SOIL AGGREGATE STABILITY AS INFLUENCED BY TIME AND WATER CONTENT

by

JEFFREY BRYAN LAYTON

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Approved by:

Co-major Professor

Co-major Professor

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INTRODUCTION

The status of surface soil aggregates is of extreme importance in consideration of soil erodibility by wind. Abrasion resistance (dry aggregate stability), resistance to destruction when wetted (wet aggregate stability), and size distribution all influence soil wind erodibility. Cohesive forces bonding soil particles into aggregates determines abrasion resistance. Abrasion breaks down larger nonerodible soil fractions into smaller erodible particles. This fragmentation intensifies wind erosion. Cohesive forces counteract abrasive forces and determine the degree of aggregate destruction. Cohesive forces also determine the resistance to disruption when soil is wetted by irrigation or rainfall. This aggregate disruption on wetting leads to crust development, altering soil erodibility (Chepil, 1958). A crusted surface allows higher wind velocities at the soil surface because of its reduced roughness. Counteracting this effect, consolidation of highly erodible particles decreases erodibility. In addition to aggregate stability, aggregate size distribution is important in determining susceptibility to wind erosion . Particles less than 0.84 mm diam are generally considered erodible while those larger than this size are nonerodible (Chepil, 1943).

The purpose of this experiment was to determine if there are changes in aggregate properties as a result of extended dry periods or cyclical wetting and drying. This will provide useful information for modelling soil surface conditions as influenced by rainfall patterns and irrigation.

There are three parts to this experiment. The first part examines the influence of cyclical wetting and drying and extended drying on aggregate stability and some other soil physical properties. The second part examines the changes in dry aggregate stability with storage time. The third part studies the influence of incubating aggregates at different water contents over time.

LITERATURE REVIEW

Wetting and drying cycles affect aggregate stability and aggregate size distribution of soil. Stresses develop due to changes in the thickness of water films as the soil is wetted and subsequently dried. Mechanical stresses created by cyclical wetting and drying generate planes of weakness within aggregates, creating the initial faces of new aggregates (Towner and Childs, 1972). These stresses lead to aggregate breakdown and reduce aggregate stability. Sillanpaa and Webber (1961) showed that stability changes of aggregates exposed to wetting and drying cycles depended on size.

Cyclical wetting and drying has been shown to increase microbial activity (Agarwal et al., 1971), which increases aggregation due to formation of organic bonding agents. Willis (1955) showed decreased wet aggregate stability as a result of wetting and drying cycles. A single wetting and drying cycle was shown to decrease wet aggregate stability in another experiment (Rovira and Greacon, 1958), which is supported by the results of Soulides and Allison (1961). Dexter et al. (1984) showed that wetting resulted in mellowing of artificial aggregates, and that the mellowing effect of multiple wetting and drying cycles is cumulative. In non-saturated soil, cyclical wetting and drying first increased wet aggregate stability of aggregates disturbed by tillage. Furthur wetting and drying decreased water stability. For undisturbed aggregates, wet aggregate stability decreased continuously with increased numbers of wetting and drying cycles (Utomo and Dexter, 1982).

Extended dryness causes changes in the aggregate status of soil. These effects are the result of biological and physical mechanisms. Harris et al. (1966) concluded that although the exact mechanisms involved in increased aggregate stability with excessive drying are unknown, it is possibly a result of slowly reversible and irreversible dehydration of organic and inorganic colloids. Such a decrease in hydrophilicity would strengthen aggregate bonds against the disruptive forces of water. Soulides and Allison (1961) showed that prolonged drying increased the rate of organic matter decomposition and that multiple dryings had a cumulative effect. They also concluded that over long periods this decomposition improved aggregation. Tisdall et al. (1978) determined that severe restriction of microbial activity by intense drying increases the effect of stability loss caused by exposure of soil by physical disruption. In a study of chemical changes that occured during dry storage of soil samples, Bartlett and James (1980) concluded that alteration of surface properties by drying leads to the water-solubilization of organic matter and that properties of dry, stored soil continue to change with time. Kemper and Rosenau (1984) determined that cohesion of dry soil increased with time. They indicated that diffusion of bonding components to particle-to-particle contacts continues even when a single layer of water molecules is present on particle surfaces. The rates involved in bond strengthening were dependent upon the amount of water present. The results of these research efforts indicate that even when extremely low quantities of water are present in the soil, changes are occuring that have an effect on soil aggregation.

