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Freezing Effects on Aggregate Stability Affected by Texture, Mineralogy, and Organic Matter

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ABSTRACT

Aggregate stability, an important property influencing a soil's response to erosive forces, is affected by freezing. The objectives of this laboratory study were to determine how constrainment, number of freeze-thaw cycles, and water content at freezing affect the aggregate stability of six continental USA soils differing in texture, mineralogy, and organic-matter content. Moist aggregates, after being frozen and thawed either zero, one, three, or five times, were vapor wetted to 0.30 kg kg^{-1} and analyzed by wet sieving. Soils with clay contents of 17% or more and organic-matter contents >3% were the most stable after freezing. Aggregate stability for fine- and medium-textured soils generally decreased linearly with increasing water content at freezing. This linear decrease in stability was more rapid for constrained samples than for unconstrained samples. The stability of field-moist aggregates generally increased from zero to one or three freeze-thaw cycles. For at least one low-organic-matter soil, stability increased from one to three freeze-thaw cycles, but then decreased at five cycles. After thawing, aggregates at water contents of 0.15 kg kg^{-1} or more that were constrained when frozen were always significantly less stable than aggregates that were unconstrained when frozen.

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. Freezing affects aggregate stability, though not in the same manner for all soils. Consequently, it was hypothesized that soils differing in texture, mineralogy, and organic matter content would respond differently to freezing. A laboratory experiment was designed to test this hypothesis.

Recently, numerous studies of aggregate response to freezing have been reported. Aggregate stability was usually 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 certain poorly aggregated soils, however, were 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 decreased (Logsdail and Webber, 1959; Mostaghimi et al., 1988; Willis, 1955) but, under certain conditions, increased for some soils (Mostaghimi et al., 1988; Richardson, 1976). The stability of aggregates constrained from expanding, especially in the horizontal direction, 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).

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Some of these inconsistencies were caused by the use of different soils from experiment to experiment. This laboratory investigation was conducted under a uniform set of conditions with six different soils having paired soil properties. The objective was to determine the effects of constrainment, number of freeze-thaw cycles, and water content at freezing on the aggregate stability of six soils differing primarily in texture, mineralogy, and organic matter.

MATERIALS AND METHODS

Samples of the six naturally occurring soils (Ap horizons only) were obtained from across the USA. The soils differing primarily in texture were a Barnes loam (fine-loamy, mixed Udic Haploboroll) from Morris, MN, and a Sharpsburg silty clay (fine, montmorillonitic, mesic Typic Argiudoll) from Lincoln, NE. The soils differing in mineralogy were a Cecil sandy loam (clayey, kaolinitic, thermic Typic Kanhapludult) from Watkinsville, GA, and a Sverdrup sandy loam (sandy, mixed Udic Haploboroll) from Elbow Lake, MN. The soils differing primarily in organic-matter content were a Palouse silt loam (fine-silty, mixed, mesic Pachic Ultic Haploxeroll) from Pullman, WA, and a Portneuf silt loam (coarse-silty, mixed, mesic Durixerollic Calciorthid) from Kimberly, ID. Properties of the six soils (Table 1) were determined (Soil Conservation Service, 1984) by the personnel of the National Soil Survey and Soil Mechanics Laboratories, Lincoln, NE.

The six soils studied differed to varying degrees in some properties other than the primary property being compared. For any given soil pair, however, the difference between the soils in their primary property was much greater than any differences in secondary properties. For example, the organic matter of the Palouse was >240% that of the Portneuf, while its clay content was 67% of the Portneuf. Thus, the difference in organic matter is more than three times the clay-content difference. Nevertheless, a minor portion of any effects on aggregate stability that may be attributed to the primary property may be due to differences in other properties of the paired soils.

All soils had a common cropping and tillage history. In the growing season prior to sample collection, either corn (*Zea mays* L.), sorghum (*Sorghum bicolor* [L.] Moench), or a small grain (but never soybean [*Glycine max* (L.) Merr.] or a forage or hay-type crop) was grown. After harvest, crop residues were removed from the soil surface and the sampling sites were moldboard plowed, then lightly disked. Thereafter, the sites were maintained weed- and grass-free for 3 to 12 mo to allow roots and other organic residue to decompose before sampling.

