.51	0.92
10	11.5	2.09	1.01
11	13.9	1.60	0.83
13	16.5	1.81	1.29
16	18.5	3.27	1.32

Water-consolidated bulk density

For cores compressed to a constant bulk density, probe resistance is not related to any of the Soil Conservation Service textural classes except for silt under special circumstances. By contrast, probe resistance is related to texture for water-consolidated cores (Table III). Probe resistance is significantly correlated to sand, clay and organic matter content. The positive correlation with sand indicates that as sand content increases, probe resistance increases. The negative correlation with clay and organic matter indicates that as clay and organic matter content increase, probe resistance decreases. This is consistent with previous work that shows similar relationships between density and sand, clay and organic matter (Gupta and Larson, 1979). These cores also vary in water content and bulk density[1], which are also related to texture (Table III). It is unclear whether the probe measurements are reflecting this or textural differences. Nevertheless, the multiple regression of probe resistance with texture (sand, clay and organic carbon) is 0.90 (coefficient of determination), which is larger than probe resistance with water content (0.56), with bulk density (0.71) or even with combined water content and bulk density (0.77)[2]. This implies that there is a relationship between probe resistance at WCBD and texture even if that relationship is seen, in part, indirectly through water content or bulk density.

When a sample is compacted to a specific bulk density, say 1.65 mg m^{-3}, some particles, such as organic matter and clay, which may not normally compact to high bulk densities (Gupta and Larson, 1979), are forced to do so or force other particles to compact to higher bulk densities. For WCBD, however, soils of differing texture and organic matter are compacted by a constant force (gravity) rather than to a constant volume. Here probe resistance, and consequently compactability, is correlated to individual particle classes. Stated more generally, if a soil is compacted by a constant force rather than to a constant volume, its compaction as measured by probe resistance is correlated to texture. Water consolidation, which may be a naturally occurring compaction by a constant force, is an example of such a condition.

An indirect evaluation of this was made by comparing the correlation coefficients of particle size classes versus WCBD with those for particle size classes versus Proctor bulk density (uses constant compactive force) or Gupta model bulk density (assumes constant compactive force). This comparison indicates correlation coefficients which are similar in both sign and value (Table III). In fact, bulk densities are also very similar (Table V).

[1] Water content varied from 3.8 to 38.1% on a dry weight basis; WCBD varied from 0.69 to 1.61 mg m^{-3}.
[2] 0.90 and 0.56 are significantly different at the 5% level; the hypothesis that 0.90 is as small as 0.71 can be rejected; for 0.77 it cannot (at the 5% level).

For the WCBD, silt showed a poor correlation with probe resistance (Table III). In an effort to isolate the effect of silt, correlation coefficients (relating probe resistance of water-consolidated samples to particle size classes) were calculated using data for the 9 soils that contained low organic matter (less than 1.0% organic carbon) and low clay (Table IV). In this comparison, silt was highly and positively correlated (r = 0.92) with probe resistance. This again suggests that at relatively low levels of organic matter (and clay), increasing silt content was associated with increased probe resistance.

TABLE V

Correlation coefficients of various calculated and measured values of bulk density

	Bulk densities		
	Proctor maximum	Gupta model	
		Minimum	Random
CRBD[1]	0.93	0.93	0.94
WCBD	0.93	0.94	0.93

[1] The correlation of CRBD with WCBD is 0.89.

Critical rooting bulk density

When samples of differing textures are compacted by a constant force or constant methodology (such as WCBD), probe resistance appears to vary with texture. The key may be compaction by constant force.

To further examine this, mechanically compacted samples (Fig. 1) were re-analyzed at a root-restricting level of probe resistance of 2 MPa. Although this value may be related to clay content, it was chosen since some references (Taylor et al., 1966; Camp and Lund, 1968) show essentially no root growth in soils with 5-mm, flat-tipped probe resistances greater than 2 MPa. Thus, the bulk density values that produce 2 MPa probe resistance at 100 kPa soil—water tension are identified as critical rooting bulk density (CRBD). CRBD values were calculated for each soil in Fig. 1. These were compared with several other measures of bulk density (Table V). The WCBD and Proctor maximum dry density tests represent extremes in compactive force. Each test involves a fixed level of compactive force. The Random Packing Model (Gupta and Larson, 1979) utilizes particle size classes and organic matter as input, and is obviously influenced by texture. Critical rooting bulk density compares with bulk densities obtained by water-consolidation, Proctor tests and the Gupta—Larson model. According to these correlations, the densities are not significantly different (at the 0.05 level).