Differences in water content influence aggregation and aggregate properties. As the upper layer is wetted and dried, the surface will dry faster than zones below. This difference in water content could then cause differences in aggregation during wetting and drying cycles. Using artificial aggregates, Blake and Gilman (1970) showed that cohesion develops at a slower rate when their soils contained less water. Additionally, increased water stability of these newly formed aggregates was independent of the influence of organic matter. They did not, however, include a determination of how stability differences develop as a function of water content. Age hardening, in which moist aggregates increase in strength with time, was still observed after sterilization and removal of organic matter (Utomo and Dexter, 1981). Chepil (1954) determined mechanical stability as a function of depth to six inches using repeated rotary sieving. Although his results show an increase in stability with depth, the conclusions were not statistically significant. This effect would be significant after tillage operations bring unexposed soil to the surface.

Extended dryness and cyclical wetting and drying influence aggregate properties. Dry aggregate stability, a measure of cohesional resistance to aggregate abrasion, is influenced by these processes. This influence on aggregate stability and size distribution will influence soil wind erodibility.

MATERIALS AND METHODS

The soil used in this experiment was a Keith silt loam (fine-silty, mixed, mesic Aridic Argiustoll) taken from the surface (0-100 mm depth) of a cultivated field at the Colby Agricultural Experiment Station at Colby, Kansas in September 1985. Some properties of the Keith silt loam are shown in Table 1. Particle size distribution was determined using standard pipette procedures (Day,1965).

PART 1

The soil was air-dried and approximately 12 kg was placed into each of 15 plastic containers. These containers of soil were then exposed to three water treatments. Five of the containers remained air-dry throughout the experiment. The other two groups were wetted with simulated rainfall until the gravimetric water content was one-half field capacity and field capacity values. Field capacity was defined to be the gravimetric water content at a soil matric potential of -33 kPa using pressure cell apparatus (Klute, 1965). The water was applied at an intensity of 2.5 cm hr^{-1} . After applying water, the soil was dried in a greenhouse for two weeks. At the end of each drying period the soil containers were weighed, and enough water was applied to bring water content up to the appropriate values. This cycle was repeated five times. At the conclusion, the soil in each container was split into top and bottom halves, and placed in pans to air-dry .

After drying, the following physical measurements were made. Mechanical stabilities were determined by repeated

Table 1. Selected properties of Keith silt loam.

Particle size distribution			Organic Matter	Bulk Density	Soil Erodibility Index
Sand	Silt	Clay			
---------------%			----------------	$Mg\ m^{-3}$	$Mg\ ha^{-1}$
16.5	70.1	13.4	1.5	0.97	65

Table 1. (continued)

Soluble salts	pH	Ca^{2+}	Mg^{2+}	Na^{+}
$dS\ m^{-1}$		----------	$mg\ kg^{-1}$	---------
0.60	7.8	2943	486	25

sieving using the method of Chepil (1962) and the improved rotary sieve (Lyles et al.,1970). Mechanical stability was determined by resieving aggregates > 0.84 mm one time. Results are expressed as the fraction still > 0.84 mm after the second sieving. The data from the first pass through the rotary sieve was used to determine geometric mean diameter (GMD) for aggregate size distribution (Gardner, 1956; Kemper and Chepil, 1965). Additionally, data from the first sieving were used to calculate the percentage aggregates larger than 0.84 mm diam. This value is used to determine soil erodibility index, I , in the wind erosion equation (Woodruff and Siddoway, 1965). After the final sieving, aggregates 12.5- to 17.0-mm and 0.84- to 2.0-mm diam were removed for testing.

The 0.84- to 2.0-mm diam aggregates were used to determine wet aggregate stability using the method of Kemper (1965) after wetting the aggregates under vacuum. Aggregate densities were determined by coating the 12.5- to 17.0-mm aggregates with paraffin and utilizing Archimedes Principle (Blake, 1965).

