Soil Strength Indices as Indicators of Consolidation

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ABSTRACT

SHEAR strength indices are often used to estimate soil characteristics related to erosion. The purpose of this study was to evaluate the effectiveness of using soil strength indices as indicators of soil changes caused by consolidation. Fall-cone, torvane shear, and pocket penetrometer measurements were obtained on clay, silt loam, and fine sand soils as a function of soil water stress history and time. Also, wet aggregate stability was measured for the clay soil. Prestress suction was the dominant mechanism for strengthening the three soils. Time effects were less pronounced. The fall-cone was the best indicator of consolidation and the pocket penetrometer was also effective with some limitations. The torvane shear device was the least effective index for detecting strength changes, although it worked well on the silt loam soil. The three index tests did not rank the three soils the same in order of increasing strength, suggesting that the validity of using index tests to rank or compare soils is questionable. The results of the study indicated that proper strength index tests may be effective in characterizing relative changes in stability of a given soil over time.

INTRODUCTION

Soil shear strength has been used, with varying degree of success, to predict soil resistance to erosion or erosion related processes. Flaxman (1963) related soil compressive strength to critical shear stress in stream channels. Dunn (1959) developed an equation which related critical tractive stress to vane shear strength. Lyle and Smerdon (1965) and Kamphius and Hall (1983) also used a vane shear test in an attempt to predict critical shear stresses; and Watson and Laflen (1985) related interrill erosion losses to vane shear strength on three soils, each with varying slope. Al-Durrah and Bradford (1981) correlated the soil detachment by strength as measured with a Swedish fall-cone device. The fall-cone was also useful in studying the mechanism of splash, especially with regard to splash angle (Al-Durrah and Bradfor, 1982). Soil aggregate stability as an index of erodibility has been extensively studied (Middleton, 1930; Young 1984; Anderson, 1951; Bathke and Blake, 1984; Alberts and Wendt, 1985). Current efforts to develop process based erosion prediction models include measurement of soil strength indices using fall-cone, vane shear, and pocket penetrometer, as well as aggregate stability indices (Foster, 1987).

Soil erodibility varies during the year (Mutchler and Carter, 1983). Seasonal erodibility has been characterized using both aggregate stability tests (Imeson and Vis, 1984) and shear strength indices (Dickinson et al., 1982; Pall et al., 1982). The mechanisms of consolidation which cause seasonal soil changes were studied by Nearing et al. (1988) who showed that unconfined compressive strength, tensile strength, and density was a function of soil water stress history and time. They found when soil was equilibrated under suction for a period of time, subsequently rewet to a lower suction, and then tested, that the rewet woil maintained a portion of its compressive strength gain from consolidation. They defined this phenomenon as a prestress effect, because the previously applied soil water stress determined the amount of strength retention when the soil was rewet. The effect of prestress due to soil water suction has particular applicability to erosion processes. Between erosion events soil consolidates due to time and drying stresses, which causes increased soil stability. During an erosion event soil is rewet, yet a portion of the consolidation related strength gain is retained because of the prestress effect.

Aggregate stability also increases as a function of soil water stresses induced by drying (Kemper and Rosenau, 1984; Utomo and Dexter, 1982) and as a function of time due to thixotropic effects (Blake and Gillman, 1970; Utomo and Dexter, 1981; Kemper and Rosenau, 1984). Only for the study of Kemper and Rosenau (1984) were both effects studied on the same soil, and in that case there was no opportunity to compare consolidation effects between aggregate stability and bulk soil stability (shear strength).

Soil shear strength index tests, such as fall-cone, vane shear, and pocket penetrometer, are estimators of compressive (as opposed to tensile) strength (Hansbo, 1957; Holtz and Kovacs, 1981). Flate (1965) analyzed correlations between the vane shear, fall-cone, and unconfined compression test for many soils, but did not study the effect of consolidation due to time or drying on strength by vane or fall-cone. Towner (1973) found for several soils that strength as measured by fall-cone decreased with increasing water content. Effects of prestress due to suction and duration of prestress on strength indices or aggregate indices have not been explicitly studied.

The overall objective of this study was to evaluate

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several soil strength index tests to characterize soil changes as a function of consolidation processes. Specific objectives were: (a) to evaluate soil strength indices for characterizing soil consolidation on samples of varying texture; (b) to compare the strength indices, originally developed to estimate compressive strength of clays, with unconfined compression test data for a clayey soil; and (c) to compare the consolidation effects on aggregate stability with consolidation effects on bulk shear strength for a clayey soil. The results have practical implications in terms of appropriate index tests to use to characterize soil changes with time as a function of consolidation processes.

