EFFECTS OF FREEZING ON AGGREGATE STABILITY OF SOILS DIFFERING IN TEXTURE, MINERALOGY, AND ORGANIC MATTER CONTENT

by

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INTRODUCTION

Aggregate stability, a measure of a soil aggregate's resistance to breakdown, influences many soil physical and hydraulic characteristics, such as surface sealing rate, infiltration rate, and hydraulic conductivity. Thus, because aggregate stability is so important, processes that may increase or decrease it should be studied.

Different soils have been observed to respond differently to the freezing process. Hence, it was hypothesized that soils differing in texture, mineralogy, and organic matter content would be affected differently. A laboratory experiment was designed to test this hypothesis.

Recently, numerous studies of aggregate response to freezing have been reported. Aggregate stability has usually been inversely proportional to soil water content at the time of freezing (Bullock et al., 1988; Benoit, 1973; Bryan, 1971; Logsdail and Webber, 1959). Aggregates from poorly aggregated soils, however, are more stable when frozen at intermediate water contents (Mostaghimi et al., 1988; Sillanpaa and Webber, 1961). The number of freeze-thaw cycles to which aggregates have been subjected is important. With increasing freeze-thaw cycles, aggregate stability usually decreases (Logsdail and Webber, 1959; Mostaghimi et al., 1988; Willis, 1955) but may increase for some soils (Mostaghimi et al., 1988; Richardson, 1976).

Aggregates in soil samples constrained from expanding, especially in the horizontal direction, may respond to freezing differently than unconstrained aggregates. The stability of constrained aggregates has decreased more than that of unconstrained aggregates, though affected to an extent by the aggregate's size and water content at freezing (Bullock et al., 1988).

The influence of inorganic bonding agents on aggregate stability has also been widely studied. For example, Al-Ani and Dudas (1988) found that mean weight diameter increased with additions of calcium carbonate from 0 to 4% by weight but thereafter decreased with $CaCO_3$ additions from 4 to 32%. In contrast, Chepil (1954) reported that 3% calcium carbonate had no effect on aggregate stability but that 10% increased it. Others (Kemper and Koch, 1966; Toogood, 1978) found no significant effect due to lime content.

Many of the inconsistencies noted above may be due to different soils being used from experiment to experiment. The current investigation was conducted under a uniform set of conditions with six soils quite different in character, yet having paired soil properties. The experiment was composed of two studies. The objective of Study I was to determine the effects of constrainment, number of freeze-thaw cycles, and water content at freezing on the aggregate stability of six continental U.S. soils differing in texture, mineralogy, and organic matter. In Study II, two potential inorganic bonding agents at two rates were added as additional factors to a subset of the treatments of Study I.

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MATERIALS AND METHODS

The six soils studied (surface horizons only) were obtained from widely separated locations across the United States. The soils were: a Cecil sandy loam (clayey, kaolinitic, thermic Typic Hapludult) from Watkinsville, GA; a Barnes loam (fine loamy, mixed, Udic Haploboroll) from Morris, MN; a Sverdrup sandy loam (sandy, mixed Udic Haploboroll) from Elbow Lake, MN; a Sharpsburg silty clay (fine, montmorillonitic, mesic Typic Argiudoll) from Lincoln, NE; a Portneuf silt loam (coarse silty, mixed, mesic Xerollic Calciorthid) from Kimberly, ID; and a Palouse silt loam (fine silty, mixed, mesic pachic Ultic Haploxeroll) from Pullman, WA. Properties of the six soils (Table 1) were determined (Soil Conservation Service Staff, 1984) by the personnel of the National Soil Survey and Soil Mechanics Laboratories, Lincoln, NE.

Table 1. Soil properties.

Soil type	Particle size distribution			Bulk density	Predominant mineral type	pH	Organic matter content*
	Sand	Silt	Clay				
	%			g cm^{-3}		(in $CaCl_2$)	%
Barnes Loam	49	34	17	1.25	2:1	7.1	3.41
Cecil sandy loam	67	16	17	1.69	1:1	4.6	1.24
Palouse silt loam	10	70	20	1.15	2:1	4.5	3.03
Portneuf silt loam	22	66	12	1.24	2:1	7.8	1.24
Sharpsburg silty clay	3	56	41	1.33	2:1	5.4	3.19
Sverdrup sandy loam	76	15	9	1.43	2:1	6.0	2.21

*as estimated from the organic C content using the Van Bemmelen 1.724 factor.

