Tensile Strength of Thirty-Three Saturated Repacked Soils

M. A. Nearing,* S. C. Parker, J. M. Bradford, and W. J. Elliot

ABSTRACT

Interaggregate strength in saturated soils is important in terms of erosion processes and surface sealing during rainstorms. The objective of this study was to ascertain the soil properties that influence interparticle binding of unconsolidated, saturated soil as measured by tensile failure of disturbed samples. Tensile strength of 33 soils was measured in the laboratory. The measurements were performed on 0- to 1-mm, 2- to 4-mm, and mixed aggregate size class materials. Factor analysis was used to understand the patterns of relationships and correlations among all the variates, and then to select appropriate variables (from among 39 measured soil properties) for use in regression relationships for tensile strength. Clay amount and surface properties were dominant in terms of explaining the variance of tensile strength. Other important factors included variables related to soil dispersion (Na and Na-adsorption ratio), silt, coarse sand, aggregation, and electrical conductivity. This study presents the use of a laboratory tensile test for loose, saturated soil as applied to a wide variety of soil types from across the USA.

TENSILE STRENGTH of unsaturated soil has been investigated in numerous studies (Snyder and Miller, 1985a,b; Al-Hussaini and Townsend, 1973; Farrell et al., 1967; Gill, 1959). Tensile strength of saturated soils has received little attention even though soil tensile strength under saturated or near-saturated conditions plays an important role in soil erosion and surface sealing processes. One reason that tensile strength of saturated soil has not been adequately studied is related to the difficulty of the measurement. Most existing tensile measuring techniques are not applicable to saturated, unconsolidated samples.

Tensile failure is one of the mechanisms by which particles are detached from soil surfaces by flowing water during the erosion process. Soil grains or aggregates must be lifted from the surface against the cohesive interparticle forces that are represented by soil tensile strength under near-saturated conditions. Martin (1962) was perhaps the first to hypothesize that soil tensile strength might be an appropriate indicator of soil erodibility. Previous studies have attempted, with mixed results, to relate soil detachment by water flow to soil strength. These investigations, however, have always used compressive strength rather than tensile strength (Lane, 1955; Dunn, 1959; Lyle and Smerdon, 1965; Partheniades and Paaswell, 1970; Elliot et al., 1990).

Tensile failure also occurs under the impact of a raindrop,which causes soil particle detachment and surface sealing. Huang et al. (1983) investigated the deformation of soil under raindrop impact by numerical modeling, assuming the soil to be an elastic medium. The analysis indicated that tensile stresses are induced at the edges of the raindrop impact crater, which act to destabilize the soil there. They hypothesized that the destabilized soil is subsequently removed from the surface by lateral jetting of water from the center of the impact area. As with the case of detachment by surface flow of water, detachment by raindrops has been related to soil compressive shear strength (Al-Durrah and Bradford, 1982; Cruse and Larson, 1977), but not to soil tensile strength.

It is difficult to measure tensile strength of soils with high water contents and low bulk densities. Under these conditions, soil samples will not stand under their own weight and their strengths are very low. Direct tensile-strength measurement methods that involve adhering the ends of the samples to the loading device (Farrell et al., 1967; Al-Hussaini and Townsend, 1973) or gripping the sides of the samples (Gill, 1959) are not applicable. Likewise, these types of samples are not appropriate for testing with indirect methods that utilize the application of compressive stresses (Kirkham et al., 1959) or bending moments (Farrell et al., 1967) in such a way as to induce tensile failure.

Nearing et al. (1988) developed a test to measure direct tensile failure under conditions of low density and high water contents and used it to study the consolidation behavior of an illitic clay soil. The test involves statically compacting disturbed soil into acrylic cylindrical cells, each cell being cut in half but held together by a clamp for packing and handling prior to the test. The cell contained porous stones on both ends to facilitate movement of water so that the samples could be satiated, drained, or have water suction applied. Measurements of tensile strength from this test were successfully correlated to soil detachment by flow under controlled laboratory conditions using two soil types (Nearing et al., 1990).