MATERIALS AND METHODS

The soils used in this study were: a Paulding clay (very-fine, illitic, non-acid, mesic Typic Haplaquept) from Ohio, a Russell silt loam (fine silty, mixed, mesic Typic Hapluadalf) from Indiana, and an Oakfield fine sand (mixed, non-acid, mesic Typic Udipsamment) from Indiana. The Paulding contained 550 g kg^{-1} clay, 350 g kg^{-1} silt, and 100 g kg^{-1} sand. The Russell had 220 g kg^{-} clay, 640 g kg^{-1} silt, and 140 g kg^{-1} sand. The Oakfield had 30 g kg^{-1} clay, 60 g kg^{-1} silt, and 910 g kg^{-1} sand. The soils were air dried and ground to pass a 4.75 —mm sieve. The soil was wet by spraying to a water content of 270 g kg^{-1} for Paulding, of 190 g kg^{-1} for the Russell, and of 70 g kg^{-1} for the Oakfield and stored in a plastic bucket for 48 h to allow the water to distribute evenly through the soil.

Samples for fall-cone, vane shear, pocket penetrometer, and aggregate stability were formed by static compaction of the moist soil within acrylic cylinders 57—mm long by 76—mm diam to bulk density of 1.10 Mg m^{-3}. The samples were gradually satiated by increasing the water level until even with the top of the samples and leaving for three days. The samples were then desorbed to 0, 2, 4, 8, 16, and 32 kPa suction for four days. After desorption, they were resatiated slowly over a period of 8 h, then allowed to re-equilibrate at 0.4 kPa suction for 16 h before testing. To test the effect of time on strength indices, samples of the three soils were equilibrated at 4 kPa suction for 4, 8, 16, and 32 days, resatiated for 8 h, and subsequently re-equilibrated at 0.4 kPa suction for 16 h before testing.

Shear strength indices were measured with Soiltest* torvane shear device and pocket penetrometer and a Geonor fall-cone device. For the torvane the large vane with a scale factor of 0.2 was used, for the pocket penetrometer a 0.635—cm (1/4 in.) adapter was used, and 10 and 60 g cone weights were used for the fall-cone. Strength index measurements were replicated three times using three different samples.

Further tests were performed on Paulding clay samples as companion samples to the unconfined compression tests of Nearing et al. (1988). These tests were intended to provide further information on the characteristics of the index tets as a function of consolidation within the context of their original purpose; as predictors of compressive strength for clay soils. Samples were kept for 4, 8, 16, and 32 days at suction of 4, 16, and 64 kPa and subsequently tested at those suctions. Shear strength indices were measured with fall-cone, torvane shear device, and pocket penetrometer. Cone weights used for the fall-cone were 100 and 400 g. For the torvane, the medium sized vane with scale factor 1 was used. For the pocket penetrometer, it was necessary to make measurements both with and without the 0.635—cm (1/4 in.) adapter to cover the range of strengths tested. Three fall-cone, one torvane, and one penetrometer measurements were made on each sample; three to four samples were used per treatment. Wet aggregate stability was measured on each of these clay samples subsequent to the strength measurements. Samples were placed on a nest of sieves and wet slowly with the water at the level of the top sieve. The nest of sieves (2, 1, 0.5, and 0.25 mm) was oscillated for 10 min and hand sieved through 0.105 and 0.053—mm mesh sieves. Samples were oven dried and mean weight diam (MWD) was calculated. Experimental methods for the unconfined compression tests were reported by Nearing et al. (1988), and correspond to those given here for the same clay soil.