It was stated earlier that texture was not related to probe resistance for soils compacted to a specific bulk density. However, when corrected for a constant strength, CRBD's are well correlated to densities that are related to textures, especially the packing model of Gupta and Larson (1979). These corrected values may then be directly related to texture. In fact, a regression of CRBD with texture (sand, silt and organic matter) yields a coefficient of determination of 0.92 which is statistically significant at the 1% level.

CONCLUSIONS

For samples mechanically compacted to a fixed bulk density, there was poor correlation between particle size classes and probe resistance. When probe resistance was measured on samples prepared with comparable forces of consolidation, such as WCBD, there was a correlation between particle size classes and probe resistance. Also, in soils with low relative levels of clay and organic matter, increasing silt content appears to increase probe resistance for both mechanically and water-consolidated samples. Furthermore, for soils compacted to constant force, such as CRBD, bulk density is related to texture.

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REFERENCES

American Society for Testing Materials, 1958. In: Book of ASTM Standards, Part 4. Am. Soc. Test. Mater., Philadelphia.

Barley, K.P., Farrell, D.A. and Greacen, E.L., 1965. The influence of soil strength on the penetration of a loam by plant roots. Aust. J. Soil Res., 3: 69—79.

Black, C.A. (Editor), 1965. Methods of Soil Analysis, Part 1. American Society of Agronomy, Madison, WI.

Box, J.E. and Langdale, G.W., 1984. The effects of in-row subsoil tillage on corn yields in the Southeastern Coastal Plains of the United States. Soil Till. Res., 4: 67—78.

Byrd, C.W. and Cassel, D.K., 1980. The effect of sand content upon cone index and selected physical properties. Soil Sci., 129: 197—204.

Camp, C.R., Jr. and Lund, Z.F., 1968. Effect of mechanical impedance on cotton root growth. Trans. A.S.A.E., 11: 188—190.

Campbell, R.B., Reicosky, D.C. and Doty, C.W., 1974. Physical properties and tillage of Paleudults in the Southeastern Coastal Plains. J. Soil Water Conserv., 29: 220—224.

Gerard, C.J., Sexton, P. and Shaw, G., 1982. Physical factors influencing soil strength and root growth. Agron. J., 74: 875—879.

Gupta, S.C. and Larson, W.E., 1979. A model for predicting packing density of soils using particle-size distribution. Soil Sci. Soc. Am. J., 43: 758—764.

Ide, E., Hofman, G., Ossemerct, L. and Van Ruymbeke, M., 1984. Root-growth response of winter barley to subsoiling. Soil Till. Res., 4: 419—431.

Mirreh, H.F. and Ketcheson, J.W., 1972. Influence of soil bulk density and matric pressure on soil resistance to penetration. Can. J. Soil Sci., 52: 477—483.

Peterson, C.M., Klepper, B., Pumphrey, F.V. and Rickman, R.W., 1984. Restricted rooting decreases tillering and growth of winter wheat. Agron. J., 76: 861—863.

Stitt, R.E., Cassel, D.K., Weed, S.B. and Nelson, L.A., 1982. Mechanical impedance of tillage pans in Atlantic Coastal Plains soils and relationships with soil physical, chemical and mineralogical properties. Soil Sci. Soc. Am. J., 46: 100—106.

Taylor, H.M., Robertson, G.M. and Parker, J.J., Jr., 1966. Soil strength—root penetration relations for medium- to coarse-textured soil materials. Soil Sci., 102: 18—22.

Vorhees, W.B., Farrell, D.H. and Larson, W.E., 1975. Soil strength and aeration effects on root elongation. Soil Sci. Soc. Am. J., 39: 948—953.