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FACTORS THAT INFLUENCE CLOD STRUCTURE AND ERODIBILITY OF SOIL BY WIND: II. WATER-STABLE STRUCTURE

W. S. CHEPIL

U. S. Department of Agriculture[1]

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Water-stable particles, as conventionally determined by sedimentation, elutriation, or sieving of soil in water, are the building blocks of field structure of soils. Some of these particles are primary particles of sand, silt, and clay, and some are water-stable aggregates, often referred to as primary aggregates. Few primary particles and aggregates exist individually in soils. They are usually grouped into secondary aggregates such as granules, blocks, columns, or clods. The size-distribution of the water-stable particles influences in large measure the size-distribution of the secondary aggregates or clods and consequently erodibility by wind.

In a previous study (1) data were presented to show in part the relationships that exist between the water-stable and dry clod structure and erodibility by wind. It was shown that both coarse (>0.42 mm.) and fine (<0.02 mm.) water-stable particles increased cloddiness and decreased erodibility by wind. The effect of fine water-stable particles on erodibility was evaluated, but the effect of the coarse water-stable particles could not be determined definitely because insufficient data were available at that time.

The purpose of the present investigation was to make a detailed study of the relative influence of the various phases of water-stable structure on clod structure and erodibility by wind.

MATERIALS AND PROCEDURE

Samples of one group of soils were obtained in April 1951 from 112 wheat fields chosen at random from black, chestnut, and brown soil zones of western Nebraska and central and western Kansas. The samples ranged in texture from sand to clay. They were taken to 1-inch depth and only when the land was dry. The samples were placed in shallow trays to minimize breakdown of structure. Five individual samples chosen in each field were combined to form composite samples. The composite samples were transported to the laboratory and thoroughly dried.

Another group of soil samples from 24 fields was chosen in March 1952 from Roosevelt and Curry Counties of New Mexico.[2] The method of sampling was similar to that of the first group, except that samples from below 1-inch depth were taken also.

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[2] With assistance from the personnel of the New Mexico research and operations offices of the Soil Conservation Service and the New Mexico A & M College.

An attempt was made to learn the influence, if any, of seasonal changes in water-stable structure on clod structure and erodibility by wind. Soil samples from surface to 1-inch depth were obtained from a particular location on each of several soil classes in early fall and early spring. In these seasons, extremes of differences in soil cloddiness and erodibility by wind are usually apparent.

A greenhouse experiment was completed to determine the effect of ground wheat straw on water-stable soil structure and the possible effects of changes in water-stable structure on clod structure and erodibility by wind.

Another experiment was performed to determine directly the possible relation between fine water-stable particles and soil structure and erodibility by wind. Soils were immersed and shaken in water for 2 minutes, and the water-stable particles <0.05 mm. were removed by repeated decantation after an appropriate period of settling. The water-stable particles >0.05 mm. then were dried.

Analyses consisted of the following determinations: (*a*) size-distribution of dry aggregates or clods by use of the rotary sieve (2), (*b*) size-distribution of water-stable particles by the Yoder method (6) modified in accordance with the latest Soil Conservation Service recommendations, and (*c*) relative erodibility measured in either the stationary or the portable wind tunnel used regularly in this work. This last determination was made by placing the soil in a tray 5 feet long and 8 inches wide, and exposing it to a wind of a drag velocity of 61 cm. per second on the first group of soils and a drag velocity of 40 cm. per second on the second group. The duration of exposure was 5 to 10 minutes, depending on when removal of soil ceased.

In connection with determination (*b*), the water-stable particles >0.42 mm. were dispersed in sodium hexametaphosphate solution and resieved to determine the proportion of primary particles >0.42 mm.

RESULTS

There was an inverse relationship between soil erodibility by wind and the percentage of water-stable particles <0.02 mm. in equivalent diameter (table 1). Thus, the most highly erodible soils (sands) contained the least amount of these fine particles, and the least erodible soils (silty clay loam) contained almost the highest amount of these particles. As seen through the microscope, some of these particles were primary mineral particles (silt); others were aggregates of mineral and also probably of organic origin.