This study was undertaken to ascertain the soil properties that influence interparticle binding of unconsolidated soil as measured by tensile failure of disturbed samples under saturated conditions. The soils used were the 33 soils studied in the WEPP (Elliot et al., 1989) for characterizing erodibility of cropland soils. Tensile strengths were measured on each of the soils and related to soil chemical and physical properties using multivariate factor analyses and subsequent regression techniques in order to better understand tensile-strength behavior for a wide range of soil types.

MATERIALS AND METHODS

Soils

The soils used in this study are listed in Table 1. Chemical and physical properties of the soils were measured at the USDA-SCS National Soil Survey Laboratory in Lincoln, NE.

M.A. Nearing, Dep. of Agricultural Engineering, Univ. of Georgia, Athens, GA 30602; S.C. Parker and J.M. Bradford, USDA-ARS National Soil Erosion Research Lab., West Lafayette, IN 47907; and W.J. Elliot, Dep. of Agricultural Engineering, Ohio State Univ. Columbus, OH. Supported by state and Hatch funds allocated to the Georgia Agric. Exp. Stn. and the USDA-ARS National Soil Erosion Lab. Received 25 Feb. 1991. *Corresponding author.

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Abbreviations: EC, electrical conductivity; WEPP, Water Erosion Prediction Project; OM, organic matter; COLE, coefficient of linear expansion; CEC, cation-exchange capacity; LL, liquid limit; PL, plastic limit; PI, plasticity index; SSA, specific surface area; SAR, sodium adsorption ratio.

Table 1. Soils, sampling locations, and classifications.

Soil Series	Location	Classification
Sharpsburg	Lincoln, NE	Fine, montmorillonitic, mesic Typic Argiudoll
Hersh	Ord, NE	Coarse-loamy, mixed, nonacid Typic Ustorthent†
Keith	Albin, WY	Fine-silty, mixed, mesic Aridic Argiustoll
Amarillo	Big Spring, TX	Fine-loamy, mixed, thermic Aridic Paleustalf
Woodward	Woodward, OK	Coarse-silty, mixed, thermic Typic Ustochrept
Heiden	Waco, TX	Fine, montmorillonitic, thermic Udic Chromustert
Whitney	Fresno, CA	Fine-loamy, mixed, thermic Mollic Haploxeralf
Academy	Fresno, CA	Fine-loamy, mixed, thermic Mollic Haploxeralf
Los Baños	Los Baños, CA	Fine, mixed, thermic Typic Haploxeroll†
Portneuf	Twin Falls, ID	Coarse-silty, mixed, mesic Durixerollic Calciorthid
Nansene	Pullman, WA	Coarse-silty, mixed, mesic Pachic Haploxeroll
Palouse	Pullman, WA	Fine-silty, mixed, mesic Placic Ultic Haploxeroll†
Zahl	Bainville, MT	Fine-loamy, mixed, Entic Haploboroll
Pierre	Wall, SD	Very-fine, montmorillonitic, mesic Typic Torrert†
Williams	MacClusky, ND	Fine-loamy, mixed Typic Argiboroll
Barnes	Goodrich, ND	Fine-loamy, mixed Pachic Argiboroll†
Sverdrup	Wall Lake, MN	Sandy, mixed, Udic Haploboroll
Barnes	Morris, MN	Fine-loamy, mixed Udic Haploboroll
Mexico	Columbia, MO	Fine, montmorillonitic, mesic, Udollic Ochraqualf
Grenada	Como, MI	Fine-silty, mixed, thermic Glossic Fragiudalf
Tifton	Tifton, GA	Fine-loamy, siliceous, thermic Plinthic Kandiudult
Bonifay	Tifton, GA	Loamy, kaolinitic, thermic Grossarenic Plinthic Kandiudult
Cecil (Eroded)	Watkinsville, GA	Clayey, kaolinitic, thermic Typic Kanhapludult
Hiwassee	Watkinsville, GA	Clayey, kaolinitic, thermic Rhodic Kanhapludult
Gaston	Salisbury, NC	Clayey, mixed, thermic Humic Hapludult
Opequon	Flintstone, MD	Clayey, mixed, mesic Lithic Hapludalf
Frederick	Hancock, MD	Clayey, mixed, mesic Typic Paleudult
Manor	Ellicot City, MD	Coarse-loamy, micaceous, mesic Typic Dystrochrept
Caribou	Presque Isle, ME	Fine-loamy, mixed, frigid Typic Haplorthod
Collamer	Ithaca, NY	Fine-silty, mixed, mesic Glossoboric Hapludult†
Miamian	Dayton, OH	Fine-loamy, mixed, mesic Typic Hapludalf†
Lewisburg	Columbia, IN	Fine, illitic, mesic Typic Hapludalf†
Miami	Waveland, IN	Fine-loamy, mixed, mesic Typic Hapludalf