RESULTS AND DISCUSSION

Strength Indices on the Three Soils

Prestress was the dominant mechanism for strengthening the three soils: increases due to time were less than those caused by prestress suction for each soil and index (Tables 1 and 2). Also, correlations between indices and prestress suction were greater than those between indices and time (Table 3). Also, increases due to time were not consistent, i.e., indices did not increase with each increment of time in every case (Table 2). Considering the high variability that would be expected in a field environment, it appears doubtful from the data presented here that strength indices would be effective in

TABLE 1. STRENGTH INDICES ON THE THREE SOILS AS A FUNCTION OF PRESTRESS SUCTION

Soil	Prestress suction	Fall-cone index	Torvane shear index	Pocket penetrometer index
	kPa	kPa	kPa	kPa
Paulding	0	6.21b*	4.19b	2.25d
	2	7.20b	4.51ab	3.48c
	4	8.84b	4.77ab	3.48c
	8	14.17a	5.49a	4.09b
	16	14.11a	5.30a	4.09b
	32	14.76a	5.56a	4.71a
Russell	0	0.47e	0.00e	0.00b
	2	1.32d	0.65e	0.00b
	4	1.42d	1.57d	0.00b
	8	2.18c	2.55c	0.00b
	16	3.23b	4.45b	1.74a
	32	5.19a	6.08a	2.30a
Oakfield	0	0.83c	0.78b	1.02c
	2	1.55b	1.83a	2.97b
	4	2.19a	1.63a	3.07b
	8	2.37a	1.83a	2.86b
	16	2.55a	2.29a	4.91a
	32	2.37a	2.35a	5.21a

*Means within each soil and index grouping which are followed by the same letter are not statistically different at P = 0.05 as determined by Duncan's multiple range tests.

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*Trade names and and company names, included for the reader's benefit, do not imply endorsement or preferential treatment of the product listed by the USDA.

TABLE 2. STRENGTH INDICES ON THE THREE SOILS AS A FUNCTION OF TIME WITH PRESTRESS SUCTION OF 4 kPa

Soil	Prestress suction	Fall-cone index	Torvane shear index	Pocket penetrometer index
	days	kPa	kPa	kPa
Paulding	4	8.84a*	4.77a	3.48b
	8	11.21a	5.10a	3.68b
	16	9.62a	4.91a	3.58b
	32	12.61a	5.56a	4.50a
Russell	4	1.42b	1.57b	0.00a
	8	1.95ab	1.77b	0.00a
	16	1.89ab	2.35a	0.00a
	32	2.23a	1.97ab	0.00a
Oakfield	4	2.19b	1.63c	3.07a
	8	2.48ab	2.55ab	5.01a
	16	3.01a	2.74a	3.99a
	32	2.83a	1.83bc	4.20a

*Means within each soil and index grouping which are followed by the same letter are not statistically different at P = 0.05 as determined by Duncan's multiple range tests.

characterizing short term changes in soil stability due to time alone. The results also suggest that the drying, or prestress, effect may be the dominant mechanism in the consolidation process, and that the index tests may be useful in characterizing consolidation caused by drying.

The fall-cone was effective on all three soils in characterizing consolidation caused by prestress. Correlation between fall-cone index and prestress were highly signficant for each soil (Table 3). The torvane did not show substantial differences on the Paulding clay, and was the poorest of the three indices on the Oakfield fine sand for detecting prestress effects (Tables 1 and 3). However, for the Russell silt loam the torvane was quite effective. The pocket penetrometer indices were highly correlated to prestress suction for all three soils. For the Russell silt loam, however, the pocket penetrometer gave zero readings for all but the two greatest prestress levels.

The Russell silt loam had the greatest increase in strength with prestress suction. As measured by the fall-cone the Russell increased 11.0 times, the Oakfield increased 2.9 times, and the paulding increased 2.4 times in strength index as prestress suction increased from zero to 32 kPa. This may be due to soil structural effects as discussed by Nearing et al. (1988). The strongly structured Paulding had an effective particle size due to aggregation which was of the sand to small gravel size range. Similarly, particles of the Oakfield fine sand were also relatively coarse, although largely primary particles rather than aggregates. However, the Russell had the greatest percentage of small aggregates (Fig. 1) and hence the the smallest pore sizes of the three soils. The smaller pores would have drained less readily under suctions and maintained a greater relative effective stress than the other two soils. Thus strength increase due to prestress suction would be expected to be greater.

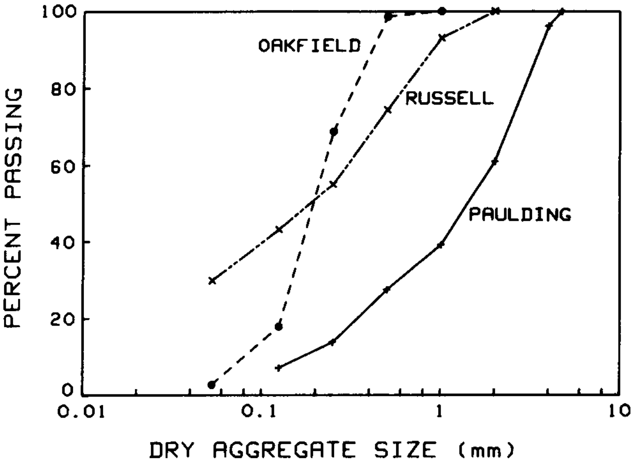

Fig. 1—Dry aggregate size distribution of the three soils as determined by sieving.