Table 1 shows that these fine water-stable particles were not the only water-stable particles that influenced erodibility, although they appeared to have the greatest influence. The percentage of water-stable particles >0.84 mm. in diameter was also associated with erodibility. Thus, if the amount of water-stable particles <0.02 mm. were the only factor, the silt loam soils containing the largest amount of these particles should have been the least erodible. Actually, the least erodible were the silty clay loam soils containing somewhat fewer fine particles but containing substantially more water-stable particles >0.84 mm. in diameter. Another more striking example of the influence of coarse water-stable particles was shown by comparative condition of silty clay and clay soils. Both

TABLE 1

Relation of water-stable structure to dry soil structure and erodibility by wind

Summarized data from Kansas and Nebraska, March 1951

SOIL CLASS	NUMBER OF FIELDS	WATER-SOLUBLE FRACTIONS							DRY FRACTIONS				AMOUNT ERODED IN TUNNEL*
		>0.84 mm.		0.84–0.42 mm.		0.42–0.05 mm.	0.05–0.02 mm.	<0.02 mm.	>6.4 mm.	6.4–0.84 mm.	0.84–0.42 mm.	<0.42 mm.	
		Primary particles	Aggregates	Primary particles	Aggregates	Primary particles and aggregates							
		%	%	%	%	%	%	%	%	%	%	%	ton/A.
Sand	3	4.3	0.5	18.8	5.8	61.6	7.3	1.7	0.6	2.7	15.7	81.0	49.8
Loamy sand	12	2.9	0.9	11.4	4.1	65.5	12.2	3.0	1.3	5.6	16.6	76.5	29.4
Sandy loam	13	2.9	0.1	5.2	3.4	55.9	22.5	10.0	19.9	16.7	20.1	43.3	5.4
Loam	25	0.7	2.5	2.1	7.6	42.7	30.6	13.8	24.3	20.1	19.3	36.3	2.2
Silt loam	35	0.3	2.7	0.5	10.7	35.3	32.7	17.8	26.7	21.9	18.3	33.1	1.9
Clay loam	5	0.2	4.3	1.2	20.3	40.0	20.0	14.0	17.5	26.1	29.8	26.6	1.5
Silty clay loam	10	0.1	5.1	0.4	26.0	35.7	18.3	14.4	25.1	24.3	27.3	23.3	1.2
Silty clay	1	0.2	3.7	0.3	41.9	31.3	11.8	10.8	2.3	16.9	41.4	39.4	3.4
Clay	8	0.2	1.7	0.3	21.2	50.6	15.2	10.8	2.5	17.7	28.2	51.6	6.7

* Drag velocity of wind, 61 cm. per second.

of these groups of soils contained the same amount of water-stable particles <0.02 mm., but the silty clay contained substantially more water-stable particles >0.84 mm. than the clay soils and, consequently, was substantially less erodible.

Each unit per cent change in water-stable fraction <0.02 mm. influenced erodibility about as much as each unit per cent >0.84 mm. The amount of water-stable fraction >0.84 mm. and the range of its variation were low in the soils studied and, therefore, the great differences in erodibility were due primarily to the differences in percentage of water-stable fraction <0.02 mm. in diameter.

The water-stable particles 0.02 to 0.05 mm. and 0.42 to 0.84 mm. tended to reduce the erodibility much less than did fractions <0.02 mm. and >0.84 mm. (table 1) In many cases the soils that had a large proportion of water-stable fractions between 0.02 and 0.05 mm. and between 0.42 and 0.84 mm. also had a relatively large proportion of fractions <0.02 mm. and >0.84 mm. Hence, the proportionate amount of only the finest and the coarsest fractions served as an approximate indicator of erodibility.

The coarse primary particles apparently reduced the erodibility somewhat less than did the water-stable aggregates of the same size. Thus the relatively large proportion of water-stable fraction >0.42 mm. in the sands was not so important as in other soils because more of this fraction was composed of primary particles rather than aggregates. Nevertheless, the effect of these coarse primary particles on erodibility was considerable, especially of those >0.84 mm., and could not be ignored.