† Classifications given for these soils deviate from the USDA-SCS classification of soil series, 1990 ed., based on renewed sampling.

These properties included particle-size distributions, OM, Fe (dithionate–citrate extractable), Al (dithionate–citrate extractable), COLE, 33-kPa water content, 1500-kPa water content, Ca, Mg, Na, K, CEC, $CaCO_3$, pH, EC, water-dispersible clay, wet aggregate stability, LL, PL, PI, and SSA. In addition to these variables, certain common combinations of these parameters were used in this study, including activity of clay (ratio of PI to amount of clay), coarse plus very coarse sand, sum of bases (Ca, Mg, Na), SAR, and base saturation. Methods used were standard USDA-SCS testing procedures (Soil Conservation Service, 1984). Results from the laboratory tests were reported elsewhere and are very lengthy (Elliot et al., 1989, 1990), hence they will not be duplicated here.

Tensile-Strength Measurements

Tensile-strength measurements were made using the technique of Nearing et al. (1988). Briefly, dry soils were sieved through 4-, 2-, and 1-mm sieves and particle (including aggregate) size fractions were separated. Three types of materials from the fractions were used in the experiments: (i) the <1-mm size fraction, (ii) the 2- to 4-mm size fraction, and (iii) a mix of the <1-mm and the 2- to 4-mm materials. Soil was wetted by light spraying to approximate optimum compaction water content (Holtz and Kovacs, 1981) and samples were formed by static compaction into tensile cells to a density of 1.20 Mg/m^3 in most cases. Several of the sandy soils could not be packed at that density because their density was >1.20 as poured into the cells. Those soils included: the Bonifay, Academy, Whitney, and Amarillo, which were packed at 1.60 Mg/m^3; the Tifton, which was packed at 1.65 Mg/m^3; and the Sverdrup, which was packed at 1.45 Mg/m^3.

The samples in the tensile cells were 7.5 cm long by 3.88 cm in diameter. Each cell had a porous stone (from Soiltest[1]) at each end to facilitate movement of water through the ends of the samples. A small metal tube, connecting the porous stone with the outside of the cell, could be used for allowing movement of water or air to or from the sample. Samples were allowed to satiate at zero matric potential in the tensile cells for 24 h prior to testing. This was done by placing the cells with the soil in them on one end in water with the top tube open to the atmosphere. This allowed water to flow freely through the soil core from the bottom. The tubes connecting the stones to the outside were used by Nearing et al. (1988) to apply a water tension to the samples. The remainder of the tensile cell was sealed so that air and water movement did not take place prior to or during the test except through the porous stone.