The relative rankings in average overall strength indices (for all times and prestress suctions) of the three soils were not the same for the different index test (Table 4). The fall-cone and the torvane ranked the clay soil greater in strength index than the fine sand and silt loam soils. For the pocket penetrometer, however, both the clay and fine sand soils had greater average indices than did the silt loam soil. The index tests were developed for clay soils only, and hence it is perhaps not surprising that the rankings of the soils differ with the different tests, each with different failure conditions. The results do, however, imply serious questionability of using index tests to rank soils in terms of erodibility or overall strength. This does not necessarily diminish their potential value in characterizing relative changes on a given soil which are caused by consolidation.

TABLE 3. COEFFICIENTS OF DETERMINATION FROM REGRESSION ANALYSES

Soil	Device	Variable tested					
		Suction, time		Suction		Time	
		R^2	n	r^2	n	r^2	n
Paulding	Fall-cone	0.69†	27	0.82†	18	0.31	12
	Torvane	0.52	27	0.54	18	0.42	12
	Penetrometer	0.87†	27	0.90†	18	0.72*	12
Russell	Fall-cone	0.98†	27	0.99†	18	0.63*	12
	Torvane	0.98†	27	0.98†	18	0.62*	12
	Penetrometer	0.86†	27	0.85†	18	0.00	12
Oakfield	Fall-cone	0.90†	27	0.93†	18	0.64*	12
	Torvane	0.72†	27	0.67*	18	0.66*	12
	Penetrometer	0.77†	27	0.85†	18	0.42	12

*,† represent significant (α=0.5) and highly significant (α=0.1) correlations, respectively.

TABLE 4. AVERAGE SOIL STRENGTH VALUES FOR EACH SOIL AND TEST TYPE

Soil	Fall-cone index	Torvane index	Pocket penetrometer index
	kPa	kPa	kPa
Paulding	10.97a	5.04a	3.76a
Russell	2.22b	2.38b	0.45b
Oakfield	2.24b	1.98b	3.70a

*Means within each index grouping which are followed by the same letter are not statistically different at P = 0.05 as determined by Duncan's multiple range tests.

Strength Indices and Unconfined Compression on the Paulding

Fall-cone, torvane, and pocket penetrometer shear strength indices as a function of soil water suction, Ω, at the time of testing for times of 4, 8, 16, and 32 days for the Paulding clay are shown in Fig. 2. The penetrometer data was plotted as one-half the compressive strength index in order to be compatible with the fall-cone and vane index data (Holtz and Kovacs, 1981). Results for companion samples of unconfined compressive strength were presented and discussed by Nearing et al. (1988). For comparison with data presented here, strength of the Paulding in those tests increased between 360 and 460%, depending upon the time factor, with increase in suction from 4 to 64 kPa, and increased between 90 and 130%, depending upon suction level, as time increased from 4 to 32 days. The strength from the unconfined compression tests consistantly increased with each increment of suction or time.

Differences in fall-cone index as a function of soil water suction were highly significant for all cases (Fig. 2a). Strength index increase was between 200 and 520%, dependent upon time, as suction at the time of testing increased from 4 to 64 kPa. Differences in fall-cone index due to time was not consistant. For each suction level, the 16 and 32 day treatment's indices were greater ($\alpha = 0.05$) than the 4 and 8 day treatments, but the 8 day indices were not consistently greater than the 4 day indices and likewise for the 32 vs. 16 day treatments.

The vane shear test was the least sensitive of the three tests to consolidation effects on the Paulding due to soil water stresses (Fig. 2b). Vane index increased between 70 and 190%, depending upon time factor with increase in suction at the time of testing from 4 to 64 kPa. Vane index was also less sensitive to consolidation with time than was unconfined compressive strength. For the 4 kPa samples, strength at times 16 and 32 days were significantly ($\alpha = 0.01$) greater than those at 8 and 4 days. For the 16 kPa samples no differences in strength were significant ($\alpha = 0.10$). For the 64 kPa samples, only the 32 day treatment was different ($\alpha = 0.10$) from the others. In other words, the differences in strength as a function of time which were detected with unconfined compression tests (Nearing et al., 1988) were not consistently detected with the vane test.

