A VERTICAL SOIL CRUSHING-ENERGY METER

L. J. Hagen, B. Schroeder, E. L. Skidmore

ABSTRACT. *An energy-based index of dry soil stability is related closely to abrasion susceptibility of soils during wind erosion, as well as other soil physical processes. Unfortunately, the currently used soil-aggregate crushing-energy meter (SACEM) requires aggregates to have a uniquely defined break force in order to measure dry stability. Users have found many conditions of interest where this break force is absent. Thus, the objective of this study was to design a vertical soil crushing-energy meter (VSCEM) that did not require an initial break force, used commercially available components, and obtained measurements faster than the SACEM.*

The design objective was met by using two nearly vertical plates pivoted at their base to form a crushing vise. A weigh cell was used to measure crushing force, and a unislide, powered by an electric stepping motor, was used to provide the crushing motion. These components were connected to an 8086-based personal computer through a data acquisition board. A C-language program was written to control the stepping motor and compute crush energy at each of 600 steps as the plate moved through 6° to a vertical position during a crushing cycle.

Dry stabilities measured with VSCEM agreed closely to those of the SACEM. Because the VSCEM does not require an initial break force, it can be applied to a wider range of soils and conditions than the SACEM.

Keywords. *Wind erosion, Crushing energy, Abrasion, Aggregate stability.*

Primary soil particles often are cemented together by organic and inorganic bonding agents to form aggregates. The size distribution and stability of the aggregates influence many physical processes in soils, including susceptibility to wind erosion (Chepil, 1953; 1955).

In the dry state, the resistance of the aggregates to breakdown by physical forces has been referred to as the mechanical or dry-aggregate stability. Problems with a number of procedures to measure dry-aggregate stability were reviewed by Skidmore and Powers (1982). They concluded that most methods used to estimate aggregate stability applied an unmeasured force, or a measured force without knowledge of transfer, to single or groups of aggregates. In response, they developed an improved stability index based on the energy required to break interparticle bonds and create new external surface areas. Experimental results showed that the new surface area created from soil aggregates was proportional to the logarithm of the aggregate crushing-energy (CE).

Further work was undertaken to develop direct application of the dry stability index to wind erosion processes. During wind erosion, immobile aggregates and crusts are broken down by repeated impacts of saltating particles. The major factors controlling this soil abrasion process are the saltation discharge and the abrasion susceptibility of the surface aggregates and crust (Hagen, 1991). Thus, it was demonstrated that the soil abrasion can be modeled as:

$$G_{an} = \sum_{i=1}^{n} (F_{ani}\, C_{ani})\, q \qquad (1)$$

where

G_{an} = vertical abrasion flux from the surface ($ML^{-2}T^{-1}$)

F_{ani} = fraction of abrader impacting the *ith* target (typical targets are aggregates, crust, residue, or rock)

C_{ani} = coefficient of abrasion (L^{-1})

q = saltation discharge ($ML^{-1}T^{-1}$)

Next, direct measurements of the crushing energy and wind tunnel measurements of G_{an} and q were made on a wide range of soils; C_{ani} then was calculated using equation 1 (Hagen et al., 1992). The results showed that C_{ani} could be predicted accurately using ln(CE) as an independent variable in the equation:

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

where

a = –2.07

b = –0.077

c = –0.119

X = ln(crushing energy (J/kg)), with lower limit 0.1

Article was submitted for publication in August 1994; reviewed and approved for publication by the Soil and Water Div. of ASAE in January 1995. Presented as ASAE Paper No. 94-2056.

The use of trade names in this publication does not imply endorsement of the products named.

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Based on the research results, the energy-based dry stability is an important temporal soil parameter that can be used to characterize dry soil stability. Thus, devices to conveniently measure dry stability would enhance research progress.

To facilitate measurement of dry stability, an initial soil-aggregate crushing-energy meter (SACEM) was constructed (Boyd et al., 1983). The system consisted of two main parts—a pair of horizontal plates used as a crushing vise and a computer module. A weigh cell mounted beneath the lower, immobile plate measured the applied force, while a linear voltage differential transformer measured travel of the upper mobile plate as the soil sample was crushed. Using these inputs, the computer module then calculated crushing energy.