The percentage of dry soil fraction <0.42 mm. in diameter varied inversely with the sum of the percentages of water-stable fraction <0.02 mm. and >0.84 mm. (fig. 1, left, based on table 1). It is evident, as in previous studies, that the key to erodibility of soil by wind is the dry aggregate soil structure and that the proportion of dry erodible fractions <0.42 or <0.84 mm. in diameter as determined by dry sieving is one of the most important indexes of erodibility by wind. Any effect that the water-stable structure had on erodibility was determined by the dry aggregate structure that it formed.

The relationships between the percentage of dry fraction <0.42 mm. in diameter, the amount of erosion, and the percentage of water-stable fractions <0.02 mm. and >0.84 mm. in diameter are shown graphically in figure 1. The relationship between the dry fraction and the water-stable fractions conformed with the simple arithmetic equation

$$A = a + bX \qquad (1)$$

where A is the percentage of dry fraction <0.42 mm. and X is the percentage of water-stable fractions <0.02 and >0.84 mm. in the first inch of soil. The constants a and b have values of 100 and -3.67, respectively. The coefficient of correlation between the percentage of dry fraction <0.42 mm. and the percentage of water-stable fractions <0.02 mm. and >0.84 mm. computed from the 112 cases analyzed is 0.74. This is very highly significant, since the required value for significance at the 0.1 per cent level is 0.31.

The relation between the amount of erosion and the percentage of water-stable fractions <0.02 mm. and >0.84 mm. was semiexponential and conformed with the equation

$$\log q = a + bX \qquad (2)$$

where q is the amount of erosion in tons per acre and X is the percentage of water-stable fractions <0.02 mm. and >0.84 mm. in the first inch of soil. For the units used, the constants a and b have values of 2.47 and −0.13 respectively. The coefficient of correlation between erodibility and the percentage of water-

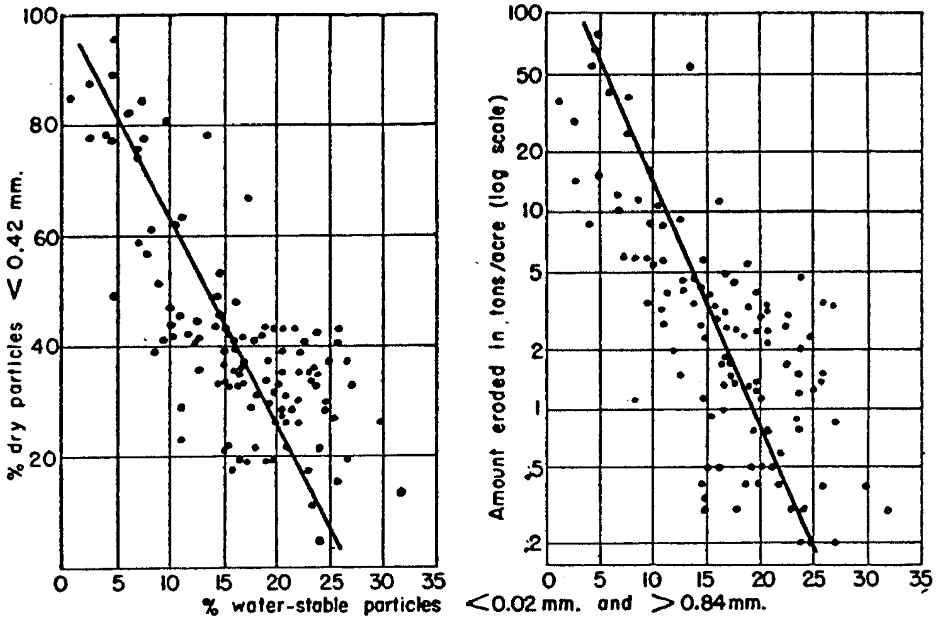

FIG. 1. RELATION OF PERCENTAGE OF DRY SOIL FRACTION ERODIBLE BY WIND, SOIL ERODIBILITY, AND PERCENTAGE OF WATER-STABLE PARTICLES <0.02 MM. AND >0.84 MM. IN DIAMETER AT 0 TO 1-INCH DEPTH.

