Reprinted from the *Soil Science Society of America Journal*
Volume 52, no. 3, May–June 1988
677 South Segoe Rd., Madison, WI 53711 USA

Soil Cohesion as Affected by Freezing, Water Content, Time and Tillage

M.S. BULLOCK, W.D. KEMPER, AND S.D. NELSON

Soil Cohesion as Affected by Freezing, Water Content, Time and Tillage

M.S. BULLOCK, W.D. KEMPER,* AND S.D. NELSON

ABSTRACT

This study was developed to determine whether there are substantial annual changes in soil cohesion and to identify major factors causing those changes. Aggregate stability was measured throughout the year on soils in Utah and Idaho using wet sieving techniques. Stability generally increased during spring and summer months. Major decreases of cohesion, found when minimum daily air temperatures fell to or below 0 °C during winter and early spring months, were attributed to pressures and associated shearing forces caused by freezing at high water contents. Equivalent disruption occurred when confined soils were frozen in controlled laboratory studies. Disruption also increased as water content at the time of freezing increased for all soils studied. Disruption of soil by rototilling and compaction significantly decreased soil cohesion.

Additional Index Words: **Aggregate stability, Compaction, Disruption, Seasonal change, Bond destruction, Bond formation.**

SEVERELY DISRUPTED SOILS slowly regain their cohesion over a period of weeks or months depending on the water content of the soil (Blake and Gilman, 1970; Utomo and Dexter, 1981; Kemper and Rosenau, 1984). Rapid drying of moist disrupted soils increases particle-to-particle associations, but time and moisture are still needed for enduring bonds to develop (Kemper et al., 1987). Cohesion of soils is thus a function of the degree of disruption, time since disruption, and the interim water content.

Slater and Hopp (1949) noted reductions in stability due to freezing. Gish and Browning (1948) noted a small increase in aggregate stability of cultivated soil during the spring months, but their method of directly immersing dry aggregates destroyed most of the aggregates and there was question as to whether the small increases noted were significant.

Alderfer (1946) ran stability determinations on samples at field moisture contents. Since these water contents tend to be higher during the winter and spring months, and since higher water contents prior to immersion decrease disruption, the results were confounded. Most investigators (Gish and Browning, 1948; Slater and Hopp, 1949; Alderfer, 1946; Logsdail and Webber, 1959; Imeson and Vis, 1984) dried their samples before making stability measurements which increases the stability and decreases the sensitivity of the measurement of cohesion compared to differences which could have been observed if the soils had been kept at field moisture and vapor wetted to a standard high water content (e.g., 0.30 kg H_2O kg^{-1} soil) immediately prior to wet sieving.

Processes which can cause seasonal increases or decreases in soil cohesion and literature documenting most of these processes are given in Fig. 1.

Originally this study was proposed to evaluate decreases in cohesion due to tillage. As these initial studies progressed through the spring and summer, cohesion of the check soils with no tillage was also increasing significantly. Consequently, this study was expanded to include a year-round evaluation of soil cohesion including relationships with freezing, water content, time, and tillage of three western U.S. soils.

MATERIALS AND METHODS

Soils and Sites

Soil samples were taken from the cultivated layers of Portneuf silt loam (coarse-silty, mixed, mesic, Xerollic Calciorthids), Timpanogos loam (fine-loamy, mixed, mesic, Calcic, Argixerolls), and Walla Walla silt loam (coarse-silty, mixed, mesic, Typic Haploxerolls) series. The Portneuf silt loam in southcentral Idaho is a wind-deposited soil composed of about 20% sand, 60% silt, and 20% clay. An intensively row-cropped irrigated field was disked in the fall and left idle until experimental treatments were performed in the spring.

The Timpanogos loam series in northcentral Utah is composed of about 40% sand, 35% silt, and 25% clay. The site selected for sampling was an intensively row-cropped irrigated field.

The Walla Walla silt loam was from plots in a dry-farm area in eastern Oregon and is composed of 25% sand, 55% silt, and 20% clay. Both plots from which samples were taken had been in wheat-fallow rotations for 50 yr. On plot 16 of the Walla Walla soil, the stubble was burned and on plot 18 manure was added at a rate of 22 t ha^{-1} each growing season (for details see Pikul and Allmaras, 1986).