In operation, the SACEM determined an initial break force, defined as the force from which the force first drops 25%, as illustrated in figure 1. The crushing cycle ends when the crushing force reaches 1.5 times the initial break force.

Although the SACEM provided a large amount of useful information, it could not be used on all soils or conditions. Users found that the defined break force was sometimes absent in the crushing process. In addition, the break force was slightly dependent on aggregate size.

The objective of this study was to develop a vertical soil crushing-energy meter, VSCEM, which included the following design criteria:

- Measurement of energy-based dry stability independent of initial break force.
- Measurement of dry stability comparable to that by SACEM on soils with an initial break force.
- Programming and control possible with a personal computer.
- Crushing and sample analysis faster than those provided by SACEM.

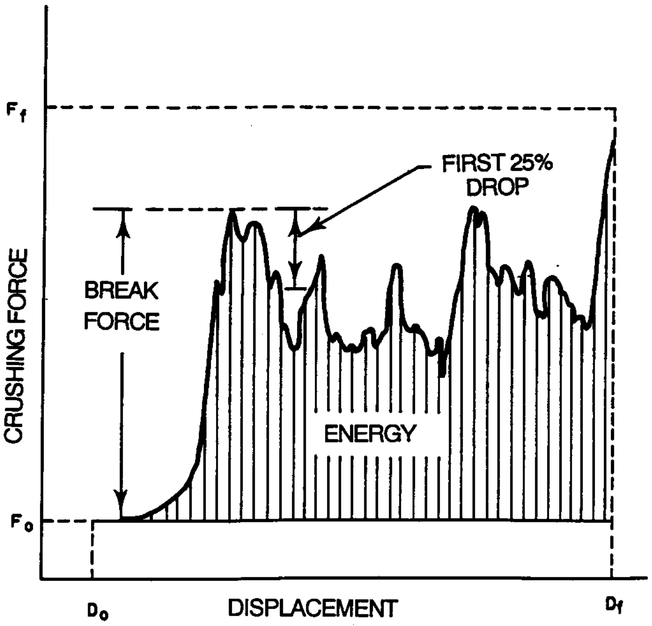

Figure 1–Typical soil-crushing curve illustrating the defined break force needed for the SACEM.

SYSTEM DESIGN

A schematic depicting the crushing plates of the VSCEM and two of the forces acting on them, F_1 and F_2, is illustrated in figure 2. When the system is in static equilibrium, the summation of moments about pivot points on a common reference plane, points a and b, must be equal to zero.

When the plate attached to pivot a is moved through angle θ, a crushing energy is applied to the soil aggregate between the plates. Part of F_1 must be used to overcome gravitational forces generated by the aggregate and plate mass in addition to crushing the aggregate. In contrast, the force normal to the vertical plate on pivot b, F_2, reacts only to force caused by crushing action on the aggregate. By moving the plate on pivot a slowly, so that inertia forces can be neglected, the crushing energy (CE) is:

$$CE = \int_0^\theta F_2 L_2 d\theta \qquad (3)$$

A prototype VSCEM was assembled that embodied the principles illustrated in the schematic (fig. 2) using two aluminum plates each 180 × 95 × 15.6 mm. A weigh cell (294, 98, and 29 N weigh cells, Tedea Inc., 7800 Deering Ave., Canoga Park, Calif.) was mounted on a frame to measure F_2 at L_2 equal 162 mm, and a unislide (Velmax Inc., P. O. Box 38, E. Bloomfield, N.Y.) powered by an electric stepping motor (Bodine Electric Co., 2500 W. Bradley Place, Chicago, Ill.) was used to provide the force F_1 (fig. 3).

