Wind Erosion: Prediction of Aggregate Abrasion Coefficients

L. J. Hagen, E. L. Skidmore, A. Saleh
Member
ASAE

Abstract

Among the major factors controlling wind erodibility of soils are the abrasion coefficients of the soil crust and aggregates. Here, the abrasion coefficient is defined as the abraded soil loss per unit area for each unit mass of abrader passing a unit across-wind width and has units (1/m). However, measuring abrasion coefficients directly in the field is not convenient. So, in field plot studies, energy to crush aggregates (CE) has been measured and related to intrinsic soil properties. In this study, wind tunnel tests were used to develop a prediction equation for aggregate abrasion coefficients as a function of Ln(CE) of aggregates and crusts. **Keywords.** Wind erosion, Abrasion, Aggregates, Crush energy.

Introduction

A modeling team (Hagen, 1991b) in the United States Department of Agriculture is developing technology to replace the current wind erosion equation (Woodruff and Siddoway, 1965) with a computer model, dubbed WEPS for Wind Erosion Prediction System. Using a series of submodels, WEPS simulates wind erosion, as well as the daily weather, hydrology, soil, tillage, and biomass conditions that control wind erosion on a field scale. A field measurement program also is being carried out to validate WEPS.

In the erosion submodel of WEPS, the soil moving in the saltation and creep transport modes is modified by a series of sources and sinks, using the principle of mass conservation applied to a control volume (fig. 1). The sinks are trapping (deposition) of saltation and creep in sheltered areas and loss by diffusion of the suspension-size particles through the top of the control volume. The sources are emission of loose aggregates from the crust or from among the large clods and abrasive breakdown of clods and crust to wind-erodible size from impact of saltating aggregates (Hagen, 1991a).

The erosion submodel is designed to simulate the physical processes that occur in the field. But in order to predict the soil abrasion process in the erosion submodel, abrasion coefficients for soil clods and crusts are needed. Because the coefficients are temporal properties and also vary widely among soils, many laboratory and field plot measurements would be needed to develop prediction equations for this variable. Unfortunately, measuring abrasion coefficients directly is not convenient, because specialized, expensive equipment, such as wind tunnels, is required.

Thus, in the WEPS structure, dry stabilities of clods and crust were selected as the temporal variables for daily updating in the model, because they are much easier to measure, by both the researchers developing the prediction equations and users seeking to validate the model in the field. The remaining problem is then to determine the abrasion coefficients as functions of the dry aggregate and crust stabilities. A series of wind tunnel studies was carried out to determine this relationship and is the focus of this report.

Literature Review

Surface soils in the tillage zone, particularly after wetting and drying, are not homogeneous, but rather, are composed of various structural units. Chepil (1953) reported the relative dry stability of these structural units from highest to lowest as follows: (a) water-stable aggregates, (b) secondary aggregates or clods, (c) surface crust, and (d) consolidated fine materials among the clods. Because water-stable aggregates are generally less than 1.0 mm in diameter, only the other structural units are capable of providing a stable surface cover against wind erosion.

The importance of the abrasion process in the breakdown of the soil structural units during wind erosion

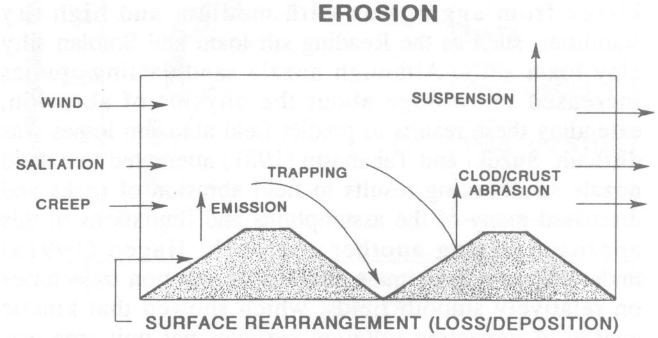

Figure 1–Diagram of a control volume for the EROSION submodel with bare soil, illustrating sources and sinks for soil moving in saltation and creep transport modes.

