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ABSTRACT

This study was undertaken to determine the general influence and the specific quantities of moisture that soils must have to resist wind.

Erodibility by wind was about the same for soil that was oven-dried or air-dried in sun or in shade when moisture did not exceed one-third of the 15-atmosphere percentage. Beyond this range of moisture a distinct decrease in erodibility was manifested. Erodibility decreased rather slowly at first, then more rapidly with each successive increment of moisture added, reaching zero, on the average, at about 15-atmosphere percentage. Increasing the moisture even slightly above the 15-atmosphere percentage required a relatively great increase in wind velocity to produce movement of soil.

It was shown that erodibility by wind is a function of the cohesive force of adsorbed water films surrounding the soil particles. Equations were derived indicating the relationships between cohesive force due to adsorbed water films, quantity of adsorbed water, and erodibility by wind.

DEFICIENCY of moisture is associated normally with erosion of soil by wind. Only relatively dry soil particles are susceptible to movement by wind (7). Consequently, wind erosion is limited primarily to arid and semi-arid regions. In humid and sub-humid regions, on the other hand, wind erosion occurs much less frequently and usually affects only the soils subject to rapid surface drying, such as sandy soils and dune sands.

Information has been lacking on the general influence and the specific quantities of moisture various soils must have to resist wind. Experiments were undertaken in an attempt to supply some of the necessary data. This paper presents and analyzes results of one of the initial experiments in which dry soils were moistened by various quantities of water and describes some physical properties of moisture films and their effect on erosion by wind.

Experimental Procedure

The soils used in this study were dune sand, Pratt sandy loam, Baca silt loam, and Sutphen silty clay. They were partly air-dried, passed through an 0.84-mm. sieve, and thoroughly mixed. Size-distribution of dry soil particles was determined by sieving on a rotary sieve. A 15-atmosphere percentage, which corresponds approximately to percent water at permanent wilting point of plants, was determined by the method of Richards (12). Each soil was then subdivided into 8 uniform parts, each weighing about 30 pounds. The first part was dried in an oven at 105° C., the second in hot sun, and the third in the shade where temperature did not exceed 80° F. Water was added in the form of fine mist to each of the other 5 parts until the soil felt barely damp, moderately damp, extremely damp, moist, and wet, respectively. The soil was stirred as the spray was applied. Each part was then placed in an air-tight container and stored for 4 to 5 weeks.

Measurements of soil erodibility were made in a return-flow type wind tunnel used regularly at this location. On exposure to wind, some absorption of moisture by soil and some soil drying occurred, depending on the relative amounts of moisture in the soil and in the air. To reduce absorption or drying to the minimum, the duration of exposure of a given sample to wind was limited to 15 or 30 seconds. This duration of exposure of soils composed entirely of erodible particles was sufficient for reasonably accurate measurement of erodibility. The soil samples were

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Table 1.—Soil properties at different levels of equivalent moisture.

Degree dryness or wetness	Cohesion between discrete soil particles	Equivalent moisture after exposure to wind			
		Dune quartz sand	Pratt sandy loam	Baca silt loam	Sutphen silty clay
Oven-dried at 105° C	None, except between minute dust particles	0.03	0.01	0.01	0.01
Air-dried in hot sun	None, except between minute dust particles	0.23	0.15	0.25	0.29
Air-dried in cool shade	None, except between minute dust particles	0.31	0.26	0.29	0.32
Barely damp	Dust clings strongly to larger particles	0.39	0.36	0.42	0.43
Moderately damp	Barely stick together when pressed in hand	0.55	0.54	0.71	0.64
Extremely damp	Form a fragile ball when pressed in hand	0.78	1.03	1.04	0.87
Moist	Plasticity noticeable, but not in sand	1.17	1.54	1.34	1.06

Table 2.—Additional properties of soils utilized for study.

Soil	Dust <0.05 mm.	15-atmosphere percentage	Equivalent moisture at which erosion rate reached zero		
			20-mph. wind	26-mph. wind	32-mph. wind
	%	%			
Dune sand	0.3	1.28	0.93	0.98	1.02
Pratt sandy loam	21.0	3.89	1.00	1.09	1.13
Baca silt loam	34.2	11.21	0.99	1.04	1.16
Sutphen silty clay	3.1	20.71	0.82	0.90	0.97

exposed to wind having a velocity of about 20, 26, and 32 miles per hour at 6 inches above the surface where velocity measurements were made. Such wind has a velocity of about 38, 49, and 60 miles per hour at 50 feet above the type of soil surface used. The soils were exposed in trays 5 feet long, 8 inches wide, and 1¼ inches deep. Eroded soil was caught in a specially designed soil trap and weighed within 5 seconds after each exposure to wind. A representative sample of eroded material was taken to determine the moisture content after each exposure. Samples for the same purpose and down to ¼-inch depth also were taken from soil in the tray. The soil was mixed thoroughly before each duplicated test.