The VSCEM motor and load cell were connected to an 8086-based personal computer (Telex model 1260, Telex Computer Products, 6929 N. Lakewood Ave., Tulsa, Okla.), which contained an internal data acquisition board (C10-DAS08-PGA, Computer Boards, Inc., 44 Wood Ave., Mansfield, Mass.). A top loading balance (Metler PM 300, Metler Instrument Corp., Box 71, Hightown, N.J.) with digital output also was connected to the PC using the data

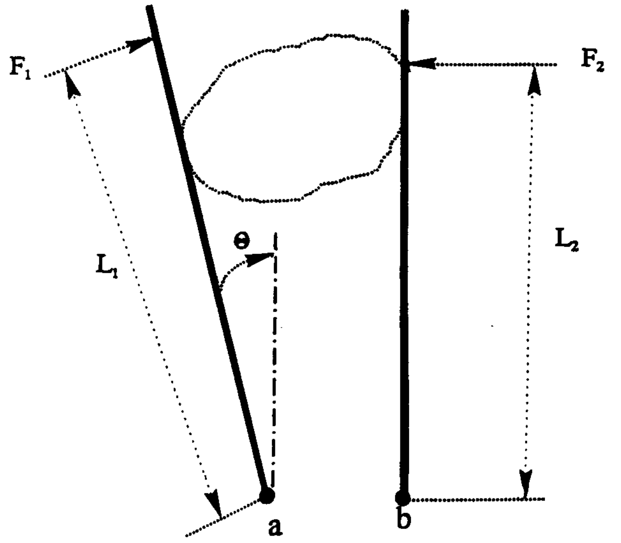

Figure 2–Diagram of crushing plates for VSCEM. The Force F_1 is applied by a motor and force F_2 is measured by the load cell.

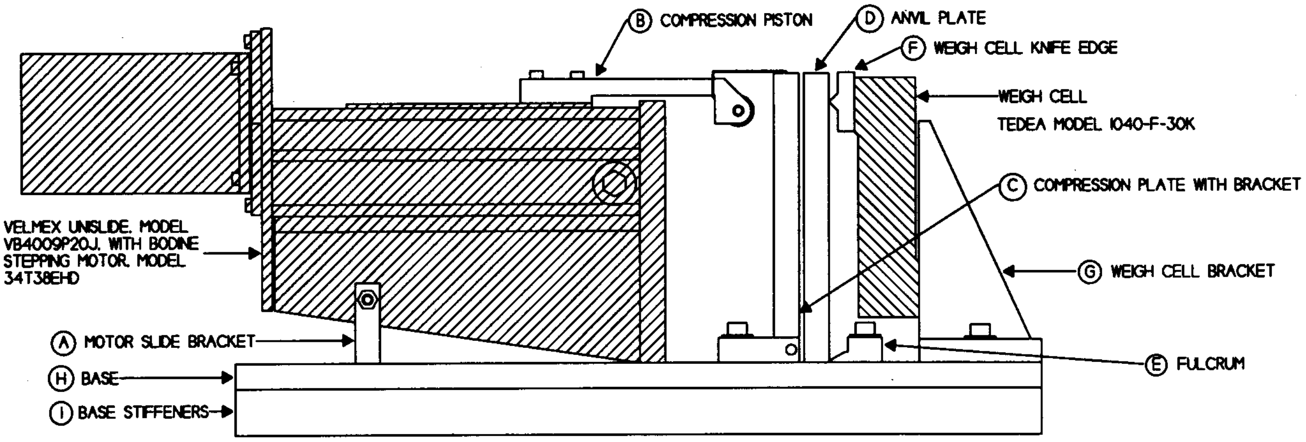

Figure 3–Side view of VSCEM.

acquisition board. The balance was used to weigh individual samples before crushing, so crushing energy per unit mass could be calculated.

A computer program in C-language was written to allow the VSCEM operator to control the sequence of events, while the computer automatically records the data and calculates the crushing force. In a typical crushing operation, the plate on pivot a pivots through 6° in 600 steps. The crushing energy is computed for each step and then summed over all steps. This results in a numerical integration of equation 3.