Cells were split in the middle (perpendicular to the axis of the cell) so that the cell halves could be pulled apart during the test. The split was sealed with a light oil so that air could not enter the cell prior to failure at the failure area. The failure of the sample occurred instantaneously, so separation of the cell halves and subsequent movement of air at the middle of the sample did not occur prior to tensile failure. The strain of the system prior to failure was taken by the nylon line that attached the cell halves to the load cell. Air entered the cells only through the ends of the cells, which meant that the air-entry value for all the sample was essentially the same (and very low), being that for the movement of air through the small tube connecting the porous stone to the outside air. In other words, the inside of the cell remained satiated prior to tensile failure of the sample.

Water content of each sample was measured after each test, and saturation level was calculated. Degree of saturation for the samples wet from the bottom and satiated at zero matric potential ranged from 86 to 91%.

Force required to cause tensile failure of a soil sample was measured with a load cell. Force was applied very slowly so that water-movement rates within the sample did not affect the results (Fountaine, 1954). The potential effect of water-movement rates on the tensile strength was also ameliorated

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[1] Trade names and company names, included for the benefit of the reader, do not imply endorsement or preferential treatment of the product by the USDA.

by the fact that little significant volume change occurred prior to failure, as discussed above. Treatments were replicated six times. Blank sample cells, which were the same as the soil samples except for the inclusion of the soil, were used to test for the possible effect on the measured tensile strengths of adhesion induced by the light oil. The tensile strength of the blanks was negligible. For further details regarding the tensile-test procedure, including a schematic diagram of the test equipment, see Nearing et al. (1988).

Statistical Analyses

Statistical techniques used to analyze the data included multivariate factor analysis and linear regression. The data set using all 33 soils was analyzed for each of the three tensile-strength measurements: the 0- to 1-mm, 2- to 4-mm, and mixed aggregate size classes. For the tensile strength of the mixed material, analyses were also performed on subsets of the entire data set. The soils were broken into four groups based on soil primary particle-size distribution: (i) clay >29% (n = 7), (ii) silt >50% (n = 9), (iii) sand >52% (n = 9), and (iv) other soils (n = 9). One of the soils, the Sharpsburg silty clay, fell into both the clay and silt groups. The same general approach was used to analyze the large (full) and small (particle-size groups) data sets, but details such as criteria for selecting primary factors and representative independent variables were different for the two cases, as discussed below.

The full data set used in this study contained 39 independent variables and 33 observations. Many of the independent variables (such as several of the clay and clay-surface characteristics) were highly correlated. The first task in analyzing this data set was to understand the patterns of relationships and correlations among all the variates, and then to select appropriate variates for explaining the variance of tensile strength. Stepwise regression is not an appropriate tool for selecting independent variables to represent a dependent variable for the case where large numbers of interdependent variables are being considered. For that reason, multivariate factor analysis was used. Multivariate factor analysis delineates groups of variates into mutually independent (orthogonal) factors that are related to the original variate set through a series of matrix transformations (McCuen and Snyder, 1986; Bruce et al., 1988). Factor analysis is a method of analyzing a matrix of correlation coefficients of a set of variates (McCuen and Snyder, 1986). Transformation of the correlation matrix of the variates to orthogonal space allows the determination of mutually independent factors. Each variate has some loading into each factor. Those with high loadings in a particular factor are considered to be potential candidates for representing that factor in explaining the variance of the dependent variable.

The basic structure of the method used here was to first select factors that explained the greatest amount of variance of the dependent variable, and then to select a single variable with a high loading within each factor to represent that factor in explaining the variance of the dependent variate. Once the independent variables were chosen from the factors analysis, then regression was used to relate tensile strength to the reduced set of independent variables. Variables that did not contribute to the regression prediction of the dependent variable were dropped. In other words, stepwise regression was performed on the greatly reduced variate set.