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The authors are **Larry J. Hagen**, Agricultural Engineer, **Edward L. Skidmore**, Soil Scientist, USDA-ARS, Kansas State University, Manhattan; and **A. Saleh**, Soil Scientist, USDA-ARS, Big Spring, TX.

was clearly recognized in early studies (Chepil, 1955; Chepil and Woodruff, 1963). However, much of the early work had two problems. First, the measurements of dry stability were inferred from multiple sieving of the soil samples, modulus of rupture, or other tests. Unfortunately, these tests were not sensitive indicators of abradability over the whole range of stabilities present in the various soil structural units. Second, and more importantly, the definition selected for coefficient of abrasion and the subsequent test procedures developed to measure it could not be interpreted in terms of abrasion losses from fields. Hence, in development of the wind erosion equation (Woodruff and Siddoway, 1965), stability of the soil structural units was not included as an explicit input variable.

Since the early work of Chepil, further research related to abrasion has been reported and will be summarized, including: (a) studies with calibrated sandblasting nozzles to determine the importance of various physical parameters on the abrasion process, (b) derivation of a new definition for a coefficient of abrasion applicable to field abrasion losses and subsequent development of measurement techniques, and (c) derivation of new measures for dry stabilities of clods and crusts, coupled with development of measurement procedures and instruments to quantify dry stability.

Much of the current knowledge about the physics of abrasion of soil aggregates (Hagen, 1984) and rocks (Suzuki and Takahashi, 1981; Greeley et al., 1982; Greeley and Iversen, 1985) has been deduced from experiments using calibrated sandblasting nozzles. In general, the nozzle tests demonstrated that neither rocks nor soil aggregates respond to abrasion as strictly brittle or ductile materials, but rather as composite materials with properties between these regimes. In the case of soil, abrasion loss per unit mass of abrader was proportional to the kinetic energy of the impacting particles, but loss increased somewhat with abrader diameter. Impact angles of 15 to 30° caused more abrasion loss than did larger impact angles. In addition, sand abrader also caused slightly more abrasion loss from target aggregates than did soil abrader.

In another study, aggregates were abraded at various moisture contents with a sandblasting nozzle (Hagen, et al., 1988). For aggregates with low dry stabilities, such as Carr sandy loam and Haynie loam soils, increasing aggregate moisture content to 50% of field capacity reduced abrasion loss rates to 45 and 10%, respectively, of their air-dry rates. However, moisture increased or did not affect the abrasion losses from aggregates with medium and high dry stabilities, such as the Reading silt loam and Smolan silty clay loam soils. Although nozzle sandblasting studies increased knowledge about the physics of abrasion, extending these results to predict field abrasion losses was difficult. Suzuki and Takahashi (1981) attempted to extend nozzle sandblasting results to field abrasion of rocks and discussed many of the assumptions and limitations in this approach. Using another approach, Hagen (1991a) undertook an approximate analysis of saltation trajectories on relatively smooth fields, which showed that kinetic energy of impacting saltation particles per unit area was mainly dependent on saltation discharge and largely independent of the accompanying wind speed. Based on this information, an expression for the field soil abrasion process was derived and validated in the form:

$$G_{ani} = \sum_{i=1}^{m} \left(F_{ani}\, C_{ani}\right) q \qquad (1)$$

where

G_{ani} = vertical abrasion flux ($ML^{-2}T^{-1}$)
F_{ani} = fraction of abrader impacting the *ith* target
C_{ani} = coefficient of abrasion (L^{-1})
q = saltation discharge ($ML^{-2}T^{-1}$)

By using a single target surface, where F_{ani} = 1 in wind tunnel tests, the coefficient of abrasion for surfaces can be calculated using equation 1. Recently, this procedure has been used to investigate simulated rain-drop crusts on a range of soils (Zobeck, 1991) and the value of various clays for sand stabilization (Diouf et al., 1990).

