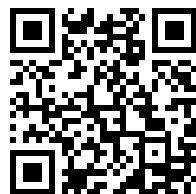

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AGGREGATE STABILITY OF SOILS FROM WESTERN UNITED STATES AND CANADA

- **Measurement Procedure**
- **Correlations With Soil Constituents**

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AGGREGATE STABILITY OF SOILS FROM WESTERN UNITED STATES AND CANADA

• Measurement Procedure

• Correlations With Soil Constituents ¹

By W. D. KEMPER, *soil scientist, Agricultural Research Service and agronomist, Colorado Agricultural Experiment Station*, and E. J. KOCH, *biometrician, Soil and Water Conservation Research Division, Agricultural Research Service*

INTRODUCTION

The close mechanistic relations between aggregate stability and processes such as infiltration or erosion by wind and water are obvious. However, the relation between aggregate stability and plant growth is not so direct. Some of the major factors contributing to crop yield are shown in figure 1. This figure illustrates the indirect nature of the effect of aggregate stability on crop yield.

Because so many factors influence crop yield, experiments attempting to correlate it with aggregate stability have met with limited success. Even those which have shown statistically significant correlations have been criticized when the authors suggested that the aggregate stability was the causative factor. The basis of such criticisms usually is that there is a strong probability that aggregate stability is associated with one or more of the many other factors that affect crop yields more directly.

The evaluation of the relations between aggregate stability, soil structure, and yield will involve many carefully designed and complicated field and laboratory studies. As indicated in figure 1, there appear to be fairly direct relations between soil constituents and the aggregate stability of soils. The present study was designed to evaluate these relations and present them in the form of nonlinear multiple regression equations.

This bulletin reports the development of a simple reproducible method for evaluating aggregate stability and a correlation of aggregate stability with constituent variables in 519 soils from the Western United States and Canada.² To allow continuity in the presentation of the correlation study, the extensive studies leading to the selection of the aggregate stability procedure are reported in the appendix. The content of the appendix will be of greatest importance to some readers.

¹ Approved by the Colorado Agricultural Experiment Station as Scientific Series Paper 829.

² Appreciation is expressed to the personnel of the State Agricultural Experiment Stations, the Soil Conservation Service, and the Agricultural Research Service of the U.S. Department of Agriculture, and the Canadian Agricultural Research Service of the Canadian Department of Agriculture who cooperated in collecting these samples.

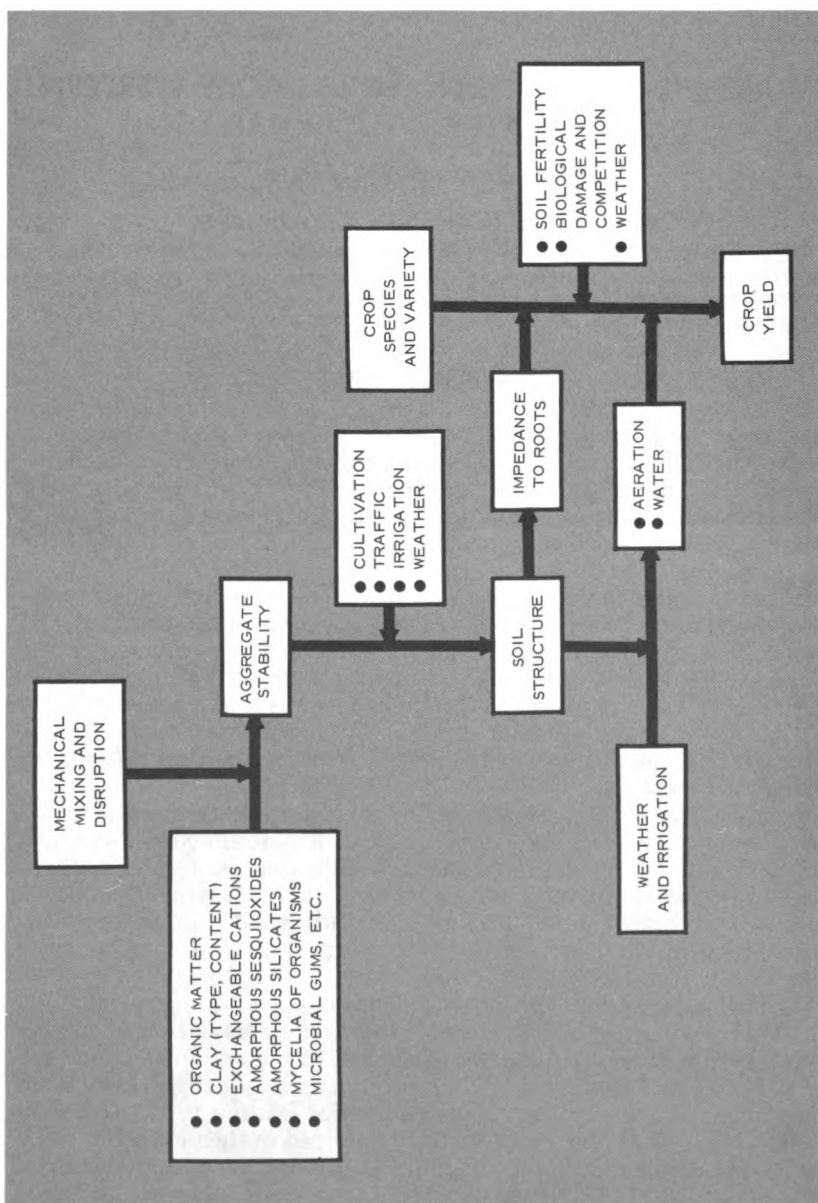


FIGURE 1.—Factors contributing to soil structure and crop yield.

PAST STUDIES

Aggregate Stability Measurements

The aggregates first recognized and studied were those distinctly defined units of soil having clay "skins," iron oxide coatings, and so forth. Such aggregates are usually found in undisturbed soils and are largely a result of the genetic factors that formed the soils. They are usually visually distinct and often have a high degree of mechanical stability.

Some aggregates are simply a result of planes of weakest mechanical strength in the soil and the disrupting force which breaks them free from the soil mass. Such aggregates are transitory in that particles making up an aggregate after one cultivation may be a part of two or more aggregates after another cultivation if they are incorporated into the soil mass and subjected to wetting and drying in the interim. The majority of aggregates in western cultivated soils are transitory. In most cases, they cannot be discerned as aggregates until they are broken away from the rest of the soil mass by some disruptive force.

The size of an aggregate is determined by the strength of the "stability forces" holding the soil particles together and the strength of the disruptive force. If a uniform disruptive force is applied to several soils, the soils having the strongest "stability forces" will generally produce the largest aggregates. Consequently, the results of procedures designed to determine size of aggregates and of procedures designed to measure stability of aggregates are highly correlated.

Equipment and procedures designed to cause uniformly abrasive forces on dry soil aggregates and clods have been developed by Chépil (5)^{*} and his coworkers.

Much of the earliest work on the stability of hydrated aggregates utilized elutriation through various sized tubes to separate the aggregates into several size groupings, the effective sizes of which were calculated according to Stokes' law. Yoder (36) pointed out the deficiencies of this method and mechanized and modified a wet sieving procedure used by Tiulin (30). In Yoder's procedure, a nest of six sieves was placed in a holder and suspended in a container of water. Fifty grams of air-dry soil was placed on the top sieve of each nest, and the nest was lowered to the point where the top screen was just covered with water. A motor and a mechanical arrangement lowered and raised the nest of sieves through a distance of 3.18 mm. at a rate of 30 cycles per minute for 30 minutes. The amounts of soil retained on each sieve were determined by drying and weighing. Size fractions smaller than 0.1 mm. in diameter were determined by a procedure utilizing sedimentation, decanting, drying, and weighing. Much of the work on aggregate stability has utilized Yoder's method or some variation of it.

The statistical analysis of treatments, or the ranking of soils with respect to each other, requires that a measurement be expressible in terms of a single number. Yoder's method yields a size distribution, and van Bavel (32) proposed a mean weight diameter, which is easily estimated by the method of Youker and McGuinness (37), for converting Yoder-method data to a single parameter. A Yoder-type pro-

^{*} Italic numbers in parentheses refer to Literature Cited, p. 29.

cedure was used and results were expressed as mean weight diameters in a study conducted by the Soil Science Society of America Committee on Physical Analyses (van Bavel, 32). The Committee concluded that it "... does not recommend the [Yoder] procedure as a standard. However, the method as given appears to be compatible with availability of equipment in most laboratories."

The determination of six aggregate size fractions involves a considerable amount of work. Bryant, Bendixen, and Slater (4) used a two-sieve method for evaluating water stability of aggregates. They used 3- to 5-mm. aggregates from the soil sample, placed them on a 10-mesh sieve (2-mm. openings) that was nested on top of a 35-mesh sieve (0.5-mm. openings). The aggregates retained on the two sieves were dried, weighed, and expressed as a percentage of the total initial sample. The purpose of the top sieve was to separate out the gravel larger than 2 mm. in diameter. Observations of Bryant, Bendixen, and Slater (4) and data by Strickling (29), Schaller and Stockinger (27), and Panabokke and Quirk (20) all indicate that results from simple one- and two-sieve methods of determining aggregate stability are closely correlated with results obtained with Yoder's method and expressed in terms of mean weight diameters. Consequently, most workers have adopted a single-sieve method for measuring aggregate stability. However, De Boodt, Deleenheer, and Kirkham (7) still advocate a time-consuming variation of Yoder's method that measures changes in mean weight diameter when soils are wetted and subjected to sieving action for a specified time.

Aggregate Stability and Soil Constituents

Since aggregate stability must be measured under some arbitrary disintegrating force, aggregate stability values are empirical. For this reason, they have meaning only when compared to values on other soils, related to soil phenomena, or related to soil constituents. The following is a résumé of past studies in which relations have been established between aggregate stability and soil constituents.

Aggregate Stability and Clay

Clay content and aggregate stability were observed to be closely correlated by Baver (2), and Chesters, Attoe, and Allen (6). Mazurak (18) studied the role of different clay minerals in aggregation. Under most conditions, given quantities of high-surface-area clays (i.e., bentonites) seemed to cause greater aggregation than equal quantities of low-surface-area clays (i.e., kaolinite).

Aggregate Stability and Organic Matter

Demolon and Henin (8) found colloidal organic matter to be more effective than equal amounts of colloidal clay in stabilizing aggregates. Baver (2) found a correlation coefficient of 0.687 between aggregates larger than 0.1 mm. and the organic matter content of 75 soils. He noted that effects of the organic matter were more pronounced in soils containing smaller amounts of clay.

Fresh organic matter serves as a substrate for biological activity. McCalla (14) and Martin (16, 17) attributed increased aggregation of

soil after addition of fresh organic matter to polysaccharides formed during microbial decomposition of the fresh organic matter. Kroth and Page (11) suggested that the polar substances resulting from decomposition of fresh organic matter were most effective in aggregating cultivated soils.

Chesters, Attoe, and Allen (6) found microbial gums to be an important aggregating factor. The filamentous soil fungi were also observed to bind soil particles together in stable aggregates. Peerlkamp (21) concurred in these observations. Peerlkamp (21), and Miller and Kemper (19) found the increased stability resulting from added organic matter to be transient and to decrease to the original level after a few months. However, the temporary increase in stability was large, and Anderson and Kemper (1) concluded that if the soil is cultivated and wetted when the stability is high, the resulting large pores may persist even after the aggregate stability has returned to normal levels.

Aggregate Stability and Free Iron and Aluminum Oxides

A close relation between the free iron oxides and aggregation of southeastern soils was found by Lutz (13). Weldon and Hide (34) noted that stable aggregates were usually high in sesquioxides. This was particularly true in soils from sodium-affected spots, where the stable aggregates were those cemented together by large amounts of sesquioxides. Although the procedure used by Weldon and Hide extracted both iron and aluminum oxides, they considered most of the cementation effects to be due to iron oxides.

Aggregate Stability and Calcium Carbonate

Massive applications of sugar lime (a sugar refinery waste product, largely CaCO_3) have increased the aggregate stability of Belgian soils (De Boodt, 7). The improvement of structure and yield of these soils as a result of added sugar lime is well documented.

Aggregate Stability and Adsorbed Ions

The deleterious effect on soil structure of replacing divalent with monovalent ions has been observed by many investigators (e.g., Brooks, Bower, and Reeves, 3; and Puri, Asghar, and Dua, 23). This effect is so well known as to provide the basis of most techniques for completely breaking soil aggregates into primary particles.

Aggregate Stability and Soluble Silicates

The addition of sodium silicate to calcium-saturated soils usually results in the cementation of the soil particles (Laws and Page, 12). The mechanism of this cementation probably involves the replacement of sodium in the silicate by calcium. The calcium silicate is only slightly soluble in water and probably provides the strong, water-proof bonds observed. Water extracts of calcareous soils invariably contain micro amounts of silicate. The extent to which aggregate stability is improved by solution of silicates from minerals and deposition of these silicates at point of contact between particles as the soil solution evaporates is not known.

Aggregate Stability and Other Factors

There are other constituents that may play minor roles in the aggregate stability of soils. Organic iron complexes have been suggested by McIntyre (15). Potassium plays a role in bonding some clay sheets into packets of larger size. The degree of drying determines the extent to which slightly reversible cementations can be broken. One recurring phenomenon which influences stability is mechanical disruption. Anderson and Kemper (1) showed that severe mechanical disruption of soils in the air-dry state could reduce their aggregate stability from 70 to 30 percent. After a few months of wetting, drying, and biological activity, the severely disrupted soils had regained practically all their stability. Variations in such factors undoubtedly cause variations in aggregate stability.

STUDY OF RELATIONS BETWEEN AGGREGATE STABILITY AND SOIL CONSTITUENTS

The main shortcomings of past studies have been the small number of soils and the limited number of factors and interactions considered. To overcome these shortcomings the present study includes many samples from a broad area and relates aggregate stability to all the soil constituents considered to affect stability that can be measured by routine analyses.

Origin of Samples

The soils studied were from the arid, semiarid, and the subhumid regions of the United States and Canada. Five hundred and nineteen soil samples were included in the study. Their distribution by States and Provinces is shown in figure 2.

Some of the samples from Wyoming, Colorado, and New Mexico were taken from successive horizons in profiles. Most of the other samples were surface samples.

The majority of the samples were representative of series that are widely distributed and are agriculturally important. The majority were from cultivated areas, but a large number were taken from virgin or replanted grasslands.

Measurement Procedures

Because of the extensive studies leading to the development and selection of the procedures, the details have been placed in the appendix to maintain continuity in the presentation of the correlation study. In brief, organic matter was determined by chromic acid oxidation; free iron oxides were determined by an oxidation-reduction titration utilizing SnCl_2 and $\text{K}_2\text{Cr}_2\text{O}_7$; calcium and magnesium carbonates were determined from the volume of CO_2 evolved on treatment with acid; nitrogen was determined by Kjeldahl analysis; and exchangeable sodium percentage was estimated from the amounts of Na^+ and $\text{Ca}^{++} + \text{Mg}^{++}$ found in saturation extracts. Clay content was estimated from hydrometer analyses and aggregate stability was determined by a wet sieving technique preceded by vacuum saturation of the aggregates.



FIGURE 2.—Distribution of soil samples collected for study of relations between aggregate stability and soil constituents.

The portion of large-size (greater than 0.25 mm.) sand is an independent variable of the soil. Consequently the correlation between aggregate stability and constituent factors causing stability is increased if large-size sand particles are not considered as stable aggregates. Rejecting large-size sand from consideration as aggregates biases aggregate stability in favor of low-sand-content soils unless the weight of the large-size sand is also subtracted from the weight of the initial sample. To avoid this bias, percentage of aggregate stability (AS) was determined according to equation [1],

$$\text{Pct. } AS = \frac{100 (\text{wt. of stable aggregates and sand}) - (\text{wt. of sand})}{(\text{weight of sample}) - (\text{weight of sand})} \quad [1]$$

where "sand" is sand larger than 0.25 mm. diameter. Clay, organic matter, free iron oxides, etc. were determined on samples from which this large-size sand had been removed.

RESULTS AND DISCUSSION

The extent to which the measured constituent variables affect aggregate stability and the degree to which these variables account for the aggregate stability variance are evaluated in this section.

General Relations for Western Soils

Plots of Aggregate Stability Versus Soil Constituents

The initial step in determining the type of relation existing between aggregate stability and the amounts of various constituents in the soil was to calculate the average value of aggregate stability for all samples whose content of the constituent fell within a given class interval. These average aggregate stability values were then plotted against the medians of the class intervals for the constituent.

