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Dry-Soil Aggregate Stability as Influenced by Selected Soil Properties

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ABSTRACT

Dry aggregate stability is an important soil physical property for evaluating tillage and wind-erosion research. Research in this study was aimed at developing a model for predicting soil aggregate stability as influenced by intrinsic soil properties, with particular application to wind erosion. Aggregates from 10 Kansas soils with a wide textural range were tested periodically for stability during a 3-yr period. The logarithm of aggregate stability was regressed against the intrinsic soil properties (geometric mean diameter of primary particles, specific surface area, water content at −1500 J/kg matric potential, and clay content). Clay content and water content at −1500 J/kg were both good predictors of mean aggregate stability. A resulting empirical model estimates mean aggregate stability from either clay or water content with coefficients of determination of 0.97 and 0.96, respectively. Further testing is planned by running the model with several independent data sets to estimate the probability of aggregate stability within specified limits for particular soils.

WIND-EROSION RESEARCH SCIENTISTS have been charged with developing improved wind-erosion prediction technology as a possible replacement for the wind-erosion equation (Hagen, 1991a). Improved wind-erosion prediction technology requires that we improve our ability to measure and predict, in time and space, the susceptibility of soil to wind erosion.

The main properties of dry soil aggregates affecting their susceptibility to wind erosion are stability and size distribution. Soil aggregate stability and size distribution vary widely in time and space. Aggregate density affects soil erodibility to a lesser extent but is much less variable than stability and size distribution.

Chepil (1950), using a wind tunnel, determined relative erodibility of soil as a function of the proportions of dry soil aggregates in various sizes. Chepil (1960) later converted relative erodibility to actual field soil loss for specified conditions, which was the basis for soil -erodibility factor of the wind-erosion equation (Woodruff and Siddoway, 1965). Their data show nonaggregated sandy soils with only 1% of the sand having diameters >0.85 mm are 100 times more erodible than aggregated soils with 77% of their aggregates >0.85 mm (Woodruff and Siddoway, 1965). Similarly, dry AS may differ a hundredfold between soils.

Aggregates with low stability fracture easily and break into small sizes. Hagen (1991b) found that AS was the dominant predictor of soil erosion from surface abrasion. He concluded that major improvements in predicting the abrasion coefficient of the abrasive flux equation can come only from improved predictions of the stability of aggregates and crusts.

The aggregate status of a soil at any instant in time is the result of many aggregate-forming and -degrading processes. Those processes comprise a complex interrelationship of physical, chemical, and biological

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Abbreviations: AS, aggregate stability; SD, standard deviation; CDN, calendar-day number; CDMAX, calendar-day number when aggregate stability is at maximum; GMD, geometric mean diameter; GSD, geometric standard deviation; CV, coefficient of variation; PWP, water content at −1500 J/kg.

reactions. Aggregates may form by the breakdown of consolidated soil mass into smaller sizes or by the coalescing of finer materials.

Chepil (1955) observed a definite relationship between amounts of erosion in a wind tunnel and the percentage of clay contained in the soil. Soils containing 20 to 35% clay were least erodible. Coarse-textured soils apparently lack sufficient amounts of silt and clay to bind individual sand particles together, or they may form weakly cemented clods that are readily broken down and eroded. On medium-textured soils, the proportions of silt and clay appear to be sufficient to bind the sand grains together, yet not so high as to cause excessive cleavage by weathering and consequent granulation.

This research was aimed at developing a model for predicting soil AS as influenced by intrinsic soil properties, with particular application to wind erosion.

THEORY

The factors affecting dry soil AS may be divided into two categories: invariant and dynamic. Intrinsic soil properties, i.e., primary particle-size distribution, mineral constituents, adsorbed ions, etc., change slowly in time and are relatively invariant. However, crop, weather, and tillage affect aggregate status in the short term. The values of these dynamic variables change with time, so they are sometimes called *temporal* properties. Because the dynamic factors are thought to be strongly seasonal, and the amplitude of the annual swing of AS is expected to be sensitive to soil texture and climate, it is reasonable to assume

$$\mathrm{AS} = A + BX_1 + CX_2 + \ldots + D\cos\left[\left(\frac{\mathrm{CDN} - \mathrm{CDMAX}}{365}\right)2\pi\right]. \quad [1]$$

The first three terms on the right side of the equation are the regression variables and coefficients expressing the influence of intrinsic soil properties on AS. The variable D of the last term is the amplitude of the annual variation of AS.