The 12.5- to 17.0-mm aggregates were used to estimate crushing energy and rupture stress values as described by Skidmore and Powers (1982) with the Soil-Aggregate Crushing-Energy Meter (SACEM) of Boyd et al. (1983). This device diametrically loads an aggregate between parallel plates until it is crushed to a chosen endpoint. The device measures force applied and distance travelled during crushing, then integrates to determine the amount of energy applied to the aggregate. Crushing energy is defined as the amount of energy needed to crush an aggregate of unit mass between parallel plates until all remaining coherent particles pass through a 6.35 mm sieve. By knowing the aggregate mass, crushing energy (J kg^{-1}) can be calculated. The load at the initial failure of the aggregate was also recorded, and was used to calculate rupture stress. Eight aggregates from each replication were crushed to determine aggregate resistance to crushing.

The experiment design was a split plot. There were 15 whole plots (soil containers), and the whole plot factor was the amount of applied water. The three amounts of water were replicated five times. The subplot factor was depth within soil containers.

PART 2

Aggregates from the top half of the containers were tested again after ten weeks of storage in the second part of this experiment. The aggregates were stored air-dry in sealed containers. Eight aggregates were crushed from each container, and the mean was used in statistical analysis. Time and applied water were the main treatment effects .

PART 3

This part of the experiment examined the effects of water content and time on aggregate crushing energy. Air-dry aggregates 12.5- to 17.0-mm diam were separated from the bulk soil by sieving. These aggregates were then sorted to obtain the most spherical, and to remove aggregates that had visible signs of tillage shearing or compression forces. Ten of these aggregates were then placed into each of 60 containers. Each container was randomly assigned to 12 water content-time treatment combinations. There were five replications of each combination.

The three aggregate water contents were 0.035, 0.077, and 0.285 kg kg^{-1}. The 0.035 and 0.077 kg kg^{-1} contents were obtained by placing the aggregates in air-dry and water-vapor saturated environments, respectively. The high moisture content was applied by placing the aggregates on filter paper lying on a bed of fine sand, and slowly wetting from beneath. After applying each of these treatments, one aggregate was removed from each container to determine water content. The above water contents represent the mean of twenty aggregates. The remaining nine aggregates, sealed in air-tight containers, were then stored in a constant temperature room at $20^{o}C$.

One, two, three, and four weeks later the containers were unsealed, and one aggregate was removed to determine water content. The remaining aggregates were dried at $32^{o}C$ for 24 h before testing. Crushing energy was measured using the SACEM. The mean of eight aggregates was used in the statistical analysis. Time and water content were the main effect variables.

All analysis of variance (ANOVA) calculations were performed by the Statistical Analysis System (SAS Institute, 1979). Main effects and interaction were tested for significance using F tests. If the F test for interaction was not significant, least significant difference (LSD) was calculated to compare main effect means. If the interaction term was significant , LSD was used to compare main effect means within fixed levels of the other main effect. Regression analysis was used in part 3 to model the response of crushing energy to water content and time.

RESULTS

Examination of data distributions revealed that crushing energy and rupture stress were not normally distributed. The data was normalized by natural log transformation. All results and statistical analysis concerning these variables will be in natural log form.

PART 1

Aggregate crushing energy and rupture stress values (Table 2) were most influenced by amount of water received by the soil. Depth in the container did not influence crushing energy or rupture stress. The ANOVA for both of these parameters showed a significant interaction between water and depth factors. In the low water treatment, aggregates from the top half of the containers were more resistant to crushing than those from the bottom. Opposite results were obtained with depth in the high water treatment.

Mechanical stability (Table 2) was influenced by both amount of water received and depth in the containers. The ANOVA F test for interaction between water and depth was significant. Both levels of applied water decreased mechanical stability in the top portion of the containers. In the bottom half of the containers, the low water treatment decreased and the high water treatment increased mechanical stability.

Aggregates from the top half of the containers were more water-stable than those from the bottom. Wet aggregate stabilities, expressed as the fraction of aggregates remaining on the sieve after sieving in water, were 0.57 and

Table 2. Crushing energy, rupture stress, and mechanical stability as influenced by amount of applied water and depth in container.