If the independent variables (constituents) are not correlated with each other when aggregate stability is plotted against a particular constituent, the effects of other variables should average out if large numbers are included in each class. The number adjacent to each point on figures 3 to 9 indicates the number of samples from which the average was obtained.

Organic Matter

The relation between aggregate stability and organic matter for these soils is shown in figure 3. As expected, aggregate stability increases with organic matter. The most striking aspect of these data is the sharp change in the slope of the curve occurring between 1-

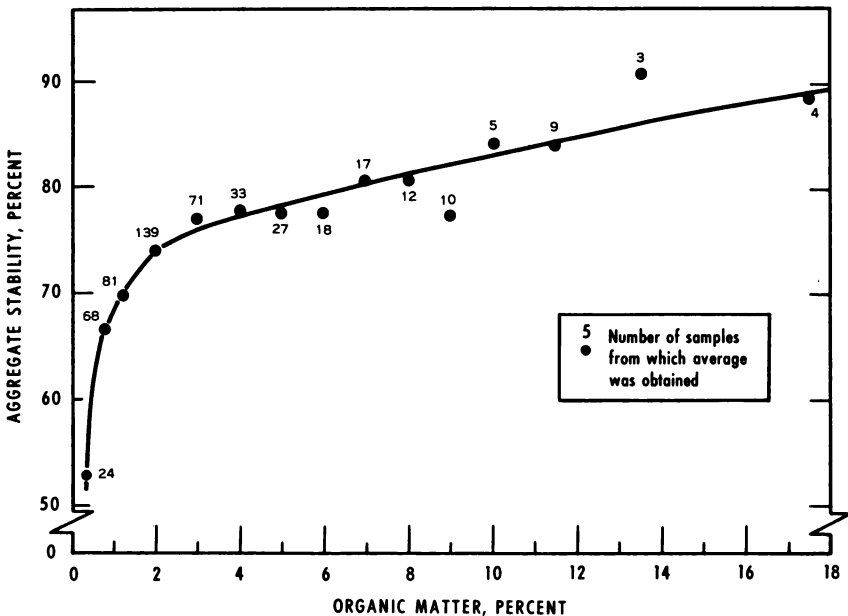


FIGURE 3.—Relation of aggregate stability to organic matter in western soils.

and 2-percent organic matter. This indicates that increases of organic matter above 2 percent increase the aggregate stability comparatively little.

On the other hand, decreases in organic matter below 1 percent are associated with large reductions in aggregate stability. The shape of this curve also illustrates the necessity for using curvilinear rather than linear regression analysis for the aggregate stability versus organic matter relationship. A logarithmic curve furnished the closest approximation of this relationship. Note that points varying considerably from the line were averages for small numbers of samples.

Nitrogen

The relation between the aggregate stability and nitrogen content is shown in figure 4. The change in slope of the curve is not as sharp as the change in figure 3. The curve relating aggregate stability to nitrogen is a more "common" diminishing-returns-type curve than the curve relating aggregate stability to organic matter.

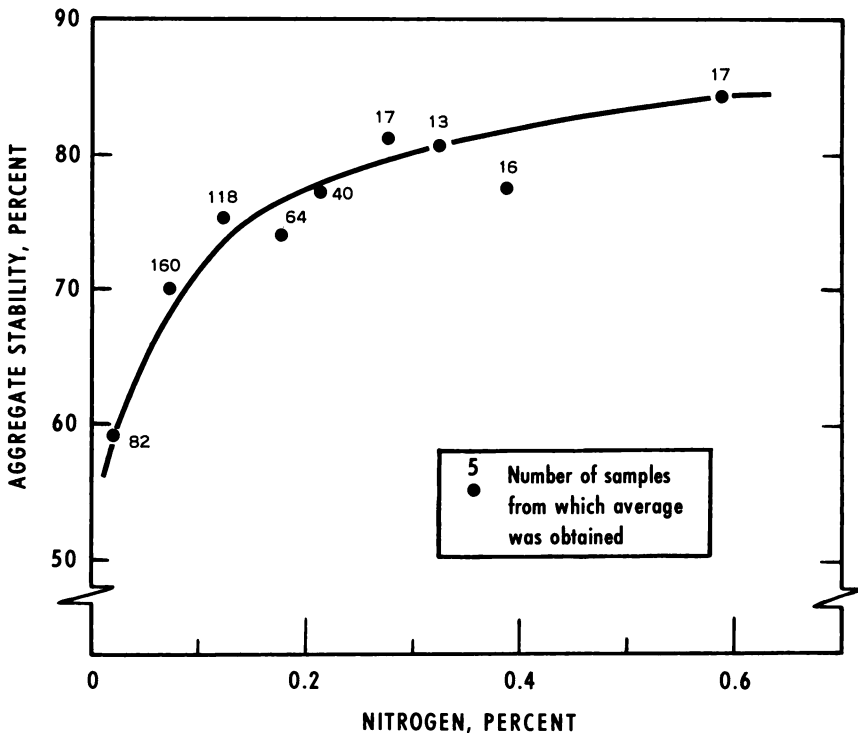


FIGURE 4.—Relation of aggregate stability to nitrogen in western soils.

Clay

The relation between aggregate stability and clay content for these soils is shown in figure 5. There is no apparent sharp break in the slope of the curve. However, the curve is hyperbolic, showing a "diminishing returns" effect of clay on aggregate stability.

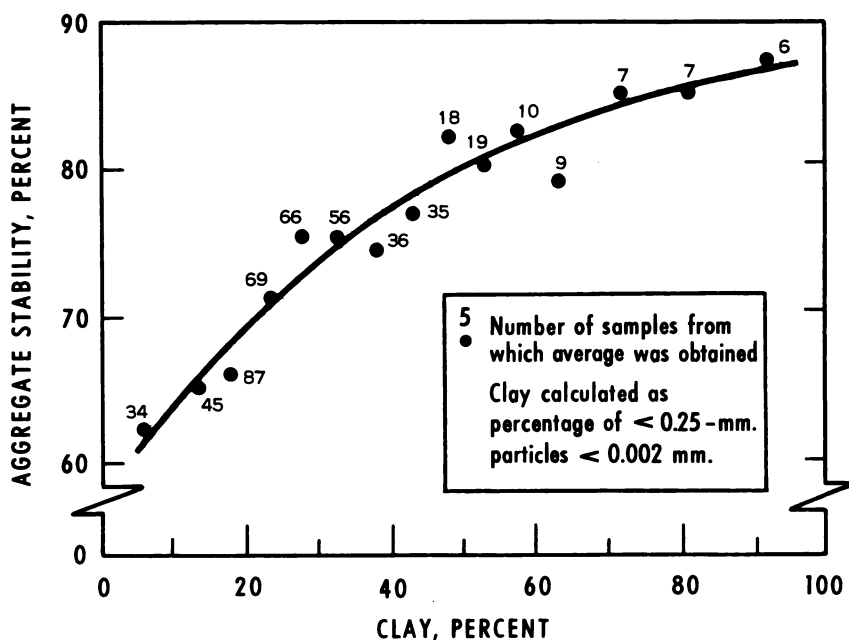


FIGURE 5.—Relation of aggregate stability to clay content in western soils.

Free Fe_2O_3

The relationship between aggregate stability and free Fe_2O_3 is shown in figure 6. Previous analyses of some Southeastern U.S. soils (Cecil, Durham, and Appling series) with large amounts of Fe_2O_3 showed them to be almost 100-percent water stable as measured by this method. Western soils do not have enough free Fe_2O_3 to cause this degree of stability. However, the small amounts of free Fe_2O_3 present in our western soils are apparently sufficient to make it a measurable and important factor affecting aggregate stability.

Free Al_2O_3

The relationship between aggregate stability and free Al_2O_3 is shown in figure 7. Because of similarities in their chemical properties it has often been inferred that aluminum and iron oxides should aggregate soil particles to approximately the same extent. Comparison of figures 6 and 7 indicates that this inference may not be true. Higher contents of Al_2O_3 (as measured by the procedure used in this study) were not associated with significantly higher aggregate stability.

In samples with an appreciable amount of exchangeable sodium (more than 4 percent) there was a negative correlation between free Al_2O_3 and aggregate stability. Since there is no apparent reason for free Al_2O_3 to decrease aggregation, the logical interpretation seems to be that high exchangeable sodium, which destroys structure, also is associated with (and perhaps causes) high levels of free Al_2O_3 .

Exchangeable Sodium

Although appreciable amounts of exchangeable sodium (*ES*) are not found in most western soils, when they are present they are a

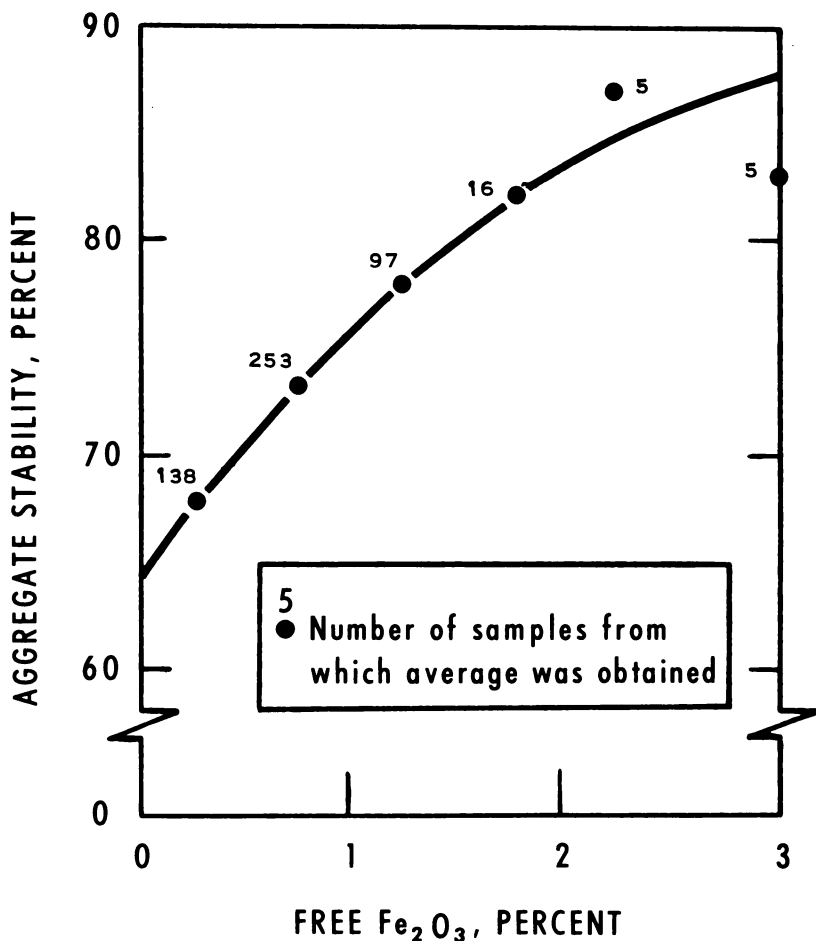


FIGURE 6.—Relation of free Fe_2O_3 to aggregate stability in western soils.

dominant factor in reducing aggregate stability. The effect is illustrated in figure 8. The number of soils with exchangeable sodium values greater than 6 percent, from which the major portion of this curve was drawn, is small. However, its general shape agrees with numerous other published and unpublished data. At exchangeable sodium percentages greater than 20, aggregate stability is practically zero in most western soils.

The study by Weldon and Hide (34) indicates that aggregates stabilized by large amounts of free Fe_2O_3 are stable at exchangeable sodium percentages higher than 20.

Calcium Carbonate

Aggregate stability is plotted against calcium carbonate in figure 9. The curve is not significantly different (statistically) from the dashed straight line shown on figure 8, which represents complete independence of aggregate stability on amount of CaCO_3 in these soils.

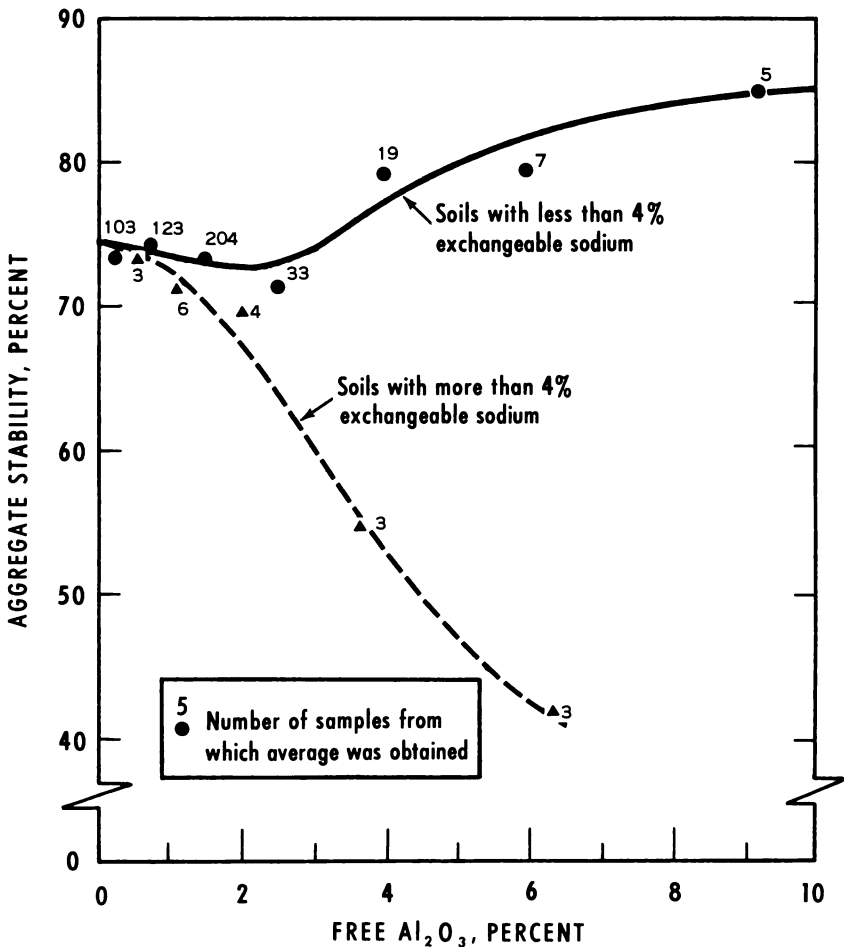


FIGURE 7.—Relation of aggregate stability to free Al_2O_3 in western soils with and without appreciable exchangeable sodium.

It is believed that the positive correlations between sugar lime and aggregate stability obtained by Belgian workers (e.g., De Boodt, Deleenheer, and Kirkham, 7) are associated with either the higher rainfall and more acidic soils of Belgium or the organic matter included in the sugar lime.

Statistical Analysis

Selection of Variables for Multiple Regression Analysis

On the basis of the data shown in figures 7 and 9 and preliminary statistical analyses, it was concluded that the probabilities that free Al_2O_3 or CaCO_3 were correlated with aggregate stability were less than 6 in 10. Consequently, these variables were not included in the multiple regression analysis. The high degree of correlation ($r=.95$) between nitrogen and organic matter indicated that inclusion of nitro-

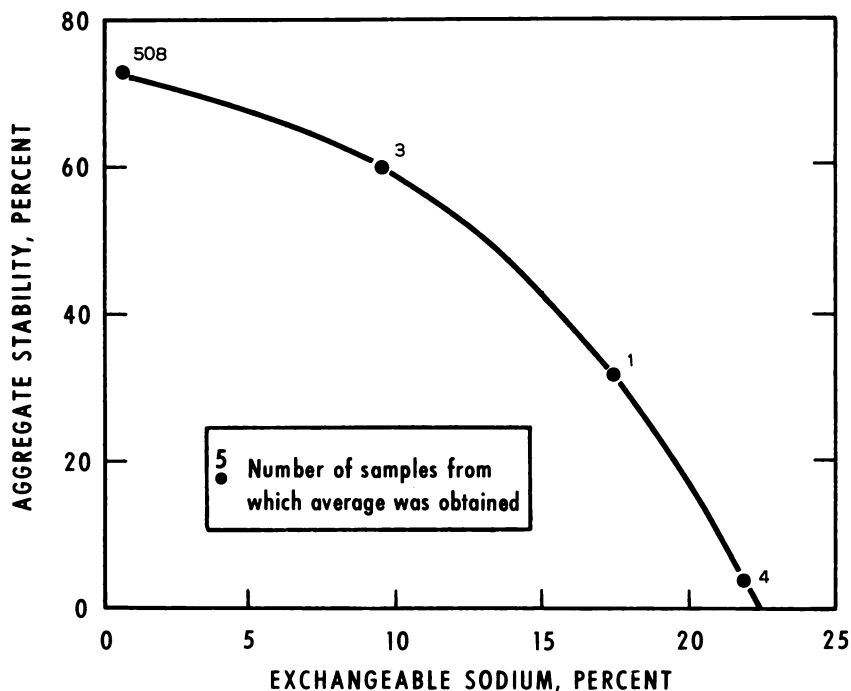


FIGURE 8.—Relation of exchangeable sodium percentage to aggregate stability in western soils.