The reason that the vane shear did not detect as much difference in strength due to consolidation as was evident from the unconfined compressive strength from Nearing et al. (1988) may be related to stress-strain behavior.

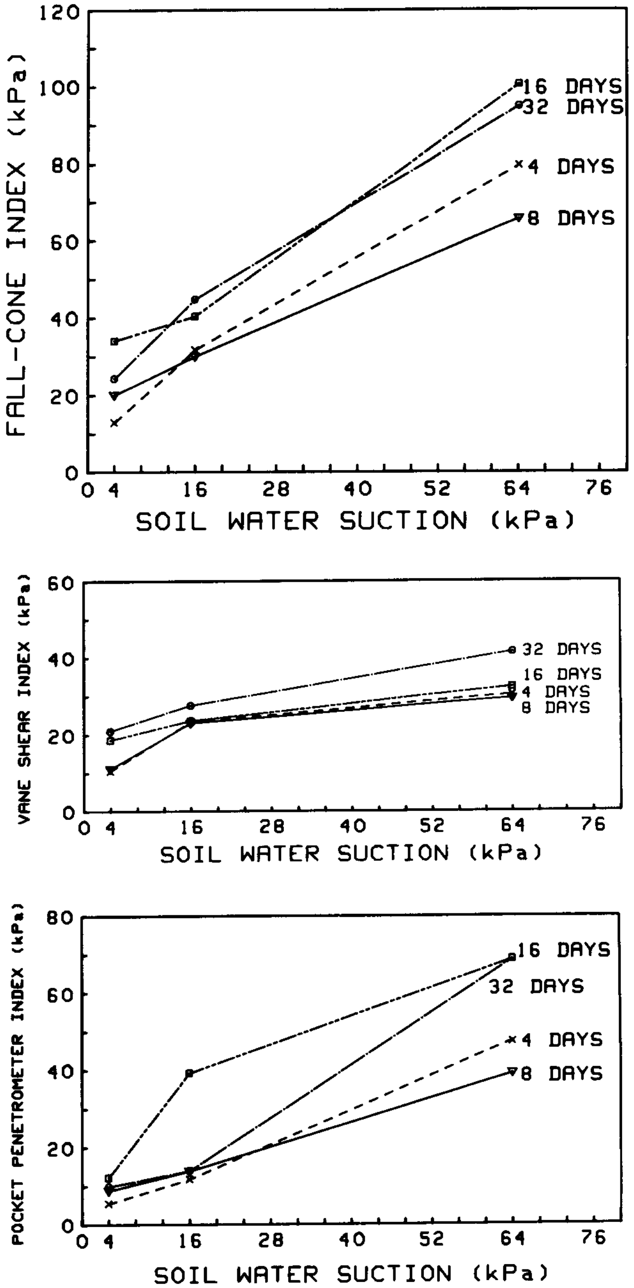

Fig. 2—Shear strength indices on the Paulding clay as a function of soil water suction at the time of testing for the (a) fall-cone, (b) torvane shear, and (c) pocket penetrometer tests.

Failure strain of the unconfined tests from Nearing et al. (1988) decreased as a function of both time and level of water stress, i.e., the samples became more brittle with consolidation. Brittle soils are more sensitive to disturbance than non-brittle soils (Holtz and Kovacs, 1981). If the soil structure was disturbed upon insertion of the vane then consolidation effects would not have been as evident. In other words, the vane may have to some degree measured the residual (post peak) soil strength, which is relatively independent of stress history (Holtz and Kovacs, 1981).