Based on 112 measurements summarized in table 1

stable fractions <0.02 mm. and >0.84 mm. is 0.72. This correlation is very highly significant, as in the previous case. The curves on the left and the right hand side of figure 1 are drawn in conformance with equations (*1*) and (*2*), respectively.

The results obtained with the second group of soils confirm those of the first group where the depth of sampling was the same (table 2). Curves (not shown) based on table 2 for soil samples taken from 0 to 1 inch in depth almost coincide with the curves for soils of the first group (fig. 1) taken from similar depth, despite the fact that this second group of soils had markedly different physical characteristics and a much higher level of erodibility than was common to the first group of soils.

The percentage of dry fraction <0.42 mm. and erodibility were lower at

TABLE 2

Relation of water-stable structure to dry soil structure and erodibility by wind

Summarized data from Clovis and Portales, New Mexico, April 1952

SOIL CLASS	NUMBER OF FIELDS	DEPTH*	WATER-STABLE FRACTIONS					DRY FRACTIONS				AMOUNT ERODED IN TUNNEL†
			>0.84 mm.	0.84–0.42 mm.	0.42–0.05 mm.	0.05–0.02 mm.	<0.02 mm.	>6.4 mm.	6.4–0.84 mm.	0.84–0.42 mm.	<0.42 mm.	
		in.	%	%	%	%	%	%	%	%	%	*ton/A.*
Loamy sand (low lime)...	4	a	0.4	4.7	88.8	4.5	1.6	2.0	1.6	4.0	92.4	289.0
		b	0.3	1.8	91.9	4.5	1.5	13.3	4.5	3.0	79.2	16.2
		c	0.8	3.8	87.2	5.8	2.4	35.4	7.8	4.2	52.6	2.6
Sandy loam (low lime)...	7	a	0.8	2.8	83.1	10.1	3.2	17.0	8.6	3.5	70.9	37.1
		b	1.0	3.0	80.9	10.4	4.7	36.0	12.8	3.5	47.7	2.7
		c	5.8	4.4	70.6	12.3	6.9	65.9	13.9	3.3	16.9	0.34
Sandy loam (high lime)..	4	a	2.2	3.4	85.5	6.9	2.0	6.3	6.3	3.8	83.6	81.6
		b	3.6	5.1	76.6	9.7	5.0	36.2	14.2	5.2	44.4	1.1
		c	7.2	7.0	67.8	12.2	5.8	60.2	13.6	5.2	21.0	0.13
Loam and clay loam (mostly low lime).....	7	a	1.1	3.7	68.3	20.0	6.9	10.7	12.3	6.7	70.3	13.5
		b	2.0	4.1	66.6	18.8	8.5	40.5	15.7	5.5	38.3	1.3
		c	11.0	8.2	52.4	17.3	11.1	67.4	20.0	3.8	8.8	0

* Depth "a" is 0 to 1 inch, depth "b" is 0 or 1 to 5 or 8 inches, depth "c" is 0 or 5 to 15 or 20 inches.

† Adjusted from amount eroded under a drag velocity of 40 cm. per second to that of 61 cm. per second in accordance with figure 3, *Soil Sci.* 72: 387–401, 1951.

depths below 1 inch. These conditions were due partly to higher percentages of water-stable fractions <0.02 mm. and >0.84 mm. Greater compaction at lower depths apparently was responsible also in lowering the proportion of dry fraction <0.42 mm. and in lowering the erodibility. Nevertheless, the water-stable fractions <0.02 mm. and >0.84 mm. increased markedly with depth (Table 2), thereby working together with the force of compaction in decreasing the proportion of dry fraction <0.42 mm. and consequently in decreasing the erodibility. Although the water-stable fractions <0.02 and >0.84 mm. increased with depth, the proportion of one fraction to the other varied in different soils.