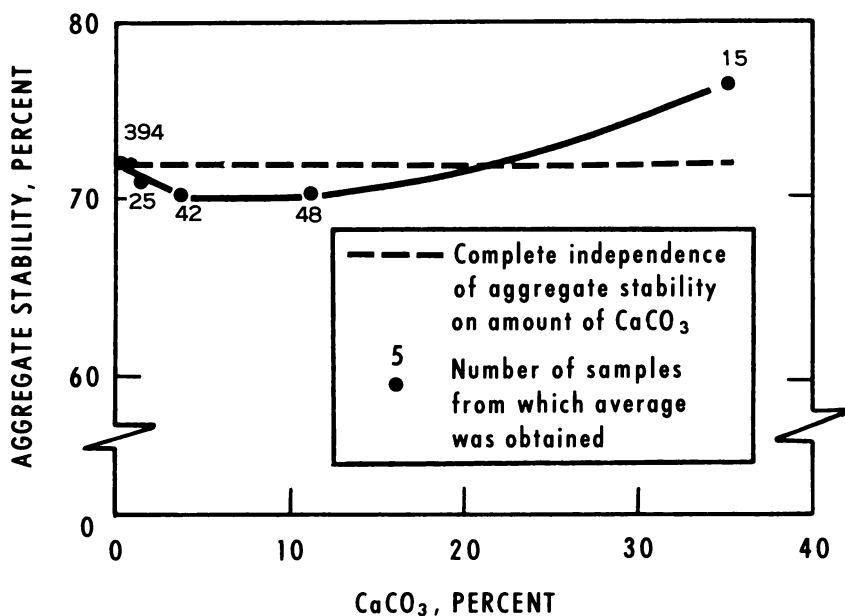


FIGURE 9.—Relation of aggregate stability to CaCO_3 in western soils.

gen in the regression analysis would be superfluous if organic matter was already included. Consequently, nitrogen was not included in the multiple regression analysis.

The shape of the curve shown in figure 3 indicated that the relationship between aggregate stability and organic matter (*OM*) was logarithmic in nature. Consequently, the logarithm of organic matter was used.

Figures 5, 6, and 7 indicated hyperbolic relations between aggregate stability and percentage of clay, percentage of Fe_2O_3 , and percentage of exchangeable sodium (*ES*) of soils; therefore, these variables were entered in the regression analysis as both linear and quadratic terms.

Eight-Variable Multiple Regression Equation

The equation obtained from multiple regression analysis was:

$$AS = 49.7 + 13.7 \log OM + 0.61 \text{ clay} - 0.0045 (\text{clay})^2 + 9.0 \text{ Fe}_2\text{O}_3 - 1.6 (\text{Fe}_2\text{O}_3)^2 - 0.28 ES - 0.060 (ES)^2 \quad [2]$$

where aggregate stability and all constituents are given in percent.

Note that the logarithm of organic matter has negative values when the organic matter is less than 1 percent. The multiple correlation coefficient, *R*, (coefficient of determination) of this equation was 0.56, and thus the fraction of the variance of aggregate stability associated with variables considered in equation 2, R^2 , was equal to 0.31.

The standard errors of the partial regression coefficients of equation 2 are given in table 1 along with the probabilities of real relations between the independent variables and aggregate stability (i.e. the probabilities of the *t* value for the partial regression coefficients). The *t* values of the partial regression coefficients in the multiple regression are also shown in table 1. These *t* values evaluate the relative importance of the various variables in the aggregate stability of soils. It is apparent that $(\text{Fe}_2\text{O}_3)^2$, *ES* and $(ES)^2$ were not very important in the

TABLE 1.—*Significance and relative importance of variables in the eight-variate multiple regression equation*

Variable ¹	Partial regression coefficient	Standard error of partial regression coefficient	<i>t</i> value of partial regression coefficient in the multiple regression ²	Probability of real relation between variable and aggregate stability ³
Log <i>OM</i>	13.7181	1.7005	8.07	> 0.99
Clay.....	.6117	.1249	4.90	> .99
(Clay) ²	-.0045	.0014	3.32	> .99
Free Fe_2O_3	8.9508	3.8790	2.31	.98
Free $(\text{Fe}_2\text{O}_3)^2$	-1.5956	1.5332	1.03	.70
<i>ES</i>	-.2814	.8327	.33	.25
$(ES)^2$	-.0598	.0374	1.12	.74

¹ All soil constituents are expressed in percent in the multiple regression equation.

² Evaluates relative importance of the variable in the aggregate stability of soils.

³ Probability of the *t* value for the partial regression coefficient.

aggregate stability of these soils. The small importance of ES and $(ES)^2$ can be attributed to the fact that there were few soils containing an appreciable concentration of sodium ion in this study. The insignificance of the $(Fe_2O_3)^2$ term results from low amounts of Fe_2O_3 in these soils and a nearly linear relationship between Fe_2O_3 and aggregate stability in this range of Fe_2O_3 concentration.

Simple correlation coefficients between the constituent variables are given in table 2.

TABLE 2.—*Simple correlation coefficients between soil constituent variables*

Variable ¹	Log OM	Clay	(Clay) ²	Fe ₂ O ₃	(Fe ₂ O ₃) ²	ES	(ES) ²
Log OM-----	1. 00	0. 19	0. 16	0. 11	0. 10	−0. 18	−0. 16
Clay-----		1. 00	. 95	. 28	. 21	−. 05	−. 06
(Clay) ² -----			1. 00	. 25	. 20	−. 03	. 04
Fe ₂ O ₃ -----				1. 00	. 92	−. 10	−. 08
(Fe ₂ O ₃) ² -----					1. 00	−. 07	−. 05
ES-----						1. 00	. 92
(ES) ² -----							1. 00

¹ All soil constituents are expressed in percent in the multiple regression equation.

Climatic Factors and Aggregate Stability

Mean Annual Temperature

Averages for aggregate stability versus mean annual temperature are plotted by 5° F. classes in figure 10A. Reduction in aggregate stability occurs when mean annual temperatures increase beyond 45° F. A major mechanism by which temperature could affect aggregate stability would be through the effect of temperature on organic matter.

Averages for organic matter versus mean annual temperature are plotted by 5° F. classes in figure 10B. From a comparison of figures 10A and 10B, it is apparent that the large organic matter contents, occurring at mean annual temperatures lower than 40° F., are not effective in stabilizing aggregates. This is in agreement with the aggregate stability versus organic matter plot (fig. 3), which indicates that organic matter in excess of 2 or 3 percent is associated with little increase in stability of aggregates.

Both organic matter and aggregate stability decrease as temperature increases above 45° F. (where organic matter contents averaged less than 2½ percent). This indicates that organic matter could be the factor responsible for the decrease in aggregate stability. Such a conclusion is supported by the marked reduction in aggregate stability as organic matter decreases to less than 2 percent, as shown in figure 3. For these reasons, it appears probable that most of the effect of mean annual temperature on aggregate stability occurs as a consequence of the effect of mean temperature on organic matter content.

Mean Annual Precipitation

Averages for aggregate stability versus mean annual precipitation are plotted by 5-inch rainfall classes in figure 11A. Aggregate stability increases as mean annual precipitation increases up to 20 inches.

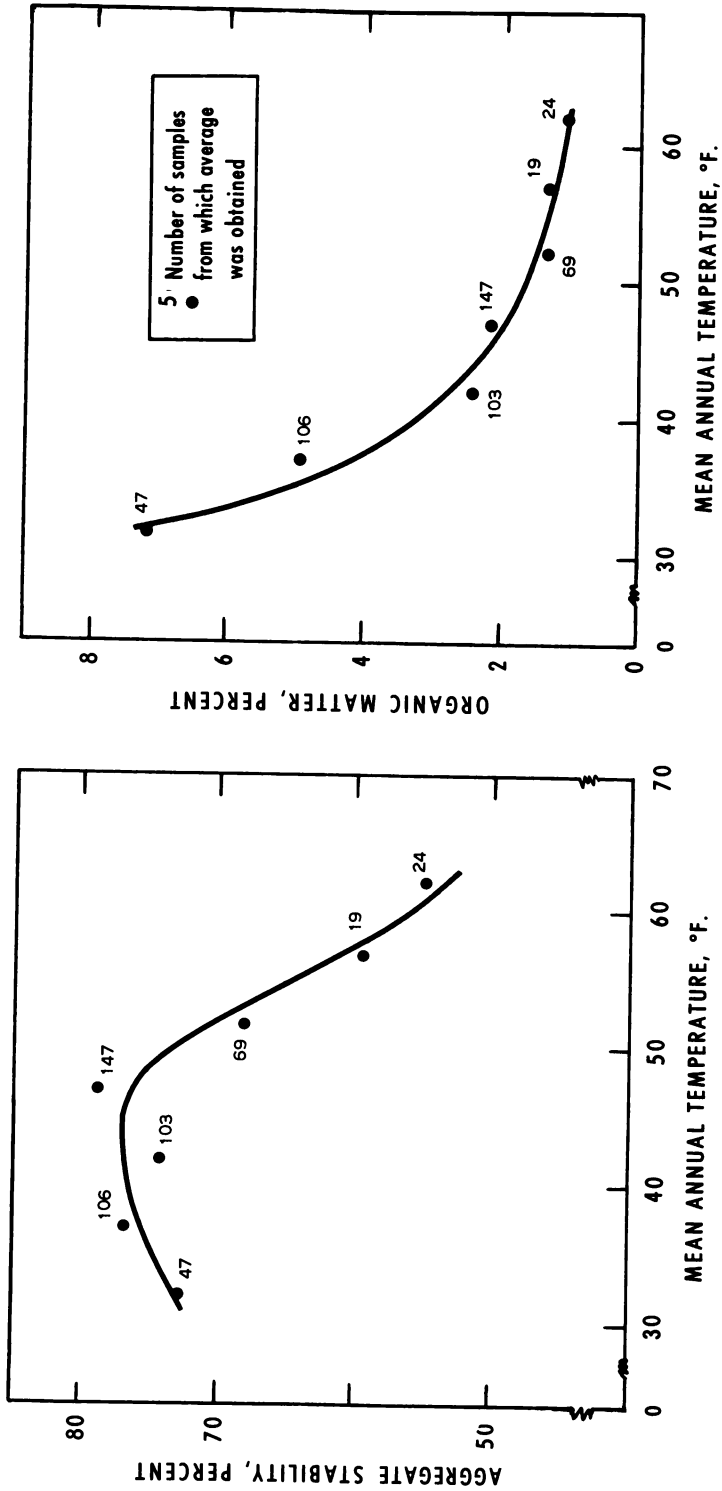


FIGURE 10.—Aggregate stability and organic matter related to mean annual temperature.

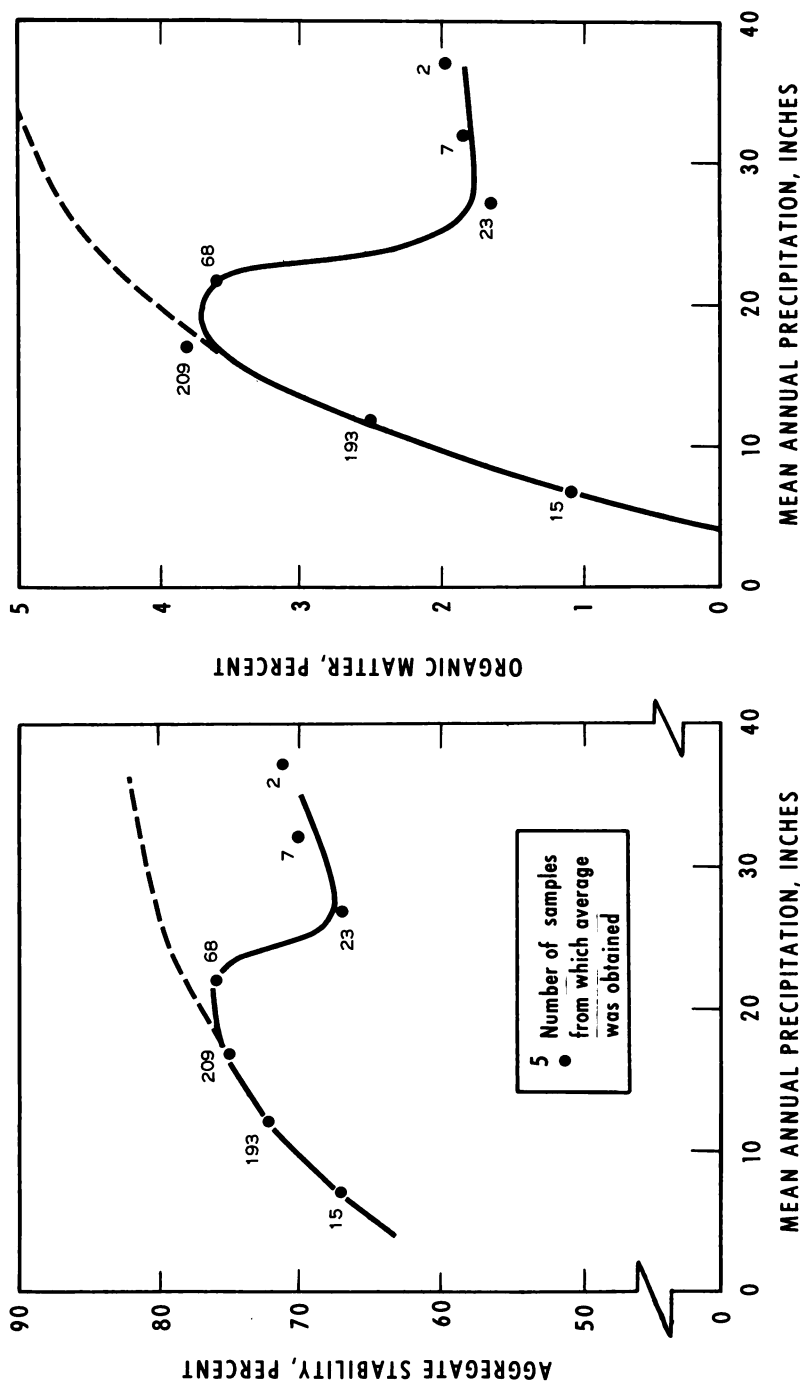


FIGURE 11.—Aggregate stability and organic matter related to mean annual precipitation. (Dashed lines indicate the trend expected had there been no correlation between precipitation and temperature.)

The deviation from this trend at large mean annual precipitations is believed to be due to positive correlation between mean annual precipitation and temperature at the higher levels of precipitation. The 32 samples showing such marked deviation from the dashed line in figure 11A are from Texas and Oklahoma. Apparently, the effect of high temperature on the stability of the aggregates was dominant over the effect of high precipitation. If there had been no correlation between temperature and rainfall, it is likely that the data would have followed the dashed line indicated in figure 11A.

The strong similarity of the relation between organic matter and mean annual precipitation (fig. 11B) and aggregate stability and mean annual precipitation (fig. 11A) indicates that mean annual precipitation affects aggregate stability through its effect on organic matter.

Since both rainfall and temperature appear to influence aggregate stability through their effect on the organic matter of the soil, the organic matter factor in the multiple regression equation probably accounts for the major portion of the variation that would be attributed to these climatic factors. Consequently, the climatic factors were not included in the multiple regression equation.

Relation of Aggregate Stability and Soil Constituents by Soil Category

On the basis of the information obtained from the suppliers of the soil samples, it was possible to place most of the samples in one of the following categories:

1. Subsurface layers: samples from below the A horizon.
2. Surface sod layers: samples from A horizons that were in grass (most of these were virgin sods, but some had been cultivated at some time during their history).
3. Surface cultivated layers: samples from the cultivated layers (parts of A and B horizons) of soils producing crops other than grasses.