Water level##	Crushing Energy	Rupture Stress	Mechanical Stability
	$\ln(J\ kg^{-1})$	$\ln(kPa)$	$kg\ kg^{-1}$
		TOP	
Dry (0.04)	3.69	4.68	0.86
Low (0.14)	3.59	4.79	0.81
High (0.28)	2.53	3.81	0.79
		BOTTOM	
Dry (0.04)	3.49	4.77	0.85
Low (0.14)	3.21	4.47	0.80
High (0.28)	3.02	4.17	0.90
$LSD_{0.05}$	0.35	0.27	0.03

Numbers in parentheses refer to gravimetric water content ($kg\ kg^{-1}$) immediately after rainfall treatment.

Table 3. Aggregate water stability, density, and size distribution as influenced by amount of applied water.

Water level##	Aggregate Density	Wet Aggregate Stability	GMD	Sample > 0.84 mm
	$Mg\ m^{-3}$	$kg\ kg^{-1}$	mm	$kg\ kg^{-1}$
Dry (0.04)	1.47	0.62	1.2	0.49
Low (0.14)	1.48	0.54	1.8	0.58
High (0.28)	1.36	0.48	12.5	0.82
$LSD_{0.05}$	0.06	0.05	1.3	0.03

Numbers in parentheses refer to gravimetric water content ($kg\ kg^{-1}$) immediately after rainfall treatment.

0.53 kg kg^{-1} for the top and bottom halves, respectively. Wet aggregate stability was the only property influenced by depth when interaction was not present.

There were significant differences in main effect means for several of the measured properties (Table 3). Aggregates from all water treatments were statistically different from each other in terms of wet stability. Aggregates from the dry treatment were most resistant to slaking and disruption, and the high water treatment was least resistant. The density of aggregates from the high water treatment was lower than aggregates from the other treatments. The size distribution parameters, GMD and fraction of aggregates > 0.84 mm, were significantly different across water main effect means. The high water treatment had many more large aggregates than the other treatments. Geometric mean diameter was similar for the dry and low water treatments, and was much larger for the high water treatment. Analysis of the fraction > 0.84 mm also show increased aggregate size distribution with increased amount of water. The means from all three treatments were statistically different.

PART 2

The ANOVA showed that there was no interaction between time and water treatment, and that water treatment did and time did not influence crushing energy. The changes in crushing energy due to cyclical wetting and drying were still evident ten weeks later. Dry storage of aggregates (short term), does not appreciably change crushing energy.

PART 3

The F tests for main effects indicated that water decreased and time increased crushing energy with no interaction. Air-dried aggregates required similar amounts of energy to crush as aggregates incubated at 0.077 kg kg^{-1} water content. The wettest treatment had the lowest crushing energy (Table 4).

Length of incubation also influenced crushing energy (Table 5). Comparisons using LSD indicate that aggregates crushed after one week of incubation exhibited lower resistance to crushing. Aggregates incubated two, three, and four weeks were more resistant to crushing, and were statistically similar.

The regression model that best fits the response of crushing energy to time and water content is

$$\ln(CE) = 3.8 - 6.4\ W + 11.7\ W^2 + 0.1\ T \qquad r^2 = 0.57$$

where W is gravimetric water content (kg kg^{-1}), T is time in weeks, and CE is crushing energy (J kg^{-1}). By ignoring time, a quadratic function describes the influence of water content on crushing energy.

$$\ln(CE) = 3.9 - 6.7\ W + 12.4\ W^2 \qquad r^2 = 0.54$$

As aggregate water content during incubation increases, crushing energy decreases to a minimum and then increases as water content continues to increase. This minimum occurs at a gravimetric water content of 0.3 kg kg^{-1}, which is approximately the water content at a soil matric potential of -33 kPa. For the purposes of this experiment, this value was assumed to be equal to field capacity. Aggregates incubated at matric potentials greater than -33 kPa increase in resistance to crushing.

Table 4. Crushing energy as influenced by aggregate water content during incubation.

Aggregate Water Content	Crushing Energy
kg kg^{-1}	ln(J kg^{-1})
0.035	3.67
0.077	3.59
0.285	3.10
$LSD_{0.05}$	0.14

Table 5. Crushing energy as influenced by time of incubation for all water contents.