Study I

A randomized complete block design with three replications and a factorial arrangement of treatments was used. Sources of variation were soils, number of freeze-thaw cycles, constrainment, and water content. Freeze-thaw cycles were either 0, 1, 3, or 5 with the 0 level signifying no freezing. The constrainment factor was at one of two levels, either constrained (in brass cylinders 5 cm high with an inside diameter of 2.75 cm) or unconstrained (aggregates placed loosely on Al weighing dishes). The water content factor (qualitatively either low, medium, or high) was quantitatively either 0.05, 0.15, or 0.25 g/g for the coarse-textured Sverdrup and Cecil soil or 0.10, 0.20, or 0.30 g/g for the remaining soils. It should be noted that subsequent figures, for the sake of uniformity, will indicate Sverdrup and Cecil soil samples to have water contents of 0.10, 0.20, or 0.30 g/g. Because some data were missing due to sample mistreatment in the laboratory, statistical analyses were performed using a linear model (SAS Institute, Inc., 1985). Aggregate stability values were reported as least-squares (or marginal) means (Searle et al., 1980). These least-squares means, estimates of the means that would have been obtained had no data been missing, were separated, utilizing a significance probability of 5%, using an option available in SAS (SAS Institute, Inc., 1985).

Samples were prepared by sieving field-moist soil (gravimetric water contents ranged from 7 to 22% and averaged 13%) through a 4-mm sieve. Soil was not permitted to air dry between the time it was sampled in the field and analyzed in the laboratory. To prepare constrained samples, the water content of the sieved soil was first adjusted slowly to the desired level, i.e., either lowered by drying in air or raised by misting in a vaporizer (Kemper and Rosenau, 1986). Moist soil was packed by tapping into each brass cylinder until a dry bulk density of 1.15 g/cm^3 was reached. Each packed cylinder was sealed in a polyethylene bag to both inhibit water loss and prevent water uptake, inserted into a styrofoam tray, and stored at +6°C until the remaining cylinders were packed. The styrofoam, a minimum of 7 cm underneath and 2 cm around each cylinder, served as insulation so that freezing occurred primarily downward from the surface. Unconstrained samples were prepared by sieving the less than 4-mm field-moist soil through a 1-mm sieve and placing the equivalent of 10 g of oven-dry 1- to 4-mm aggregates in an Al weighing dish. Our interest was in the response of the 1- to 4-mm aggregates. When studying unconstrained samples, the less than 1-mm aggregates would by design exert no confining pressure on the desired size fraction of aggregates and thus could be omitted from the unconstrained samples. Each dish was sealed in a polyethylene bag, placed on a plastic tray, and stored at +6°C until the remaining unconstrained samples were prepared.

All prepared samples were subjected to either 0, 1, 3, or 5 freeze-thaw cycles. One cycle was completed when prepared soil samples were frozen at -14°C for 24 hours, and subsequently thawed at +6°C for 48 hours. Samples were convectively frozen without access to water. Freezing-induced vertical expansion of the soil in the cylinders was measured. For all samples, a data logger within each enclosure recorded ambient air temperatures. The 0 cycle samples were not frozen but were stored at +6°C for a minimum of 48 hours. Before the aggregate stability analysis, all samples were brought to room temperature on a lab bench for 2 hours. Aggregate stability was determined using the procedure of Kemper and Rosenau (1986) modified so that field-moist 1- to 4-mm aggregates were vapor-wetted to 0.30 g/g prior to wet sieving.

Study II

The experimental design was the same as for Study I but the sources of variation were different. Factors were soils, number of freeze-thaw cycles, water content, potential bonding agents, and bonding agent addition rates. Freeze-thaw cycles were either 1 or 3. All samples were constrained in brass cylinders. The water content factor was either 0.05 or 0.25 g/g for the coarse-textured Sverdrup and Cecil soil or 0.10 or 0.30 g/g for the remaining soils. Finely ground reagent grade $CaCO_3$ or $CaSO_4$ was added as a bonding agent at a rate of either 0.2 or 1.0% by weight of oven-dry soil. The statistical analysis was similar to that of Study I. Least-squares means were separated utilizing a significance probability of 5%.