A randomized complete-block design with three replicates and a factorial arrangement of treatments was used. The four sources of variation were soils, number of freeze-thaw cycles, constrainment, and water content. Freeze-thaw cycles were either zero, one, three, or five with the zero level signifying no freezing. The constrainment factor was at one of two levels, either constrained (in brass cylinders 5 cm high with an i.d. of 2.75 cm) or unconstrained (aggregates loosely placed on weighing dishes). The water-content factor (qualitatively either low, medium, or high) was quantitatively either 0.05, 0.15, or 0.25 kg kg^{-1} for the coarse-textured Cecil and Sverdrup soils or 0.10, 0.20, or 0.30 kg kg^{-1} for the remaining soils. For each soil, water contents at matric potentials of −1500 and −33 kPa are given in Elliot et al.

Table 1. Soil properties.

Soil type	Particle-size distribution Sand	Silt	Clay	Bulk density†	Predominant mineral type	pH (in $CaCl_2$)	Organic-matter content‡	COLE§
	%			g cm^{-3}			%	cm cm^{-1}
Barnes loam	49	34	17	1.25	2:1	7.1	3.41	0.030
Sharpsburg silty clay	3	56	41	1.33	2:1	5.4	3.19	0.086
Cecil sandy loam	67	16	17	1.69	1:1	4.6	1.24	0.010
Sverdrup sandy loam	76	15	9	1.43	2:1	6.0	2.21	0.014
Palouse silt loam	10	70	20	1.15	2:1	4.5	3.03	0.026
Portneuf silt loam	22	66	12	1.24	2:1	7.8	1.24	0.012

† Measured using the excavation method.
‡ Estimated from the organic-C content using the Van Bemmelen 1.724 factor.
§ Coefficient of linear extensibility.

(1989). Statistical analyses were performed on arcsin $(x)^{0.5}$-transformed data using an analysis of variance (SAS Institute, 1985)[1]. For presentation, the treatment means have been back-transformed to the original scale of measurement. Because of the large number of error degrees of freedom and the resultant powerful F tests, a significance probability of 0.01 was used to identify significant sources of variation in the analysis of variance table. The subsequent results and discussion have focused mainly on two highly significant three-way interactions that describe the variation in aggregate stability caused by all four factors. In the statistical analysis, water content was modeled as a continuous variable to identify statistically significant trends in the response of aggregate stability to water content. Freeze-thaw cycle and constrainment means were separated using confidence intervals constructed to be equivalent to tests of significance at the 0.05 level. Additional preplanned, single degree-of-freedom comparisons of selected treatments were also made.

Samples were prepared by passing field-moist soil (initial water contents ranged from 0.07 to 0.22 and averaged 0.13 kg kg^{-1}) through a 4-mm sieve. Soil was prevented from drying between field sampling and laboratory use by storage in air-tight containers at 6 °C. To prepare constrained samples, the water content of the sieved soil was first raised to the desired level in a vaporizer (Kemper and Rosenau, 1986). Vapor-moistened soil was packed (to a dry bulk density of 1.15 g cm^{-3}) into each brass cylinder by tapping the cylinder on a hard surface. Each packed cylinder was sealed in a polyethylene bag to inhibit water loss and prevent water uptake, then inserted into a polystyrene foam tray, and stored at 6 °C until the remaining cylinders were packed. The polystyrene foam, a minimum of 7 cm underneath and 2 cm around each cylinder, served as insulation so that freezing occurred primarily downward from the surface (this was confirmed by subsequent investigations utilizing thermocouples placed in packed cylinders). Unconstrained samples were prepared by sieving the <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 primary interest was in the response of the 1- to 4-mm aggregates. When studying unconstrained samples, the <1-mm aggregates would, by design, exert no confining pressure on the 1- to 4-mm aggregates and thus could be omitted from study. 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 soil samples were subjected to either zero, one, three, or five freeze-thaw cycles. One cycle was completed when samples were frozen convectively (without access to additional water) at −14 °C for 24 h, then thawed at 6 °C for 48 h. Little, if any, freezing-induced vertical expansion of the soil in the cylinders occurred. For all samples, a data logger within each enclosure recorded ambient air temperatures. The zero-cycle samples were not frozen but were stored at 6 °C for a minimum of 48 h. Before the aggregate-stability analysis, all samples were brought to room temperature on a lab bench for 2 h. Aggregate stability was determined using the procedure of Kemper and Rosenau (1986), modified by Lehrsch and Jolley (1989), so that field-moist 1- to 4-mm aggregates were vapor-wetted to 0.30 kg kg^{-1} prior to wet sieving.