The pocket panetrometer measurements on these Paulding samples may have been inconsistent due to the use of more than one adapter. The adapter was not used for the t = 16 day, Ω = 16 kPa treatment, nor for the Ω

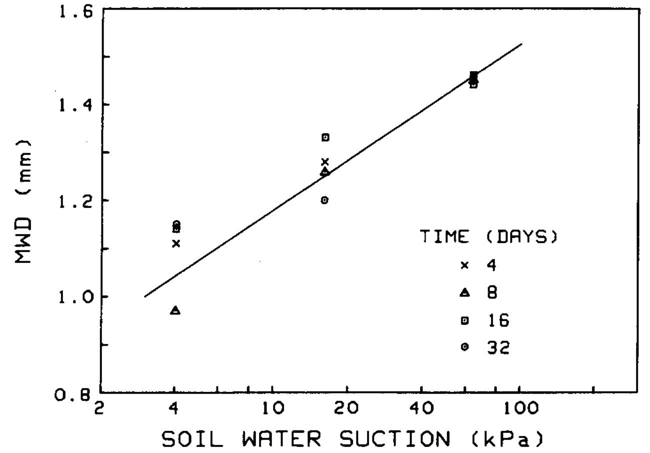

Fig. 3—Aggregate mean weight diameter, MWD, for the Paulding clay soil as a function of soil water suction immediately prior to wet sieving.

= 64 kPa treatments, but was used for the other treatments (Fig. 2c). For the $\Omega = 16$ kPa treatments, penetrometer index was 11.7, 13.8, 39.2, and 13.9 kPa for times 4, 8, 16, and 32 days, respectively. The indices for times 8 and 32 days were not different ($\alpha = 0.01$), but for the 16 day test for which the adapter was used the index was three times greater than for the 8 and 32 day treatments. For the treatments where the adapter was consistantly used, differences due to suction and time were relatively small compared to differences between values obtained using different adapters.

The index test as a whole gave values of shear strength that were greater than those from unconfined compression tests (Nearing et al., 1988). The ratio of fall-cone shear strength to compression shear strength for the companion samples ranged from 4.3 to 12.5. For the torvane shear device the ratio ranged from 1.8 to 7.9 and for the penetrometer from 1.6 to 5.5. If estimates of absolute values of soil strength are desired, index tests should be calibrated to unconfined compression samples for the soil and test used. Also, the user should be aware that the calibration constant for the test used may not be a constant with varying soil conditions due to reasons related to changes in stress-strain relationships as discussed previously.

Aggregate Stability

Aggregate mean weight diameter increased linearly with logarithm of applied suction, but was independent of time of applied suction (Fig. 3). These results are consistant with those of Kemper and Rosenau (1984) if it is considered that the air-dry storage time was the time factor which controlled aggregate strength. This soil was collected after tillage and stored air-dry in the laboratory for 3 years. As in the study of Kemper and Rosenau (1984), aggregate stability increased as soil water content increased (i.e., as water stress decreased) immediately prior to wetting.

The percent fraction of all aggregate size classes greater than 0.25 mm diameter increased as suction increased from 4 to 64 kPa. Greatest increases were in the 2.0 to 4.75 mm range which increased from 17% of total soil weight at 4 kPa suction to 27% at 64 kPa suction, and in the 1.0 to 2.0 mm range which increased from 15 to 21%. Percent fractions decreased between 2 and 5% for each of the six classes less than 0.25 mm diam. as suction increased from 4 to 64 kPa. The results indicated that formation of aggregates greater than 1.0 mm was the primary cause of the increase in MWD with increased suction.

IMPLICATIONS

This study presents several implications for the use of index tests in characterizing soil consolidation and changes in erodibility related soil properties:

1. Strength indices increased more with prestress suction effects than with time effects for all three soils, indicating that prestress suction was the dominant mechanism for increasing strength for the range of conditions tested.
2. The fall-cone was effective on all three soils in characterizing consolidation caused by prestress soil water suctions. Increases in strength as measured by fall-cone on the Paulding clay soil with increase in suction at time of test were of approximately the same magnitude as for unconfined compression test results.
3. The torvane shear device was ineffective in detecting consolidation effects on the Paulding clay and Oakfield fine sand. The problem with the torvane in characterizing consolidation effects may have been related to disturbance of soil structure as the vane was inserted.
4. The pocket penetrometer was reasonably effective in detecting consolidation effects, with some limitations. Zero values of strength were measured on the Russell silt loam soil for all but the two greatest prestress treatments. Also, the measurements obtained appeared to be inconsistent when more than one adapter was used.
5. The index tests were not consistent in ranking the three soils in order of average strength. Therefore, the validity of using the strength index tests to rank or compare different soils is questionable.
6. MWD is influenced by water stress effects in a manner similar to that of bulk soil strength, indicating that the bonding mechanisms which strengthen aggregates are similar to those which strengthen interaggregate structure. Formation of aggregates with increased soil water suction was primarily in the greater than 1.0—mm ranges.

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