Samples were prepared by coating less than 4-mm field-moist soil with ground $CaCO_3$ or $CaSO_4$. The desired mass of $CaCO_3$ or $CaSO_4$ was distributed as evenly as possible over all surfaces of a known mass of sieved soil on plastic sheeting, and thoroughly mixed. Thereafter, in a vaporizer, soil water content was raised to the desired level as described earlier. This moist, coated soil was then packed into a brass cylinder using the procedure of Study I. All packed cylinders were subjected to either 1 or 3 freeze-thaw cycles. After the soil had thawed the last time, it was permitted to warm to room temperature over a 2-hour period, removed from the cylinder, and analyzed for aggregate stability using the procedure of Study I.

RESULTS AND DISCUSSION

Study I

Aggregate stability (averaged over freeze-thaw cycles) is shown as a function of water content in Figure 1 for constrained samples and in Figure 2 for unconstrained samples. Figure 1 reveals that, for each soil, aggregate stability decreased as water contents increased from 10 to 30%. The stability of the Sharpsburg, Palouse, and Barnes soils (all medium-textured or finer with organic matter contents of 3% or more) decreased twice as much from 20 to 30% than from 10 to 20% water content. The stability of the Portneuf silt loam, with nearly 60% less organic matter (1.24%, Table 1), however, dropped just as much from 20 to 30% as it did from 10 to 20%. Thus, elevated organic matter, known to improve the stability of aggregates with diameters over 0.25 mm (Tisdall and Oades, 1982), was also more effective in stabilizing aggregates frozen at lower than at higher water contents. The coarse-textured Cecil exhibited the greatest drop in aggregate stability from 10 to 20%. Large differences in aggregate stability exist from soil to soil even at the same water content. For example, Portneuf and Palouse, two silt loams from the Pacific Northwest, differ in stability by over 25 percentage points at a 10% water content.

Findings for constrained samples (Fig. 1) were similar to those for unconstrained samples (Fig. 2). Some differences were noted, however. In Figure 2, though the difference was not significant, aggregate stability tended to increase slightly from 10 to 20% for the Sharpsburg, Palouse and Barnes soils. Figure 2 also indicates that the Sharpsburg, Palouse, and Barnes, the soils highest in organic matter, had the highest percentages of stable aggregates when frozen at a water content of 10%. These same three soils were still the most stable when frozen at 30%.

