CATENA SUPPLEMENT 24 p. 115–127 Cremlingen 1993

Freezing Effects on Aggregate Stability of Soils Amended with Lime and Gypsum

G.A. Lehrsch, R.E. Sojka & P.M. Jolley

Summary

Aggregate stability, which influences soil response to raindrop impact and other erosive forces, is affected by freezing. We hypothesized that lime or gypsum added at agriculturally feasible rates may act as bonding agents to mitigate the effects of freezing on the stability of aggregates from different soils. Thus, the objectives of the laboratory study were to determine the effects of freeze-thaw cycles, water content at freezing, and lime and gypsum additions on the aggregate stability of six soils differing in texture, mineralogy, and organic matter. To all samples but the control, either $CaCO_3$ or $CaSO_4 \cdot 2H_2O$ was added at a rate of either 0.2 or 1.0% by weight of oven-dry soil. Field-moist aggregates were vapor-wetted to either a low water content (5-10% w/w) or a high water content (25–30%), then frozen and thawed either 0, 1, or 3 times in brass cylinders. After thawing, they were vapor-wetted to 0.30 g g^{-1} and their stability was characterized by wet sieving. For all soils, aggregate stability decreased significantly with increasing water content at freezing. When averaged over bonding agents and addition rates, soils commonly increased in stability, at times significantly, after one freeze-thaw cycle. Soils with clay contents of 20% or more and organic matter contents over 3% were the most stable after freezing. When averaged over soils and freeze thaw cycles, aggregate stability was not affected by bonding agents at low water contents. At high water contents, however, stability increased significantly ($P<0.05$) when $CaSO_4$ at a rate of 0.2% was added. Though the differences from agent to agent at high water contents were not significant at the 0.05 level, $CaSO_4$ appeared to increase aggregate stability more than $CaCO_3$. Surprisingly, stability tended to be greater at the lower rather than higher application rates. In conclusion, aggregate stability

1. decreased with increasing water content at freezing, and
2. increased after $CaSO_4$-amended soil samples at high water contents were frozen.

1 Introduction

Aggregate stability, a measure of a soil aggregate's resistance to breakdown, influences many soil physical and hydraulic characteristics, such as surface sealing, infiltration, and hydraulic conductivity. Processes that affect aggregate stability are not well understood

ISSN 0722-0723
ISBN 3-923381-33-6

38162 Cremlingen-Destedt, Germany
3-923381-33-6/93/5011851/US$ 2.00 + 0.25

and should be studied further.

Freezing is one process that has been shown to affect aggregate stability. Several studies have indicated that aggregate stability decreases with increasing soil water content at the time of freezing (Bullock et al. 1988, Bryan 1971, Lehrsch et al. 1991, Logsdail & Webber 1959). Aggregates from poorly aggregated soils, however, are more stable when frozen at intermediate water contents (Mostaghimi et al. 1988, Perfect et al. 1990b, Sillanpaa & Webber 1961). The number of freeze-thaw cycles to which aggregates have been subjected is important. The stability of air-dried aggregates generally decreases with increasing number of freeze-thaw cycles (Logsdail & Webber 1959, Mostaghimi et al. 1988) but may increase for some soils (Mostaghimi et al. 1988, Richardson 1976). For aggregates maintained at field moisture levels until analyzed, Lehrsch et al. (1991) found stability to increase with the first few freeze-thaw cycles.

No consensus exists in the literature regarding the effects of lime and/or gypsum amendments on soil aggregation and aggregate stabilization in non-sodic soils. For sodic soils, however, gypsum is commonly used to improve drainage. Gypsum amendments enhance the flocculation of clays and thus facilitate both the formation and stabilization of soil aggregates. The effects of gypsum additions to non-sodic soils, however, are less clear. Rimmer & Greenland (1976) noted that $CaCO_3$ can act as a bonding or cementing agent between soil particles and, since it is slightly soluble, as a source of Ca ions which reduce diffuse double layer thicknesses of clay domains. Kemper et al. (1974) suspected both $CaCO_3$ and $CaSO_4$ to be bonding agents, whereas Uehara & Jones (1974) discounted $CaCO_3$ and $CaSO_4$ as cementing agents. Uehara & Jones (1974) stressed that silica was most important in arid and semiarid regions. They also noted the importance of the bonding agent's solubility in water (affecting diffusion to contact points) as well as the equilibrium attained (if any) between the agent's solid phase and dissolved phase.

The dissolution of lime or gypsum does affect soil structure. Exchangeable polyvalent cations (e.g., Ca) near clay particle surfaces reduce the thickness of the diffuse double layer and thus the repulsive forces acting between clay particles (Emerson 1983) and cause strong flocculation of clays and increased resistance to dispersion (the Schultze-Hardy rule). Calcium rather than Mg or K on the exchange complex was associated with stable aggregates in Australian subsoils (Emerson & Bakker 1973). Pojasok & Kay (1990) found aggregate stability to increase with Ca concentrations in soil solution.