Problems with a number of qualitative and quantitative methods to characterize dry aggregate stability were reviewed by Skidmore and Powers (1982). In response, they developed an improved stability index based on the energy required to break interparticle bonds and create new external surface areas. They found that the new index was applicable to the wide range of stabilities present among soils, but sensitive enough to easily distinguish the stability differences. Subsequently, instrumentation and standardized procedures were developed to permit convenient measurement of aggregate crushing energy (Boyd, Skidmore, and Thompson, 1983).

Experimental Methods

The experiments were conducted using similar procedures at two locations: Manhattan, Kansas, and Big Spring, Texas. The data sets were then combined for analyses. Aggregates 12.7 to 19.0 mm in diameter were gently sieved from the first 17 field soils listed in Table 1. Subsamples of 30 aggregates from each soil were individually crushed in a crushing meter (Boyd, Skidmore, and Thompson, 1983) using procedures outlined previously (Skidmore and Powers, 1982). In these studies, the dry aggregate stability was expressed as the natural log of the crushing energy per unit mass. These data were averaged to provide a mean dry aggregate stability value for each soil.

Aggregate abrasion tests were conducted as follows: a 30 to 40% cover of clods was placed on coarse screens 300×300 mm in size and placed in a downwind portion of a wind tunnel with simulated, nonabradable aggregates surrounding the screens (fig. 2). The minimum clod cover was selected, so that sand abrader would always impact on target clods when crossing the screens (Hagen, 1991a). At least four screens of each soil were used and two soils were placed in the tunnel for each test run.

Next, abrader sand, 0.29 to 0.42 mm in diameter, was either placed on the upwind tunnel floor or fed to the upwind floor through tubes. Sand was then blown across the test soils at freestream wind speeds ranging from 12.5 to 15.0 m/s. For each test run, abrader crossing the screens per unit width across the tunnel was measured. After each run, the screens and clods were reweighed and the abraded loss per unit of tunnel floor area was calculated. Using

TABLE 1. Study soils used in wind tunnel abrasion tests

Soil Series	Sand (%)	Silt (%)	Clay (%)	Organic Matter Concentration (g / kg)	Taxonomic Classification
Acuff fine sandy loam	74.0	13.7	12.2	8.6	Aridic Paleustoll, fine-loamy, mixed, thermic
Alliance fine silty loam	29.0	49.9	21.1	25.3	Ardic Argixerolls, fine-silty, mixed, mesic
Amarillo fine sandy loam	75.8	12.9	11.3	5.6	Ardic Paleustalf, fine-loamy, mixed, thermic
Amarillo fine sandy loam	67.1	18.1	14.8	4.7	Aridic Paleustalf, fine-loamy, mixed, thermic
Amarillo loamy fine sand	79.8	11.7	8.5	3.4	Aridic Paleustoll, fine-loamy, mixed, thermic
Barnes clay loam	26.3	42.1	31.6	47.4	Udic Haploboroll, fine-loamy, mixed, udic
Carr sandy loam	58.8	35.5	5.5	11.0	Typic Udifluvent, coarse-loamy, mixed, mesic
Cherry silty clay loam	14.6	59.4	26.0	22.5	Typic Ustochrepts, fine-silty, mixed, frigid
Drake fine sandy loam	77.3	11.5	11.2	3.2	Typic Ustorthent, fine-loamy, mixed (calcareous)
Gilford fine sandy loam	85.1	9.9	5.0	33.8	Typic Haplaquolls, coarse-loamy, mixed, mesic
Haynie silt loam	33.7	58.4	8.7	19.0	Mollic Udifluvent, coarse, silty, mixed, mexic
Inavale loamy sand	81.5	12.6	5.9	8.0	Typic Ustipsamment, mixed, mesic
Kimo silty clay loam	20.0	44.0	36.0	22.0	Fluvaquentic Hapludoll, clayey over loamy, montmorillonitic, mesic
New Cambria silty clay	14.3	46.6	39.3	26.0	Cumulic Haplustoll, fine, mont, mesic
Pullman clay loam	29.3	33.1	31.6	8.5	Torrertic Paleustoll, fine, mixed, thermic
Reading silt loam	6.4	70.1	23.6	23.0	Typic Argiudoll, fine, mixed, mesic
Reagan silty clay loam	22.0	48.6	29.4	20.2	Ustollic Calciorthid, fine-silty, mixed, thermic
Wymore silty clay	7.8	63.8	28.4	24.0	Aquic Arguidoll, fine, mont, mesic