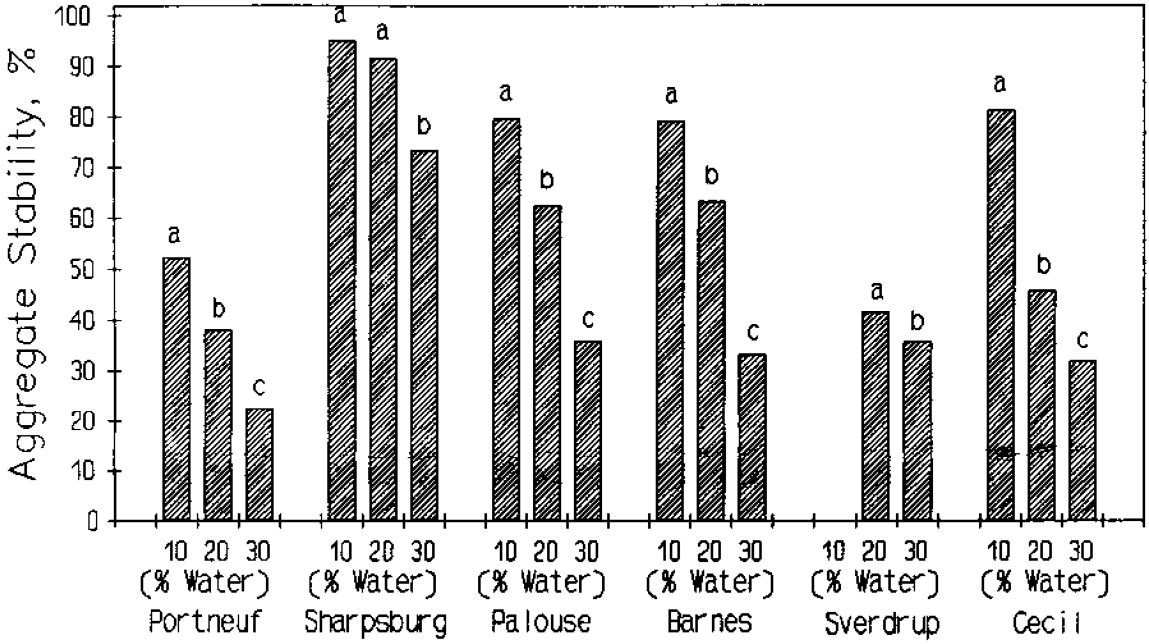

Figure 1. Aggregate stability (averaged over freeze-thaw cycles) as a function of water content for constrained samples of each soil. Within each soil, means without a common letter differ significantly at the 0.05 level.

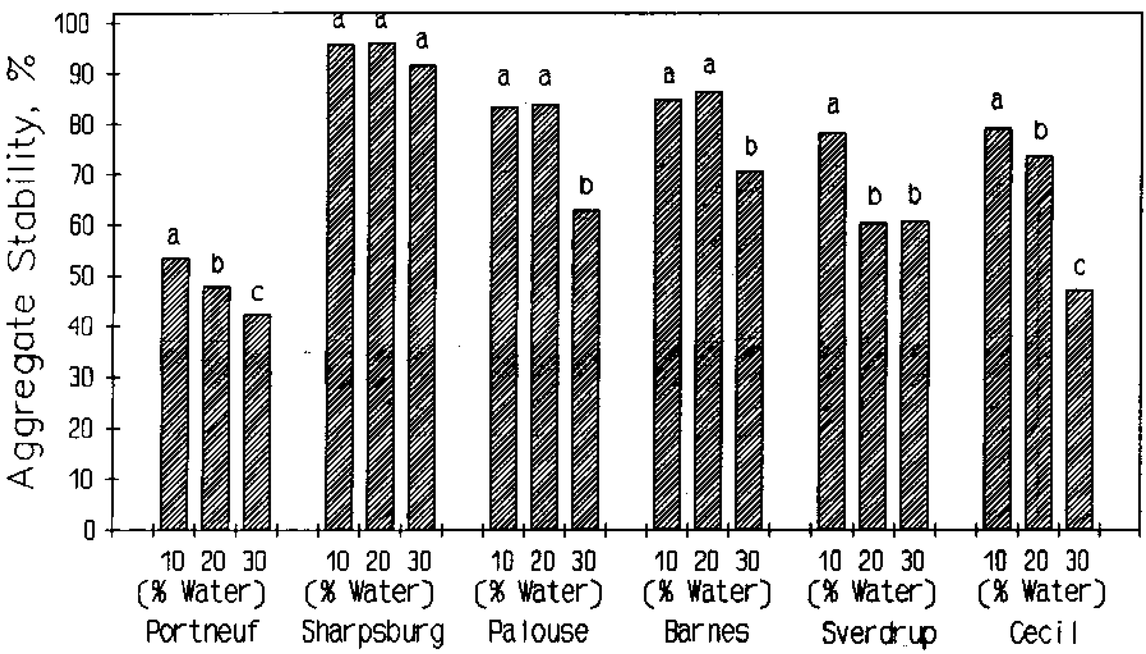

Figure 2. Aggregate stability as a function of water content for unconstrained samples of each soil. Within each soil, means without a common letter differ significantly at the 0.05 level.

In Figure 3, the data (again averaged over freeze-thaw cycles) for a Palouse silt loam illustrate a typical response to constrainment of aggregates while frozen at different water contents. For every soil, constrainment decreased the stability of aggregates frozen at higher (20-30%) water contents. Expansion of ice crystals likely caused planes of weakness in the aggregates whose horizontal displacement was limited by the confining pressure of the brass cylinders. These planes of weakness subsequently manifested their presence during the wet sieving process. Figure 3 also indicates that aggregate stability decreased faster with increasing water content when frozen constrained rather than unconstrained.