When AS does not vary periodically in a predictable manner or is random about a central value, a stochastic approach is more feasible. The probability of AS being greater or less than some value may be represented by use of the error function of the normal distribution. This function associated with the normal curve is

$$\frac{1}{2}\,\mathrm{erf}\left(\frac{t}{\sqrt{2}}\right) = \int_0^t \phi(x)\,\mathrm{d}x \quad [2]$$

where the right side of Eq. [2] is the area integral of the normal probability curve and x is measured in SD units from the mean (Hodgman et al., 1957, p. 237). The error function is defined by

$$\mathrm{erf}(Z) = \frac{2}{\sqrt{\pi}}\int_0^Z e^{-t^2}\,\mathrm{d}t \quad [3]$$

where t is a dummy variable of integration (Gautschi, 1965). In our application of the error function,

$$Z_i = (\ln\mathrm{AS}_i - \overline{\ln\mathrm{AS}})/(\sqrt{2}\ \mathrm{SD}) \quad [4]$$

where $\ln\mathrm{AS}_i$ is the natural logarithm of AS corresponding to a probability, P_i, for a soil with a mean log stability of $\overline{\ln\mathrm{AS}}$ and SD. Because Eq. [3] is for only one-half of the area integral, it follows that

$$P_i = 0.5 + \mathrm{erf}(Z_i)/2 \quad [5]$$

where P_i is the cumulative probability that AS will not exceed the value specified in Eq. [4] for the soil with the given mean and SD. Combining Eq. [4] and [5] gives

$$P_i = 0.5 + \mathrm{erf}[(\ln\mathrm{AS}_i - \overline{\ln\mathrm{AS}})/(\sqrt{2}\ \mathrm{SD})]/2. \quad [6]$$

MATERIALS AND METHODS

Field soil samples were collected to obtain data needed to test the feasibility of using Eq. [1] and [6] for estimation of AS and using intrinsic soil properties to estimate a mean AS.

Kansas soils with a wide textural range within each of the udic, ustic, and aridic moisture regimes and the mesic temperature regime were selected for study (Table 1). Some basic soil properties that might affect soil behavior but were expected to remain relatively constant for the duration of the experiment were measured (Table 2). Particle-size distribution was determined by sieving the sand fraction and pipetting the clay fraction, according to the method of Gee and Bauder (1986). The GMD of primary particles was calculated by

$$\mathrm{GMD} = \prod_{i=1}^{n} (x_i)^{m_i} \quad [7]$$

where Π is the product operator, m_i is the mass fraction represented by size class i, and x_i is the GMD of glass i (Gardner, 1956; Campbell, 1985). The GSD was calculated

Table 1. Location and description of ten Kansas soils tested for aggregate stability.

Location	*Moisture regime*	*Soil series*	*Taxonomic classification*
Riley County (Manhattan)	udic	Carr sandy loam	Coarse-loamy, mixed (calcareous), mesic Typic Udifluvent
		Haynie silt loam	Coarse-silty, mixed (calcareous), mesic Mollic Udifluvent
		Reading silt loam	Fine-silty, mixed, mesic Typic Argiudoll
		Smolan silty clay	Fine, montmorillonitic, mesic Pachic Argiustoll
		Wymore silty clay	Fine, montmorillonitic, mesic Aquic Argiudoll
Ellis County (Hays)	ustic	Harney silt loam	Fine, montmorillonitic, mesic Typic Argiustoll
		Inavale loamy sand	Sandy, mixed, mesic Typic Ustifluvent
		New Cambria silty clay	Fine, montmorillonitic, mesic Cumulic Haplustoll
Greeley County (Tribune)	aridic	Richfield silt loam	Fine, montmorillonitic, mesic Aridic Argiustoll
		Lincoln loam	Sandy, mixed, thermic Typic Ustifluvent

Table 2. Particle-size distribution, geometric mean diameter and standard deviation, organic-matter content, specific surface area, and gravimetric water content of 10 Kansas soils.