For the case where all 33 soils were analyzed, the number of independent variables was reduced from 39 to between 6 and 7, which represented the most important mutually independent (orthogonal) factors from the factor analysis. A series of three stepwise regressions (two forward with different selection limits, and one backward) were performed on the reduced variate set. When a subset (particle-size group) of the soils was being studied, only two or three factors were considered (and thus two or three variables were being used in the regression tests) and all of the possible combinations of variables were used in the regression and the best prediction equation was selected based on the F statistic and the R^2 (coefficient of determination).

RESULTS AND DISCUSSION

Measured tensile strengths for all 33 soils are listed in Table 2. The average tensile strength for the 33 soils for the 0- to 1-mm material was 1.66 kPa with a standard deviation of 0.45 and, for the 2- to 4-mm material, the average was 1.35 kPa with a standard deviation of 0.43. Comparison of mean values showed that the average tensile strength of the 0- to 1-mm material was significantly higher at the 0.05 confidence level than the tensile strength of the larger 2- to 4-mm material. The strength of the mixed material was between that of the other two, with an average of 1.48 kPa and standard deviation of 0.56.

The higher tensile strength for the smaller size soil material was also observed by Nearing et al. (1990) for a more limited data set. This effect may be partially due to the differences in the amount of clay, which may contribute more toward interparticle cohesion. The effect may be also explained in terms of differences in particle arrangements for the two groups of materials. Aggregates have a greater density than the overall soil bulk density, which was made to be the same for both the 0- to 1-mm and 2- to 4-mm size class ma-

Table 2. Soil textures and measured tensile strengths for saturated 0- to 1-mm, 2- to 4-mm, and mixed soil materials.

Soil series	Texture†	Tensile strength 0–1 mm	 2–4 mm	 Mixed
		kPa		
Sharpsburg	sic	2.25	1.85	2.33
Hersh	sl	2.29	2.32	2.23
Keith	sil	1.14	1.27	1.05
Amarillo	ls	2.12	1.88	2.18
Woodward	sil	1.26	1.52	1.32
Heiden	c	1.84	1.58	1.88
Whitney	sl	1.92	1.40	1.20
Academy	l	1.56	1.45	1.46
Los Bãnos	c	2.99	2.41	3.23
Portneuf	sil	1.85	1.08	1.33
Nansene	sil	1.40	1.22	1.33
Palouse	sil	1.40	1.16	1.27
Zahl	l	1.11	1.34	1.12
Pierre	c	2.64	2.48	3.21
Williams	l	1.65	1.10	1.12
Barnes	l	1.99	1.61	1.75
Sverdrup	sl	1.32	1.29	1.49
Barnes	l	1.28	1.25	1.22
Mexico	sil	1.25	1.21	1.23
Grenada	sil	1.41	1.30	1.18
Tifton	ls	1.65	1.06	1.35
Bonifay	s	1.55	1.55	1.55
Cecil (Eroded)	scl	1.34	0.97	1.10
Hiwassee	sl	1.58	0.90	0.93
Gaston	cl	1.41	1.05	1.21
Opequon	cl	1.53	1.10	1.15
Frederick	sil	1.55	1.23	1.20
Manor	l	2.40	0.91	1.25
Caribou	gl	1.45	0.92	1.17
Collamer	sil	1.40	0.96	1.27
Miamian	l	1.58	0.89	1.21
Lewisburg	c	1.29	1.00	1.11
Miami	sil	1.29	1.11	1.18

† sic, silty clay; sl, sandy loam; sil, silt loam; ls, loamy sand; c, clay; l, loam; s, sand; scl, sandy clay loam; cl, clay loam; gl, gravelly loam.

terials. Since overall bulk density, and hence porosity, was the same for each size class material for a soil, that would imply that the more aggregated 2- to 4-mm material had a greater portion of pore space in the interaggregate regions and less in the intraaggregate regions compared with the lesser aggregated 0- to 1-mm material. The failure plane of the tensile test is presumably in the weaker interaggregate region rather than the intraaggregate region. In other words, it is not likely that tensile stresses, as applied in this test, would rupture a significant number of aggregates. It is reasonable, therefore, that the 2- to 4-mm material, with the greater fraction of pore space in the interaggregate region, would have less interaggregate bonding and thus less tensile strengths than the 0- to 1-mm material.