[1] Trade names are included for the benefit of the reader and do not imply endorsement of or preference for the product by the USDA.

RESULTS AND DISCUSSION

Interaction between Soils, Constrainment, and Water Content

Aggregate stability (averaged across freeze-thaw cycles) as a function of water content is shown in Fig. 1 for both constrained and unconstrained samples. In nearly every case, constrainment decreased the stability of aggregates. The decrease was always statistically significant at water contents of 0.15 kg kg^{-1} or more. While it is possible that aggregates were weakened during the packing process, a more likely explanation is related to ice formation. Pressure exerted by expansion of ice crystals within the constrained samples could have formed planes of weakness in the aggregates, whose horizontal displacement was limited by the confining pressure of the brass cylinders. These potential fracture planes probably manifested their presence during subsequent wet sieving.

In >85% of the cases, aggregate stability decreased as water contents increased (Fig. 1). Statistical trend analyses revealed that, for each level of constrainment, the response of aggregate stability to changing water content was linear (across the range of water contents studied) for the medium- and fine-textured soils. The quadratic (curvilinear) trend for each of these four soils was not significant ($P \geq 0.10$). Moreover, with increasing water content, aggregate stability decreased at a faster rate for constrained samples than for unconstrained samples (see, for example, the Sharpsburg and especially the Portneuf soils in Fig. 1). At similar water contents, the pressure exerted on confined aggregates, rather than on unconfined aggregates, was probably more effective in developing new or further weakening old potential failure planes. Figure 1 also shows that, for constrained samples of the coarse-textured Cecil and Sverdrup soils, by far the greater decrease in aggregate stability occurred when the water content increased from 0.05 to 0.15 rather than from

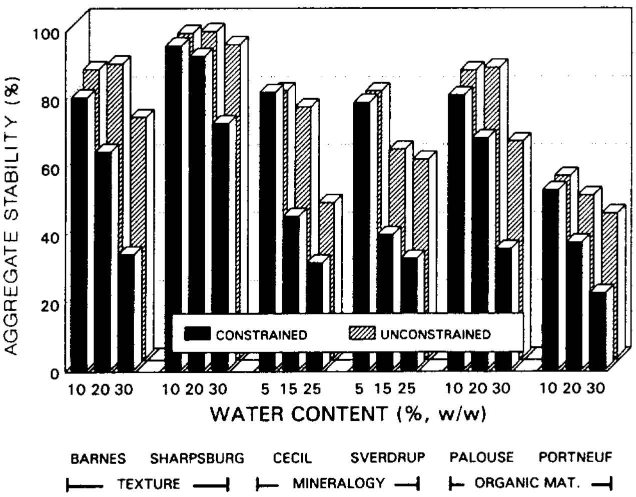

Fig. 1. Aggregate stability as a function of water content for both constrained and unconstrained samples of each soil.

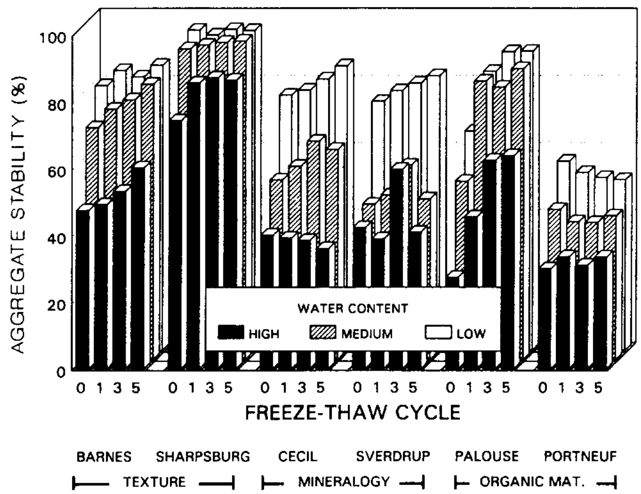

Fig. 2. Aggregate stability as a function of freeze-thaw cycle for each soil at each water content. The water contents were 0.05, 0.15, and 0.25 kg kg^{-1} for the Cecil and Sverdrup soils and 0.10, 0.20, and 0.30 kg kg^{-1} for the remaining soils.