Some factors influencing aggregate stability would be different in these categories.

On the basis of such probable differences, the soils of this study which could be positively identified were separated into these three categories for analysis. Averages for aggregate stability were plotted by soil constituent range interval, and regression analyses were run within each of the three categories.

Since the data in table 2 indicate an insignificance of effects of $(\text{Fe}_2\text{O}_3)^2$, ES , and $(ES)^2$ on aggregate stability, only organic matter, clay, and free iron oxide were included in the regression analyses. Soils with more than 4 percent of ES were excluded from the study.

Aggregate Stability Versus Organic Matter

Aggregate stability is plotted as a function of organic matter in figure 12. In general, at a given organic matter level, subsurface layers have greatest stability, followed by surface sod layers and surface cultivated layers, in that order. The higher stability of the subsurface layers might be due in part to the higher clay contents (see table 3) or to lack of cultivation. However, the steeper slope of the

aggregate stability-versus-organic matter curve for subsurface layers indicates that the organic matter contained in the subsurface layers is more effective in causing stability than the organic matter in surface sod layers and cultivated layers.

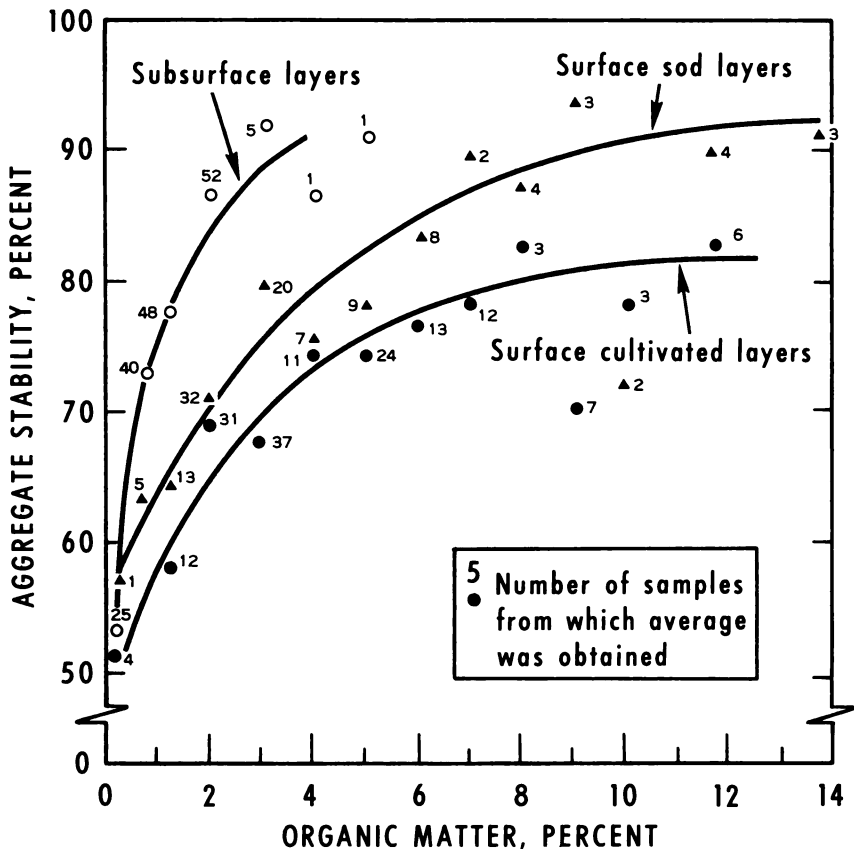


FIGURE 12.—Relation of aggregate stability to organic matter in subsurface layers, sod layers, and cultivated layers.

TABLE 3.—Average value of soil constituents and aggregate stability for subsurface layers, surface sod layers, and surface cultivated layers ¹

Factor	Subsurface layer	Surface sod layer	Surface cultivated layer
	Percent	Percent	Percent
Organic matter	1. 12	3. 00	2. 86
Clay	36. 6	32. 0	30. 2
Free Fe ₂ O ₃ .....	. 89	. 79	. 84
Aggregate stability	76. 4	76. 1	68. 2

¹ Percentage based on weight of soil particles smaller than 0.25 mm.

Aggregate Stability Versus Nitrogen

The relation between aggregate stability and nitrogen for these categories of soils (fig. 13) is similar to the relations between aggregate stability and organic matter. However, the slope of the aggregate stability-versus-nitrogen curve for subsurface layers is nearly equal to the slope of the curves for surface sod layers and surface cul-

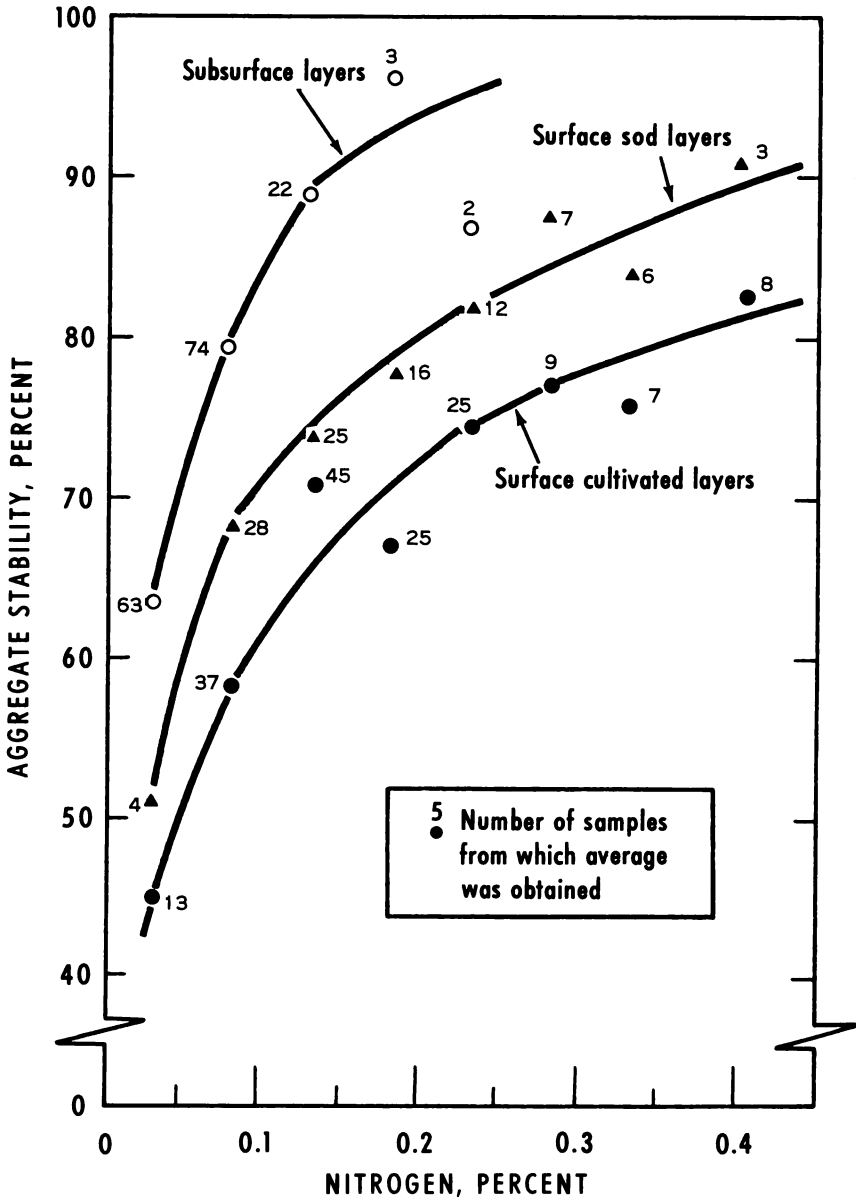


FIGURE 13.—Relation of aggregate stability to free Fe_2O_3 in subsurface layers, surface sod layers, and surface cultivated layers.

tivated layers. This indicates that the nitrogen content of the organic matter is an important index of the degree to which organic matter is effective in stabilizing soil aggregates. Organic matter with high nitrogen content will be more effective in this respect.

Aggregate Stability Versus Free Iron Oxide

The plot of aggregate stability versus free Fe_2O_3 in figure 14 indicates that free Fe_2O_3 is more effective in stabilizing aggregates in sub-surface layers and surface cultivated layers, and least effective in surface sod layers.

Multiple Regression Analyses by Soil Category

Aggregate Stability as a Logarithmic Function of Organic Matter, Quadratic Function of Clay Content, Linear Function of Clay Content, and Linear Function of Free Iron Oxide

The regression equations relating $\log OM$, clay, $(\text{clay})^2$, and free iron oxide are given in equations 3, 4, and 5 for surface cultivated layers, surface sod layers, and subsurface layers, respectively.

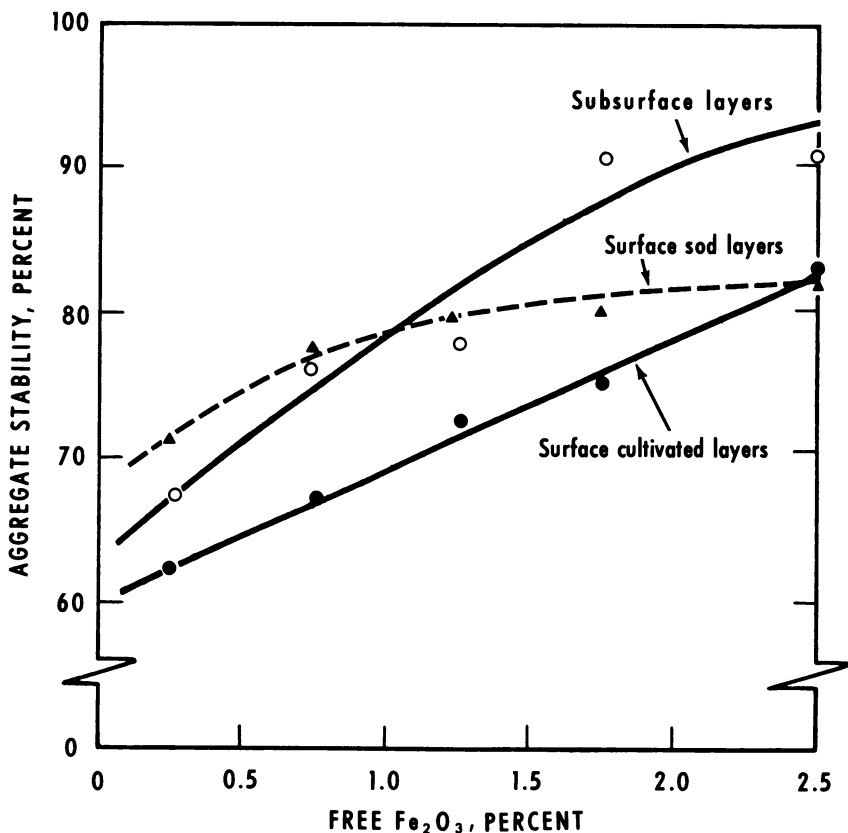


FIGURE 14.—Relation of aggregate stability to free Fe_2O_3 in subsurface layers, surface sod layers, and surface cultivated layers.

Surface cultivated layers:

$$AS = 40.8 + 17.6 \log OM + 0.73 \text{ clay} - 0.0045 (\text{clay})^2 + 3.2 \text{ Fe}_2\text{O}_3 \quad [3]$$

Surface sod layers:

$$AS = 45.1 + 22.6 \log OM + 0.28 \text{ clay} - 0.0021 (\text{clay})^2 + 1.5 \text{ Fe}_2\text{O}_3 \quad [4]$$

Subsurface layers:

$$AS = 65.6 + 32.8 \log OM - 0.05 \text{ clay} + 0.00080 (\text{clay})^2 + 6.0 \text{ Fe}_2\text{O}_3 \quad [5]$$

In surface cultivated layers the regression of these four variables accounted for 44 percent of the total variance in aggregate stability (R^2), while in surface sod layers and subsurface layers the regression accounted for 35 and 38 percent, respectively. In each soil class a greater portion of the variance is accounted for by the regression than the 31 percent accounted for by regression when all soils were together. This bears out the initial supposition that aggregate stabilities of these three categories of soils are affected in different manners by the factors studied or are a function of other variables not considered in the regression.

Similar increases in variance accounted for by constituent factors were found when soils were divided into smaller classes on the basis of their geographical location. This was also noted by Chesters, Attoe, and Allen (6), who correlated aggregate stability with organic carbon, and microbial gum, clay, iron oxide, and pH. They were able to associate up to 69 percent of the aggregate stability variance with the regression in particular soil series, but when all soils were combined, only 36 percent of the aggregate stability variation could be associated with this regression.

The constant of the regression equation is greatest for subsurface layers and least for surface cultivated layers, with surface sod layers being intermediate in this respect. Since some of the surface sod layers had also been cultivated at some time in their history, it seems likely that the lower constants associated with surface cultivated layers result from the cultivation and factors affected by cultivation. Disintegration by mechanical impact, exposure of new soil material to raindrop impact, and extreme temperatures would be direct causative factors in lowering the average aggregate stability of these surface cultivated layers.

Coefficients associated with the $\log OM$ terms show that organic matter is more effective in causing aggregate stability in subsurface layers than in surface cultivated layers. Some of the organic matter in subsoil is well-decomposed, low-carbon/nitrogen-ratio material that is apparently more effective in stabilizing soil structure. The standard errors of the partial regression coefficients, the t values, and the probabilities of real relationship between the various constituents and aggregate stability are given in table 4. It is surprising to note, from the t values, that organic matter was more closely associated with good structure in subsurface layers than in topsoils, whether the topsoils were surface sod layers or surface cultivated layers.

Partial regression coefficients associated with the clay terms indicate that clay is a much more important factor in surface cultivated layers than in surface sod layers. In subsurface layers this coefficient was actually slightly negative. The t values associated with clay in these

TABLE 4.—Standard errors and *t* values of the partial regression coefficients and the probabilities of real relationships between the various constituents and aggregate stability for equations 3, 4, and 5

Variable ¹	Standard error of partial regression coefficient			<i>t</i> value of the partial regression coefficient in the multiple regression ²			Probability of real relationship with aggregate stability ³		
	Surface cultivated layers	Surface sod layers	Sub-surface layers	Surface cultivated layers	Surface sod layers	Sub-surface layers	Surface cultivated layers	Surface sod layers	Sub-surface layers
Log OM.....	2.8	3.5	4.3	6.20	6.50	7.71	>0.99	>0.99	>0.99
Clay.....	.21	.21	.25	3.51	1.37	.20	>.99	.82	.15
(Clay) ².....	.0024	.0020	.0026	1.89	1.02	.30	.94	.69	.25
Fe ₂ O ₃	2.3	2.5	2.8	1.41	.60	2.14	.83	.45	.96

¹ All soil constituents are expressed in percent in the multiple regression equation.

² Evaluates relative importance of the variable in the aggregate stability of soils.

³ Probability of the *t* value for the partial regression coefficient.

soil categories also indicate the importance of clay in aggregate stability of surface cultivated layers and its ineffectiveness in subsurface layers. Cultivation is a mixing process, and it follows that surface cultivated layers will have their clay particles more intimately mixed with the silts and sands. Subsurface layers usually have not undergone such intensive mixing and, consequently, their clay, silt, and sand particles are likely to have remained segregated in those locations where they were deposited or formed. It is generally suspected that the fine clay particles help bind the larger particles together. If this is true, an analogy may be drawn between the strength of a soil aggregate and the strength of concrete. In both cases, the strength would be increased by more thorough mixing of the constituents, the binding material being clay in soil and cement in concrete. The intermediate position of surface sod layers with respect to the clay-aggregate stability correlation is consistent with the above analogy, since some of these soils have been cultivated in the past. However, mixing of soil constituents by biological processes has also occurred in the surface sod layers and may be a major factor responsible for this intermediate position.

The probabilities of the (clay)² term having a real effect on aggregate stability for surface cultivated layers, surface sod layers, and subsurface layers, were 0.94, 0.69, and 0.25, respectively (table 4). These probabilities were lower than for the percentage-clay term but were in the same order with regard to the soil categories. Even in the surface cultivated layers, the (clay)² term was a relatively minor factor affecting aggregate stability, as indicated by the *t* value (table 4) of aggregate stability with this variable.