TABLE 3

Seasonal variation in the water-stable and dry soil structure and erodibility by wind

Based on 0 to 1-inch depth of soil

SOIL CLASS	DATE	WATER-STABLE FRACTIONS			DRY FRACTIONS <0.84 MM.	ERODIBILITY
		>0.84 mm.	0.84–0.02 mm.	<0.02 mm.		
		%	%	%	%	ton/A.
Silt loam	Sept. 1950	5.3	80.1	14.6	23.4	0.1
	Mar. 1951	2.2	85.0	12.8	33.1	0.3
	Sept. 1951	7.2	75.1	17.7	18.7	0.05
	Mar. 1952	2.6	85.4	12.0	52.3	1.3
	Aug. 1952	6.1	75.3	18.6	18.2	0.04
Silty clay loam	Sept. 1950	21.8	59.0	19.2	13.8	0.02
	Mar. 1951	4.1	80.9	15.0	46.3	0.8
	Sept. 1951	10.2	72.8	17.0	20.6	0.06
	Mar. 1952	5.0	81.6	13.4	57.7	1.9
	Aug. 1952	9.7	74.1	16.2	33.3	0.3
Clay	Sept. 1950	3.9	82.5	13.6	24.3	0.01
	Mar. 1951	2.0	90.2	7.8	64.6	3.0
	Sept. 1951	9.6	77.4	13.0	8.7	tr.
	Mar. 1952	2.4	88.8	8.8	66.7	3.5
	Aug. 1952	6.8	81.6	11.6	38.0	0.4

* Erodibility estimated from percentage dry fractions <0.84 mm. in accordance with figure 6, *Soil Sci.* 75: 473–483, 1953.

A study of a seasonal variation in soil structure and erodibility confirmed the important influence of water-stable structure on dry structure and erodibility (table 3). In all soils studied the proportion of water-stable fractions <0.02 mm. and >0.84 mm. was higher in fall than in spring. Consequently, the proportion of dry fraction <0.84 mm. and the erodibility were lower in fall than in spring. The action of freezing and thawing during winter tended to break down the coarse water-stable aggregates and tended to consolidate the fine particles to an intermediate size of water-stable aggregates, especially between 0.05 and 0.42 mm. in diameter. This size of aggregate, if unconsolidated into larger secondary aggregates, is highly erodible by wind. The breakdown of water-stable aggregates >0.84 mm. during winter was always associated with aggregation of water-stable particles <0.02 mm.—as if deaggregation of particles >0.84 mm. was responsible for aggregation of the other phase, or *vice versa*. Greater seasonal changes occurred in clay than in silt loam soil.

Wheat straw 1 year after the initial application to the soil caused an increase in water-stable aggregates >0.84 mm. and a decrease in water-stable particles

TABLE 4

*Effect of ground wheat straw on soil structure and erodibility by wind 1 year after initial application**

AMOUNT GROUND WHEAT STRAW	WATER-STABLE FRACTIONS			DRY FRACTIONS <0.84 MM.	ERODIBILITY
	>0.84 mm.	0.84–0.02 mm.	<0.02 mm.		
%	%	%	%	%	*ton/A.*
0	1.9	83.0	15.1	50.0	1.05
2†	9.6	82.2	8.2	49.0	1.00

* Averages based on five different soils of sandy loam and silt loam texture.

† Amount of wheat straw added was 2 per cent of the weight of dry soil at the initiation of the experiment and 2 per cent 6 months later.