Soil moisture in this paper is expressed by equivalent moisture W which is equal to $\frac{w}{w'}$ where w is the amount of water held in soil and w' is the amount of water held by the same soil at the 15-atmosphere percentage.

Experimental Results

Erodibility was about the same for soil that was oven-dried or air-dried in sun or in shade (table 1 and figure 1). Beyond this range of moisture a distinct decrease in erodibility was manifested. Erodibility decreased rather slowly at first, then more rapidly with each successive increment of moisture added. Dust particles less than 0.05 mm. in diameter began to cling strongly to the larger soil particles and to each other when the soil felt barely damp (table 1). At this point the soil failed to produce a cloud of dust when stirred. The larger particles appeared quite free at this moisture content and moved readily with the wind.

A rapid decrease in erodibility occurred near the 15-atmosphere percentage (equivalent moisture equal to 1). At this stage of moisture the soil felt distinctly damp and all erodible particles up to 0.84 mm. in diameter tended to stick to each other and failed to separate completely when poured slowly from a container. When pressed in the palm of the hand, the soil particles formed a fragile ball that crumbled readily as it was pressed between the fingers (table 1). Erodibility reached zero, on the average, at about the 15-atmosphere percentage (figure 1 and table 2). Above this point, the soil was moist, plastic, and nonerodible under the wind velocities used. Increasing the moisture content even slightly above the 15-atmosphere percentage required a relatively great increase in wind velocity to produce movement of soil.

The downward swing in erodibility for all three wind velocities was more gradual for silt loam than for other soils. This soil had the greatest proportion of dust particles less than 0.05 mm. in diameter, as indicated by dry sieving (table 2). It is probable that moisture on the dust particles in quantities below the 15-atmosphere percentage had a greater restraining effect on erodibility than had the same percentages of moisture associated with the larger grains.

ANALYSIS AND INTERPRETATION OF RESULTS

The soil moisture contents in this investigation range from approximately zero to the 15-atmosphere percentage. This moisture is hygroscopic. Baver (3) stated that at about 15-atmosphere percentage when permanent wilting occurs "Water is probably held as a thin film around the particles at this tension. At least, any water wedges at the point of contact of the par-

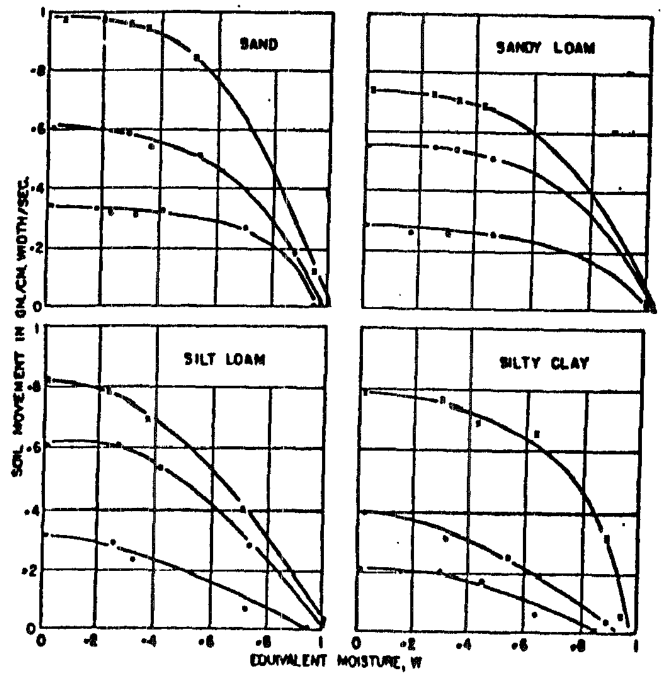

FIG. 1.—The influence of equivalent moisture in soil on the rate of erosion under 20-, 26-, and 32-mph. wind at 6-inch height.

ticles must be very small. Movement of the water within the soil takes place in the vapor phase, since the capillary conductivity is zero." Briggs (5), Zunker (13), and Lebedeff (10) described hygroscopic water in essentially similar terms as water adsorbed on surface of particles by free surface energy forces. Heat is evolved when this water is adsorbed on the surface. Bouyoucos (4) visualized at least a portion of the hygroscopic water as "unfree" water, or that which is held so tightly to the colloidal particles that it is not readily frozen and is only slightly available to plants. Nutting (11) indicated that "bound" water is held against a silica surface at a minimum pressure of 800 atmospheres and that it cannot be driven off by oven drying. The weakly adsorbed water, generally considered as hygroscopic water, ranges from this point to approximately the permanent wilting point where the adsorptive force is equal to about 15 atmospheres and the heat of wetting is approximately zero.