The partial regression coefficient associated with free Fe₂O₃ was highest in subsurface layers, intermediate for surface cultivated layers, and lowest for surface sod layers. The probabilities of real relationships between free Fe₂O₃ and aggregate stability were 0.96, 0.83, and 0.45 for these soil categories, respectively. As shown in table 3, subsurface layers had a slightly higher free Fe₂O₃ content than surface sod layers, with surface cultivated layers being intermediate. These average differences are not large enough to account for the greater importance of free Fe₂O₃ in subsoils. Aeration and consequent valence state and solubility of the iron may be factors in the greater effectiveness of this free iron oxide in stabilizing aggregates of subsurface layers as compared to surface sod layers and cultivated layers.

Aggregate Stability as a Logarithmic Function of Organic Matter and as a Linear Function of Clay and Free Iron Oxide

Since the (clay)² term was found to be a minor variable when soils were divided into these three classes, this variable was deleted and another set of regression equations (equations 6, 7, 8) was determined, in which the log *OM*, clay, and Fe₂O₃ were included as the independent variables.⁸

Surface cultivated layers: $R^2 = 0.43$ = fraction of variance associated with regression;

⁸ Partial regression coefficients marked with an * are significant at the 5-percent level of probability; those with ** are significant at the 1-percent level.

$$AS = 46.1 + 19.2^{**} \log OM + 0.35^{*} \text{ clay} + 3.0 \text{ Fe}_2\text{O}_3 \quad [6]$$

Surface sod layers: $R^2 = 0.35$;
 $AS = 61.5 + 22.9^{**} \log OM + 0.079 \text{ clay} + 1.5 \text{ Fe}_2\text{O}_3 \quad [7]$

Subsurface layers: $R^2 = 0.38$;
 $AS = 68.8 + 32.3^{**} \log OM + 0.22 \text{ clay} + 5.9^{*} \text{ Fe}_2\text{O}_3 \quad [8]$

The same general conclusions regarding the importance of the remaining variables may be drawn as were drawn in the analysis where the quadratic function of clay was considered. The regressions accounted for the same percentages of the total variance in the subsurface layers and surface sod layers—38 and 35 percent, respectively. In the surface cultivated layers the regression accounted for 1 percent less (43 percent) of the variance than when the $(\text{clay})^2$ term was included in the regression.

Aggregate Stability as a Function of Three Linear Constituent Variables

The relatively small amount of variance accounted for by the curvilinear term of the clay component suggested an evaluation of the use of a linear term for organic matter rather than a logarithmic term. This was done by running a linear multiple regression using organic matter, clay content, and free Fe_2O_3 as the independent variables and aggregate stability as the dependent variable.

Comparison of the R^2 values obtained (0.21 for all soils, 0.35 for cultivated soils, 0.27 for sod soils, and 0.25 for subsoils) indicates that use of the logarithmic rather than the linear term resulted in the regressions accounting for 8, 8, and 13 percent more of the variance in aggregate stability in the surface cultivated layers, surface sod layers, and subsurface layers, respectively. These differences in associated variance support the assumption that the real relation between aggregate stability and organic matter is more accurately described by a logarithmic than by a linear function.

Another important difference between the completely linear regression equations and the equations where organic matter is considered a logarithmic function lies in the minimum value of aggregate stability they can predict. The minimum values are 48.3, 63.3, and 56.4 for surface cultivated layers, surface sod layers, and subsurface layers, respectively, when organic matter is considered a linear function. The constants in the equations where organic matter is a logarithmic function have similar values, but when the organic matter is less than 1 percent, the $\log OM$ term becomes negative (since organic matter is expressed in percent). Thus, for a subsurface layer with 0.1 percent organic matter, the term involving $\log OM$ would have a negative value of 32.7 percent and the predicted value of aggregate stability could be very low if clay and free Fe_2O_3 were also low. This property of the logarithmic term for organic matter, which allows a very steep gradient for the aggregate stability-versus-organic matter term at low organic matter contents, is apparently responsible for the better predictions of the aggregate stability.

Other Sources of Aggregate Stability Variance

Since less than half of the variance could be associated with the constituent variables considered, other possible sources of aggregate stability variance should be mentioned.

Storage time before sampling was a variable in this study. Some samples were analyzed within a month of the sampling date, whereas others had been taken 3 or 4 years prior to analysis. The data in figure 18 of this study indicate that this storage time factor can cause considerable variance in the measured values of aggregate stability.

The difference between the constants of the cultivated and non-cultivated soil layers indicates that the overall effect of cultivation is usually deleterious, although it may have a positive factor associated with mixing clays with the larger particles. Anderson and Kemper (1) showed that water stability of aggregates could be reduced to a very low level if the sample had been mechanically disintegrated in its recent history. For instance, cultivation at high speeds and rototilling generally reduce stability.

Separation of the soils into cultivated and noncultivated classes allowed the regressions to account for much more of the aggregate stability variance. However, it was not possible to evaluate the intensity of cultivation in the history of the cultivated soils. Moreover, as mentioned before, some of the surface sod layers had been cultivated one or more times in the past. Consequently, it appears likely that the intensity-of-cultivation variable caused part of the unaccounted for variation in surface sod layers and surface cultivated layers.

Several investigators (McCalla, 14; Martin, 16; Miller and Kemper, 19) have noted that addition of organic matter to the soil is followed by a flush of biological activity and an increase in aggregate stability. The binding mechanisms probably involve gummy polysaccharide by-products of microbial activity and filamentous mycelia of the micro-organisms. Whatever the mechanism, the temporary increase in aggregate stability following incorporation of fresh organic matter is an established fact. It is likely that some of the samples were taken at a time when their aggregate stability was at a high level due to such a temporary flush of microbial activity, while most of the samples were probably taken when microbial populations were at more normal levels. Consequently, a portion of the unaccounted for aggregate stability variance can probably be attributed to this variable.

In this study, all particles less than 2 microns in diameter were described simply as clay and were lumped together as a single factor. Peterson (22), Mazurak (18), and others have shown that the higher-surface-area clays are generally more effective in stabilizing aggregates than the lower-surface-area clays. This lack of differentiation between clays in the present study probably reduced the portion of aggregate stability variance that could have been accounted for by the clay factor.

That types of organic matter differ in their ability to affect aggregate stability is demonstrated by the different coefficients associated with organic matter in the regression equations for subsurface layers, surface sod layers, and cultivated layers. It was also pointed out that, while they exist, polysaccharides and fungal mycelia are extremely good aggregating agents. In the present study, all types of organic matter were combined and entered the regression equation as a

single factor. Differentiation of types of organic matter would probably allow regression of organic matter components to account for more of the variance in aggregate stability than did bulk organic matter alone.

Experimental error in the various analyses undoubtedly reduced the portion of aggregate stability variance accounted for by the constituent variables included in the study. It is likely, however, that perfect analyses of all variables would have increased the variance accounted for by less than 10 percent.

Many other materials (e.g., amorphous silicates, aluminum oxides, volcanic ash and its weathering products) are present in soils. Although the contribution of any one of these may not be a major factor in aggregate stability, it is not unlikely that the total effect of all such minor factors is appreciable in causing the variance of aggregate stability from the regression.

SUMMARY AND CONCLUSIONS

The place of aggregate stability in the soil structure-crop yield picture was diagrammed. Soil constituents were shown to be a major factor influencing aggregate stability which, when acted upon by traffic, cultivation, weather, and irrigation, determines the soil structure (arrangement of particles and voids).

The following factors involved in the determination of aggregate stability by wet sieving were evaluated (see appendix): (1) moisture content at sampling time; (2) tools used for sampling; (3) temperatures at which samples are dried; (4) humidity during storage; (5) length of storage time; (6) temperature during storage; (7) size of aggregates used; (8) methods of wetting the sample; (9) period of soaking prior to wet sieving; (10) temperature of water in which samples are wetted and sieved; (11) sieve and sample size; (12) sieve stroke length and frequency; and (13) length of sieving time. On the basis of these evaluations a standardized procedure was proposed that will yield meaningful and reproducible results with sub-humid, semiarid, and arid region soils, and yet will require only a moderate amount of time and equipment.

The proposed method was used to evaluate the aggregate stability of over 500 samples from western parts of the United States and Canada (see fig. 2). These aggregate stabilities were then correlated in a multiple regression equation with measured values of organic matter, clay, free iron oxide, and exchangeable sodium. Free Al_2O_3 and CaCO_3 were not included in the regression because of apparent lack of relation to aggregate stability.

The correlation of two variates does not prove a cause-and-effect relationship. However, the constituent variables—free Fe_2O_3 , clay, organic matter, and exchangeable sodium—have all been shown by previous experimental work to be causative agents in stabilizing or destroying soil aggregates. Consequently, it is fairly safe to assume that correlations found in this study between aggregate stability and these constituent variables are the results of cause-and-effect relationships.

The regression equation relating aggregate stability to organic matter, clay, free iron oxide, and exchangeable sodium, including all soil samples, was:

$$AS = 49.7 + 13.7 \log OM + 0.61 \text{ clay} - 0.0045 (\text{clay})^2 + 9.0 \text{ Fe}_2\text{O}_3 - 1.6 (\text{Fe}_2\text{O}_3)^2 - 0.28 ES - 0.060 (ES)^2 \quad [2]$$

where aggregate stability and soil constituents are all expressed in percent. The last three variables in this equation were of doubtful significance and were of little importance in the soils studied. The regression accounted for 31 percent of the total variance of aggregate stability.

The consistent correlation of organic matter with aggregate stability in all soil categories implies that organic matter is always an important factor in the aggregate stability of soils. Clay was found to be an important factor only in surface soils where clay had been thoroughly mixed with the other soil components by cultivation and perhaps by biological processes. Free iron oxide was an appreciable factor in subsoils and may be a minor factor in cultivated topsoils. While exchangeable sodium when present, was a dominant factor in destroying aggregate stability, it was not present in enough of these soils to be an important factor in their overall aggregate stability.

Classifying the soils into surface cultivated layers, surface sod layers, and subsurface layers allowed the regressions to account for 44, 35, and 38 percent of the aggregate stability variance in their respective categories. The regression equations were:

For surface cultivated layers:

$$AS = 40.8 + 17.6 \log OM + 0.73 \text{ clay} - 0.0045 (\text{clay})^2 + 3.2 \text{ Fe}_2\text{O}_3 \quad [3]$$

For surface sod layers:

$$AS = 45.1 + 22.6 \log OM + 0.28 \text{ clay} - 0.0021 (\text{clay})^2 + 1.5 \text{ Fe}_2\text{O}_3 \quad [4]$$

For subsurface layers:

$$AS = 65.6 + 32.8 \log OM - 0.05 \text{ clay} + 0.0008 (\text{clay})^2 + 6.0 \text{ Fe}_2\text{O}_3 \quad [5]$$

These equations indicate: (1) the superior effectiveness of the organic matter in subsurface layers, as compared to organic matter in surface layers, in stabilizing aggregates; (2) that clay was a consistently effective binding agent only in those soils that had been cultivated; and (3) that free iron oxides were a significant factor in stability of these subsurface layers, but not of these surface layers.

It was found that, in general, organic matter in excess of 2 percent added little to aggregate stability, but that reduction of organic matter to values less than 1 percent caused rapid decrease in aggregate stability. Aggregate stability was found to be a logarithmic function of organic matter.

Since the constants of the regression equations have different values for the different categories of soils, factors other than those considered in the regression are apparently operating on these categories of soil to different degrees.

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APPENDIX

This appendix contains the details of the measurement procedures used in the foregoing study. It also includes a review of factors affecting aggregate stability measurements and the results of several original studies designed to determine the conditions necessary for meaningful and reproducible measurements of aggregate stability.

The Proposed Aggregate Stability Measurement Procedure

The following procedure was developed on the basis of a series of studies of factors involved in each step of the procedure. Since this procedure, with variations, was used in these studies of the various factors, it is presented here so it may be referred to in the presentation of those studies.

Usual Steps

1. Take the soil sample, using a shovel or core sampler, when the moisture content is between field capacity and the wilting point. Dry the sample at room temperature.
2. Break and sieve the sample, saving the aggregates that pass through a 2-mm. sieve and are retained on a 1-mm. sieve.
3. Weigh out 4 g. of the air-dried 1- to 2-mm. aggregates, to an accuracy of 0.01 g., into a weighing dish. (If the relative humidity of the laboratory is above 30 percent, an additional 4 g. of aggregates should be oven-dried to determine the moisture content of the sample.)
4. Transfer the air-dry aggregates to a 60-mesh (openings 0.25 mm. square) sieve 38 mm. in diameter and place the sieve on filter paper on a ceramic plate in a vacuum desiccator that contains a few milliliters of water and has an inlet through which additional water can be brought to the bottom of the desiccator from the outside.
5. Evacuate the desiccator. This causes the water to boil, which produces water vapor, which tends to sweep out other gases. Keep a small (6 to 8 cm. high) barometer in the desiccator to make it possible to be sure that the pressure is reduced to 1 to 2 cm. of mercury.
6. Let de-aerated water flow into the bottom of the desiccator until the aggregates are covered with water. (The de-aerated water is prepared by reducing the pressure over it in a desiccator and allowing it to boil for 10 minutes; the water is then allowed to come to room temperature.)
7. Place the sieve containing the sample into a sieve holder, and sieve in salt-free ($<10^{-5}$ mhos/cm.) water for 5 minutes at 42 cycles

8. At the end of 5 minutes, remove the sieve from the holder and wash the remaining aggregates and sand into a weighing dish. Pour off the excess water and dry the remaining aggregates and sand in an oven at 105° C.
9. Weigh the dish containing the stable aggregates and sand and record the weight in column 4 of the suggested data sheet (fig. 15).

AGGREGATE STABILITY DATA SHEET

1	2	3	4	5	6	7	8	9
SAMPLE NO.	DISH NO.	DISH WEIGHT	WEIGHT OF DISH PLUS STABLE AGGREGATES PLUS SAND	WEIGHT OF DISH PLUS SAND	WEIGHT OF SAND; COL. 5 MINUS COL. 3	WEIGHT OF STABLE AGGREGATES COL. 4 MINUS COL. 5	WEIGHT OF AGGREGATE SAMPLE * MINUS SAND; 4.00 G. MINUS COL. 6	AGGREGATE STABILITY: $\frac{100 \times \text{COL. 7}}{\text{COL. 8}}$
		<u>GRAMS</u>	<u>GRAMS</u>	<u>GRAMS</u>	<u>GRAMS</u>	<u>GRAMS</u>	<u>GRAMS</u>	<u>PERCENT</u>

* USE WEIGHT OF 4 G. OF AIR-DRIED AGGREGATES AFTER OVEN DRYING IF RELATIVE HUMIDITY OF LABORATORY IS OVER 30 PERCENT.

FIGURE 15.—Suggested data sheet for laboratory measurement of aggregate stability.

Wash the aggregates and sand back into the sieve and agitate the sieve for 5 minutes in a solution containing approximately 5 g. of calgon ⁴ per liter. At the end of this time, only the sand with diameter larger than 0.25 mm. should remain. (If soil aggregates still persist, they may be broken down with a rubber-tipped rod or with a jet of water from a wash bottle.) When only the sand

^a Common designation for dispersing agents approaching sodium metaphosphate in composition.

remains, wash it back into the weighing dish, pour out the excess water, and oven-dry the sand. Weigh the dish containing the sand and record the weight in column 5 of the suggested data sheet.

10. The percentage of aggregate stability is equal to the following expression :

$$\frac{100 (\text{wt. of stable aggregates and sand}) - (\text{wt. of sand})}{(\text{weight of sample}) - (\text{weight of sand})}$$

It can be calculated by filling out the data sheet (fig. 15).

Treatment of Concretions

Those aggregates that do not break down under a rubber-tipped rod or a jet of water from a wash bottle are referred to as concretions. They may contain many soil particles and are held together by CaCO_3 , iron oxides, and other cementing materials. They may be considered and treated in two ways.

Since they are extremely stable and will not break down under normal cultivation practices, the concretions may be considered to be sand. If they are so considered, no special attempts should be made to break them down and wash them through a sieve.

On the other hand, since they usually have some porosity and appreciable internal surface area and exchange capacity, the concretions may be considered to be stable aggregates. If they are so considered, they must be broken down so that the primary particles can pass through the sieve or go off as gases. Concretions bonded by CaCO_3 disintegrate completely when soaked in 1 *N* HCl. Organic or iron-bonded concretions usually disintegrate when soaked in 0.5 *N* NaOH.

Of the 519 samples studied from Western United States and Canada about 60 contained concretions. For the purpose of this study, concretions were considered to be stable aggregates. All these concretions were disintegrated by the acid or the base treatment.