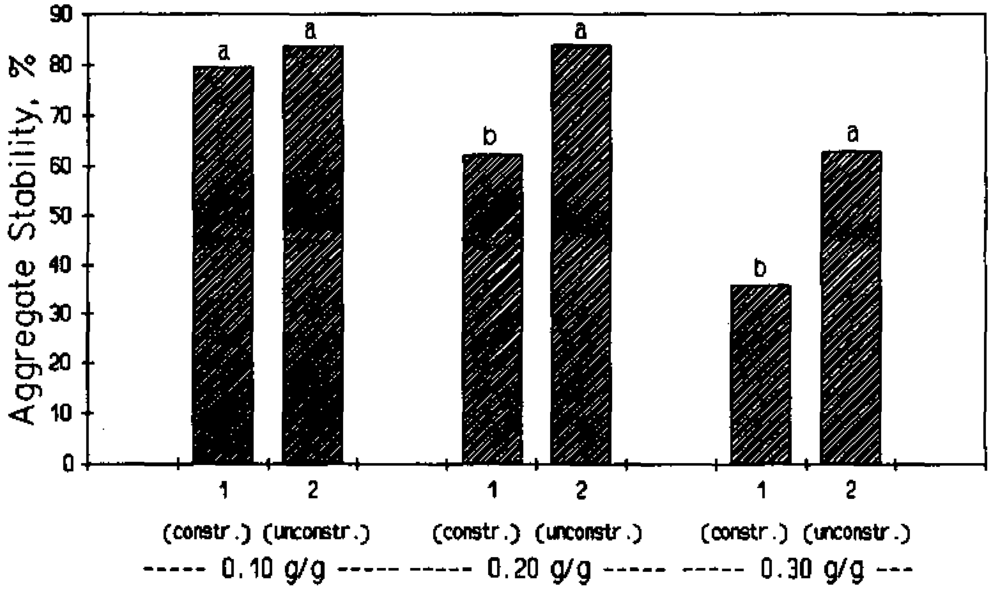

Figure 3. Stability of Palouse aggregates as affected by constrainment at each water content. Within each water content, means without a common letter differ significantly at the 0.05 level.

Table 2 lists aggregate stabilities, averaged over water content, of constrained samples of each soil after each freeze-thaw cycle. The Palouse and Barnes soils increased significantly in stability with increasing number of freeze-thaw cycles. Both are medium-textured soils with relatively high organic matter contents.

Table 2. Effect of freeze-thaw cycles on aggregate stability (constrained samples only).

	Aggregate stability			
	Number of freeze-thaw cycles			
Soil	0	1	3	5
	%			
Barnes	53.0 c*	56.3 bc	59.6 ab	65.4 a
Cecil	49.5 a	55.1 a	55.8 a	51.5 a
Palouse	43.5 c	60.6 b	71.1 a	62.1 b
Portneuf	38.1 a	38.1 a	36.5 a	38.4 a
Sharpsburg	82.8 a	86.0 a	88.7 a	89.1 a
Sverdrup	45.8 a	46.5 a	-	50.6 a

*Means within a row not followed by a common letter differ significantly at the 0.05 level.

When unconstrained, four soils (Fig. 4) increased significantly in aggregate stability with freeze-thaw cycles. In contrast, when constrained, the stability of only two soils increased with freeze-thaw cycles (Table 2). Figure 4 reveals that the coarse-textured Sverdrup and Cecil and, as before, the Palouse and Barnes soils increased in stability. The aggregate stability of Cecil and Palouse increased with each subsequent freeze-thaw cycle, but the response of Sverdrup and Barnes was more variable. The Palouse silt loam was the only soil whose stability increased statistically (and likely practically) from 0 to 1 freeze-thaw cycle. For the remaining three soils, the improvement in stability was minimal, averaging less than nine percentage points over the entire range of cycles studied.