Soil	Particle size			Geometric mean diameter	Geometric standard deviation	Organic matter	Specific surface area	Water content at −1500 J/kg
	Sand	Silt	Clay					
	%			mm		g/kg	m^2/g	kg/kg
Smolan	6.7	60.1	32.9	0.0033	7.91	19	40	0.125
New Cambria	14.3	46.6	39.1	0.0035	13.31	26	46	0.159
Wymore	7.8	63.8	28.4	0.0039	7.30	24	43	0.111
Harney	9.8	61.1	29.3	0.0040	8.01	14	39	0.120
Reading	6.4	70.1	23.6	0.0046	6.40	23	29	0.100
Richfield	27.5	51.0	21.4	0.0089	10.03	15	35	0.108
Haynie	33.7	58.4	8.7	0.0146	5.44	19	14	0.053
Lincoln	49.7	34.9	15.4	0.0255	13.00	17	7	0.079
Carr	58.8	35.5	5.5	0.0290	4.98	11	7	0.029
Inavale	81.5	12.6	5.9	0.1197	7.51	8	7	0.032

by

$$\mathrm{GSD} = \exp\left[\sum m_i (\ln x_i)^2 - (\ln \mathrm{GMD})^2\right]^{1/2}. \qquad [8]$$

Seven particle-size classes (clay, silt, and five sand fractions, as determined by mechanical analysis) were used to calculate GMD and GSD. Organic-matter concentration was determined by a modified Walkley-Black method (Schulte, 1988) at the Soil Testing Laboratory, Kansas State University. Specific surface area and PWP were determined by the National Soil Survey Laboratory, Lincoln, NE.

Soil samples of ≈5 kg were taken with a flat shovel from the top 5 cm of the Ap horizon at each site every few weeks for a total of 20 times throughout a period of 3 yr. Samples were air dried in the laboratory and passed through a set of flat sieves. Aggregates that passed through a 19.1 and collected on a 12.7-mm sieve were tested for stability (Skidmore and Powers, 1982; Boyd et al., 1983).

Individual aggregates were crushed by diametrically loading them between parallel plates. As force was slowly increased on an aggregate, it usually remained frigid until fracture. The force (N) being applied to the aggregate at the time of fracture is called the *initial break force*. After initial fracture, crushing continued to a specified end point. The work required to crush each aggregate was divided by the mass of the aggregate being crushed to give a measure of AS (J/kg).

Stability of 15 aggregates in each of the four replications (reduced to three replications after the first year) was measured. Since stability measurements followed more log-normal than normal distribution, the mean SD and CV were calculated from the log-transformed data. Equations [1] and [6] both require an estimate of mean AS. the mean, SD, and CV of the initial break force were also calculated.

Mean AS was regressed on primary particle-size distribution, GMD, soil specific surface area, PWP, and clay content.

Intrinsic soil properties were used for predicting mean AS, Eq. [9]. The $\overline{\ln AS}$ was calculated from PWP, hereafter referred to simply as *water content*.

$$\overline{\ln \mathrm{AS}} = 0.48 + 40.0\ \mathrm{PWP} - 134.5\ (\mathrm{PWP})^2. \qquad [9]$$

Then using the CV of AS from an earlier part of this study, the SD of aggregate stability as estimated from

$$\mathrm{SD} = 0.16\ \overline{\ln \mathrm{AS}} \qquad [10]$$

where 0.16 is the mean CV.

A random number was generated between 0 and 1.0 and substituted for P_i in Eq. [6]. Equation [6] was solved for $\ln AS_i$ by successive bisection of $\ln AS_i$ and iterative solution of erf (Z_i) to satisfy

$$\mathrm{erf}(Z_i) - (2P_i - 1) < 0.001. \qquad [11]$$

This process was repeated 20 times for each of the 10 soils. The distribution of AS determined by this simulation procedure was compared with the measured aggregate distribution.

Aggregate-stability data for 20 measurements during 3 yr were examined for appropriateness of Eq. [1] and [6], where CDMAX and *D* were determined from the sequence of AS measurements. The mean AS, SD, and CV were determined.

RESULTS AND DISCUSSION

The relationship between AS and specific soil surface area was better than that with GMD (Table 3), but neither predicted AS as well as water content and clay fraction (Table 3; Fig 1). Within limits of the data set, with clay content ranging from 5 to 39% and water content ranging from 0.03 to 0.16 kg/kg, either factor could be used to reasonably predict mean AS. Fortunately, water content and clay fraction are relatively easy to measure and are often reported in soil information data bases.

Mean soil AS is sensitive to clay content until it reaches 25% (Fig. 1). Chepil (1955) found a definite relationship between the amount of erosion in a wind tunnel and the percentage of clay contained in the soil. Soils containing 20 to 35% clay were least erodible, which agrees with the results of this study (Fig. 1).