0.15 to 0.25 kg kg^{-1}. Indeed, the trend analysis indicated this quadratic response to be significant ($P < 0.013$). Little energy (few freeze-thaw cycles) was needed to substantially weaken the aggregates of the sandy loams.

The effects of clay and organic-matter content can be seen in Fig. 1. The soil highest in clay content (Sharpsburg, 41%, Table 1) had the highest aggregate stability at all water contents and constrainment levels. Mostaghimi et al. (1988) predicted that aggregate stability would increase with clay content. More clay implies more or stronger clay bridges between soil particles. This suspected high degree of bridging was apparently little affected by water content or constrainment in this experiment (Fig. 1). The stability of constrained samples of Barnes, Sharpsburg, and Palouse soils (all medium-textured or finer with organic-matter contents of 3% or more) decreased less from 0.10 to 0.20 than from 0.20 to 0.30 kg kg^{-1} water content. The stability of the Portneuf silt loam, with nearly 60% less organic matter (1.24%, Table 1), however, decreased more from 0.10 to 0.20 than from 0.20 to 0.30 kg kg^{-1}. Thus, elevated organic matter, which improves the stability of aggregates >0.25 mm (Tisdall and Oades, 1982), was also more effective in stabilizing frozen aggregates, but only at lower water contents. The data in Fig. 1 also indicate that, when frozen at water contents of 0.10 kg kg^{-1}, unconstrained samples of Barnes, Sharpsburg, and Palouse (three highest in both clay and organic matter) had the most stable aggregates (>84%). These same three soils were still the most stable (>63%) when frozen at a water content of 0.30 kg kg^{-1}.

The two soils differing primarily in organic-matter content can also be compared. Aggregates of a Palouse silt loam (2.5 times as much organic matter as Portneuf, Table 1) were more stable than aggregates of Portneuf, regardless of constrainment (Fig. 1). Drying that could have caused reduced wettability of the Palouse (leading to less water freezing in intraaggregate pores) was not a factor because all soils were kept moist between sampling and analysis. Elasticity provided by organic matter may have enabled Palouse aggregates at low water contents to withstand ice-lens expansion pressures before fracturing. By contrast, at high water contents, there may have been insufficient elasticity present to prevent fracture. Indeed, stability differences among these two soils were least at these highest water contents. Where constrainment differed, the decrease in stability due to constrainment was more pronounced at every water content for Palouse aggregates than for Portneuf aggregates (Fig. 1). While the drop in stability was greater, the high-organic-matter Palouse aggregates nonetheless were more stable than the Portneuf aggregates at every water content. In any case, the shape of the response of the two soils was similar but the magnitude of the change was greater for the soil higher in organic matter.

Interaction between Soils, Freeze-Thaw Cycles, and Water Content

In the statistical analysis, freeze-thaw cycle was considered to be a discrete rather than continuous variable for a number of reasons. We initially modeled freeze-thaw cycles as continuous to identify significant trends but found that a trend for freeze-thaw cycles, when statistically identified, was usually cubic. Cubic trends don't aid interpretation and summarization well, only indicating that the curve illustrating the effect of freeze-thaw cycles was not monotonic. One implication of a cubic trend is that at least one threshold in the number of freeze-thaw cycles existed. Such a threshold seemed reasonable. Below it, aggregate stability could either change little or increase. Above the threshold, however, aggregate stability could decrease. The implication of the threshold thus indicated that freeze-thaw cycles would be more appropriately modeled as discrete. Second, though trends seemed to exist when the means were examined visually, those trends, if indeed present, were seldom found to be linear, quadratic, or cubic. Thus, the trend analysis using contrasts often failed to identify the trend.