TABLE 5

Relation between dry aggregate (secondary aggregate) formation and percentage of water-stable particles <0.02 mm. in diameter

SOIL MATERIAL AND TREATMENT	SOIL CLASS	WATER-STABLE PARTICLES <0.02 MM.	DRY AGGREGATES >0.42 MM. AFTER TREATMENT
		%	%
Dry sieve fraction <0.42 mm., consolidated*	Sandy loam	10.2	17.0
	Silt loam	19.3	28.1
	Silty clay loam	18.2	27.3
	Clay	9.8	17.4
Dry sieve fraction <0.42 mm. from which particles <0.05 mm. were removed by shaking and repeated decantation in water, consolidated*	Sandy loam	0	0
	Silt loam	0	0
	Silty clay loam	0	0.09
	Clay	0	0.23

* Consolidation was accomplished by spraying dry soil material in a column 2 inches high with 1 inch of water followed by drying.

<0.02 mm. (table 4). The decrease in the fine particles almost counterbalanced the increase in the coarse ones, so that the total proportion of the two was about the same. Consequently, as would be expected from the initial results of this study, the proportion of dry erodible fraction <0.84 mm. and soil erodibility by wind remained about the same. The relative effect of water-stable fractions <0.02 mm. and >0.84 mm. on clod structure and erodibility was evidently about the same. The data of table 4 indicate an additional fact not shown in table 3, namely, that the amount of water-stable particles <0.02 mm. can vary independently of the amount >0.84 mm.

Removal of water-stable particles <0.05 mm. from four widely different soil classes left the water-stable aggregates >0.05 mm. unconsolidated or virtually so after they were wetted and dried (table 5). Only those aggregates of fine textured soils cohered slightly, but the force of cohesion was so small the individual aggregates fell apart under slight pressure of the hand. The water-stable fractions >0.05 mm., irrespective of whether they were primary particles or aggregates, acted much like sand grains in that they failed to cohere. Obviously, the water-stable particles <0.05 mm. and especially <0.02 mm. are responsible for holding the water-stable aggregates >0.05 mm. together to form secondary aggregates, or clods.

The percentage of dry aggregates >0.42 mm. was proportional to the percentage of water-stable particles <0.02 mm. (table 5). Evidently, the presence of large amounts of water-stable particles <0.02 mm. in the soil tends to produce clods that are resistant to wind erosion but not particularly conducive to good tilth.

DISCUSSION AND CONCLUSIONS

The water-stable particles <0.02 mm. and >0.84 mm. in diameter, irrespective of whether they are primary particles or aggregates, greatly influence the dry aggregate structure and erodibility of soil by wind. Both of these fractions tend to increase soil cloddiness and decrease erodibility by wind. Their influence in this respect, per unit per cent, is about equal. The amount of water-stable particles <0.02 mm. and the range of its variation are usually high in cultivated dryland soils compared to the amount >0.84 mm. Therefore, the great differences in erodibility of cultivated dryland soils are due primarily to differences in the proportion of water-stable particles <0.02 mm. in diameter.

The water-stable particles between 0.02 and 0.05 mm. and between 0.42 and 0.84 mm. tend to increase cloddiness and decrease erodibility by wind, but only slightly compared to the effect of fractions <0.02 mm. and >0.84 mm. The soils most erodible by wind are usually those containing the greatest proportion of water-stable particles between 0.05 and 0.42 mm. in diameter. It is to be recognized that erodibility varies with the actual diameter of soil particles and not with increments of diameter as determined by wet sieving. The estimated influence of the different sieve fractions on erodibility is, therefore, only approximate. The limits of size of soil fractions used in this study are purely arbitrary.

Primary particles >0.42 mm. (sand and gravel) tend to reduce erodibility somewhat less than do water-stable aggregates of the same size. Nevertheless, the effect of these coarse primary particles on erodibility is considerable, especially of these >0.84 mm. in diameter. No information is available on the relative influence of primary particles and aggregates <0.02 mm.

The water-stable fractions <0.02 mm. and >0.84 mm. may vary together with or independently of each other. No single criterion, such as a percentage of water-stable aggregates above or below a certain size, can be used, therefore, as an indicator of erodibility by wind. The whole size-distribution of water-stable fractions must be taken into account.