Because of the lack of consensus in the literature, the influence of inorganic bonding agents on the aggregate stability of non-sodic soils has been widely studied. For example, Rimmer & Greenland (1976) presented evidence that $CaCO_3$ cemented clay tactoids 0.1 to 0.3 microns apart. Al-Ani & Dudas (1988) found that aggregate 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 the addition of 3% calcium carbonate to a soil had no effect on aggregate stability but that 10% increased it. Others (Kemper & Koch 1966, Shanmuganathan &

Oades 1983, Toogood 1978) found no significant effect due to lime content.

Some of the above inconsistencies were related to the nature and properties of the soils studied. This study was conducted under a uniform set of conditions with six different soils having paired soil properties. Since soils respond differently to the freezing process and to amendments, it was hypothesized that aggregate stability, after freezing, of soils differing in texture, mineralogy, and organic matter would be affected by lime and gypsum additions. A laboratory experiment was designed to test this hypothesis. The objective was to determine the effects of number of freeze-thaw cycles, water content at freezing and the addition of two common inorganic amendments at two agriculturally feasible rates on the aggregate stability of six continental U.S. soils differing in texture, mineralogy, and organic matter.

2 Materials and methods

Samples of six agriculturally important soils (A_p horizons only) were obtained from across the United States. 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 (tab. 1) were determined (Soil Conservation Service Staff 1984) by the personnel of the National Soil Survey and Soil Mechanics Laboratories, Lincoln, NE.

These six soils also differed in properties other than the contrasted primary property (clay content, mineralogy, or organic matter). For any given soil pair, however, the difference between the soils in their primary property was much greater than any difference in a secondary property. For example, the organic matter of the Palouse is 144% greater than that of the Portneuf while the clay content differs by less than half that amount, the clay in the Palouse being only 67% greater than that in the Portneuf. Even so, lesser effects on aggregate stability may be related to differences in other properties among the soil pair.

All soils had a similar cropping and tillage history. In the growing season prior to sample collection, a monocot crop species, either corn, sorghum, or a small grain, 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 fallowed for three to twelve months to allow roots and other organic residue to decompose before sampling.

This study which focused on the effects of lime and gypsum amendments on aggregate stability was similar in experimental approach to but separate from an earlier study (Lehrsch et al. 1991). For this study, a randomized complete block design with three replications and a factorial arrangement of treatments was used. Sources of vari-

Soil type	Particle size distribution Very fine sand %	Total sand %	Silt %	Clay %	Base sat. %	Exch. Ca $cmol_c\ kg^{-1}$	CEC[‡]	Predominant mineral type	pH (in $CaCl_2$)	Organic matter content[§] %
Barnes loam	11	49	34	17	100[†]	—[†]	19.5	2:1	7.1	3.41
Sharpsburg silty clay	3	3	56	41	94	19.4	29.4	2:1	5.4	3.19
Cecil sandy loam	6	67	16	17	87	2.2	3.5	1:1	4.6	1.24
Sverdrup sandy loam	4	76	15	9	100	9.5	11.8	2:1	6.0	2.21
Palouse silt loam	9	10	70	20	82	12.7	19.6	2:1	4.5	3.03
Portneuf silt loam	20	22	66	12	100[†]	—[†]	12.6	2:1	7.8	1.24

[†] Acid-equivalent lime was present.

[‡] Determined using NH_4OAc at pH 7.

[§] As estimated from the organic C content using the Van Bemmelen 1.724 factor.

Tab. 1: *Soil properties.*

ation were soils, number of freeze-thaw cycles, water content, and potential inorganic bonding agents added at two rates. Freeze-thaw cycles were either 0, 1, or 3 with the 0 level signifying no freezing. All samples were constrained in brass cylinders 5 cm high with an inside diameter of 2.75 cm. Before freezing, the water content (qualitatively either low or high) was adjusted to either 0.05 or 0.25 g/g for the coarse-textured Cecil and Sverdrup soil or 0.10 or 0.30 g/g for the remaining soils. For each soil, water contents at matric potentials of -1500 and -33 kPa are given in Elliot et al. (1989). Statistical analyses were performed on arcsin $(x)^{0.5}$-transformed data (to stabilize the variance) using an analysis of variance (SAS Institute, Inc., 1985)[1]. For presentation, the treatment means have been back-transformed to the original scale of measurement. The subsequent results and discussion have focused mainly on three statistically significant interactions that describe the variation in aggregate stability caused by all four factors. Means were separated using confidence intervals constructed to be equivalent to tests of significance at the 5% level. Additional pre-planned, single degree-of-freedom comparisons of selected treatments were also made.