For test purposes, the prototype VSCEM has several useful features. The length, L_2, can be changed easily by mounting the load cell at different positions to obtain adequate load cell response for weak aggregates and still crush strong aggregates by using a large L_2 to prevent load cell overload. Alternatively, various capacity load cells can be used. The spacing between pivots a and b is adjustable, so maximum size of crushed samples can be controlled.

Finally, using the computer program, the operator can control the sequence of crushing motions by sending various signals to the stepping motor.

TEST METHODS

In order to compare operational results of SACEM and VSCEM, a sample of Haynie silt loam, Keith silt loam, and two samples of Wymore silty clay were collected and air dried (table 1). The two samples of Wymore soils had different strengths and were tested separately.

For each test treatment, 30 aggregates of 2- to 5-g mass were selected at random from the test soil, weighed, and then crushed. The crush treatments were designed to compare the SACEM and various configurations of the VSCEM on the test soils. Variations in the VSCEM configuration included use of 2- and 4-mm gaps between pivots and use of various load cells. Treatment effects for each soil were analyzed using analysis of variance in a completely random design with subsamples (Steele and Torrie, 1960). When significant differences were found between treatments, Duncan's new multiple range test was used to determine which treatment means were different. All statistical analyses were performed on measured aggregate crushing energy divided by aggregate mass. Finally, the crushed soil aggregates were combined and sieved to determine aggregate size distribution created by each treatment.

RESULTS AND DISCUSSION

A scatter-diagram of the treatment means showed that the 4-mm gap between pivot points a and b on the VSCEM produced crush energies with a slope similar to those of the SACEM over the test range of the three soil samples (fig. 4). For Keith and both weak and strong Wymore soil aggregates, statistical analyses showed that the mean crush energies measured by the SACEM and the VSCEM with 4-mm gap were not significantly different (table 2).

In contrast, the the VSCEM crush energy with the 2-mm gap was much larger than that of the SACEM for the Wymore soil. The sieve results also confirmed that only the 4-mm gap produced a size distribution near that of the SACEM on the Wymore soil (fig. 5). The VSCEM tends to orient and pass aggregates with a minor axis less than the gap, even if the major axis is greater than the gap. However, some of the aggregates with a large major axis were retained on the sieve with openings larger than the gap.

For the Haynie soil, the crush energies of the VSCEM using a 4-mm gap were slightly less than those of the SACEM, and the difference was statistically significant (table 2). Using different load cells on the VSCEM did not alter the mean crush energies at the 4-mm gap. However, similar to the Wymore soil, the aggregate size distribution

Table 1. Study soils used in crushing tests

Soil Series	Sand (%)	Silt (%)	Clay (%)	Organic Matter Concentration (g/kg)	Taxonomic Classification
Haynie silt loam	33.2	58.1	8.7	19.0	Mollic Udifluvent, coarse, silty, mixed, mesic
Keith silt loam	19.5	58.4	22.1	15.0	Aridic Argiustolls fine, silty, mixed, mesic
Wymore silty clay	7.8	63.8	28.4	24.0	Aquic Arguidoll, fine, moist, mesic

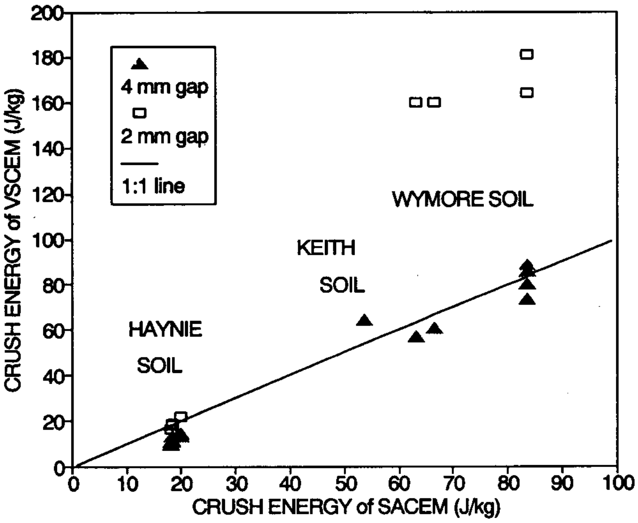

Figure 4–Scatter diagram of mean crush energies measured by the SACEM and VSCEM with two different gap widths at the base of the plates.