The coarsest and the finest water-stable fractions increase with depth in the soil. This is one factor that tends to increase cloddiness and decrease erodibility of soil from lower depths. Obviously, degree of compaction, which increases with depth, also tends to increase cloddiness and decrease erodibility. For proper evaluation of the influence of water-stable structure on dry soil structure and erodibility by wind it is important that the depth of sampling in all comparable cases be the same.

The relatively high erodibility of soil by wind in late winter and spring is evidently due to both aggregation and deaggregation of some phases of water-stable structure by the action of frost. The coarse water-stable aggregates, especially those >0.84 mm., tend to break down; and the fine water-stable particles, especially those <0.02 mm., tend to aggregate under repeated freezing and thawing. As shown from this study, both processes tend to decrease soil cloddiness and increase erodibility by wind.

Jung (3) made an extensive study on the nature of frost action on soils and showed that freezing may cause either aggregation or dispersion of water-stable particles. With slow freezing, such as usually takes place in the field, large ice crystals are formed in the pore spaces and cause the loosening effect on the soil. The crystals also dehydrate the soil particles and cause pressure against them. Both pressure and dehydration cause appreciable aggregation of the fine soil particles. On the other hand, with quick freezing at −190°C. and a moisture content not exceeding 100 per cent, a large number of small crystals is formed, which tends to break down the fine water-stable soil particles. It seems unlikely that effects produced by freezing at such low temperature occur in the field. No information is available from the experiments of Jung on the effect of freezing on the larger water-stable aggregates. Slater and Hopp (4, 5), on the other hand, emphasized the fact that the action of frost tends to disintegrate the larger soil aggregates (>0.5 mm.), omitting from investigation the possible aggregating effects of frost on fine soil fractions.

A reduction in the proportion of the water-stable particles <0.02 mm. resulting from freezing and thawing apparently produces soils that are friable and have "good tilth." One detrimental feature of freezing and thawing of moist soil, however, is the destruction of coarse water-stable aggregates. These aggregates possess a high degree of stability against the forces of cultivation and, if large enough, against the forces of erosion too. Many dryland soils, however, contain relatively small amounts of these coarse aggregates but contain a considerably greater proportion of the fine water-stable particles <0.02 mm. in diameter. These fine particles are responsible, in part, for the formation of secondary aggregates, or clods, of sufficient size to resist the wind. Consequently, resistance of dryland soils to wind action depends primarily on the relatively high content of water-stable particles <0.02 mm. in diameter.

SUMMARY

An inverse relationship was found between soil erodibility by wind and the percentage of water-stable particles <0.02 mm. and >0.84 mm. in diameter. Water-stable particles between 0.02 and 0.05 mm. and between 0.42 and 0.84

mm. tended to reduce erodibility, but only slightly compared to those <0.02 mm. and >0.84 mm. Water-stable particles between 0.05 and 0.42 mm., on the other hand, tended to increase soil erodibility.

The influence of water-stable structure on erodibility was determined by its influence on the dry aggregate soil structure, especially the dry erodible fraction <0.42 mm. or <0.84 mm. in diameter as determined by dry-sieving.

REFERENCES

(1) CHEPIL, W. S. 1943 Relation of wind erosion to the water-stable and dry clod structure of soil. *Soil Sci.* 55: 275–287.

(2) CHEPIL, W. S. 1952 Improved rotary sieve for measuring state and stability of dry soil structure. *Soil Sci. Soc. Amer. Proc.* (1951) 16: 113–117.

(3) JUNG, E. 1931 Untersuchungen über die Einwirkung des Frostes auf den Erdboden. *Kolloidchem. Beih.* 32: 320–373.

(4) SLATER, C. S., AND HOPP, H. 1949 Action of frost on water-stability of soils. *J. Agr. Research* 78: 341–345.

(5) SLATER, C. S., AND HOPP, H. 1951 Winter decline of soil structure in clean-tilled soils. *Agron. J.* 43: 1–4.

(6) YODER, R. E. 1936 A direct method of aggregate analysis and a study of the physical nature of erosion losses. *J. Am. Soc. Agron.* 28: 337–351.