Samples were prepared by sieving field-moist soil (gravimetric water contents at sieving ranged from 7 to 22% and averaged 13%) through a 4-mm sieve. After the soil was sampled in the field, it was not dried but rather stored at field water content in airtight containers at +6°C until analyzed in the laboratory. The moist, freshly sieved soil was coated with powdered reagent-grade $CaCO_3$ or $CaSO_4 \cdot 2H_2O$ (as a potential inorganic bonding agent) at a rate of either 0.2 or 1.0% by weight of oven-dry soil. To coat the soil, the desired mass of $CaCO_3$ or $CaSO_4$ was distributed over all surfaces of a known mass of sieved soil on plastic sheeting. The soil was then thor-

---

[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.

oughly mixed. The water content of the amended soil was then adjusted to either the low or high level. The soils' water content was lowered, if necessary, by evaporating slowly in air or raised using a non-heating vaporizer (Humidifier Model No. 240, Hankscraft, Reedsburg, WI)[1]. Each soil sample was subsequently packed by tapping into a brass cylinder to a dry bulk density of 1.15 g/cm^3. 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 (confirmed by subsequent thermocouple measurements).

All prepared samples were subjected to either 0, 1, or 3 freeze-thaw cycles. One cycle was completed when prepared soil samples were frozen convectively (without access to water) at -14°C for 24 hours, then thawed at +6°C for 48 hours. 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 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 & Rosenau (1986) modified by Lehrsch & Jolley (1989) so that field-moist 1- to 4-mm aggregates were vapor-wetted to 0.30 g/g prior to wet sieving.

3 Results and discussion

3.1 Interaction between soils, freeze-thaw cycles, and water content

In the statistical analysis, freeze-thaw cycle was considered a discrete rather than continuous variable. When freeze-thaw cycle was initially modeled as continuous, a trend whenever statistically identified, was seldom a type that aided interpretation or summarization.

Freeze-thaw cycle effects on aggregate stability (averaged over amendments and addition rates) are illustrated in fig. 1. Large differences in aggregate stability existed from soil to soil even at the same water content. For example, Palouse and Portneuf, two silt loams from the Pacific Northwest, differed in stability by over 30 percentage points after one freeze-thaw cycle at a 10% water content. When frozen at least once, the most stable soils were the Sharpsburg and, to a lesser degree, the Palouse, each having 20% or more clay and over 3% organic matter.

From 0 to 1 freeze-thaw cycle (one occurrence of freezing), aggregate stability generally increased (fig. 1). Others (Mostaghimi et al., 1988, Perfect et al. 1990a and 1990b) have also found aggregate stability to increase with freeze-thaw cycles. This increase in stability was statistically significant ($P<0.05$) at water contents of 0.10 and 0.30 g/g for the Palouse silt loam and at 0.10 g/g for the Barnes loam, two of the three soils highest in organic matter (tab. 1). In contrast, stability decreased significantly only for the low organic matter Portneuf silt loam at 10% with one freeze-thaw cycle.

Several factors may have caused some

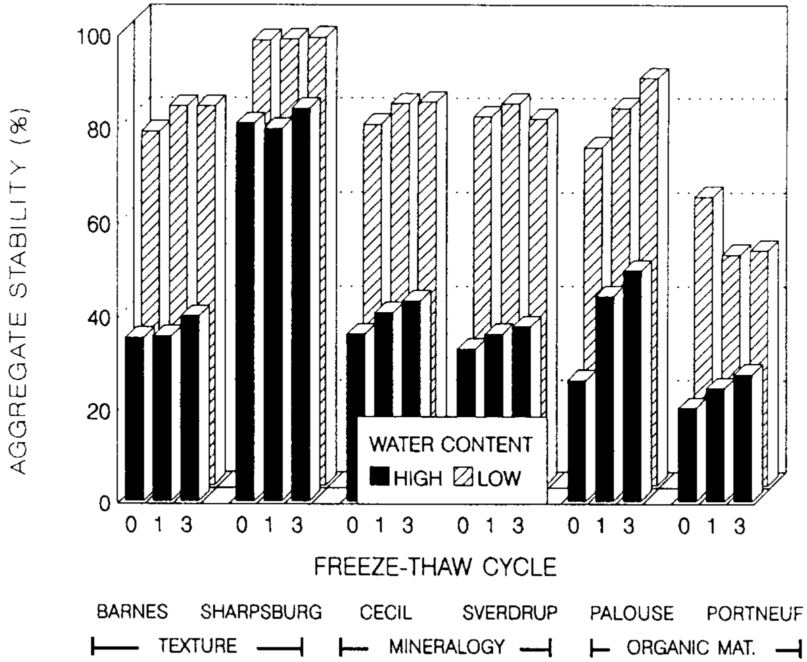

Fig. 1: *Aggregate stability as a function of freeze-thaw cycle for each soil at each water content. The water contents were 5 and 25% (w/w) for the Cecil and Sverdrup soils and 10 and 30% (w/w) for the remaining soils. The first pair of soils differs primarily in texture, the second in mineralogy, and the third in organic matter.*