Factor Analyses

Tables 3, 4, and 5 list the factors that contribute most of the total variance to tensile strength of the 0- to 1-mm, 2- to 4-mm, and mixed aggregate size materials, respectively. Six factors accounted for 83.4% of the total variance of the tensile strength of the 0- to 1-mm soil material (Table 3). Seven factors accounted for 81.7% of the total variance of the tensile strength of the 2- to 4-mm soil material (Table 4), and six factors accounted for 83.0% of the total variance of the tensile strength of the mixed soil material (Table 5). Factor 1 of each analysis contributed the greatest to the variance of tensile strength for all three cases, and in each case Factor 1 contained the same set of six variables that had high (>0.80) loadings. Each of those six variables were related to clay activity and surface properties. They were COLE index, 1500-kPa water content, Ca, CEC, SSA, and the sum of the bases. This result confirms what we would perhaps intuitively guess, that the interaggregate cohesion as expressed by tensile strength is strongly influenced by clay amount and surface properties.

For the 0- to 1-mm material, the factor that ac-

Table 3. Factors contributing to variance of tensile strength of the 0- to 1-mm aggregate size class of the 33 soils and variables within each factor with high (>0.80) loadings into each of the factors. Six factors accounted for 83.4% of the variance in tensile strength of the 0- to 1-mm soil material.

Factor 1	Factor 7	Factor 13	Factor 11	Factor 14†	Factor 2
Coefficient of linear expansion‡	Na‡	Electrical conductivity‡	Liquid limit‡		Silt
1500-kPa water	Sodium adsorption ratio				Fine silt‡
Ca					Coarse silt
Cation-exchange capacity					
Specific surface area					
Sum of bases					
Tensile strength variance accounted for					
0.264	0.192	0.159	0.103	0.072	0.044

† Factor 14 contained no variable with a loading of >0.80.

‡ Variables within each factor with highest correlation to the dependent variable.

Table 4. Factors contributing to variance of tensile strength of the 2- to 4-mm aggregate size class of the 33 soils and variables within each factor with high (>0.80) loadings into each of the factors. Seven factors accounted for 81.7% of the variance in tensile strength of the 2- to 4-mm soil material.

Factor 1	Factor 3	Factor 5	Factor 2	Factor 9	Factor 10	Factor 8
Coefficient of linear expansion index†	Fe†	Very coarse sand†	Fine silt†	Na†	Gravel†	Very fine sand†
1500-kPa water	Al		Silt	Na adsorption ratio		
Ca	Disp. Clay		coarse silt			
Cation-exchange capacity						
Specific surface area						
Sum of bases						
Tensile strength variance accounted for						
0.325	0.159	0.100	0.081	0.081	0.039	0.032

† Variables within each factor with highest correlation to the dependent variable.

Table 5. Factors contributing to variance of tensile strength of the mixed 0- to 1- and 2- to 4-mm aggregate size classes of the 33 soils and variables within each factor with high (>0.80) loadings into each of the factors. Six factors accounted for 83.0% of the variance in tensile strength of the mixed soil material.

Factor 1	Factor 9	Factor 5	Factor 3	Factor 2	Factor 11
Coefficient of linear expansion index†	Na†	Very coarse sand†	Fe†	Silt	Electrical conductivity†
1500-kPa water	Sodium adsorption ratio		Al	Fine silt†	
Ca			Dispersible clay	Coarse silt	
Cation-exchange capacity					
Specific surface area					
Sum of bases					
Tensile strength variance accounted for					
0.473	0.130	0.092	0.056	0.054	0.025

† Variables within each factor with highest correlation to the dependent variable.

counted for the second greatest amount of variance had high loadings for Na and SAR. This would indicate that physical chemistry of the pore water, and in particular the chemistry that affects swelling potential and dispersion, is an important factor in affecting interaggregate cohesion. For the 2- to 4-mm material, the factor containing Na and SAR explained only 8% of the variance in tensile strength (fifth highest of the 10 factors) compared with the case of the 0- to 1-mm material, where the factor containing Na and SAR accounted for 19% of the variance in tensile strength. It might be deduced, therefore, that the dispersion was less of an influence on the 2- to 4-mm material.