Incubation Period	Crushing Energy
Weeks	$\ln(J\ kg^{-1})$
1	3.29
2	3.53
3	3.48
4	3.51
$LSD_{0.05}$	0.17

DISCUSSION

Cyclical wetting and drying decreased aggregate resistance to crushing. The degree of aggregate weakening was a function of the amount of water the soil sorbed upon wetting. Only soil receiving the higher amount of simulated rainfall had ponded water on the surface toward the end of the application period. The steepness of the wetting fronts passing through the soil, and the associated destructive effects on aggregates, was greater in the treatment receiving the most water.

As soil aggregates are wetted and dried, the change in thickness of the advancing and receding water films creates stresses, resulting in microcracks (Towner and Childs, 1972). Tensile strength of wetted and re-dried aggregates decreased, and was progressively reduced by increased numbers of wetting and drying cycles (Dexter et al. 1984). By drying the aggregates at different rates, the decrease in tensile strength was shown to be the result of the wetting and not the drying stage. Mellowing ratio was defined as the ratio of tensile strength between wetted and control aggregates. This ratio increased linearly with increasing matric potential of the water source, up to a matric potential (critical mellowing potential) where the mellowing ratio equaled one. A mellowing ratio of zero occured at a lower matric potential (critical slaking potential). The region between these two matric potentials was called the region of mellowing. The potential of the water source used to wet the aggregates for the incubation part of the present experiment was not measured, but the free water surface was approximately five centimeters below the surface of the sand bed. According to Dexter's concept this matric potential falls in the region of mellowing.

Weakening of aggregates could also partially be due to reorientation of particle-to-particle contacts into a less oriented, weaker structure by cyclical wetting and drying. This effect is evidenced by the lower densities of aggregates from the high water treatment. Voids and microcracks that would exist in such a less dense structure would partially account for lower crushing energy values.

Bonding agents may also become water-soluble during the drying phase of the cycle (Bartlett and James, 1980), and then lose bonding effectiveness upon rewetting. Dehydration of aggregating cements increases stability of soil aggregates (Harris, et al., 1966). Aggregates from the low rainfall treatment were more resistant to crushing than those from the high water treatment, and less resistant than aggregates that remain dry. Aggregate bonds may have been weakened by hydration and subsequent dehydration of bonding agents. The lack of repeated hydration and dehydration may explain why the dry treatment had the greatest crushing energy.

Aggregates incubated at water contents greater than 0.3 kg kg^{-1} were more resistant to crushing than aggregates incubated at slightly lower water contents. This relates to the observation from part 1 that, in the high water treatment, aggregates from the bottom of the containers were more resistant to crushing than those from the top. Apparently, at the very highest water contents, some of the weakening effects are reversed and there is a slight increase in strength. This could be due to slaked soil material reforming into a more crush-resistant mass. The soil in the containers may have been wet enough over a long enough period to allow soil particles to become oriented into a more organized structure. This more organized structure would be more resistant to crushing. Consideration was given to the idea that pressure from overlying soil in the containers had caused this slight increase in aggregate strength. Results from part 3, where aggregates were incubated without pressure, do not support this idea.

Mechanical stability decreased following application of simulated rainfall. The exception was an increase for the soil in the bottom of the high water treatment containers. As the water passed through the soil, aggregate slaking and disruption occured. As the soil dries, this slaked material forms new and larger aggregates. This effect is apparent on examination of the aggregate size distribution parameters. The related changes in mechanical stability indicate that while larger aggregates are formed in the soil receiving simulated rainfall, they were less resistant to sieving abrasion than the dry treatment. The exception was the soil in the bottom of the high rainfall treatment containers, where the newly-formed aggregates were more resistant. This would indicate that under high moisture conditions, possibly in conjunction with pressure from overlying soil, aggregates form that are more resistant to sieving breakdown than aggregates that remain dry. When lower moisture conditions are present, the newly formed aggregates are less resistant than aggregates that remain dry.

Crushing energy and mechanical stability measure different aspects of aggregate stability. Crushing energy is the energy needed to break an aggregate into pieces smaller than a given size. It is a measure of the internal forces binding an aggregate together along the rupture planes where the aggregate fails under loading. Crushing energy measures the changes in aggregate structure caused by the physical stresses associated with wetting and drying, in addition to physical and chemical bonding.