or all of this increase in stability with freeze-thaw cycle(s). First, particles could have been brought into contact with one another due to ice lens growth. Second, water moving toward a developing ice lens from the soil matrix surrounding and below the lens could have encouraged soil drying (Hoekstra 1966, Miller 1980). This drying could have positioned polysaccharides on soil particle surfaces (Myers 1937; Reid & Goss 1982) and/or precipitated bonding agents at points of contact between soil particles (Kemper et al. 1987; Lehrsch et al. 1991). Third, water flowing to an ice lens would have increased the concentration of ions (notably Ca) in the soil solution near the lens. Once there, the Ca as a counter ion would diffuse into the double layer between clay platelets and help to bond the platelets to each other due to electrostatic attraction (Kemper et al., 1987). Thus, upon thawing, aggregates could have re-formed as well as increased in strength.

As portions of each soil sample dried during the first few freezes, bonding agents from the soil solution likely precipitated at particle-to-particle contact points. This precipitation would have taken place because, as water was removed from the soil below an ice lens, the meniscus at the air-water interface approached a contact point between soil particles. There, due to the agent's concentration exceeding its solubility limit in the unfrozen water film, precipitation could occur, thus bonding the soil particles to one another (Kemper et al. 1974, Wada & Nagasato 1983). Since this bonding probably involved irreversible or slowly reversible reactions (Kemper et al. 1987), these newly precipitated bonding agents did not go back into solution during the subsequent thawing period. As freeze-thaw cycles continued to accrue with additional aggregate reorientation and reshaping, more of the bonding agents that had remained in solution in the thin unfrozen water films surrounding the soil particles (Miller 1980) during the first cycle likely precipitated from the soil solution. This precipitation mechanism and/or Ca's electrostatic bonding of clay platelets mentioned above could account for the often observed gradual increase in stability with freeze-thaw cycles (fig. 1).

The aggregate stability of every soil was greatest at the low water content (0.05 or 0.10 g/g) at every level of freeze-thaw cycle (fig. 1). Moreover, aggregate stability decreased significantly from low to high water contents for all soils at all levels of freeze-thaw cycle. Packing would have weakened the wet aggregates more so than dry aggregates (Formanek et al. 1984). This would account for the observed decrease in the aggregate stability of the samples that were not frozen (freeze-thaw cycle 0). This same weakening may also have accounted for some of the decrease in aggregate stability for the frozen samples (freeze-thaw cycles 1 & 3). However, Lehrsch et al. (1991) presented evidence in their fig. 1 that demonstrated that, even for soil samples that were not subjected to stress by packing, after freezing aggregate stability decreased significantly (i.e., a statistically significant linear trend) with increasing water content. In the frozen samples at the high water content, pressure exerted by expansion of ice crystals within the constrained samples could have developed planes of weakness in the aggregates whose horizontal displacement was limited by the brass cylinder walls. During subsequent wet sieving, these aggregates likely fractured along these planes. The decrease in aggregate stability as water content increased varied from soil to soil. In general, stability decreased most for coarse-textured soils and least for fine-textured soils.

One can compare the two soils differing primarily in organic matter content. Aggregates of a Palouse silt loam (two and one half times as much organic matter as Portneuf, tab. 1) were more stable than aggregates of Portneuf (fig. 1). Elasticity provided by organic matter may have enabled Palouse aggregates at low water contents to withstand ice lens expansion pressures before fracturing. High molecular weight organic molecules, while remaining attached to mineral particles, may be able to unfold or flex to a degree before breaking. In 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 the high water content level.