The second factor in explaining the variance of the 2- to 4-mm material contained high loadings for Fe, Al, and dispersible clay. In the third factor, only very coarse sand had a high (>0.80) loading. Iron, Al, and dispersible clay are known to have an influence on aggregation. This result would indicate that the size of the particles, as influenced by aggregation and coarse sand, had a great effect on the tensile strength of the 2- to 4-mm material.

The major factors affecting tensile strength of the mixed materials were a combination of those dominating the 0- to 1- and 2- to 4-mm materials. Factor 1 contained, as mentioned above, variables associated with clay amount and surface properties. The next dominant factor contained Na and SAR, as did the second dominant factor for the 0- to 1-mm material, and the next two important factors were the same as the second and third dominant factors for the 2- to 4-mm material, those being a factor for aggregation-related variables (Fe, Al, and dispersible clay) and a factor for very coarse sand.

Two other factors that were significant and that came out of the analysis in all three cases were related to silt and EC. The silt-related factor in each case contained three variables with high loadings: silt, fine silt, and coarse silt. In each of the three factor analyses, there was a factor that contained EC only, although the factor containing EC was not one of the primary ones for the 2- to 4-mm material.

Regression Analyses

One variable was chosen to represent each of the factors from the factor analyses and used in the regression analyses. The procedure was to identify the variables within each factor that had high (>0.80) loadings to the factor (Tables 3, 4, and 5) and from those to select the one variable that had the highest correlation to the dependent variable. Table 6 shows the results of the stepwise regression analyses, including the representative variables, for the tensile strength of the 0- to 1-mm, 2- to 4-mm, and mixed soil materials. This procedure was designed to accomplish the stated goal of reducing the number of independent variables to a subset of variables that were relatively noncorrelated and that were important with regard to explaining the variance of tensile strength. In other words, the factor analyses enabled us to eliminate redundant and insignificant variables for use in the regression analyses.

Table 6. Regression coefficients from stepwise multiple regression analyses relating representative variables from factor analysis to the tensile strength of the 0- to 1-mm, 2- to 4-mm, and mixed aggregate size classes of the 33 soils.† One variable was selected from each of the factors listed in Tables 3, 4, and 5, respectively, to represent that factor in the analysis. Selection of representative variables was based on the correlation coefficient with the dependent variable (tensile strength).

Representative variable	0–1-mm aggregate size	2–4-mm aggregate size	Mixed aggregate size
Coefficient of linear expansion index	8.47	7.16	12.78
Na	2.15	1.23	2.29
Electrical conductivity	−0.38	–	–
Fine-silt content	−0.009	−0.018	−0.015
Very coarse sand	–	−0.042	–
Intercept	1.58	1.63	1.23
$P > F$	0.0002	0.0001	0.0001
R^2	0.53	0.61	0.65

† Criteria for inclusion of variable in model was $P > 0.10$.

Variables that were retained by the stepwise regression were consistent with the factor-analyses results. The COLE (representative variable for Factor 1 in all three cases) was retained, and in fact was the most significant variable in each regression equation. For the 0- to 1-mm material, the regression equation included COLE, Na, EC, and fine-silt content. For the 2- to 4-mm material, COLE, very coarse sand, fine-salt content, and Na were in the regression equation. When the significance-level criterion for inclusion of a variable into the forward stepwise method was relaxed to 0.15, Fe and EC were added to the prediction equation for the 2- to 4-mm material. Interestingly, the regression equations for the tensile strength of the mixed material contained only three variables: COLE, Na, and fine-sand content. The three-variable model for the mixed material was better in terms of significance and R^2 than either of the four-variable models for the 0- to 1- and 2- to 4-mm materials.