Freezing

Unconstrained Aggregates at Various Soil Water Contents

Aggregates 1 to 2 mm in diameter were sieved from dried field samples of Portneuf silt loam, Timpanogos loam, and Walla Walla silt loam. Four-gram samples were placed on sieves and exposed to a flow of air carrying water vapor until the desired moisture contents indicated in Fig. 1 were achieved. The sieves were then placed on an 1.6-mm thick Al plate, in an insulated box, and placed in a freezer for 24 h at − 10 °C. Aggregate stabilities were measured after thawing and vapor wetting to at least 0.30 kg kg^{-1} prior to wet sieving by the Kemper and Rosenau (1986) method.

Constrained and Unconstrained Soil Cores

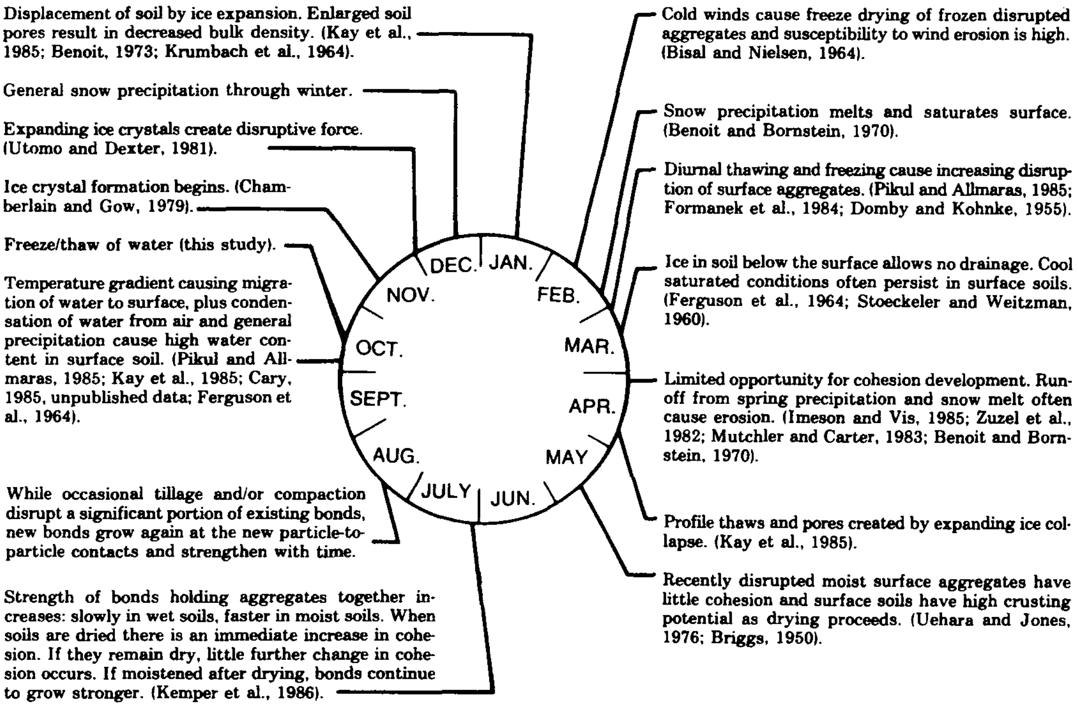
Three undisturbed cores were taken, immediately adjacent to each other in the Portneuf silt loam field. These cores were 15-cm long and 15-cm in diameter and were initially collected in open-ended PVC pipe. One of these cores was kept in its pipe at laboratory temperature and field water content.

The second was kept constrained in its PVC pipe where holes drilled at various depths allowed insertion of thermocouples into the soil to record temperature. The bottom of this soil sample was placed on a supporting screen in a pan containing water. The soil, PVC cylinder, and pan of water were placed in a styrofoam box and surrounded with styrofoam beads to the top surface of the soil which was left

---

M.S. Bullock and S.D. Nelson, Dep. of Agronomy and Horticulture, Brigham Young Univ., Provo, UT; and W.D. Kemper, formerly at USDA-ARS, Kimberly, ID, now at USDA-ARS-NPS, Beltsville, MD 20705. Joint contribution from the USDA-Agric. Res. Serv., Kimberly, ID, and Brigham Young Univ., Provo, UT. Received 26 Mar. 1987. *Corresponding author.

Published in Soil Sci. Soc. Am. J. 52:770–776 (1988).



Displacement of soil by ice expansion. Enlarged soil pores result in decreased bulk density. (Kay et al., 1985; Benoit, 1973; Krumbach et al., 1964).

General snow precipitation through winter.