As mentioned earlier, the high organic matter soils, Barnes and Palouse, usually increased significantly in stability with freeze-thaw cycles. In contrast, the Sverdrup and Portneuf soils (organic matter contents of 2.21% or less and clay contents of 12% or less) in general either decreased in stability or did not

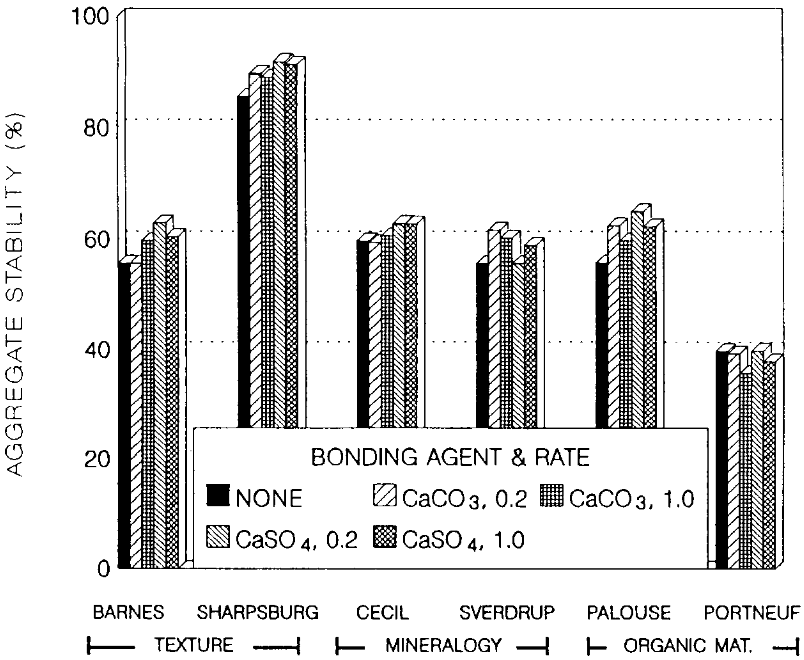

Fig. 2: *Aggregate stability of each soil as a function of bonding agent and rate of addition.*

change significantly with freeze-thaw cycles. The Barnes with its high organic matter content likely had more soluble organic matter (a potential bonding agent) in its soil solution than did the other soils. The quite stable Sharpsburg also exhibited properties (high organic matter content and relatively high base saturation, tab. 1) that could account for relatively high concentrations of bonding agents in solution. Also, the Sharpsburg's high clay content hints that clay platelets, suspended and moving in the soil solution, could form clay bridges between soil particles.

The effects of clay content can also be seen in fig. 1. The soil highest in clay content (Sharpsburg, 41%, tab. 1) had the highest aggregate stability at both water contents. Mostaghimi et al. (1988) found a similar relationship.

3.2 Interaction between soils, bonding agents, and rates of addition

Of particular interest was the influence of $CaCO_3$ and $CaSO_4$ on each soil's aggregate stability (fig. 2). Statistically significant effects of a bonding agent on aggregate stability averaged over freeze-thaw cycles and water contents were identified only for the Sharpsburg. Aggregate stability, when compared to the control, increased significantly ($P<0.05$) when $CaSO_4$ at a rate of 0.2% was added and also when $CaSO_4$ at a rate of 1.0% was added ($P<0.06$). The Sharpsburg

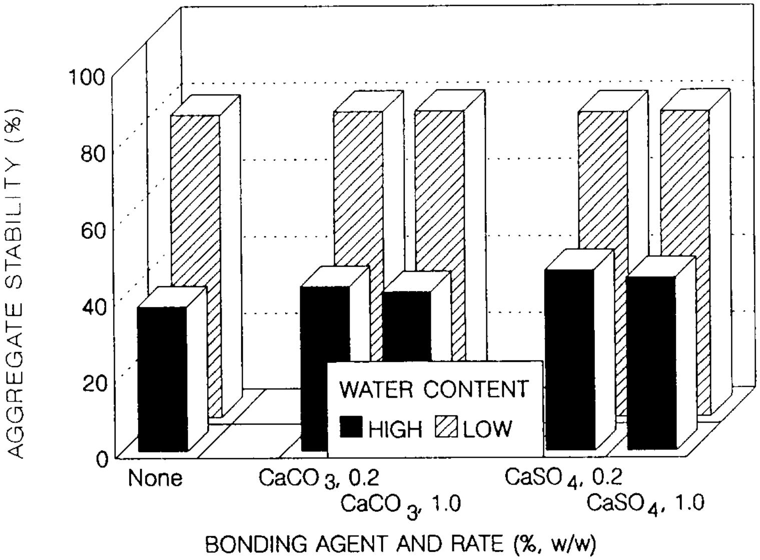

Fig. 3: *Aggregate stability (averaged over soils and freeze-thaw cycles) as a function of bonding agent and rate of addition at each water content. The water contents were 5 and 25% (w/w) for the Cecil and Sverdrup soils and 10 and 30% (w/w) for the remaining soils.*

was fine-textured with less than 100% of its exchange capacity saturated with bases, tab. 1. For five of the six soils, calcium sulfate increased aggregate stability the most, though at a probability level much higher than 0.05. The relative ranking of the two agents and rates was similar only for the two silt loams, Palouse and Portneuf. For the other soil pairs, the rankings were not consistent. On the whole, fig. 2 reveals that, on an individual soil basis, neither of the amendments at either of the applied rates exerted a marked influence on aggregate stability.