Regression Analyses by Soil Particle-Size Groups

A similar approach to analysis of the tensile strength of the mixed material was undertaken for the four subsets of soils delineated by particle size as discussed above. The final regression equations so derived are shown in Table 7. Essentially three types of variables were retained in the regression relationships: a clay-related term, coarse plus very coarse sand, and Atterberg limits. It could be reasonably argued that Atterberg limits are clay-related terms, which is certainly true. In the factor analyses, however, the Atterberg limits were represented in separate factors from the other clay surface property terms, which implies that these were distinct factors in terms of representing the tensile strength.

A term representing clay amount and surface properties was represented in three of the four equations. For the clayey soils (clay >29%) tensile strength was directly proportional to soil specific surface area (the intercept term initially derived in the regression analysis for the clays was insignificant, therefore the regression was redone with forcing the intercept to zero). This in itself is an interesting result, because it shows that, for those soils, clay surface activity is the essential

Table 7. Prediction equations for tensile strengths, T, of the mixed aggregate size soil materials by soil particle-size groups. These equations are based on selection of independent variables from factor analyses within each particle-size group. Clay group is for soils with clay content >29%, silt group is for soils with silt content >50%, sand group is for soils with sand content >52%, loam group is for soils not in the other three categories.

Soil texture group	Prediction equation†	r^2 or R^2	$P > F$
Clay	$T = 0.0680$ SSA	0.91	0.0009
Silt	$T = 13.75$ COLE $- 0.034$ PL $+ 1.668$	0.89	0.0012
Sand	$T = -0.0334$ CVCS $+ 0.0381$ BSUM $+ 1.799$	0.82	0.0056
Loam	$T = 0.00376$ PI $+ 1.142$	0.86	0.0003

† SSA, specific surface area; COLE, Coefficient of linear expansion; PL, plastic limit; CVCS, coarse plus very coarse sand; BSUM, sum of bases; PI, plasticity index.

factor affecting interaggregate cohesion, and it implies that the binding mechanism is directly proportional to clay surface area. For the silty soils COLE was important, and for the sandy soils the sum of the bases was used as the representative variable because it had, of the variables within that particular factor, the greatest correlation to tensile strength.

Coarse plus very coarse sand was a factor only for the sandy soils, as might be expected. This implies that the inclusion of the coarse-sand term in the analyses of the full data set (all 33 soils) was due to its relationship to tensile strength for the sandy soils. Plastic limit was significant in predicting tensile strength of the silty soils. For the loamy soils plasticity index alone was a good predictor ($r^2 = 0.86$) of tensile strength of the mixed soil material.

SUMMARY

The tensile test used here is essentially a test of interaggregate cohesion under near-saturated conditions. Much research has focused on the stability of aggregates, both wet and dry, but few prior studies have addressed the issue of interaggregate strength in saturated soils. Certainly part of the reason for this is due to a lack of adequate lab or field tests for measuring the tensile strength of loose soils under wet conditions. Interaggregate strength for saturated soil plays an important role for surface soils with regard to surface sealing and soil erosion. This study illustrates the use of a laboratory tensile test for loose, saturated soils as applied to a wide variety of soil types from across the USA.

Results of the factor analyses indicated several groups of independent variables that were important in explaining the variance of tensile strength. The dominant factor overall contained a group of variables related to clay amount and surface properties, which would be expected to strongly influence the soil cohesion. A second factor that was important included the variables Na and SAR, indicating the importance of the soil chemistry related to dispersion. For the larger aggregate size material (2–4 mm) factors that included very coarse sand and aggregate stability were important in explaining tensile strength. Two other factors that were important were a silt term and EC.

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