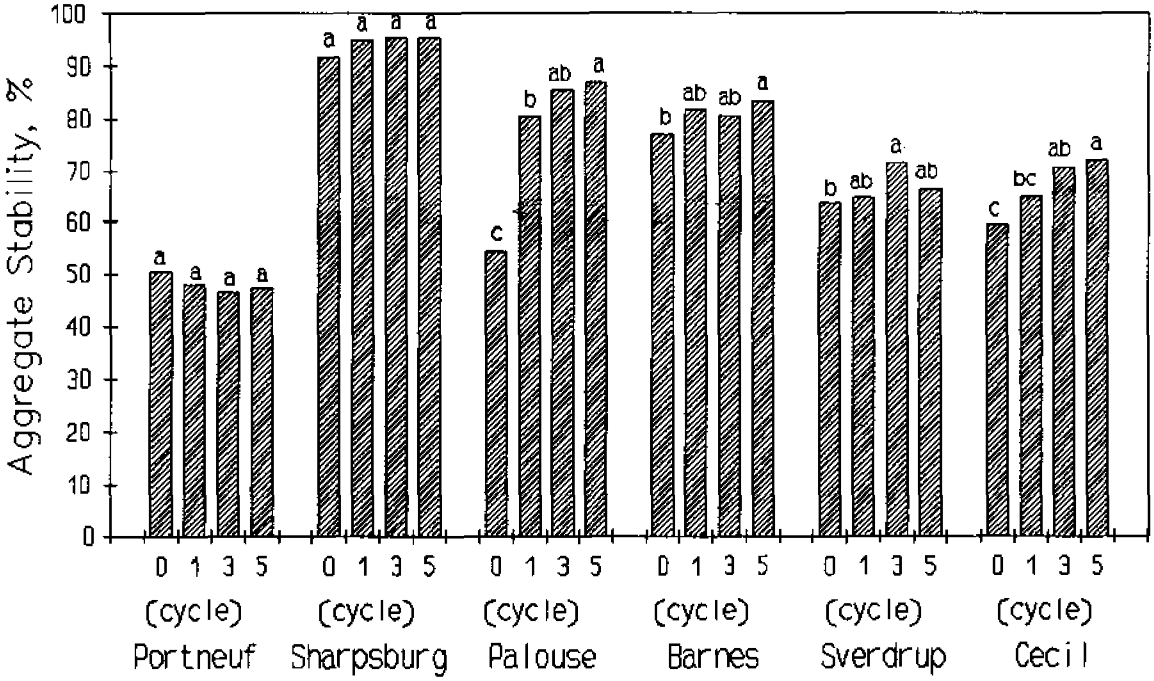

Figure 4. Effects of freeze-thaw cycles on the stability (averaged over water content) of unconstrained aggregates of each soil. Within each soil, means without a common letter differ significantly at the 0.05 level.

Figure 5 reveals that, within each freeze-thaw cycle, aggregate stability, averaged over all six soils and both constrainment levels, decreased with increasing water content. Also, at least for water contents of 20 and 30%, the stability of aggregates increased when subjected to up to three freeze-thaw cycles but then decreased when subjected to five cycles. Thus, for some soils, there seems to be some rather low number of freeze-thaw cycles beyond which aggregates may become less stable with continued freezing and thawing. This suggests that to minimize soil structural damage (and attendant erosion), soil water contents (at least at the surface of the profile) should be as low as possible entering the winter season (Benoit, 1973). Figure 5 also shows that the higher the water content, the greater the increase or decrease caused by freeze-thaw cycles. In other words, freeze-thaw cycles exerted their greatest effect, whether beneficial or detrimental, on aggregate stability at the highest water contents.

Study II

Results from Study II confirmed a number of the findings of Study I. First, aggregate stability decreased when water contents increased from 10 to 30%. Second, the decrease in aggregate stability varied from soil to soil, in general being greatest for coarse-textured soils and least for fine-textured soils. Of particular interest, however, was the influence of $CaCO_3$ and $CaSO_4$ on aggregate stability. Statistical analysis indicated that, at the 5% level, neither of the potential bonding agents affected