Mechanical stability measures the tendency of soil aggregates to lose soil particles from their outer surfaces when subjected to mechanical abrasion (i.e., rotary sieving). During rotary sieving, aggregates are abraded by contact with other aggregates and internal sieve surfaces. This technique also measures the tendency of aggregates to fracture into smaller pieces, but the forces involved are not as intense as crushing.

The fraction of aggregates > 0.84 mm increased as the amount of water applied increased. This would cause the assigned values for soil erodibility index, I, used in the wind erosion equation, to decrease. Wetting soil forms more and larger, wind-resistant aggregates, which in turn decreases wind erodibility.

Wet aggregate stability decreased with increased exposure to water and cyclical wetting and drying. These results agree with the findings of other researchers investigating this phenomenon (Sillanpaa and Webber, 1961; Willis, 1955; Rovira and Greacon, 1958; Soulides and Allison, 1961; Utomo and Dexter, 1982). This effect could be due to microcracking as water recedes and advances, diffusion of bonding components away from contact points, or water-solublization of bonding agents.

Length of incubation influenced crushing energy. This increase in crushing energy with time indicates that age hardening of the aggregates occured (Utomo and Dexter, 1981). They showed that rates at which soils harden are greatest at intermediate water contents. These water contents correspond to those used in the high water treatment in part 3 of the present experiment. In contrast to increased crushing energy of moist aggregates with incubation time, aggregates stored dry in part 2 did not exhibit age hardening. Age hardening is a process by which particle-to-particle bonds are strengthened as moist soil aggregates age. The phenomena of age hardening may be due to the formation of cementing bonds with time. Using artificial aggregates, Blake and Gilman (1970) showed that cohesion develops at a rate dependent on the amount of water present. Kemper and Rosenau (1984) determined that cohesion of dry soil, as measured by wet sieving and modulus of rupture techniques, increased with time. Diffusion of slightly soluble solutes to point-to-point contacts,and subsequent precipitation at these points, was a possible explanation for this increase in cohesion. While this mechanism may also have been active in part one of this experiment, the increases in cohesion did not counteract the processes that initially reduced crushing energy.

The purpose of this experiment was to determine what changes occur in soil aggregation due to cyclical wetting and drying and extended drying. Development of models to predict aggregate properties at the soil surface, and how they change between wind erosion events as a function of climate, would assist wind erosion prediction. The results of this experiment indicate that the influence of water on soil aggregation should be considered. Extended dryness results in aggregates more resistant to crushing, disruption by water, and breakdown of aggregates during rotary sieving, which all decrease their erodibility. Aggregates under dry conditions would be more resistant to abrasion by blowing soil particles. When these aggregates are disrupted by water, the decrease in surface roughness is not as great as for aggregates with lower wet aggregate stability. This effect translates to lower wind speeds at the immediate surface, which decreases erosion. These effects, however, may not be as important as the consolidation of small, erodible soil particles into large aggregates by wetting and drying. Aggregate properties change as a result of wetting and drying cycles and extended dryness. These changes, and the effect on soil erodibility, should be included in attempts to model soil surface conditions.

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JEFFREY BRYAN LAYTON

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Soil aggregate status is important in the consideration of soil wind erodibility. Abrasion resistance (dry aggregate stability), resistance to destruction when wetted (wet aggregate stability), and aggregate size distribution influence soil erodibility. The purpose of this experiment was to determine how extended dry periods and cyclical wetting and drying influence these aggregate properties. Samples of Keith silt loam (fine-silty, mixed, mesic Aridic Arguistoll) were subjected to treatments of extended dryness and cyclical wetting and drying. Additionally, aggregates were incubated at water contents of .035, .077, and .285 kg kg^{-1} for one to four weeks. Aggregate density, wet aggregate stability, mechanical stability by repeated rotary sieving, and aggregate size distribution were measured. Aggregates were crushed using the Soil-Aggregate Crushing-Energy Meter (SACEM) to determine dry aggregate stability. Cyclical wetting and drying decreased wet aggregate stability, aggregate density, and dry aggregate stability, and increased aggregate size distribution. The results indicate that aggregate properties important in wind erosion processes are influenced by soil moisture history prior to the dry state associated with wind erosion. Consideration should be given to these changes in developing models to predict soil surface changes between wind erosion events.