Freeze-thaw-cycle effects on aggregate stability (averaged across constrainment levels) are illustrated in Fig. 2. Aggregate stability was greatest at every level of freeze-thaw cycle for every soil at the lowest water contents (0.05 or 0.10 kg kg^{-1}). This suggests that, to preserve aggregation and reduce erosion, fall soil water contents near the surface should be as low as possible (Benoit, 1973). From zero to one freeze-thaw cycle (one occurrence of freezing), the aggregate stability of the four fine- and medium-textured soils often increased (Fig. 2). This increase was statistically significant at water contents of 0.10 and 0.20 kg kg^{-1} for the Palouse silt loam, one of the soils highest in organic matter (Table 1). Increases in soil aggregate stability with increasing freeze-thaw cycles have also been detected by others (H. Kok, 1989, personal communication; Mostaghimi et al., 1988; Perfect et al., 1990). For the Barnes loam and Portneuf silt loam at a 0.30 kg kg^{-1} water content, the increase in stability with one freeze-thaw cycle was minimal, averaging less than three percentage points.

A number of factors may have been responsible in whole or in part for this increase in stability with freeze-thaw cycle(s). First, the initiation and early enlargement of ice lenses could have increased particle-to-particle contacts. Throughout the experiment, small ice crystals were occasionally observed in both the unconstrained and constrained samples approximately 1.25 cm below the soil surface in the brass cylinders. Second, freezing at -14 °C should have allowed migration of water to ice crystals or ice lenses forming in the soil samples. Thus, the soil matrix surrounding and below the ice lens would undergo drying (Taber, 1916; Hoekstra, 1966; Miller, 1980). This drying, very similar to the common air drying of aggregates prior to stability measurement, could serve to position polysaccharides on soil particle surfaces (Myers, 1937; Reid and Goss, 1982) or precipitate bonding agents at points of contact between soil particles (Kemper et al., 1987; Lehrsch et al., 1990). These effects would promote aggregate reformation following thawing and increase aggregate strength.

While not measured in this study, the rate of water movement to a growing ice lens could influence soil aggregate response to the freezing process. This hydraulic conductivity would determine the rate at which an ice lens would thicken and thus the forces that would be exerted on aggregates. Amemiya (1965) reported hydraulic conductivities at water contents of 0.23 m^3 m^{-3} (corresponding to water contents of 0.20 kg kg^{-1} and constrained samples at a bulk density of 1.15 g cm^{-3}) for samples of two soils containing aggregates from 0.5 to 9 mm. For a Miami silt loam (fine-loamy, mixed, mesic Typic Hapludalf), texturally much like the Palouse silt loam, and for a Kranzburg silty clay loam (fine-silty, mixed Udic Haploboroll), similar in silt content but with more sand and less clay than the Sharpsburg silty clay, the hydraulic conductivities were approximately 6×10^{-5} and 1×10^{-6} cm min^{-1}, respectively. In nonisothermal regions of soil where both ice and unfrozen water films occurred simultaneously at temperatures at and below 0 °C, Hoekstra (1966) found hydraulic conductivity to be nearly independent of total soil water content (unfrozen water plus ice) but dependent on the thickness of the liquid water films, with temperature gradients providing the driving force for water flow. In such soil regions, water flux density (found for a silt-textured soil to be approximately 9×10^{-4} g cm^{-2} min^{-1} at a temperature of -2 °C) (Hoekstra, 1966) decreased rapidly with decreasing temperature because the thicknesses of the water films themselves decreased with temperature (Anderson and Hoekstra, 1965). In regions of the same soil at temperatures from 5 to 0 °C in which ice had not yet formed and through which water was moving toward the freezing front, water moved at flux densities of the same magnitude, 3 to 25×10^{-4} g cm^{-2} min^{-1} (Hoekstra, 1966). When he compared one soil to another, Harlan (1973) concluded that the rate of upward water movement through unfrozen soil (no ice present) toward a freezing front decreased as soils became finer textured.