Expanding ice crystals create disruptive force. (Utomo and Dexter, 1981).

Ice crystal formation begins. (Chamberlain and Gow, 1979).

Freeze/thaw of water (this study).

Temperature gradient causing migration of water to surface, plus condensation of water from air and general precipitation cause high water content in surface soil. (Pikul and Allmaras, 1985; Kay et al., 1985; Cary, 1985, unpublished data; Ferguson et al., 1964).

While occasional tillage and/or compaction disrupt a significant portion of existing bonds, new bonds grow again at the new particle-to-particle contacts and strengthen with time.

Strength of bonds holding aggregates together increases: slowly in wet soils, faster in moist soils. When soils are dried there is an immediate increase in cohesion. If they remain dry, little further change in cohesion occurs. If moistened after drying, bonds continue to grow stronger. (Kemper et al., 1986).

Cold winds cause freeze drying of frozen disrupted aggregates and susceptibility to wind erosion is high. (Bisal and Nielsen, 1964).

Snow precipitation melts and saturates surface. (Benoit and Bornstein, 1970).

Diurnal thawing and freezing cause increasing disruption of surface aggregates. (Pikul and Allmaras, 1985; Formanek et al., 1984; Domby and Kohnke, 1955).

Ice in soil below the surface allows no drainage. Cool saturated conditions often persist in surface soils. (Ferguson et al., 1964; Stoeckeler and Weitzman, 1960).

Limited opportunity for cohesion development. Runoff from spring precipitation and snow melt often cause erosion. (Imeson and Vis, 1985; Zuzel et al., 1982; Mutchler and Carter, 1983; Benoit and Bornstein, 1970).

Profile thaws and pores created by expanding ice collapse. (Kay et al., 1985).

Recently disrupted moist surface aggregates have little cohesion and surface soils have high crusting potential as drying proceeds. (Uehara and Jones, 1976; Briggs, 1950).

Fig. 1. Seasonal processes that affect aggregate stability.

exposed. This whole assembly was put in a freezer for 2 d where freezing occurred at temperatures of −5 °C to −10 °C.

The third core was removed from its pipe and then treated, wetted, and frozen in a manner identical to the second cylinder. After 2 d in the freezer, the frozen soil cores were placed on absorbent towels and allowed to thaw and drain for 1 d. The three cores were then sliced into 25-mm thick increments, and air dried. The 1- to 2-mm diameter aggregates were separated, vapor wet to 0.30 kg kg^{-1}, and aggregate stabilities were determined by the Kemper and Rosenau (1986) procedure.

Tillage and Compaction

Timpanogos loam tillage treatments included no-till and rototill and their respective packed counterparts on the two plots mentioned above. Packing was done immediately following the tillage operation with one pass of the front and rear tractor wheels perpendicular to the rototill direction. Samples were taken in the tracked and nontracked areas to the depth of the rototill tillage.

Samples were transported immediately to the laboratory (30 min) and moisture contents were determined gravimetrically. A subsample of the field moist soil was then gently sieved to obtain 1- to 2-mm aggregates for stability measurements (Kemper and Rosenau, 1986). These field moist aggregates (approx. 0.15 kg kg^{-1}) were vapor wet to 0.30 kg kg^{-1} prior to immersion to eliminate the disruptive effects of entrapped air which is a primary factor affecting aggregate stability. Following wet sieving, the amount of stable aggregates remaining on the sieves was determined. The fraction of stable aggregates was calculated from the weight of aggregates left on the 0.26-mm sieve divided by the total weight of soil in the sample. This total weight included both unstable aggregates that had passed through the sieve during wet sieving and stable aggregates that were disrupted by ultrasonic vibration to pass through the sieve following the wet sieving.

Another subsample of the field moist soil was spread out on plastic sheeting in the laboratory and fan dried at 32 °C to 0.02 kg H_2O kg^{-1} soil within 2 hr. Aggregates 1- to 2-mm in diameter were then separated, vapor wet to 0.30 kg kg^{-1} and wet sieved.

Field moist soil from the tillage treatments described above was also stored in plastic garbage cans and aggregate stabilities were measured after 7 d to evaluate how rapidly the soil was regaining its cohesion.