these data in equation 1, average abrasion coefficients for each soil were calculated.

Crust abrasion tests were conducted as follows. Soil trays with an area of 0.51 m^2 and depth of 50 mm were filled with sieved soil particles less than 2 mm in diameter. Trays were wetted from the bottom and air-dried in a greenhouse to provide uniform consolidation (crust) of the soil. Shrinkage cracks present after drying were filled with loose soil, wetted, and again dried. Four trays of each of two soils, Wymore silty clay and Reading silt loam, were prepared. Each tray was subjected to five abrasion runs. Next, subsamples 15×15 mm of the consolidated soil were cut from the trays and their crushing energy was measured with the crushing plates oriented parallel to the original crust surface. Finally, crust abrasion coefficients were calculated in a manner similar to that used for the clod surfaces.

Results and Discussion

Dry aggregate stability of field soils is a temporal variable. In Kansas soils, Skidmore and Layton (1992) found that both the mean and standard deviations of dry stability increased with clay content, as illustrated by the lines in figure 3. The range of dry stabilities of the aggregate samples collected in this study also are illustrated on figure 3. Although 11 of the sampled soils listed in Table 1 are from outside Kansas, their stabilities were generally within the range reported for Kansas soils. Most of the samples were collected during seasons when their stability was above average for the soil.

The measured relationships between abrasion coefficients and dry stability are illustrated in figure 4. Three nearly linear regions are seen on the response curve. Thus, the natural log of the crushing energy appears to be the correct parameter to average when determining mean dry stability of aggregates in a soil sample, because it is

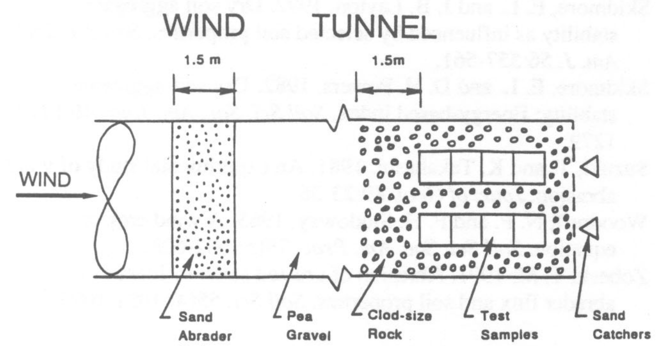

Figure 2–Diagram of wind tunnel configuration for abrasion tests.

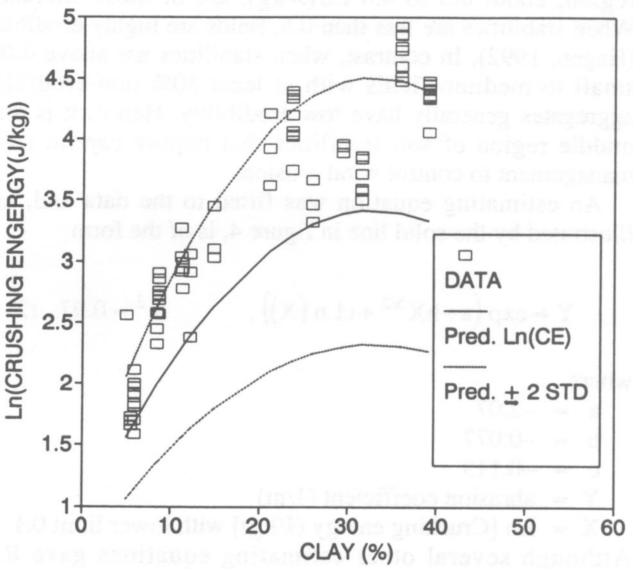

Figure 3–Predicted mean and standard deviations of temporal dry aggregate stability from field plot studies (lines, Skidmore and Layton, 1992), compared to range of measured dry stabilities of soil samples used in abrasion tests.