Decreases in wind erodibility proportionate to the amounts of hygroscopic water suggest that erodibility is a function of the cohesive force of the adsorbed water films surrounding the soil particles. Results of these experiments indicate that the greater the amount of hygroscopic water, and hence the greater the thickness of the water films, the greater is the force of attraction between the soil particles to which the water films are adsorbed. Attraction between the soil particles is apparently through the water molecules surrounding the particles.

The force between the soil particles must be overcome by the force of wind before erosion can occur. When the flow of air over a bed of erodible soil particles is increased gradually, there comes an instant when a few topmost particles become dislodged and move with the wind. At this instant the shearing force of the wind has barely overcome the opposing forces of gravity acting on the soil particle plus the force of attraction of the adsorbed water films. The shearing force or drag, τ, against a point on the ground surface lying parallel to the wind direction (2) is

$$\tau = \rho V_*^2 \qquad [1]$$

where ρ is the air density and V_* is a quantity known as the drag velocity and is equal to $\sqrt{\frac{\tau}{\rho}}$.

Factors which govern the rate of erosion of dry soil materials are known from previous studies (2,6). The rate of movement, q, of dry soil has been found to conform approximately to the general formula

$$q = C V_*'^{x} \qquad [2]$$

where C is a constant whose value depends on the size, shape, and density of the eroding particles, V'_* is the drag velocity over the eroding surface, and x is an exponent which has a value of approximately 3. V'_* is equal to $\sqrt{\frac{\tau'}{\rho}}$ in which τ' is the wind drag on the eroding surface.

It is expected that the same factors which govern the erodibility of dry soil materials also govern the erodibility of damp materials and that the cohesive force between the damp particles merely plays its contributing part. Only the force of the wind in excess of that required to overcome the force of gravity acting on the uppermost soil particle and the force of cohesion between this particle and the others with which it is in contact will contribute to the movement of the particle. Therefore, the equation expressing the rate of erosion of damp or dry soil composed only of *erodible particles* may be written

$$q = C\left[\sqrt{\frac{\tau' - \gamma}{\rho}}\right]^{x}$$

or

$$q = C\left(\frac{\tau' - \gamma}{\rho}\right)^{0.5x} \qquad [3]$$

in which γ is the *resistance* due to cohesion of the adsorbed water films exerted against the wind drag. The resistance may be visualized as a vector force acting in the direction opposite to and on the same level as the wind drag.

The values of resistance γ of equation 3 were determined from experimental values of q, C, τ', and x and plotted against equivalent moisture W (figure 2). The plotted curve of figure 2 indicates that the resistance γ for the uppermost soil particles and those below on different soil classes is, on the average, equal to 6 W^2. Quartz sand indicates slightly lower, and silty clay slightly higher, values of γ for equal values of W. One reason for these apparently minor deviations might be the absorption of variable amounts of moisture by the soil particles and a consequent change in their size, bulk density, and erodibility. Apart from this, when the equivalent moisture W equals unity,

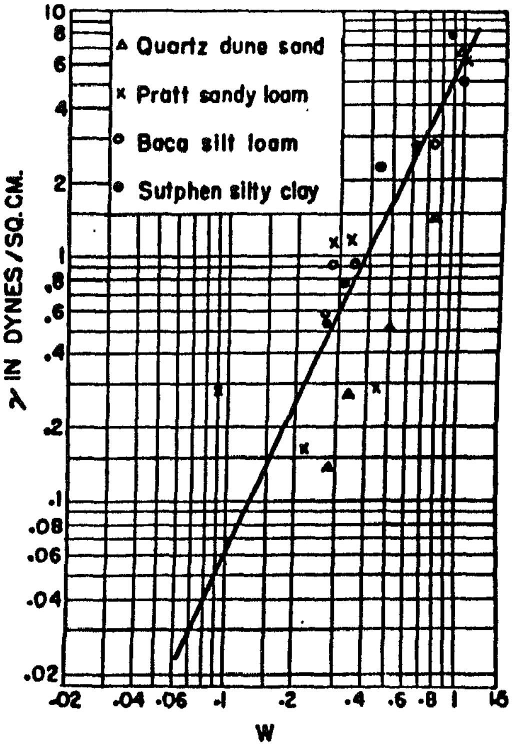

FIG. 2.—Relation between resistance γ due to cohesion of adsorbed water films and equivalent moisture W in various soils.

which corresponds to moisture at a tension of 15 atmospheres, the force of attraction (per unit area of ground) between the uppermost soil particles and those below is equal to about 6 dynes per square centimeter (figure 2). Erosion by wind will be zero at this equivalent moisture if the wind drag τ' is equal to, or is less than 6 dynes per square centimeter. On the other hand, if the wind drag is greater than 6 dynes per square centimeter, some erosion would occur, the rate of which may be computed readily from equation 3.