Table 2. Results of crushing tests and statistical analyses

Soil	Treatment	Mean Crush Energy (J/kg)*	Coefficient of Variation	Reps
Haynie	SACEM	18.6^{a}	0.70	4
	VSCEM, 4-mm gap, 294 N weigh cell	12.4^{b}	0.63	4
	VSCEM, 4-mm gap, 294 or 98.1 N weigh cell	12.3^{b}	0.74	4
	VSCEM, 2-mm gap, 294 N weigh cell	18.8^{a}	0.84	4
Keith	SACEM	53.84^{g}	0.69	2
	VSCEM, 4-mm gap, 294 N weigh cell	63.95^{g}	0.89	2
Wymore (Strong Aggregates)	SACEM	83.5^{c}	0.50	2
	VSCEM, 4-mm gap, 294 N weigh cell	81.9^{c}	0.83	4
	VSCEM, 2-mm gap, 294 N weigh cell	177.2^{d}	0.51	2
Wymore (Weak Aggregates)	SACEM	65.0^{e}	0.63	2
	VSCEM, 4-mm gap, 294 N weigh cell	58.8^{e}	0.88	2
	VSCEM, 2-mm gap, 294 N weigh cell	161.5^{f}	0.57	2

* Treatment means followed by different letters are significantly different at the 0.01 level.

produced by the VSCEM with a 4-mm gap resembled that produced by the SACEM, although the latter produced slightly more fine aggregates (fig. 6). Using the VSCEM with a 2-mm gap produced the same crush energies as the SACEM, but produced a different aggregate size distribution.

The smaller crush energies of the VSCEM at 4-mm gap compared to those of the SACEM likely were caused by their differing modes of operation. Near the end of the SACEM crush cycle, as fractured particles group together between the parallel plates, they provide confining support to each other, and some of the input energy is consumed in heat and strain (Skidmore and Powers, 1982). To minimize this problem in the VSCEM, the crush was accomplished in three equal stages, with the plates opened slightly between stages to permit aggregates less than the gap-size to exit through the gap between the nearly vertical plates. At the end of the final stage, the plate separation is slightly less than the gap. This permits aggregates to exit the gap and end the crush cycle. Hence, in VSCEM there is no need for an initial break force to establish the end of a cycle.

Because the design and operation of VSCEM minimize the energy consumed in heat and strain, it likely will

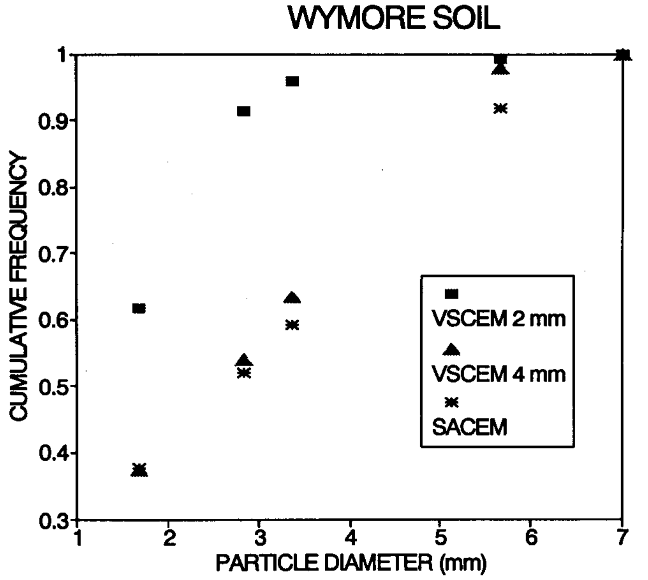

Figure 5–Cumulative fraction of mass less than sieve-cut size of Wymore soil after various crush treatments.