As mentioned above, at all water contents studied, high-organic-matter soils (Barnes, Sharpsburg, and Palouse) usually increased in stability with freeze-thaw cycles. In contrast, the Cecil, Sverdrup, and Portneuf soils (organic-matter contents of 2.21% or less and clay contents of 12% or less or dominated by 1:1-type minerals), particularly at the higher water contents, either tended to decrease in stability or increase initially then decrease as freeze-thaw cycles continued to accrue beyond three cycles (Fig. 2). Sverdrup's initial increase from one to three cycles was significant at $P < 0.07$ and its subsequent decrease from three to five cycles was significant at $P < 0.05$. The Sverdrup at 0.15 and the Cecil at 0.15 kg kg^{-1} water content responded similarly (Fig. 2), though the differences in stability between adjacent freeze-thaw means were not quite significant at $P < 0.05$. Thus, the Sverdrup and Cecil results in Fig. 2 indicate that some rather low number of freeze-thaw cycles can cause certain soils to have less stable aggregates with continued freezing and thawing. Indeed, for the Barnes and Sharpsburg soils, the threshold number of freeze-thaw cycles beyond which stability decreases may be more than five, the maximum number studied in this experiment. Mostaghimi et al. (1988), who subjected Barnes aggregates to six freeze-thaw cycles, found the Barnes' aggregate stability (as measured using mean weight diameter) to decrease from what was measured after three freeze-thaw cycles. It may be that the Barnes, while relatively low in clay but high in organic matter and pH, had relatively more charged silica species (potential bonding agents) in its soil solution than did the other soils. The Sharpsburg also exhibited properties (high clay content and relatively high base saturation) that could account for relatively high concentrations of bonding agents in solution.

Sverdrup's initial increase and subsequent decrease in stability (found at both 0.15 and 0.25 kg kg^{-1}) is of interest. Two opposing processes are probably active: (i) strengthening as a result of precipitation of slightly soluble bonding agents and (ii) weakening as a result of ice-crystal formation, compression of nearby aggregates, and development of fracture planes. Up to three freeze-thaw cycles, the strengthening process evidently is dominant. After three cycles, it may be that the strengthening process is of no consequence and the always-occurring weakening process decreases aggregate stability. Too, with the accrual of freeze-thaw cycles, more and more fracture planes may be formed in the aggregates near the location at which the ice lenses form. Thus, aggregate weakening may intensify over time.

The two opposing processes may have interacted in the following manner: As the soil dried during the first few freezes, many bonding agents from the soil solution precipitated at particle-to-particle contact points. Since this bonding probably involved irreversible or slowly reversible reactions (Kemper et al., 1987), these same already precipitated bonding agents did not go back into solution during the subsequent thawing period. After the first few freeze-thaw cycles, the bonding agents that had remained in solution in the thin unfrozen water films surrounding the soil particles (Miller, 1980) during the first or second cycle had probably been precipitated from the soil solution and no more strengthening of the aggregates took place. Weakening due to fracture-plane development induced by ice lens formation then began to play the dominant role and aggregate stability decreased.

The two soils differing in texture (clay content) can be compared. Freeze-thaw cycles had no appreciable effect on the stability of a high-clay Sharpsburg soil when frozen at water contents of 0.20 kg kg^{-1} or less. Within a freeze-thaw cycle, Sharpsburg aggregates were much more resistant to breakdown than Barnes aggregates as water contents increased. Indeed, clay-rich aggregates (Sharpsburg) frozen at water contents of 0.20 kg kg^{-1} were just as stable as when frozen at 0.10 kg kg^{-1}. In contrast, relatively clay-poor aggregates (Barnes) frozen at 0.20 kg kg^{-1} water content were always less stable than when frozen at 0.10 kg kg^{-1}. As noted above, more clay provides more and stronger clay bridges, thus stronger aggregates. Aggregates of Sharpsburg (41% clay) at water contents of 0.20 kg kg^{-1} or less were nearly unaffected by increasing number of freeze-thaw cycles. Clay bridging between particles was evidently strong.

Additional Single Degree-of-Freedom Comparisons

Comparisons of the two soils in each pair were made using single degree-of-freedom contrasts. Without exception, the texturally dissimilar Barnes and Sharpsburg responded differently to constrainment and freeze-thaw cycles at each level of water content. The soils differing in organic-matter content, Palouse and Portneuf, always responded differently to constrainment and usually to freeze-thaw cycles at each water content. The only exceptions for these two silt loams was for the zero level of freeze-thaw cycle at 0.20 and 0.30 kg kg^{-1} water contents and for one cycle at 0.30 kg kg^{-1}. In these three cases, the Palouse and Portneuf responses were the same. In contrast, the mineralogically dissimilar Cecil and Sverdrup usually responded alike. Only when unconstrained at 0.15 and 0.25 kg kg^{-1} water contents and for three freeze-thaw cycles at 0.25 kg kg^{-1} water content did these two soils respond differently. Thus, as Fig. 1 and 2 imply, texture and organic matter significantly affected aggregate stability in this experiment. Mineralogical differences, however, had little influence.