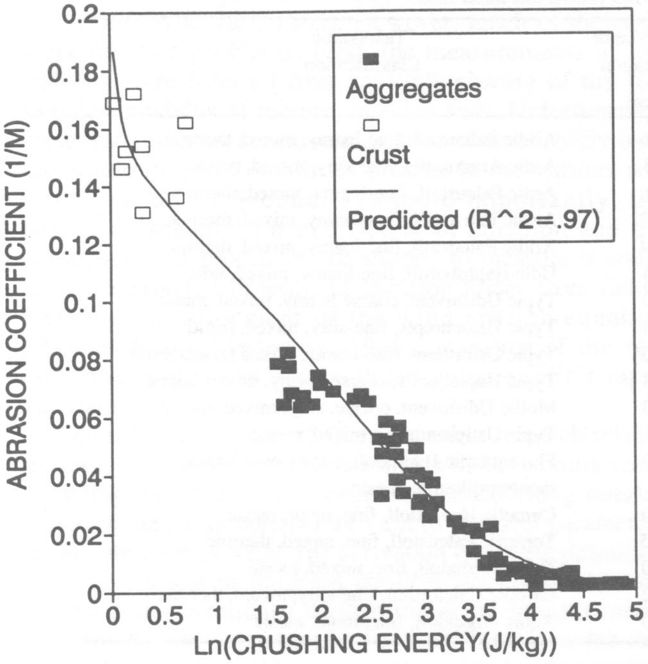

Figure 4–Measured abrasion coefficients as a function of dry stability of soil aggregates and crust.

linearly related to the abrasion coefficient over large ranges.

The effect of the abrasion coefficient on field soil loss varies with field scale. In qualitative terms, Chepil and Woodruff (1963) noted that, if the field is small, the amount of abrasion loss is small and erodibility of the field is mainly determined by the proportion of loose aggregates that can be moved by the wind. However, if the field is large, saltating particles impact the surface many times in crossing the field, so that the dry stability of the structural soil units is the most important factor in determining soil erodibility. In quantitative terms, stabilities in the middle region, about 0.5 to 4.0 Ln(J/kg), are of most interest. When stabilities are less than 0.5, fields are highly erodible (Hagen, 1992). In contrast, when stabilities are above 4.0, small to medium fields with at least 30% non-erodible aggregates generally have low erodibility. Hence, it is the middle region of soil stabilities that require careful soil management to control wind erosion.

An estimating equation was fitted to the data and, as illustrated by the solid line in figure 4, is of the form

$$Y = \exp\left(a + bX^{5/2} + c\mathrm{Ln}(X)\right), \qquad R^2 = 0.97 \quad (2)$$

where

a = –2.07
b = –0.077
c = –0.119
Y = abrasion coefficient (1/m)
X = Ln [Crushing energy (J/kg)] with lower limit 0.1

Although several other estimating equations gave R^2 values similar to that of equation 2, this one was selected because the predicted values are well-behaved near the end points. Hence, it provides a robust estimating equation for use in wind erosion models.

Conclusion

It is convenient to measure the dry stability of aggregates and crusts from field soil samples using crushing energy meters that have been developed previously. Results from the wind tunnel tests in this experiment demonstrate that accurate abrasion coefficients can be computed from the dry aggregate stability, when mean values of the natural log of the crushing energy per unit mass are selected as the independent dry stability variables. This relationship provides a unique linkage between readily made measurements of crushing energy and the abrasion coefficients required for mathematical estimates of the vertical flux of abraded soil in the WEPS erosion submodel.

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