Factors Affecting Aggregate Stability Measurements

Moisture Content at Time of Sampling

If the rate of drying influenced the aggregate stability, it would be suspected that samples taken at different field moisture contents would have different aggregate stabilities. Those taken when the soil was dry would have dried at a slow rate. Those taken when the soil was wet would dry more rapidly in a drying room or oven. There may be other ways in which moisture content at sampling time influences the aggregate stability of the soil.

To determine whether aggregate stability was affected by moisture content at sampling time, two soils were studied—Fort Collins clay loam (its clay mostly montmorillonitic) and Billings silt loam (its clay mostly illitic). The plots were in alfalfa, beets, and corn on the Billings soil and in corn on the Fort Collins soil. Samples were

taken with a slotted Hoffer tube ⁵ in the two areas a few days after an irrigation (soil moisture at approximately field capacity) and immediately before the next irrigation (soil moisture at approximately the wilting point). Four samples were taken in each plot in the immediate vicinity of marked stakes at each sampling time. Moisture content was determined on each sample and the samples were air dried. The rest of the procedure was the same as the proposed procedure except that the samples were wetted at atmospheric air pressure.

The moisture contents of the samples at time of sampling and the aggregate stabilities of the samples are presented in table 5. Each value in the table is the average for four subsamples taken within the plot.

TABLE 5.—Effect of moisture content at sampling time on the aggregate stability of two western soils

Soil and crop	Moisture content at time of sampling		Aggregate stability at—	
	Low moisture	High moisture	Low moisture	High moisture
Fort Collins clay loam:	<i>Percent</i>	<i>Percent</i>	<i>Percent</i>	<i>Percent</i>
Corn plot 1-----	12. 4	24. 1	51	53
Corn plot 2-----	15. 2	22. 4	45	49
Billings silt loam:				
Alfalfa-----	7. 2	15. 8	42	43
Beets-----	7. 9	16. 8	48	46
Corn-----	12. 4	21. 5	65	64

While there is some variation in the aggregate stability values of the samples collected at the different moisture levels, there is no consistent effect, and the variations observed are within the experimental error and sampling error of the experiment.

These data indicate that the moisture content at the time of sampling is not a critical factor in aggregate stability measurements. Samples taken when the soil moisture content is near the wilting point will have aggregate stabilities essentially the same as those of samples taken at moisture contents near field capacity.

Sampling Tools

Samples taken with a slotted Hoffer tube and samples taken with a sharp shovel had essentially the same aggregate stabilities. Aggregate stabilities of samples taken with an auger were slightly more variable than those taken with a tube or a shovel. However, the mean values were not significantly different.

⁵ Trade names are used in this publication solely to provide specific information. Mention of a trade name does not constitute a guarantee or warranty and does not signify that the product is approved to the exclusion of other comparable products.

Drying Temperature

Drying Temperature and Soil Type

Slater (28) showed small but reproducible increases in the aggregate stability of eastern soils as a result of increasing the temperature for drying samples from 4° to 82° C. This part of the study was set up to determine whether the same relation existed for western soils and to ascertain its magnitude if it did.

Billings silt loam soil was selected from rotation plots near Grand Junction, Colo., containing alfalfa, beets, and corn. Fort Collins clay loam soil was selected from four locations in a corn fertility experiment at Fort Collins, Colo. Each sample was divided into three subsamples to be dried at room temperatures of 25°, 55°, and 105° C., respectively. These subsamples were then crushed and sieved. Quadruplicate determinations of aggregate stability were made on each sample according to the proposed procedure (except that the wetting water was not de-aerated). The values of aggregate stability shown in table 6 are averages of the quadruplicate determinations. The Fort Collins clay loam had no exchangeable sodium and the Billings silt loam contained less than 3 percent exchangeable sodium.

TABLE 6.—*Effect of drying temperature on the aggregate stability of two western soils*

Soil and crop	Aggregate stability when sample is dried at—		
	25° C.	55° C.	105° C.
Fort Collins clay loam in corn:	Percent	Percent	Percent
Location 1.....	48	55	63
Location 2.....	45	49	57
Location 3.....	49	57	68
Location 4.....	45	56	62
Billings silt loam:			
In alfalfa.....	43	50	52
In beets.....	46	49	55
In corn.....	65	67	75

The effect of increase in aggregate stability of the sample with increased drying temperature which Slater noticed on his eastern soils is even more pronounced on these western soils. The aggregate stability of the montmorillonitic Fort Collins soil changed more than that of the illitic Billings soil. The clays in Slater's soils were probably largely kaolinite and, therefore, the soils were probably low in total surface area. Elevated drying temperatures cause the greatest increase in aggregate stability in soils with the highest total surface areas.

Drying Temperature and Exchangeable Sodium Percentages⁶

Sor noted that samples dried at 105° C. had high aggregate stability, even though they contained high levels of exchangeable sodium.

⁶ The authors are indebted to Kamil Sor for this study, which was part of Dr. Sor's Master of Science thesis at Colorado State University (1958).

He designed the following experiment to evaluate further this phenomenon.

Billings clay loam was used. Samples were prepared that contain 0, 8, and 16 percent of exchangeable sodium (*ES*), the complementary ion being calcium. These samples were puddled and dried at 30°, 55°, and 105° C. They were then crushed and sieved. Aggregates that passed through a 2-mm. sieve and were retained on a 1-mm. sieve were used for the stability determinations.

The procedure used to determine the aggregate stability was the same as the proposed procedure, except the samples were wetted for just 1 minute before the sieving began. The aggregate stabilities for samples from each level of exchangeable sodium are plotted as a function of the drying temperature in figure 16. As noted in the experiment summarized in table 6, when drying temperature increases, there is a small increase in the aggregate stability of the samples containing little or no exchangeable sodium; however, as shown in figure 16, there is a much larger increase in the aggregate stability of samples containing an appreciable percentage of exchangeable sodium.

The question arose as to whether retarded hydration was responsible for the apparent stability of aggregates in the soils with appreciably high exchangeable sodium percentages that were dried at high temperatures.

To answer this question, samples of the aggregates prepared for the experiment summarized in figure 16 were soaked in water for 1 minute, 6 hours, and 24 hours, respectively, prior to wet sieving. The results of the aggregate stability analyses of these samples are presented in

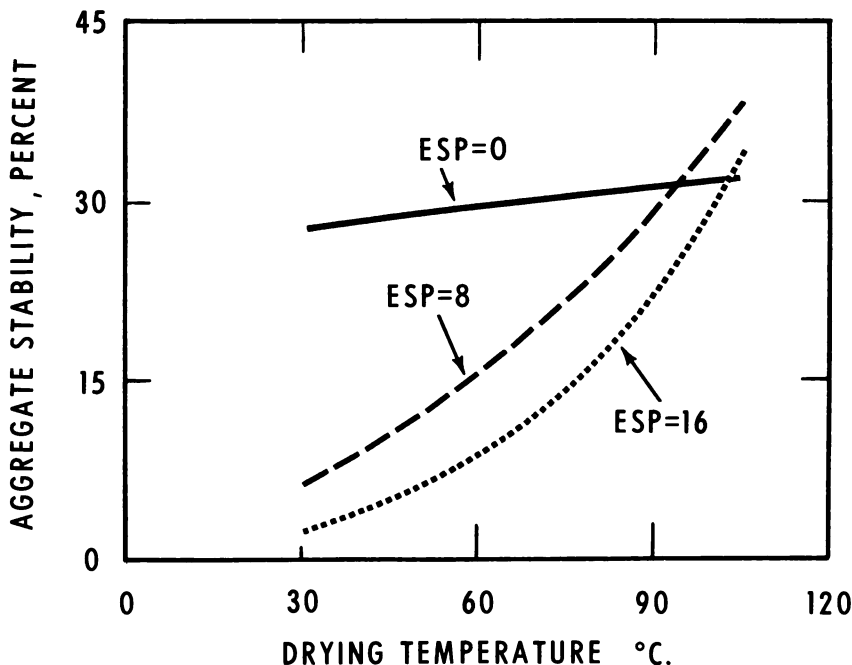


FIGURE 16.—Effect of drying temperature on aggregate stability of Billings clay loam containing exchangeable sodium percentages (*ESP*) of 0, 8, and 16.

figure 17. Each point represents the average of the aggregate stabilities of three samples with 0-, 8-, and 16-percent exchangeable sodium. Since the aggregate stability of samples dried at high temperature is initially high and decreases with increased time of soaking, retarded hydration is apparently the reason for the initially high levels of aggregate stability in the sodium-saturated systems. (Almost all of the average decrease noted was accounted for by the decrease in the samples containing exchangeable sodium.)

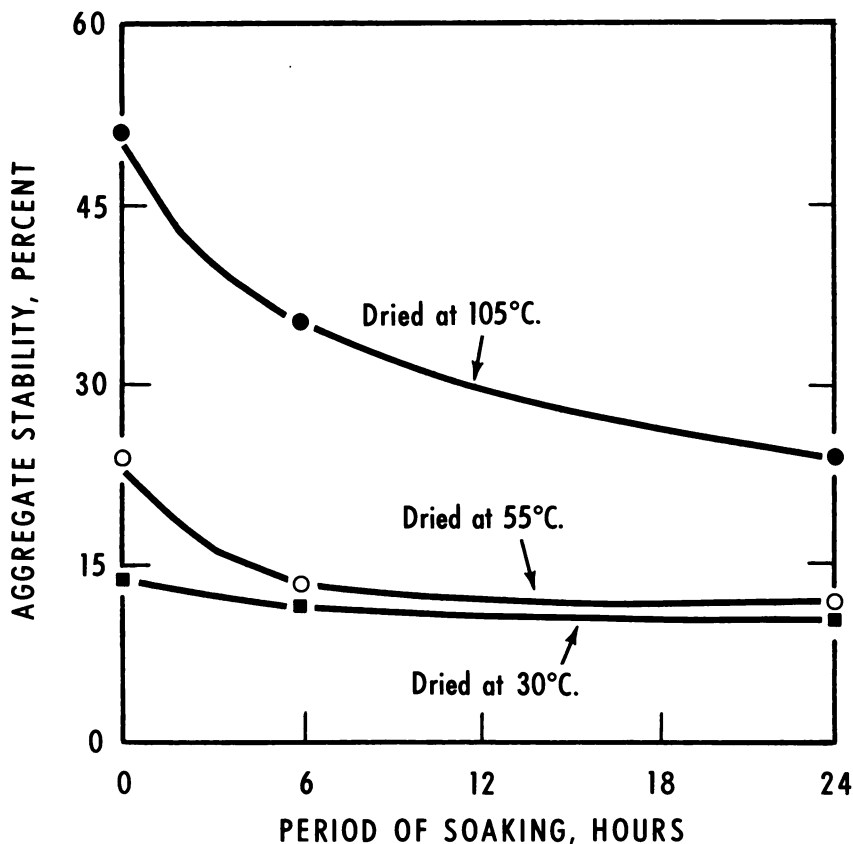


FIGURE 17.—Effect of period of soaking prior to wet sieving on aggregate stability of Billings clay loam. (Values are averages of three samples with 0-, 8-, and 16-percent exchangeable sodium.)

It is likely that the disintegration of the soil when wet, which is caused by the exchangeable sodium, allows a greater degree of orientation of clay particles with respect to each other when the soil is then dried. When the last molecular layers of water are removed from between the clay platelets by oven drying, the platelets come into contact with each other. They are probably bonded together by potassium ions, organic matter, and amorphous sesquioxides. The sesquioxides may also be slow to rehydrate and may be very strong bonding agents in the dehydrated phase.

These mechanisms are only postulates. However, it is obvious that oven drying the soil may cause a transient aggregate stability of sodium-affected soils that would not be representative of field conditions.

For the most accurate representation of stability in the field and the standardization of an otherwise variable factor, soils should be dried at room temperature (about 25° C.) before aggregate stability is measured.

Sample Storage Conditions

Relative Humidity

The question arose as to whether the relative humidity of the air during the drying or storage period might influence the aggregate stability of the samples. The following experiment was designed to investigate this possibility. Rocky Ford loam, Billings clay, Billings clay loam, and Fort Collins clay loam were used. Four samples of 1- to 2-mm. diameter air-dry aggregates from each soil were placed in each of three desiccators at 20° C. Saturated solutions of various salts in the bottom of the desiccators kept the relative humidities at 10, 52, and 93 percent, respectively.

After the aggregates had been in the desiccators for 14 days (moisture equilibrium as determined by weighing was complete within about 48 hours), they were removed, wetted under vacuum, and sieved according to the proposed procedure. The results are presented in table 7. Each value is the average of four samples.

TABLE 7.—*Effect of relative humidity during the drying period on the aggregate stability of four western soils*

Soil	Aggregate stability when relative humidity is—		
	93 pct.	52 pct.	10 pct.
	<i>Percent</i>	<i>Percent</i>	<i>Percent</i>
Rocky Ford loam.....	55	54	55
Billings clay.....	70	71	70
Billings clay loam.....	80	81	80
Fort Collins clay loam.....	70	73	73

Within this range of relative humidities (10 to 93 percent), the relative humidity during storage, or immediately prior to wetting the sample for analysis, had no appreciable effect on the aggregate stability when the samples were wetted under a vacuum. It is likely that the results would have been different if the samples had been wetted by immersion at atmospheric pressure. A large amount of air is adsorbed as a monolayer on clay surfaces when soil samples are stored at low humidities. When the humidity of the air is fairly high, water replaces the nitrogen and oxygen adsorbed on these surfaces. Since the air (nitrogen and oxygen) entrapped in the aggregates immersed at standard pressure is a major factor causing aggregates to “slake,” the

lesser amount of nitrogen and oxygen on the samples stored at high humidities would probably result in higher aggregate stability.

Length of Storage Time

According to Kolodny and Joffe (10), long periods of air drying tended to decrease the degree to which microaggregates were dispersed. To determine whether long periods of drying changed aggregate stability, the following study was initiated. Dry Fort Collins clay loam soil was powdered, mixed with 1 percent by weight of alfalfa, and incubated at approximately 24° C. and 15-percent moisture. Sixteen pots of soil were prepared in this manner. Sets of four pots were removed from the incubator at 2, 4, 8, and 16 weeks after the soils were mixed and wetted. The soils were dried and analyzed for aggregate stability within 1 week after removal from the incubator. Portions of the dried soils from each time treatment were stored at laboratory temperatures and humidity (10- to 50-percent relative humidity) and their aggregate stabilities determined after 4 months of storage. The average results are shown in figure 18. In every case, stability increased with storage time. Differences resulting from different treatments were smaller when samples had been stored for 4 months.

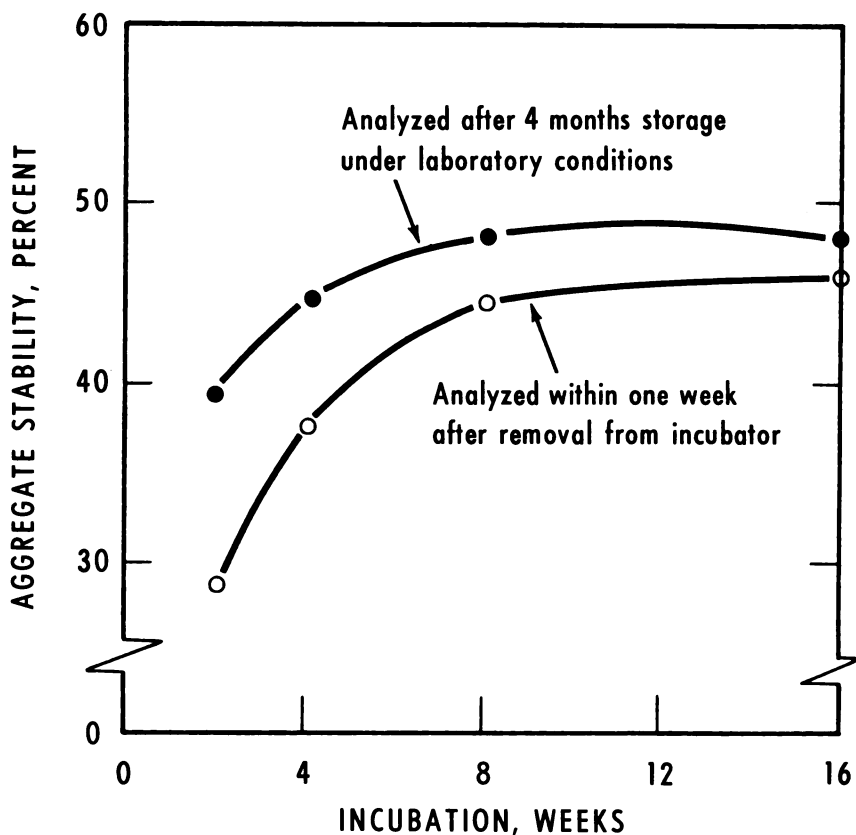


FIGURE 18.—Changes in aggregate stability of Fort Collins clay loam related to period of incubation after incorporation of alfalfa and storage time under laboratory conditions.