Both lime and gypsum additions tended to increase aggregate stability (i.e., strengthen bonds between soil particles) when compared to a control (fig. 2). Though the increases were not significant at the standard 0.05 level, the trend for five of the six soils in this experiment was clearly for stability to increase when either amendment was added. Only for the weakly stable Portneuf silt loam did the addition of potential bonding agents tend to decrease aggregate stability. The Portneuf probably responded differently because it was Ca-saturated initially, tab. 1. As such, it was among the least affected by the addition of the Ca-containing bonding agents. Complete base saturation of the exchange complex does not entirely explain this phenomenon, however, because the Barnes and Sverdrup also had base saturations of 100% yet showed improvements in stability with bonding agent additions, fig. 2.

3.3 Interaction between water contents, bonding agents, and rates of addition

When averaged over soils and freeze-thaw cycles, at the low water content, bonding agents and addition rates did not affect aggregate stability (fig. 3). At the high water content, however, the addition of $CaSO_4$ increased stability over that of the control. When gypsum was added at a rate of 1.0%, the increase was significant at $P<0.072$ and when added at a rate of 0.2%, the increase was significant at $P<0.05$. Shanmuganathan & Oades (1983) found gypsum application rates of 0.2% (w/w) to coagulate clay and thus encourage aggregate formation. For soil management, they recommended annual gypsum additions of 0.2% rather than higher rates.

In this experiment, the aggregate stability (averaged over freeze-thaw cycles) of soil samples at relatively high water contents having received either lime or gypsum, was increased more by calcium sulfate than calcium carbonate (fig. 3). This could well be attributed to $CaSO_4$ being more soluble (well over 150 times as soluble in water) than $CaCO_3$. More gypsum could have dissolved in the soil solution where the Ca could have moved by mass flow to the enlarging ice lens. Once there, due to solute exclusion upon water freezing (Miller 1980), it could have precipitated as $CaSO_4$ or some other Ca-containing molecule at points of contact between soil particles or clay domains (Rimmer & Greenland 1976), thus strengthening bonds within aggregates. Perfect et al. (1990b) detected both water and solute (Ca) movement to freezing zones of a medium-textured soil. They found as well that Ca minimized dispersion and was thus implicated as compressing the diffuse double layer surrounding clay particles. This double layer compression could permit electrostatic bonding by Ca of adjacent clay platelets, as mentioned above.

Other studies provide additional evidence of gypsum being more effective than lime as a soil additive. Shanmuganathan & Oades (1983) found exchangeable Ca to be increased more by $CaSO_4$ than by $CaCO_3$. Uehara & Jones (1974) expected gypsum to be more effective than lime as a soil amendment because $CaSO_4$ raised neither soil pH nor surface charge density.

Though the differences in stability between addition rates within a bonding agent averaged over all six soils were not significant at the 0.05 level, aggregate stability decreased consistently with increasing bonding agent addition rates. One may speculate why this would occur. Three explanations can be offered. First, supersaturation seldom occurs when a compound is present in a solution at a concentration greatly exceeding its solubility limit. At the lower rate (slightly over the solubility limit), the soil solution may have been supersaturated with Ca. As a consequence, more Ca moved in the water stream to the ice lens, there to be precipitated. In contrast, at the higher rate (far above the solubility limit), no supersaturation occurred and less Ca was transported via mass flow. Second, at the higher rate a much greater proportion of the bonding agent would have been present as undissociated molecules or discrete particles. It was likely much more difficult for these relatively large particles to pass through the unfrozen water films and come to rest at the particle contact points. Third, with increasing addition rates, precipitated lime or gypsum molecules rather than Ca ions alone may have occurred between clay platelets or clay domains. The resultant weak Ca-lime or lime-lime van der Waals bonds so formed were thus broken more easily than the stronger Ca-clay electrostatic bonds formed at the low addition rates. In other words, at the higher rates, the bonding forces per unit of separation distance were weaker than at the lower rates.

3.4 Additional single degree-of-freedom comparisons

Statistical comparisons of the two soils in each pair were made using single degree-of-freedom contrasts. Without exception, the soils differing in texture (Barnes and Sharpsburg) and the soils differing in organic matter (Palouse and Portneuf) responded differently to both freeze-thaw cycles at each level of water content and also to bonding agents and rates of addition. In contrast, the mineralogically dissimilar Cecil and Sverdrup responded alike. Thus, as figs. 1 and 2 imply, texture and organic matter significantly affected aggregate stability in this experiment. Mineralogical differences, however, had little influence.