Comparisons among Soils, Freeze-Thaw Cycles, and Water Content

Freezing (that is, one or more freeze-thaw cycles) was expected to affect the aggregate stability of most, if not all, of the soils studied in this experiment. To test this expectation for each soil, a single degree-of-freedom contrast was constructed that compared the aggregate stability for the zero level of freeze-thaw cycle (no or prefreeze) to a calculated postfreeze aggregate stability, determined by averaging the stabilities after one, three, and five cycles. The freezing effect was significant, at one or more water contents, for all soils except the Portneuf. For this soil, the aggregate stability for zero cycles was often as high or higher than the other levels that involved freezing. This does not indicate an absence of significant differences from one freeze-thaw level to another but rather that the response of the zero-cycle treatment was similar to the average response of the one-, three-, and five-cycle treatments. The Portneuf soil differed from level to level (Fig. 2), though the differences were not statistically significant.

Another single degree-of-freedom comparison was made for each soil to determine if the number of freeze-thaw cycles (either one, three, or five) significantly affected aggregate stability. The findings of this comparison were similar to the results reported above for the entire study. Some additional information was gained, however. For the Barnes loam at 0.30 kg kg^{-1} water content for one through five freeze-thaw cycles, aggregate stability appeared to increase almost linearly (Fig. 2). Its stability for one cycle was 49.4%, for three cycles it was 53.3%, and for five cycles it was 60.4%. In contrast, for the Cecil sandy loam at a water content of 0.25 kg kg^{-1} for one through five freeze-thaw cycles, its aggregate stability appeared to decrease. The rate of change was not as constant as for the Barnes soil, but the curve appeared monotonic nonetheless (Fig. 2). The stability of the Cecil was 39.3% for one cycle, 38.6% for three cycles, and 36.1% for five cycles. These responses of the Barnes and Cecil illustrate that, for some soils over some freeze-thaw levels, aggregate stability appeared to respond in a continuous or even linear manner.

Results in Relation to Other Findings

The results 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. 1), as reported by Bullock et al. (1988). As found by Mostaghimi et al. (1988) for a Barnes loam (at water contents of 0.12 and 0.28 kg kg^{-1}) and a Crofton silt loam (fine-silty, mixed [calcareous], mesic Typic Ustorthent) and Richardson (1976) for an unidentified sandy loam, aggregate stability may increase with increasing number of freeze-thaw cycles (the Barnes, Sharpsburg, and Palouse data of Fig. 2). When, as in our study, soils are not air dried prior to analysis, this increase in stability with freeze-thaw cycles may commonly occur (Fig. 2). The finding of this study, that aggregate stability for at least one low-organic-matter soil increases up to three freeze-thaw cycles but decreases significantly thereafter, (Sverdrup, Fig. 2), is supported by the results of Mostaghimi et al. (1988) for a Crofton silt loam with 0.5% organic matter. On the other hand, Mostaghimi et al. (1988) reported decreases in stability with even the first few freeze-thaw cycles for two other soils. This discrepancy may have occurred 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 often detected in this study for the first few freeze-thaw cycles (Fig. 2).

CONCLUSIONS

In general, soil texture and organic matter, but not mineralogy, affected aggregate stability after freezing. Constrained aggregates were almost always less stable (always significantly so at water contents of 0.15 kg kg^{-1} or more) after freezing than were unconstrained aggregates. The stability of field-moist aggregates usually increased with at least the first few freeze-thaw cycles. For at least one soil low in organic matter, aggregate stability first increased with increasing number of freeze-thaw cycles and then decreased. The one response most consistent throughout the experiment was that aggregate stability significantly decreased (often linearly) with increasing water content at the time of freezing.

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