The experiments were not carried substantially into the capillary moisture range because of lack of much stronger winds. However, natural winds of average force greater than those used in the tunnel are exceedingly rare. The capillary forces computed for an ideal soil by Haines (9), Fisher (8), and Alberry (1) and determined for silt by Haines (9) and for spheres by Alberry (1) are much higher than the forces of attraction developed by the adsorbed water films of the present study. Their investigations, computations and measurements indicated that the cohesive force between the spheres with a lenticular water drop at their junction was greatest at the initial stage of separation, decreased as the spheres were separated farther apart, and reached zero when the drop broke. Of further interest are the facts that cohesive force between the spheres increased and the work of completely separating the spheres decreased gradually as the water drop became smaller and reached the respective maximum and minimum values with minutest possible drop. It must be pointed out that under these conditions the spheres were in contact. Such a condition, no doubt, sometimes occurs in soil, but it is not the condition to which the present study applies. The present study depends on relatively small quantities of water added to loose beds of dry soil particles, such as beds of wind-eroded soil material. Attraction between the particles in such cases, no doubt, is much lower than it would be if wet beds of soil particles were dried to corresponding degrees. In the former cases, the dried particles would be united or consolidated, whereas in the latter they would be separated by the adsorbed water films. These two rather distinct conditions, together with conditions in which pronounced capillary forces are present, occur rather commonly under field conditions. It is probable that all sorts of conditions between those mentioned exist. It is probable also that distinct dividing points exist neither between adsorbed and capillary water nor between consolidated and discrete soil particles.

It is probable that the values of the empirical expression γ in the present study depend on the initial maximum force of attraction between the uppermost particles and those with which they are in contact and to a degree on the energy required to separate the particles. No doubt, the force of wind required to initiate movement of damp particles must be at least equal to the initial maximum force of attraction between the particles. It must be remembered, however, that values of γ are derived not from wind velocities required to initiate movement but from the rate of soil movement. It is conceivable that the rate of soil movement depends on the initial force of attraction and to some degree on the work required to separate completely the uppermost particles from those below. The initial force of attraction for different amounts of W could be measured only by determining the force of wind required barely to overcome the attraction and thereby initiate the movement. This was not done in the present experiments.

Table 3.—Concordance of measured rates of erosion q for different soils with rates computed from equation (3).*

Quartz sand		Pratt sandy loam		Baca silt loam		Sutphen silty clay	
Measured q	Computed q	Measured q	Computed q	Measured q	Computed q	Measured q	Computed q
0.64	0.62	0.52	0.51	0.58	0.56	0.47	0.45
0.62	0.54	0.52	0.49	0.57	0.50	0.43	0.40
0.60	0.53	0.51	0.47	0.51	0.49	0.42	0.39
0.57	0.50	0.50	0.46	0.47	0.48	0.34	0.38
0.46	0.20	0.49	0.45	0.25	0.42	0.32	0.28
0.04	0.03	0.04	0.0	0.03	0.0	0.12	0.17

*Rate of erosion q is in grams per centimeter width per second.

While it is true that the smallest force of attraction per unit area of contact was exhibited by the greatest lenticular drop, as shown by Haines, Fisher, and Alberry, the number of contacts and the area of each contact between soil particles of irregular shape and arrangement are probably increased as the thickness of the film becomes greater. The attraction per unit area of contact decreases as the curvature of the water at the contact area is decreased. The total area of contacts, however, probably increases much more rapidly than the curvature decreases and, consequently, the total force of attraction increases as more water is added. The present studies seem to confirm this conclusion.

In table 3 are experimental values of erosion rate q and values of q computed from equation 3, supplemented by use of γ values based on the average curve of figure 2. Only two cases show a substantial disagreement. Both of these were associated with that narrow range of equivalent moisture which is associated with the sharp downward swing in erodibility by wind. Because within this narrow range a slight change in either equivalent moisture or wind velocity produces a relatively great change in the rate of erosion, experimental errors are substantial. Apart from this, the general agreement substantiates one part of the theory described herein—that part indicating the physical behavior of water films adsorbed onto surfaces of unconsolidated soil particles. Further experiments designed along fresh lines are needed to provide decisive evidence on the relationships between cohesive forces of adsorbed water films, erodibility, and consolidation as influenced by packing and drying.

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