Temperature During Storage

Samples of Fort Collins loam and Billings clay loam were air dried at room temperature and 1- to 2-mm. aggregates were sieved from each sample. Portions of the aggregates from each soil were sealed in glass jars at room temperature and at -10° C. for 8 months. The stability of the aggregates was determined by the proposed procedure at the beginning of the storage time and after 2, 4, 6, and 8 months of storage. Stability of the aggregates stored at room temperature increased consistently from an average of 80 percent at the beginning of storage to 88 percent at the end of 8 months. Average stability of the aggregates stored at -10° C. changed by less than 1 percent during the 8-month storage period.

Size of Aggregates in Sample

Bryant, Bendixen, and Slater (4) used aggregates that were 3 to 5 mm. in diameter and achieved very good reproducibility between replicate determinations of aggregate stability. De Boodt, Deleenheer, and Kirkham (7) measured the mean weight diameter of the dry aggregates in the range from 1 to 8 mm. in diameter and then found the change in the mean weight diameter after the sample was sieved in water.

One factor agreed upon by all workers seems to be that a more reproducible measure is gained if the fine material is eliminated from the sample before the analysis. The choice seems to be between a Bryant-type procedure (4), in which the percentage of aggregates of one size range is determined, or a De Boodt-type procedure (7), in which the mean weight diameter of the dry aggregates is measured. Until it can be shown that the more complicated De Boodt-type procedure measures a much more significant parameter, the simpler Bryant-type procedure is suggested.

The following experiment was set up to determine the size range of the aggregates that should make up the initial sample. Billings clay, Billings clay loam, Fort Collins clay, and Rocky Ford loam were used. A sample of each soil was divided into four subsamples and each subsample sieved. From the first subsample, the aggregates in the 3- to 5-mm. range were saved; from the second, the 1- to 2-mm. aggregates were saved; from the third, the 0.25- to 2-mm. aggregates were saved; and from the fourth, all the material smaller than 2 millimeters in diameter was saved. Eight sub-subsamples were taken from each of these size ranges from each of the soils. Four sub-subsamples were vacuum-wetted and four were wetted at atmospheric air pressure. The remainder of the procedure was the same as the procedure for measuring aggregate stability proposed in this bulletin.

A summary of the results is presented in table 8. The average values of aggregate stability (AS) and the average coefficient of variation (CV) of this measurement for four soils are presented for each size of dry aggregates used.

The standard deviations of the aggregate stabilities resulting from the two wetting procedures were not greatly different. The larger average aggregate stability values when the samples are wetted under vacuum make the coefficients of variation much smaller. Vacuum wetting was selected as the best technique on the basis of reasons outlined in a later section ("Wetting Method" under "Wetting the

TABLE 8.—Aggregate stability (AS) and its coefficient of variation (CV) as affected by size of dry aggregates in initial sample¹

Wetting method	Size of dry aggregates in initial sample							
	< 2 mm.		0.25 to 2 mm.		1 to 2 mm.		3 to 5 mm.	
	AS	CV	AS	CV	AS	CV	AS	CV
	Per-cent	Per-cent	Per-cent	Per-cent	Per-cent	Per-cent	Per-cent	Per-cent
Immersion.....	19	32	22	28	23	11	24	8
Vacuum.....	52	10	60	4	64	2	67	3

¹ Values are averages of four samples of each of four soils.

Aggregates"). When vacuum wetting was used, aggregates 1 to 2 mm. in diameter yielded the most reproducible aggregate stability values. Aggregates 3 to 5 mm. in diameter yielded results that were nearly as reproducible.

One additional advantage of using the 1- to 2-mm. aggregates is that sieving soils through 2-mm. sieves is a common practice used by many laboratories in preparing samples for chemical analyses. These samples may then be sieved on a 1-mm. sieve to obtain 1- to 2-mm. aggregates. For these two reasons, the 1- to 2-mm. size range was the one selected for the procedure for determining aggregate stability.

Wetting the Aggregates

Wetting Method

Previous findings.—Yoder (36) discussed the mechanisms involved when aggregates are immersed in water and the aggregates slake. He pointed out that aggregates do not slake as much if they are wetted under vacuum or if they are wetted slowly by capillarity prior to wet sieving.

Robinson and Page (24) discussed the disintegrating forces brought into play when aggregates are immersed in water and air bubbles are entrapped inside the aggregates. Air absorbed on the surface of dry soil particles is replaced by water and adds to the air initially in the pores of the aggregate. These air bubbles are compressed by water pulled into the aggregate by capillarity until the air bubble bursts out of the partially wetted aggregate. In bursting out, the air bubble often disintegrates the major portion of the aggregate. This phenomenon is readily observed.

Panabokke and Quirk (20) pointed out that differential swelling as water moves through the particle to wet it is also a factor in slaking. They presented data to show the effect of initial moisture content on the aggregate stability of soils immersed in water. In general, aggregates that were wetted slowly by capillarity were more stable than those that were wetted quickly.

A study comparing wetting under a vacuum with wetting at atmospheric pressure, as part of an aggregate analysis procedure, was conducted by the Committee on Physical Analysis of the Soil Science

Society of America (van Bavel, 32). It came to the conclusion that vacuum wetting introduced random variation into the results; therefore, the committee advised against the use of vacuum wetting. It pointed out that much of this variation probably stemmed from handling the weakened aggregates when they were wet. In the vacuum-wetting procedure used in the present study, the aggregates were wetted on the sieves and therefore handling was avoided. It is also likely that some of the variation encountered in the aggregate stability of soils when wetted by vacuum in the committee's study was due to wetting the sample under incomplete vacuum. It was assumed that the pressure in the desiccator had reached the vapor pressure of water when some water left in the desiccator began to boil. It is probable that some of the technicians mistook the formation of air bubbles and their escape from the water for the onset of boiling. Therefore, they would have mistakenly assumed that the proper degree of vacuum had been reached and would have wetted the samples when there was appreciable air left in the desiccator and the samples.

It is difficult to distinguish where the escape of air from water stops and true boiling begins in a vacuum. To be sure that the boiling point has been reached, it is suggested that a barometer (6 or 8 cm. high) be kept in the desiccator to indicate the adequately low pressure (1 to 2 cm. Hg) directly.

Supplementary observations.—In the process of wetting samples under vacuum, the authors noticed that air in the incoming water was forming bubbles and escaping from the water under the reduced pressure in the vacuum desiccator. This "bubbling" was particularly violent when the water contacted the soils. Apparently, dry soils help provide the nuclei for air bubbles. When previously de-aerated water was used to wet the samples, these bubbles did not form. Aggregate stability values were generally higher and more reproducible when de-aerated water was used in vacuum wetting.

The method chosen for wetting soil samples should meet the following criteria:

1. It simulates a field phenomenon that is important to crop growth.
2. It permits differences in the aggregate stability of soils to be detected.
3. It yields reproducible results.

Under field conditions, the surface of the soil bears the brunt of the disintegrating forces. Freshly cultivated surfaces are covered with large aggregates and are open to the movement of air and water into the soil. If the soil is subjected to irrigation or to a heavy rainstorm, the surface is wetted quickly; the resulting slaking of the surface aggregates forms a dense, continuous layer at the surface that is recognizable as the surface crust when it dries.

Immersion of aggregates at atmospheric standard pressure (direct immersion wetting) prior to aggregate stability determination involves the same opportunities for slaking which cause (along with raindrop impact forces in the case of rain) the formation of soil crusts under field conditions. The formation of soil crusts is an important factor in seedling emergence, aeration, and water infiltration.

The main portion of the aggregates lies beneath the immediate surface of the soil and is wetted slowly by capillary action. Consequently, these buried aggregates undergo a lesser degree of slaking. An aggre-

gate analysis procedure that involves wetting the aggregates slowly under hydraulic tension would therefore give results more representative of what happens in soil lying beneath the surface. The physical structure of the soil beneath the surface is important in determining the conductivity of the soil to water and air.

Since both these methods—wetting by direct immersion and tension wetting—simulate important field phenomena, it was decided that these methods should be investigated in the laboratory for wetting soil samples for aggregate stability studies.

Results of present studies.—Aggregates are fragile when wet, and any procedure which involves a transfer of wet aggregates from one container to another is not satisfactory. Consequently, it was decided that the aggregates must be wetted in the sieves. Simple lowering of the sieves containing the aggregates into the water at atmospheric pressure accomplished the "wetting by direct immersion." In the case of tension wetting, the sieves containing the aggregates were placed on a mat of asbestos fiber on a tension table.⁷ Some of the asbestos fibers poked up through the holes in the sieve and conducted the water to the dry soil. This was a practical procedure only at tensions equal to or less than 15 millibars.

The tension wetting technique proved to be a time-consuming process. Fresh, fluffy, asbestos fiber surfaces had to be prepared each time. The aggregate stabilities showed a fairly high coefficient of variation. This variation appeared to depend on the degree of contact between the asbestos and the aggregates, which determined the rate of wetting. If the wetting was completed within 1 or 2 minutes, the aggregate stability was usually slightly lower than if wetting took 10 to 15 minutes.

Aggregates were also wetted under a vacuum according to the proposed procedure (immersed in water in a desiccator that had been evacuated). The aggregate stabilities of the tension-wetted and vacuum-wetted samples, determined by the proposed method, were then compared. A strong correlation between the aggregate stability of samples wetted under a tension and samples wetted under vacuum was noted. Since vacuum wetting was easier, quicker, and aggregate stabilities had a lower coefficient of variation and were closely correlated with "tension wet" values, the question arose as to whether vacuum wetting might be used instead of wetting on tension tables. Russell (25) had suggested this possibility.

The following experiment was set up to answer this question and to compare the aggregate stabilities using direct immersion, tension wetting, and vacuum wetting prior to wet sieving the aggregates. Sixteen Western United States soils were selected for this study and four Southeastern United States soils were included for comparison. Three sandy western soils were excluded from the study because immersion at atmospheric pressure caused them to have zero aggregate stability. Apparently, most soils that have an aggregate stability of less than about 30 percent when wetted on tension tables have practically no stability when wetted by immersion at atmospheric pressure. Since statistical analyses of these zero values would have little meaning, they were not included in the study.

⁷ A flat porous surface on which hydraulic tension can be controlled.

Two samples of each soil were wetted by each of the wetting methods. The rest of the aggregate stability analysis procedure was identical to the proposed procedure. The average values of the aggregate stability (*AS*) and its coefficient of variation (*CV*) for the soils wetted by the three methods are presented in table 9.

TABLE 9.—*Aggregate stability (AS) and its coefficient of variation (CV) as affected by wetting method, for 16 Western United States and 4 Southeastern United States soils*

Soil series and type	Wetting method					
	Direct immersion ¹		Tension		Vacuum	
	AS	CV	AS	CV	AS	CV
WESTERN SOILS						
	<i>Per-cent</i>	<i>Per-cent</i>	<i>Per-cent</i>	<i>Per-cent</i>	<i>Per-cent</i>	<i>Per-cent</i>
Fort Collins clay loam ²	82	0	93	0	92	1
Fort Collins clay loam ³	32	10	83	9	85	1
Fort Collins clay loam ⁴	6	10	57	10	54	5
Billings clay loam.....	32	8	83	3	80	3
Billings clay.....	40	6	70	10	70	5
Rocky Ford loam.....	26	6	65	15	58	8
Torrington clay loam.....	47	16	71	10	65	0
Terry silty clay loam.....	31	11	76	4	59	2
Tucumcari sandy loam.....	48	8	61	2	47	5
Weld loam.....	32	0	78	5	69	7
Apishapa silty clay loam.....	45	13	77	10	72	5
San Luis sandy loam.....	25	33	38	16	49	13
Berthoud sandy clay loam.....	37	3	82	3	79	1
Huntley clay.....	64	2	94	1	83	0
Dunlap loam.....	25	2	52	17	54	2
Carrington loam.....	82	1	97	1	96	1
Average.....	41	9	74	8	70	4
SOUTHEASTERN SOILS						
Cecil clay ⁵	91	1	99	0	99	1
Durham sandy clay ⁵	70	1	98	2	99	1
Appling clay ⁵	90	1	98	2	99	1
Greenville loam ⁶	82	0	97	1	98	1
Average.....	83	1	98	1	99	1

¹ At atmospheric pressure.

² Under grass.

³ After 37 years of crop rotation.

⁴ Cropped 37 years; no organic matter returned.

⁵ From North Carolina.

⁶ From Mississippi.

The average coefficient of variation of aggregate stability for samples wetted under vacuum was lower than that of samples wetted under tension. Wetting under tension gave slightly higher average aggregate stability than wetting under vacuum. The correlation coefficient between aggregate stability of samples wetted by tension and

samples wetted under vacuum was 0.91 and might have been higher if the coefficient of variation of samples wetted under tension had been lower.

Since both wetting under tension and wetting under vacuum eliminate trapping of air within the aggregates and its consequent destructive force, it is not too surprising that there is a good correlation between the aggregate stabilities resulting from these wetting methods. Therefore, although vacuum wetting is outwardly quite different from wetting below the surface in the field, it does allow aggregates to become wet without entrapping air, which is the vital factor characteristic of the field phenomena. On the basis of this degree of simulation of the field phenomena, and since the method is more reproducible and less tedious, vacuum wetting was selected rather than tension wetting for the proposed procedure.

Aggregate stability values of the southeastern (humid region) soils show that they are more stable than the western (subhumid, semiarid, and arid region) soils. The more drastic slaking caused by immersion wetting was necessary to show statistically significant differences between the stability of the eastern soils. The immersion wetting procedure was so drastic that an appreciable number of western sandy soils had aggregate stabilities of zero. On this basis, it was decided that while immersion wetting at atmospheric pressure may be the best procedure on southeastern, humid region soils, vacuum wetting allows better differentiation between the stabilities of western soils.

Period of Soaking Prior to Wet Sieving

Russell and Feng (26) found that the aggregate stability of soil was not significantly different whether the soaking periods prior to sieving were 3, 30, or 300 minutes.

This was also found to be the case in the present study when the samples were air dried and did not contain large amounts of sodium ion (fig. 17). When the samples contained appreciable amounts of sodium and were dried at room temperature, there was a tendency for the aggregate stability to decrease if the samples were soaked for longer periods of time. The decreases were small and were not statistically significant at the 95-percent level of probability.

When the soils are dried at room temperature (not oven dried), the soaking time prior to wet sieving can vary from 3 to 30 minutes without causing appreciable changes in the aggregate stability.

Temperature of Water in Which Aggregates are Wetted and Sieved

To determine whether the temperature of the water in which the aggregates were wetted and sieved affected the aggregate stability, samples of aggregates from nine soils containing more than 2 percent organic matter were wetted and sieved in water at 15°, 20°, 25°, and 30° C. The rest of the procedure was identical to the proposed procedure. The average aggregate stability of the nine soils is plotted as a function of the temperature of the water as the top curve of figure 19.

There was a slight tendency for the aggregate stability to be lower when the water was at 30° than when the water was at 20° C. Eighteen samples from other soils with organic matter contents of less than 2 percent were selected and their aggregate stabilities determined in water at 20° and 30°. The average aggregate stabilities of

these 18 samples are presented as the bottom curve of figure 19. The trend toward a slightly lower aggregate stability of samples wetted in water at 30° as compared to samples wetted in water at 20° was noted again. The tendency was not significant at the 95-percent probability level in either case. However, it was significant at the 80-percent probability level in each case. This is adequate reason to suggest that the aggregate stability be run in water at some standard temperature. It is suggested that water used to wet-sieve the sample be between 22° and 25° C.