Mean AS, initial break force, and their respective CVs are given in Table 4. Statistics were calculated for the 20 sampling periods during the 3 yr of the study. Each mean was calculated from the results of crushing >1000 aggregates. Generally, the finer textured soils had a wider range of stability. Aggregates from the finer textured soils were sometimes extremely durable and other times easily crushed, depending on the immediately previous tillage and cropping history. However, the aggregates from coarse-textured soils were never difficult to crush. Thus, the SD of the AS of coarse-textured soils was usually less than that of the fine-textured soils. Average SDs for the five coarse- and five fine-textured soils were 0.36 and 0.51 ln(J/kg), respectively. Though highly variable, the CVs were not greatly different, being 0.17 and 0.15, respectively for the coarse- and fine-textured soils.

Table 3. Regression of mean aggregate stability as a function of selected intrinsic soil properties based on 10 Kansas soils.

Intrinsic soil property	Regression coefficients† *a*	*b*	*c*	r^2
Geometric mean diameter, mm	3.07	−13.06	—	0.39
Surface area, m²/g	1.47	0.071	−0.0062	0.78
Water content, kg/kg	0.48	39.95	−134.55	0.96
Clay content, %	0.83	0.157	−0.00238	0.97

† Regression model: $\overline{\ln AS} = a + bX + cX^2$, where X is value of the soil property.

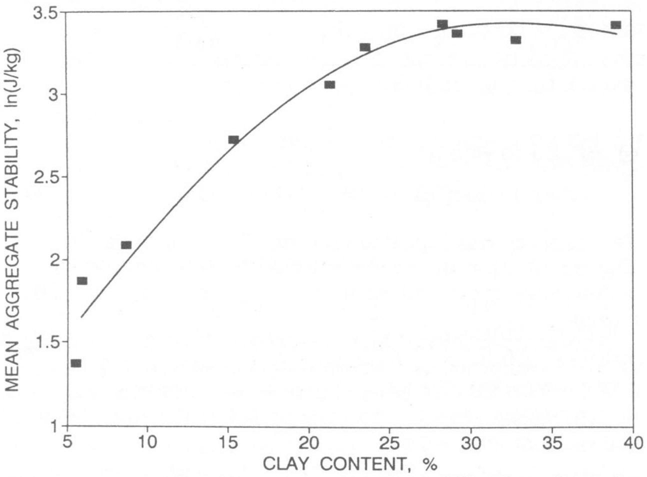

Fig. 1. Prediction of mean aggregate stability based on the clay content of 10 Kansas soils.

Table 4. Statistical summary of the three-year average aggregate stability and the initial break force for 10 Kansas soils.

Soil	Aggregate stability mean	CV	Initial break force mean	CV
	ln(J/kg)		ln(N)	
Carr	1.37	0.17	1.03	0.18
Haynie	2.09	0.27	1.60	0.32
Harney	3.36	0.11	2.86	0.11
Inavale	1.87	0.22	1.57	0.22
Lincoln	2.72	0.10	2.22	0.13
New Cambria	3.41	0.16	2.95	0.18
Reading	3.28	0.17	2.77	0.18
Richfield	3.05	0.09	2.52	0.10
Smolan	3.32	0.19	2.82	0.21
Wymore	3.32	0.14	2.81	0.16

Table 5. Yearly summaries of aggregate stability and initial break force for four Kansas soils.

Soil	Year	Aggregate stability mean	CV	Initial break force mean	CV
		ln(J/kg)		ln(N)	
Carr	1	1.58	0.13	1.17	0.20
	2	1.24	0.10	0.95	0.08
	3	1.29	0.18	0.91	0.12
Haynie	1	2.66	0.12	2.14	0.14
	2	1.84	0.21	1.37	0.23
	3	1.72	0.24	1.24	0.30
Harney	1	3.35	0.12	2.84	0.11
	2	3.36	0.09	2.90	0.09
	3	3.36	0.13	2.84	0.13
Richfield	1	3.04	0.07	2.52	0.09
	2	2.90	0.08	2.40	0.08
	3	3.25	0.09	2.67	0.11

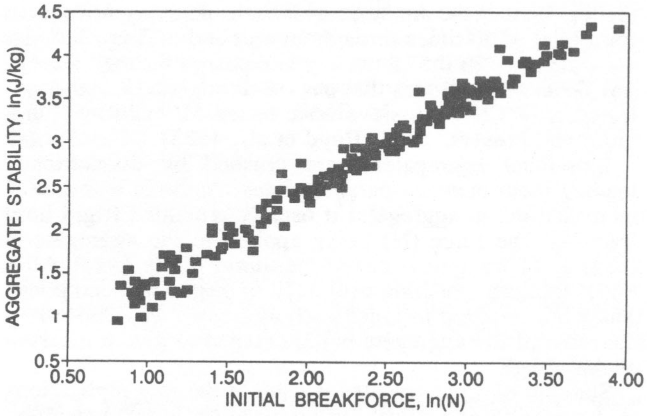

Fig. 2. Relationship between aggregate stability and the initial break force of 10 Kansas soils.