3.5 Results in relation to others' findings

The results of this investigation are similar in many but not all respects to the results obtained by other investigators. The finding of this study that aggregate stability increases with at least the first freeze-thaw cycle (the Barnes and Palouse data of fig. 1) is supported by the results of Mostaghimi et al. (1988) for a Crofton silt loam (fine-silty, mixed, mesic Typic Ustorthent) with 0.5% organic matter. On the other hand, Mostaghimi et al. (1988) reported decreases in stability with the first freeze-thaw cycle 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. 1). When, as in this study, soils are not air-dried prior to analysis, this increase in stability with freeze-thaw cycles may commonly occur (Lehrsch et al., 1991). The finding 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 & Koch (1966), and Toogood (1978) but disagrees with those of Al-Ani & Dudas (1988). There were, however, differences in both soils and procedures between the study of Al-Ani & Dudas (1988) and this study. The soil samples used by Al-Ani & Dudas (1988) were from the BC horizons of two soils with clay contents of 32 or 42% whereas the soil samples used in this study were from the A_p horizons of soils generally with much less clay (tab. 1). The pH values and/or ions present on the clays were also surely different. Procedurally, air-dry soil and 4- to 8-mm aggregates were used by Al-Ani & Dudas (1988) while field-moist soil and 1- to 4-mm aggregates were used here. A number of the earlier studies that found $CaCO_3$ to affect aggregate stability used very high calcium carbonate application rates. The application rates considered in this investigation were more feasible for agricultural production.

4 Conclusions

Soil texture and organic matter, but not mineralogy, affected aggregate stability after freezing. The stability of field-moist aggregates usually increased with at least the first freeze-thaw cycle. The addition of either lime or gypsum tended to increase aggregate stability, but at a probability level much higher than 0.05. At low water contents, neither potential bonding agents nor addition rates affected aggregate stability after freezing. In contrast, at high water contents, $CaSO_4$ added at a rate of 0.2% by weight significantly increased aggregate stability over that of a control. The one response most consistent throughout the experiment was that aggregate stability decreased significantly with increasing water content at the time of freezing.

Acknowledgement

The authors gratefully acknowledge the contributions of Dr. Russ Bruce, Dr. John Gilley, Dr. Hans Kok, and Dr. Bob Young for initial soil sampling and of Miss Michelle Garrison, Miss Tonya Pearson, Mr. Ron Peckenpaugh, and Miss Deb Watkins for sample preparation and laboratory analyses.

References

AL-ANI, A.N. & DUDAS, M.J. (1988): Influence of calcium carbonate on mean weight diameter of soil. Soil Tillage Research **11**, 19-26.

BRYAN, R.B. (1971): The influence of frost action on soil aggregate stability. Transactions of the Institute of British Geographers **50**, 71-88.

BULLOCK, M.S., KEMPER, W.D. & NELSON, S.D. (1988): Soil cohesion as affected by freezing, water content, time and tillage. Soil Science Society of America Journal **52(3)**, 770-776.

CHEPIL, W.S. (1954): Factors that influence clod structure and erodibility of soil by wind. III. calcium carbonate and decomposed organic matter. Soil Science **77(6)**, 473-480.

ELLIOT, W.J., LIEBENOW, A.M., LAFLEN, J.M. & KOHL, K.D. (1989): A compendium of soil erodibility data from WEPP cropland soil field erodibility experiments 1987 & 88. NSERL Report No. 3. USDA-ARS National Soil Erosion Research Laboratory, W. Lafayette IN.

EMERSON, W.W. (1983): Inter-particle bonding. In: Division of Soils, CSIRO, Melbourne, Australia. Soils: an australian viewpoint. Academic Press, London, 477-498.

EMERSON, W.W., & BAKKER, A.C. (1973): The comparative effects of exchangeable calcium, magnesium, and sodium on some physical properties of red-brown earth subsoils. II. the spontaneous dispersion of aggregates in water. Australian Journal of Soil Research **11**, 151-157.

FORMANEK, G.E., McCOOL, D.K., & PAPENDICK, R.I. (1984): Freeze-thaw and consolidation effects on strength of a wet silt loam. Transactions of the American Society of Agricultural Engineers **27(6)**, 1749-1752.

HOEKSTRA, P. (1966): Moisture movement in soils under temperature gradients with the cold-side temperature below freezing. Water Resources Research **2**, 241-250.

KEMPER, W.D., EVANS, D.D. & HOUGH, H.W. (1974): Crust strength and cracking: Part I. strength. In: J. W. Cary & D. D. Evans (eds.), Soil crusts. Arizona Agricultural Experiment Station Technical Bulletin **214**, 31-38.