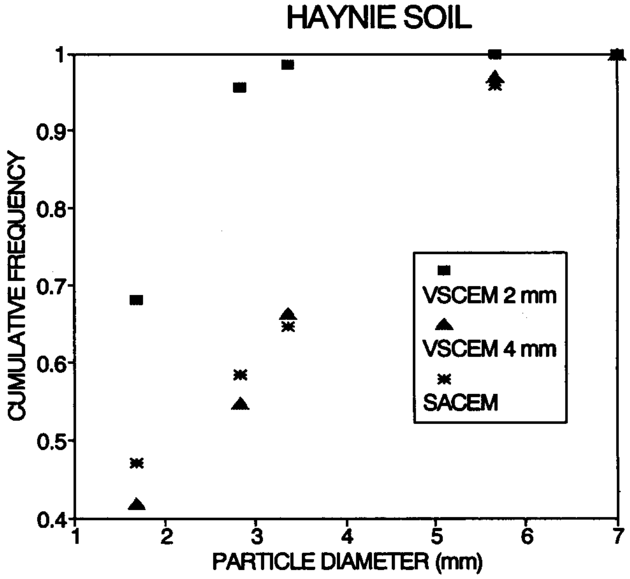

Figure 6–Cumulative fraction of mass less than sieve-cut size of Haynie soil after various crush treatments.

provide a more accurate measure of dry stability than the SACEM, particularly on weak aggregates.

The prototype SACEM used an operator-powered vise and was somewhat limited in sampling speed. The VSCEM uses a motor-powered vise and samples at higher speeds. These design changes reduced processing time from about 80 to 15 s per aggregate.

SUMMARY AND CONCLUSIONS

An energy-based index of dry soil stability is related closely to the abrasion susceptibility of soils during wind erosion. The aggregate status also determines other physical processes in soils. Moreover, it is often more convenient to measure this index, than abrasion susceptibility or other properties on field soil samples. Thus, an initial SACEM was developed to measure the index (Boyd et al., 1983). However, the design of the SACEM required measurement of a uniquely defined initial aggregate break force in order to compute crush energy. Subsequently, users found that the break force did not occur on numerous soils or conditions of interest.

The major objective of this study was to develop a VSCEM that measured crush energy independent of the break force, used commercially available components, and obtained measurements faster than the SACEM.

The objective was met using two nearly vertical plates pivoted at their base as a crushing vise. During aggregate crushing, one plate remains vertical on its pivot, and a load cell measures the crushing force at the opposite end of the plate. During crushing of soil, the second plate is rotated into a vertical position by forcing it toward the fixed plate using a unislide powered by an electric stepping motor.

The moving plate is rotated through about 6° using 600 steps to accomplish the crush. The load cell and stepping motor are connected to a personal computer through a data acquisition board. Using a C-language program, the computer calculates crush energy during each step and sums them.

The crush energies and aggregate size distributions of a range of soils crushed with the VSCEM and SACEM were compared. Using a 4-mm gap at the base of the VSCEM gave results comparable to those of the SACEM on strong aggregates. On weak aggregates, the SACEM measured greater mean crush-energy than the VSCEM with a 4-mm gap but an equal crush-energy with a 2-mm gap. However, SACEM likely overestimates crush energy slightly, because near the end of the crush cycle, as the particles group together on the horizontal plates, they provide confining support for each other, and some of the input energy is lost to heat and strain.

In general, the VSCEM can measure crush-energy values close to those of the SACEM and should be a useful instrument for measuring dry stability. Dry stability measurements with the VSCEM do not require an initial break force measurement, so they can be made for a wider range of soils and conditions than is possible with the SACEM. Finally, the VSCEM can process samples about six times faster than the initial SACEM and can be assembled from readily available, commercial components.

ACKNOWLEDGMENTS. The assistance of technicians Wayne Carstenson and Ralph Najarian in prototype construction of the VSCEM is gratefully acknowledged.

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