In an effort to determine if the AS variability was consistent throughout the 3-yr study, AS was calculated by year for several of the test soils (Table 5). The variability of AS did not appear to be unique to each soil. The CVs for Carr and Haynie soils varied greatly from year to year, whereas the CV for the Richfield soil was consistently low. Because variation in CV existed from year to year and among soils, an overall CV for modeling AS was used. The mean CV of AS calculated from the data in Table 4 was 0.16.

Because the procedure to evaluate AS from the initial break force is simple and the equipment requirements are small, it warrants further evaluation. The regression of crushing energy on initial break force (Fig. 2). shows a relatively well-defined relationship with an r^2 of 0.98. In a computed correlation matrix, the correlation between crushing energy and initial break force was 0.99. Based on the results shown in Fig. 2, crushing energy should be used to measure soil AS. If equipment to measure crushing energy is not available, however, the initial break force should be considered. Unpublished data (Skidmore and Layton, 1991) suggest that more replications are needed when using the initial-break-force method to achieve the same accuracy; however, in this study, the CVs were not very different between methods (Tables 4 and 5).

The dynamic variables influencing AS, like climate, crop, etc., were expected to be sufficiently patterned so their combined influence could be described as a function of time. This hypothesis was not confirmed after 3 yr of sampling.

Variation of AS with day of the year is typified by the Carr and Harney soils in Fig. 3. Only the two highest values and the two lowest values are significantly different from the mean ($P = 0.05$) for both

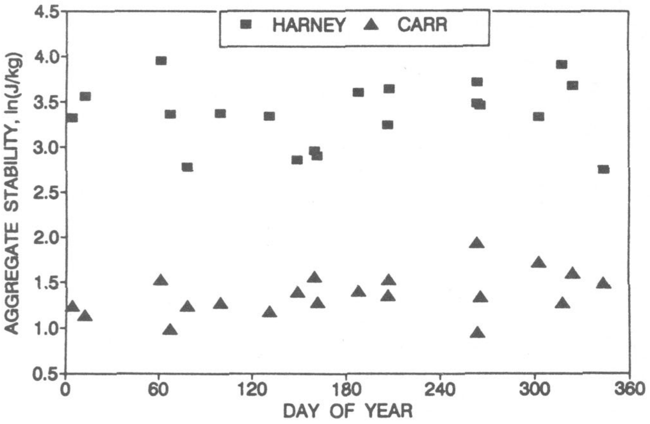

Fig. 3. Seasonal changes in aggregate stability for two Kansas soils during a 3-yr period.

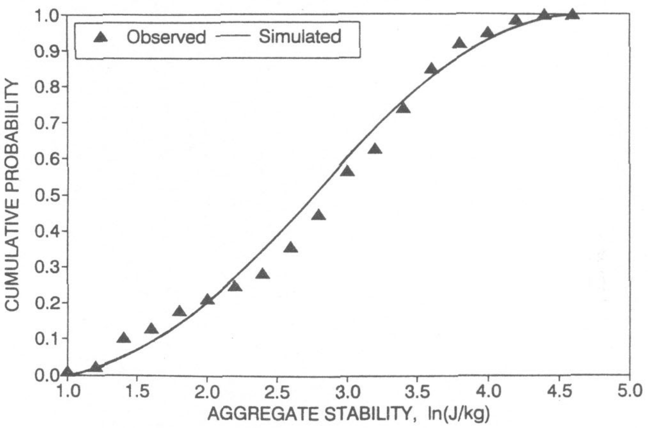

Fig. 4. A comparison of measured and simulated aggregate-stability distribution based on 10 Kansas soils.

soils according to SAS Institute's (1985) pairwise *t*-test, equivalent to Fisher's least significant difference. The most stable and least stable aggregates of the Carr soil were sampled on the same day of the year—21 Sept. 1987 and 1989. Similarly, the Harney soil had stability extremes at the same time during both years. These results did not hold with the initial contention that Eq. [1] would account for much of the variation of dry soil AS.

The AS distribution simulated by Eq. [6] agreed reasonably well with the measured AS distribution (Fig. 4). This comparison shows that the AS distribution for the soils in this study can be estimated from the average CV and predicted mean AS. Further testing is planned by running the model with several independent data sets.

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