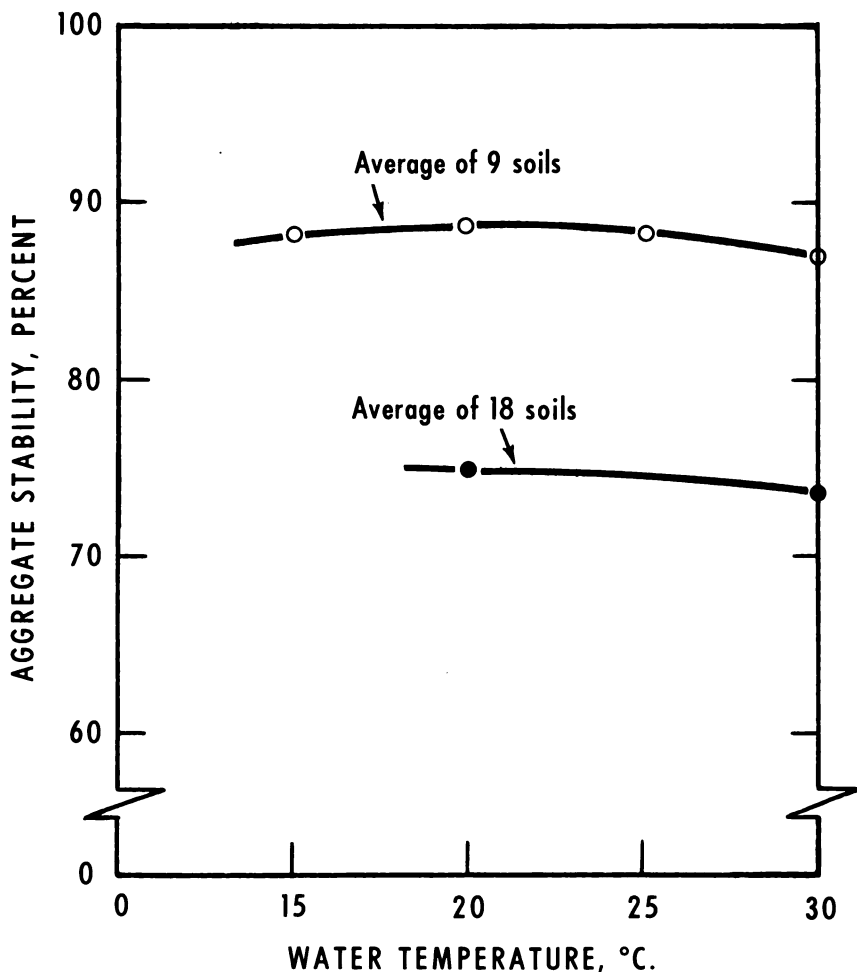


FIGURE 19.—Aggregate stability as affected by temperature of the water in which the aggregates were wetted and sieved.

Wet Sieving Factors

Sieve Size

A certain degree of arbitrary selection was involved in the selection of the size of aggregates that were to be retained on the sieve and expressed as "stable" aggregates. If a soil were composed entirely of stable aggregates of the smallest size retained on a sieve with openings 0.25 mm. square (60 mesh), it would have an adequately high infiltration capacity. After this soil was saturated, air would begin to enter it when the tension in the water reached 40 to 80 millibars.

These same statements would be approximately true of a soil containing larger aggregates if large pores were filled with these 0.25-mm. aggregates. While the aeration of such a soil would be severely limited if there were a water table 60 cm. below the surface, it would not be a poor soil under most conditions. Consequently, it is suggested that screen with openings 0.25 mm. square be used in the sieves on which the water-stable aggregates are to be retained.

Sample Size

The choice of sample size was also somewhat arbitrary. It depends, to some extent, on the size of the dry aggregates that are used. For instance, a dry aggregate with a diameter of 5 mm. may weigh as much as 0.13 g., whereas a dry aggregate with a diameter of 2 mm. will generally weigh less than 0.01 g. If one wishes to avoid splitting or selecting aggregates to achieve exact weights and also wishes to achieve an accuracy of 1 part in 400 in the weight of the sample, 50 g. of aggregates with a maximum diameter of 0.5 cm. would be needed. Four grams of aggregates with a maximum diameter of 2 mm. would be enough to satisfy these requirements. Since aggregates with diameters between 1 and 2 mm. had been selected and since common torsion balances weigh to an accuracy of about 0.01 g., 4-g. samples were suggested. This is not, however, very critical. Three- or five-gram samples work practically as well.

Stroke Length and Frequency

Yoder's apparatus (36) moved sieves up and down in the water 30 times per minute through a distance of 3.18 cm. at each stroke. Many of the machines used in wet sieving have been built to duplicate Yoder's machine. Immediate availability of slightly different equipment that could be converted to wet sieving has led other investigators to use somewhat different stroke lengths and frequencies.

A good combination of stroke length and frequency should: (1) cause complete separation of aggregates from material smaller than 60 mesh, (2) not cause excessive abrasion and mechanical breakdown, and (3) yield reproducible results.

The following experiment was designed to determine the stroke length and frequency best suited for the proposed procedure. Air-dried samples of Billings clay, Billings clay loam, Fort Collins clay loam, and Rocky Ford loam were used. Aggregates 1 to 2 mm. in size were sieved out, wetted by immersion in water at 23° C. for 5 minutes, and sieved for 5 minutes at the lengths and frequencies of stroke indicated in table 10.

TABLE 10.—Effect of length and frequency of stroke used in wet sieving on the aggregate stability (AS) and the coefficient of variation (CV) of this measurement¹

Stroke length of—																			
Stroke frequency		0.4 mm.		0.8 mm.		1.6 mm.		3.2 mm.		6.4 mm.		12.7 mm.		19.0 mm.		25.4 mm.		38.1 mm.	
	AS	CV	AS	CV	AS	CV	AS	CV	AS	CV	AS	CV	AS	CV	AS	CV	AS	CV	
<i>Cycles per minute</i>	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.
	21	—	—	—	—	—	—	—	—	(²)	(²)	(²)	5	32	16	28	16	22	15
	42	—	—	—	—	—	—	—	—	(²)	(²)	34	10	29	9	—	—	—	—
	75	—	—	—	—	—	—	—	—	(²)	(²)	31	—	—	—	—	—	—	—
	106	—	—	—	—	—	—	—	—	(²)	(²)	30	14	—	—	—	—	—	—
212	—	—	—	—	—	—	—	—	10	9	—	—	—	—	—	—	—	—	—
300	(²)	(²)	14	11	(²)	8	22	20	5	14	—	—	—	—	—	—	—	—	—

10 samples of each of 4 soils used in each treatment.

² In samples of each of the four above-mentioned compositions, there was insufficient separation and the 60-mesh dispersed particles were not sieved out of the undispersed large aggregates.

Failures to obtain adequate separation of aggregates and finer slaked material were easily observed. Sieving procedures that yielded the highest average stability were assumed to cause the least abrasive action. The average values of aggregate stability (*AS*) and coefficient of variation (*CV*) of aggregate stability of the four soils at each stroke length are presented in table 10.

At high frequencies, there seemed to be a rather narrow range of stroke lengths within which there was either a violent mechanical disruption of the aggregates or insufficient sieving action to remove the fine particles from the sample. A combination of frequency and length of stroke of 42 cycles per minute (c.p.m.) with a displacement of 12.7 mm. up and down was just sufficient speed and distance to barely lift the largest aggregates free of the brass screen when the sieves were on the downward portion of the cycle.

If different sized aggregates or if different mesh screen had been used, this optimum stroke length and frequency would probably have been different. When 1- to 2-mm. aggregates and a 0.25-mm. sieve screen are used, the optimum length of stroke and frequency appear to be 12.7 mm. and 42 c.p.m., respectively.

Length of Sieving Time

Russell and Feng (26) pointed out that "initial stability" and "rate of disintegration" with continued sieving were both important parameters in characterizing the water stability of soil aggregates. There is a fairly good, though not complete, correlation between these parameters. Bryant, Bendixen, and Slater (4) felt that initial stabilities were most important in estimating the ability of the soil to resist slumping under field conditions of wetting and drying.

It had been decided that the study of aggregate stability measurements should be limited to evaluating the stability of aggregates when wet with water. This type of stability is of major importance in determining the type and amount of pore space in soil after cultivation and rewetting. Resistance of aggregates to disintegration as a result of continued abrasion is an important factor in erosion control.

Since the objective was to evaluate the stability of soils when wet with water, it was necessary to determine the optimum length of wet sieving time for the proposed procedure for measuring aggregate stability. An experiment was performed to determine the length of sieving time that would adequately separate the fines from the aggregates of all soils. Figure 20 shows typical curves relating the portion of the sample remaining on the sieve to the length of sieving time.

On most soils, fines had gone through the sieve and only aggregates were left at the end of 2 minutes. However, with soils having very low aggregate stabilities, fines persisted in the sieve for over 3 minutes. Five minutes of sieving was adequate to move essentially all the fines through the screen for all soils studied. On this basis, 5 minutes was adopted as the standard sieving period for the proposed measurement procedure.

Correcting for Sand

In estimating aggregate stability, large-size sand must be differentiated from the aggregates. Better correlations between aggregate stability and clay, organic matter, and free iron oxides were found and lower standard deviations were encountered when the sand larger

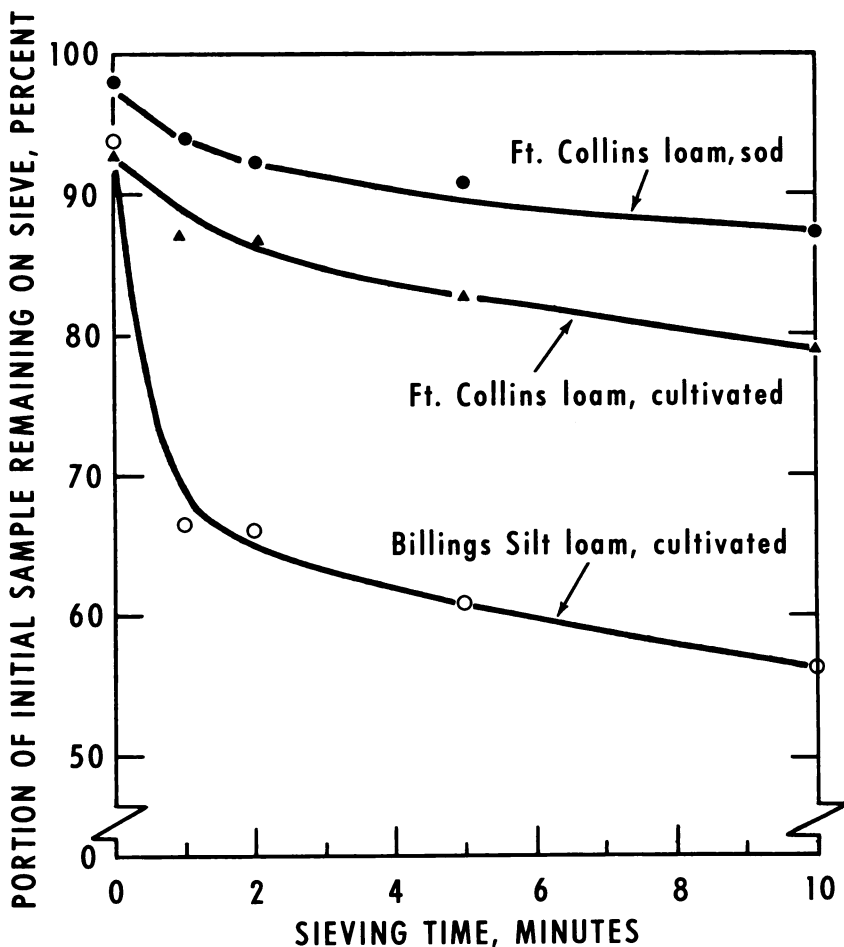


FIGURE 20.—Effect of wet sieving time on the portion of the initial sample remaining on the sieve.

than 0.25 mm. was not considered as aggregates. The standard procedure was to calculate aggregate stability as:

$$\text{Pct. } AS = \frac{100 (\text{wt. of stable aggregates and sand}) - (\text{wt. of sand})}{(\text{weight of sample}) - (\text{weight of sand})} [1]$$

Since only those sand particles larger than 0.25 mm. were retained as individual particles on the sieve, "sand" in this equation refers to sand larger than 0.25 mm.

The procedure for determining the weight of the sand involved reusing the material left on the sieves after wet sieving. After the dry weight of this material had been determined, it was placed back in the sieve and sieved in calgon solution. Calgon, a material approaching sodium metaphosphate in composition, is effective in replacing Ca^{++} by Na^{+} in Ca^{++} -saturated soils. The majority of the soils encountered in

this study dispersed completely when treated in this manner, and after they were sieved 5 minutes in this calgon solution only sand (larger than 0.25 mm.) remained in the sieves.

About a third of the soils were not completely dispersed by this treatment. The majority of these soils could be broken down with a rubber-tipped rod. Aggregates resisting this treatment were considered concretions and treated in the manner described immediately after the proposed procedure.

Precautions and Accuracy

A technician can determine the aggregate stabilities of about 40 samples a day, using the proposed method. However, it is suggested that duplicate analyses be run on different days on each sample. Any balance that will weigh to 0.01 g. is satisfactory for making the weighings.

A small barometer should be kept in the desiccators in which the samples are wetted to make sure that a pressure of only 1 or 2 cm. of Hg remains in the desiccator when wetting takes place. If a pressure of as much as 5 or 10 cm. of Hg remains in the desiccator, appreciable reductions in aggregate stability will occur.

Standard deviations of as low as 1.4 percent are possible if the proposed measurement procedure is followed carefully.

Measurement Procedures for the Other Variables

Clay Content

The Bouyoucos hydrometer method was used to estimate the percentage of <0.002 mm. clay in the sample. Large sand grains (>0.25 mm.) were not considered aggregates. Consequently, it was proper that they not be considered as part of the original aggregate sample. Thus, the initial aggregate sample weight used as the denominator for the percentage of aggregate stability calculation was the weight of the initial aggregate sample minus the weight of this large size sand. If the weight of the large sand had been included in the denominator, sandy soils would all appear as being poorly aggregated. The amounts of both clay and stable aggregates are thus expressed on the basis of their weights as a percentage of weight of the soil particles less than 0.25 mm. in diameter in the sample.

Organic Matter

Organic carbon was determined by the chromic acid technique of Walkley and Black (33). The organic carbon percentage was then multiplied by 1.7 to give the values designated as organic matter percentage.

Free Iron Oxide

A procedure developed by V. J. Kilmer (9) was used to determine free iron oxide.

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Free Aluminum Oxide

The following procedure for determining free aluminum oxide (Al_2O_3) was suggested by V. J. Kilmer. Approximately 6 g. of soil is heated in a muffle furnace at 800°C . for 30 minutes, cooled in a desiccator, and weighed. The sample is then transferred to a 125-ml. Erlenmeyer flask and 20 ml. of sodium alizarin sulfonate solution (0.5 percent in 80-percent alcohol saturated with boric acid) is added. The flask is covered with a funnel and heated at 90° for 20 minutes. After being allowed to cool, the supernatant liquid is filtered through a Gooch crucible fitted with a disk of filter paper. Twenty-five ml. of boric alcohol (saturated solution in 80-percent alcohol) is then added to the flask, which is heated again at 90° for 20 minutes. The entire sample is poured onto a Gooch filter and washed with boiling water until the washings are colorless. One hundred grams of 5-percent H_2SO_4 is heated to boiling and portions of it are used to leach the sample. The leachate is transferred to a 250-ml. beaker and heated to boiling. A solution containing 0.02 N KMnO_4 is added to the beaker from a burette with care, to avoid more than a 0.5 ml. excess at any time. To insure that the reaction is complete, a slight excess of KMnO_4 is added and boiled for 10 to 20 seconds. If the pink color disappears, additional KMnO_4 is added and boiled until the KMnO_4 is no longer reduced. A slight excess of 0.02 N $\text{Na}_2\text{C}_2\text{O}_4$ is added and titrated to the usual endpoint. One ml. of KMnO_4 is equal to 6 mg. of Al_2O_3 .

Calcium and Magnesium Carbonates

Calcium and magnesium carbonates were determined by measuring the volume of CO_2 evolved when the soils were treated with 6 N HCl . This is essentially the method proposed by Williams (35).

Exchangeable Sodium

Saturation extracts taken from the soils were analyzed for Na^+ with a flame photometer and for Mg^{++} plus Ca^{++} by titration with versenate. Exchangeable sodium percentages were then estimated from the nomogram (fig. 22) of USDA Handbook 60 (31).

Nitrogen

Nitrogen was determined by a standard Kjeldahl analysis.

Weather

Mean annual temperature and precipitation data were obtained from the weather recording station nearest the location from which the sample was obtained.