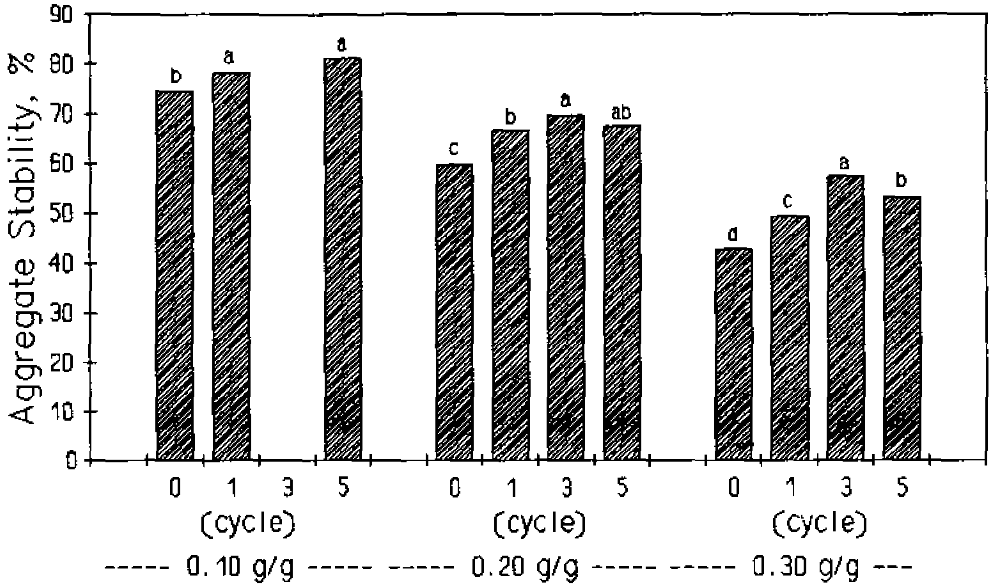

Figure 5. Aggregate stability (averaged over soils and constrainment levels) as a function of freeze-thaw cycles at each water content. Within each water content, means without a common letter differ significantly at the 0.05 level.

aggregate stability. The effect of the bonding agents did, however, approach significance at the 10% level. The trend of the response indicated that aggregate stability was higher with the addition of calcium sulfate than calcium carbonate. Moreover, aggregate stability tended to decrease with increasing rates of the bonding agents. This decrease in stability was greatest when $CaCO_3$ was added to soil samples at a water content of 30%. Statistical analyses of these data are continuing.

Results in light of the objectives

Interactions among the factors examined were the rule rather than the exception in both studies. Constrainment, number of freeze-thaw cycles, and water content at freezing were all found to significantly affect the stability of the six soils, though differently depending upon both the soil in question and the levels of the other factors. In Study I, the effect of constrainment differed depending upon the soil, the water content, and the number of freeze-thaw cycles. When the six soils were taken as a whole, the effect of freeze-thaw cycles on aggregate stability depended upon the water content at freezing. In Study II, the decrease in aggregate stability caused by an increase in water content differed according to the texture of the soil being frozen.

Results in relation to others' findings

The results of these two studies are similar in most but not all respects to the results obtained by other investigators. The decrease in aggregate stability with increasing water content, found by others for loam and silt loam soils (Bullock et al., 1988; Benoit, 1973), was confirmed and found to occur for finer- and coarser-textured soils as well (Fig. 1 and 2). We found that constrained aggregates were less stable than unconstrained aggregates after freezing (Fig. 3) as reported by Bullock et al. (1988). As found by Mostaghimi et al. (1988) for unconstrained samples of a silt loam and Richardson (1976) for a different silt loam, aggregate stability may increase with increasing number of freeze-thaw cycles (see Fig. 4, especially the Palouse silt loam). When, as in this study, soils are not air-dried prior to analysis, this increase in stability with freeze-thaw cycles may be the norm rather than the exception (Figs. 4 and 5). The finding of this study that aggregate stability (as an average response for six soils) increases with up to three freeze-thaw cycles but decreases thereafter (Fig. 5) is supported by the results of Mostaghimi et al. (1988) for a Crofton silt loam (fine silty, mixed, mesic Typic Ustorthent). In contrast, the results presented in Figure 4 showing an increase in stability with freeze-thaw cycles for unconstrained samples of four of six soils are at odds with the results presented by Mostaghimi et al. (1988) showing a decrease in stability with freeze-thaw cycles for two of three soils. Such a discrepancy may well result because their soils were air-dried before their experiment was conducted. Air-drying could have strengthened bonds within the aggregates, thus effectively masking the increase in aggregate stability detected for the first few freeze-thaw cycles (Fig. 5). The finding in Study II that $CaCO_3$ added at either 0.2 or 1.0% by weight did not significantly affect aggregate stability agrees with the results of Chepil (1954), Kemper and Koch (1966), and Toogood (1978) but disagrees with those of Al-Ani and Dudas (1988). There were, however, differences in both soils and procedures between the study of Al-Ani and Dudas (1988) and Study II. The soil samples used by Al-Ani and Dudas (1988) were from the BC horizons of two soils with clay contents of 32 or 42% whereas the soil samples used in Study II were from the surface horizons of soils generally of much lower clay content (Table 1). Procedurally, air-dry soil and 4- to 8-mm aggregates were used by Al-Ani and Dudas (1988) while field-moist soil and 1- to 4-mm aggregates were used in Study II. A number of the earlier studies that found $CaCO_3$ to affect aggregate stability used very high calcium carbonate application rates. The rates considered in Study II were more feasible application rates for agricultural production.