Seasonal Variation of Aggregate Stability

Timpanogos Loam

Soil samples from the Timpanogos loam series were taken about once a month for a year from a no-till plot in north-central Utah. A 5-cm diameter core sampler was used to randomly sample a 2 m^2 plot to a depth of 11 cm. The sampler tube was formed by brass rings inside the sampler which allowed separation of the soil sample into the 0- to 2-cm, 2- to 5-cm, 5- to 8-cm, and 8- to 11-cm depths. The soil in each of these ring increments was pushed out of the rings (after thawing, if frozen at sampling), broken into smaller aggregates, and placed in a sealable plastic container for transport to the laboratory. Moisture contents were determined within 30 min after sampling.

The 1- to 4-mm aggregates were separated to measure aggregate stability. These aggregates were vapor wet to 0.30 kg kg^{-1}, if their original field water content was below this level, and then their stabilities were measured.

Portneuf Silt Loam

Random samples of Portneuf silt loam were taken about once a month to a 15-cm depth from an intensively cropped field in southcentral Idaho. The samples were spread out on plastic sheeting and dried with an air stream in the greenhouse. When the samples reached air dryness, they were gently crushed, sieved, and the 1- to 2-mm aggregates were retained. Duplicate samples of these aggregates were left at air dryness while other pairs of samples were vapor wetted to water contents of 0.05, 0.10, 0.15, 0.20, and 0.30 kg kg^{-1} and the aggregate stabilities determined by wet sieving.

RESULTS AND DISCUSSION

Effects of Soil Water Content on Aggregate Disruption Caused by Freezing

Freezing aggregates when they were air dry did not significantly decrease their stability (Fig. 2). Stability decreased substantially when aggregates of soils were frozen at water contents greater than 0.20 kg kg^{-1}. Manuring the Walla Walla plot 18 gave the soil appreciably higher stabilities than soil from Walla Walla plot 16 which had received no manure and on which the stubble had been burned during the last 50 yr. As water content at time of freezing increased, disruption of the aggregates increased for all of the soils studied. Benoit (1973) showed similar results for soils in Maine. Forces disrupting these aggregates were probably a result of ice crystals expanding in pores between particles, breaking particle-to-particle bonds, and effectively splitting the aggregates into smaller aggregates, some of which were small enough to pass through the 0.26-mm holes in the sieve screen. Lack of disintegration as low water content soils froze indicated that the ice crystals completed their growth in the pores before they could apply significant disruptive force on the soil matrices that constitute the walls of these pores.

In the fall, rapid cooling of the soil surface induces temperature gradients which causes migration of moisture to the surface from deeper soil. Atmospheric moisture also accumulates on the cool soil surface by condensation from the warmer air (Kay et al., 1985; Pikul and Allmaras, 1985; and J.W. Cary, 1985, unpublished data). Persistence of such temperature conditions in a soil commonly increases the water content of the surface to high levels where freezing causes disintegration, even in relatively dry climates.

Effect of Confinement During Freezing on Aggregate Disruption

Aggregate stabilities of Portneuf silt loam soil as a function of depth in the profile are shown in Fig. 3 for aggregates from the interior of three cylinders of soil, each of which was initially 15-cm in diameter and depth. Two of these cylinders were frozen, one of which was contained in a section of PVC pipe which allowed expansion in only one dimension while the other was free to expand in all three dimensions. Both were frozen slowly with water available from a reservoir at the bottom of the soil column. Aggregates from the confined soil core were disrupted more than those from the unconfined soil core (i.e., compare bottom two lines in Fig. 3). Three-dimensional expansion of the unconfined core resulted in less compacting pressure than in the core constrained by the PVC pipe, where swelling in the vertical dimension ranged from 1 to 2 cm depending on final soil water content as freezing of the system occurred.

Compression in a confined zone in a freezing soil occurs as a result of migration of water to that zone and expansion of that water which accompanies its phase change. Pressures upwards of 1.4 × 10^4 kPa have been recorded when ice formation occurs in confined areas (e.g., Brady, 1984). Kay et al. (1985) reported frost heave due to either freezing of saturated soils or migration of water table moisture to the frozen zone resulting in the formation of large ice crystals.