KEMPER, W.D. & KOCH, E.J. (1966): Aggregate stability of soils from western United States and Canada. U.S. Department of Agriculture Technical Bulletin 1355. U.S. Government Printing Office, Washington DC, 52 pp.

KEMPER, W.D. & ROSENAU, R.C. (1986): Aggregate stability and size distribution. In: A. Klute (ed.), Methods of soil analysis, Part 1. Agronomy Monograph, No. **9**, 425-442.

KEMPER, W.D., ROSENAU, R.C. & DEXTER, A.R. (1987): Cohesion development in disrupted soils as affected by clay and organic matter content and temperature. Soil Science Society of America Journal **51**, 860-867.

LEHRSCH, G.A., & JOLLEY, P.M. (1989): Temporal variation in the aggregate stability of 14 U.S. soils. In: Agronomy abstracts. American Society of Agronomy, Madison WI, 284.

LEHRSCH, G.A., SOJKA, R.E., CARTER, D.L. & JOLLEY, P.M. (1991): Freezing effects on aggregate stability affected by texture, mineralogy, and organic matter. Soil Science Society of America Journal **55(5)**, 1401–1406.

LOGSDAIL, D.E. & WEBBER, L.R. (1959): Effect of frost action on structure of Haldimand clay. Canadian Journal of Soil Science **39**, 103-106.

MILLER, R.D. (1980): Freezing phenommena in soils. In: D. Hillel (ed.), Applications of soil physics. Academic Press, New York NY, 254-299.

MOSTAGHIMI, S., YOUNG, R.A., WILTS, A.R. & KENIMER, A.L. (1988): Effects of frost action on soil aggregate stability. Transactions of the American Society of Agricultural Engineers **31(2)**, 435-439.

MYERS, H.E. (1937): Physicochemical reactions between organic and inorganic soil colloids as related to aggregate formation. Soil Science **44**, 331-359.

PERFECT, E., KAY, B.D., VAN LOON, W.K.P., SHEARD, R.W. & POJASOK, T. (1990a): Rates of change in soil structural stability under forages and corn. Soil Science Society of America Journal **54**, 179-186.

PERFECT, E., VAN LOON, W.K.P., KAY, B.D. & GROENEVELT, P.H. (1990b): Influence of ice segregation and solutes on soil structural stability. Canadian Journal of Soil Science **70**, 571-581.

POJASOK, T. & KAY, B.D. (1990): Effect of root exudates from corn and bromegrass on soil structural stability. Canadian Journal of Soil Science **70**, 351-362.

REID, J.B. & GOSS, M.J. (1982): Interactions between soil drying due to plant water use and decreases in aggregate stability caused by maize roots. Journal of Soil Science **33**, 47-53.

RICHARDSON, S.J. (1976): Effect of artificial weathering cycles on the structural stability of a dispersed silt soil. Journal of Soil Science **27(3)**, 287-294.

RIMMER, D.L. & GREENLAND, D.J. (1976): Effects of calcium carbonate on the swelling behavior of a soil clay. Journal of Soil Science **27**, 129-139.

SAS INSTITUTE, INC. (1985): SAS/STAT guide for personal computers. 6th ed. SAS Institute, Inc., Cary NC, 378 pp.

SHANMUGANATHAN, R.T. & OADES, J.M. (1983): Modification of soil physical properties by addition of calcium compounds. Australian Journal of Soil Research **21**, 285-300.

SILLANPAA, M. & WEBBER, L.R. (1961): The effect of freezing-thawing and wetting-drying cycles on soil aggregation. Canadian Journal of Soil Science **41**, 182-187.

SOIL CONSERVATION SERVICE STAFF (1984): Procedures for collecting soil samples and methods of analysis for soil survey. USDA-SCS Soil Survey Invest. Rep. No. 1. U.S. Government Printing Office, Washington DC.

TOOGOOD, J.A. (1978): Relation of aggregate stability to properties of Alberta soils. In: W.W. Emerson, R.D. Bond & A.R. Dexter (eds.), Modification of soil structure. John Wiley and Sons, Inc., Chichester, 211-214.

UEHARA, G. & JONES, R.C. (1974): Bonding mechanisms for soil crusts: Part I. particle surfaces and cementing agents. In: J.W. Cary & D.D. Evans (eds.), Soil crusts. Arizona Agricultural Experiment Station Technical Bulletin **214**, 17-28.

WADA, S.A. & NAGASATO, A. (1983): Formation of silica microplates by freezing dilute silica acid solutions. Soil Science and Plant Nutrition **29**, 93- 95.

Address of authors:
Dr. G.A. Lehrsch
Dr. R.E. Sojka
Ms. P.M. Jolley
USDA-Agricultural Research Service
Soil and Water Management Research Unit
3793 N 3600 E
Kimberly, ID 83341
U.S.A.