CONCLUSIONS

Constrained aggregates at gravimetric water contents of 20% or more were less stable after freezing than were unconstrained aggregates. For some soils particularly when unconstrained, aggregate stability tended to first increase with increasing number of freeze-thaw cycles and then decrease. The mean response of all six soils showed that the effect of different numbers of freeze-thaw cycles was most pronounced at the highest water content (30%). The one response most consistent throughout the experiment was that aggregate stability decreased with increasing water content at the time of freezing.

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FREEZE THAW EFFECTS ON SOIL STRENGTH

by
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INTRODUCTION

Erosion occurs on the 4 million hectares of non-irrigated cropland in the Pacific Northwest at rates much higher than tolerable to sustain long-term productive agriculture. For example, ten percent of the Palouse river basin of eastern Washington and northern Idaho has already lost all of its topsoil (USDA, 1978) and current annual erosion rates for cropland average from 5 to 50 ton per hectare (Papendick et al., 1983). Rates as high as 224 ton per hectare have been reported (McCool et al., 1976a). Intensive tillage practices associated with common crop rotations, that frequently contain summer fallow, leave the soils pulverized and very vulnerable to erosion. The long and steep slopes in loessial soils of the region combined with the many freeze-thaw cycles (up to 120 per year) during the winter season result in extremely erodible conditions. Soils accumulate moisture prior to the freezing cycles and often freeze wet with resultant low infiltration capacities (McCool and Molnau, 1974). The majority of the precipitation occurs as low intensity rain or snow during the winter months when soils are bare and unprotected (McCool et al., 1982). Runoff detachment and transport are the dominant erosion processes (McCool et al., 1976a; 1987). More than 50 percent of the soil erosion in the Palouse region is related to rain or snowmelt on frozen or thawing ground, often accelerated by warm, moist Pacific air masses (McCool et al., 1976b; Yoo and Molnau, 1982; Zuzel et al., 1982), yet one of the least understood aspects of the physical erosion process is the effect of freeze and thaw.

This report will briefly summarize research conducted at Pullman, Washington pertaining to the effects of freeze-thaw cycles on soil properties.

FIELD RESEARCH

Field research has been conducted since 1931 at the Palouse Conservation Field Station (PCFS). A series of runoff plots have been installed since 1978 that are subjected to tillages and crop rotations common to the area. Results have been primarily used to adapt the Universal Soil Loss Equation to the Pacific Northwest (McCool and George, 1983, McCool et al., 1976a, McCool et al., 1982). On tillage weakened soils, 60 to 70 percent of the annual runoff and about 55 percent of the yearly soil loss was related to rainfall and snowmelt on frozen ground.

During the 1987-88 and 1988-89 erosion seasons, soil strength was monitored on a Palouse silt loam on a 21 percent slope at the PCFS (Kok, 1989, Kok and McCool, 1989). Several instruments were used; fall-cone, pocket penetrometer and Torvane*, a device with vertical vanes radiating from a central point. Satisfactory results were obtained only with a metal Torvane apparatus. Torvane soil strength varied drastically over the period of field testing, from virtually zero while thawing to 14 kPa under dry soil conditions in early spring.

An example of observations as obtained with the Torvane apparatus for early 1988 is shown in Figure 1, together with soil water content observations for this period. The soil had been tilled with a Lely Roterra (a tiller with vertical teeth rotating around a

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