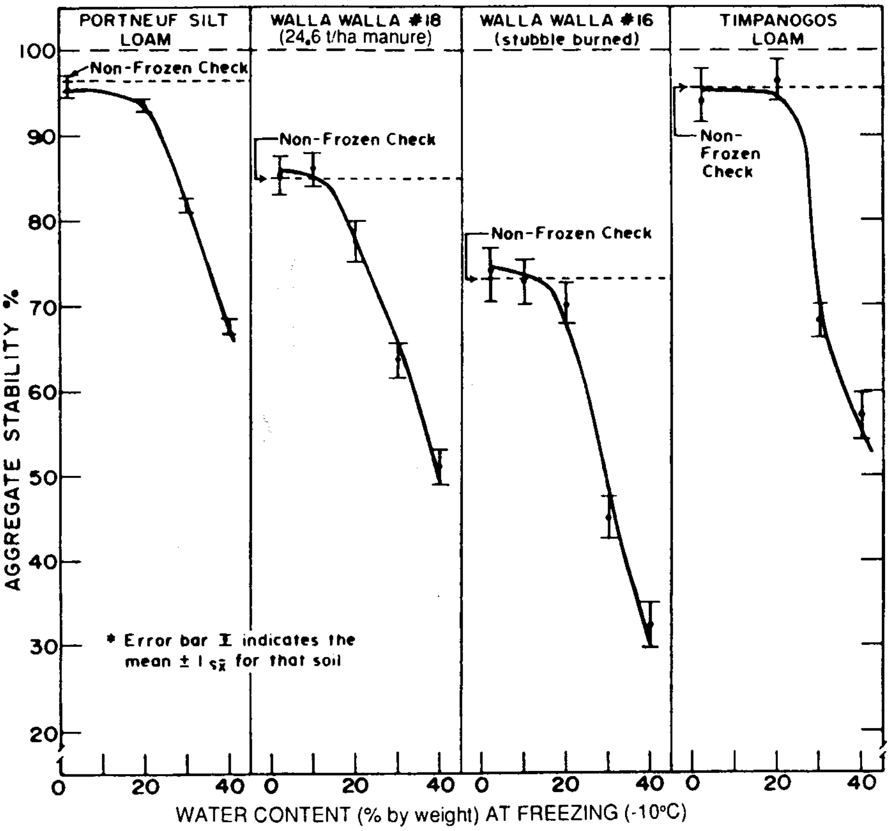


Fig. 2. Aggregate stability response to freezing at various water contents.

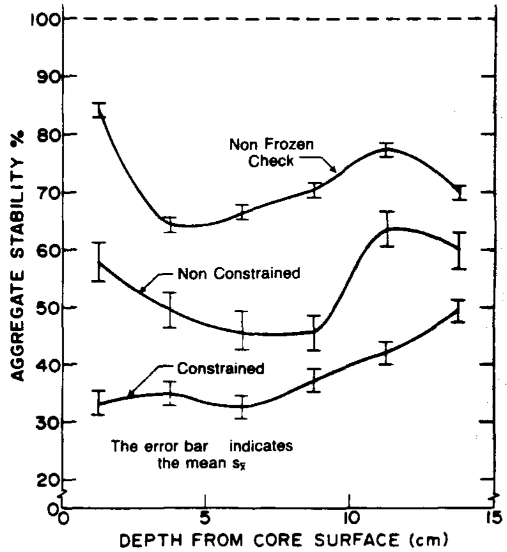


Fig. 3. Aggregate stability following freezing of wet constrained and non-constrained Portneuf silt loam cores as a function of depth compared to stabilities in an unfrozen core. (All samples were air dried and vapor wetted to 0.3 kg H_2O kg $^{-1}$ soil prior to wet sieving.).

In this soil, freezing under confined conditions caused more destruction of the bonds holding aggregates together than was caused by tillage and/or tractor tire compaction (compare Fig. 3 and samples dried prior to analysis in Fig. 4).

Aggregates at field moisture contents from the Timpanogos soil had significantly reduced stability after the soil was rototilled (Fig. 4). Packing by the tractor wheels also substantially reduced the stability of aggregates in the tilled soil. Rototilling was selected as the form of tillage because a preliminary study indicated plowing and disking caused less disruption and their effects on subsequent aggregate stability were more difficult to quantify than those of rototilling. Since tractor wheel compaction caused disruption of tilled soil that was practically as great as the effect of the rototilling, it appears probable that the passage of tractor wheels over recently plowed fields during disking, etc. causes more disruption of aggregating bonds than the tillage operations per se.

Effects of Tillage and Compaction on Aggregate Disruption

When this soil was air dried immediately following disruption, there were substantial immediate increases of stability (Fig. 4). Particles were probably pulled into direct contact as soil water tension increased and then cemented together by slightly soluble binding agents which accumulated at contact points and precipitated there as the soil dried. Moist Timpanogos soil gained appreciable cohesion during the week following disruption by tillage and compaction (Fig. 4). After the soil dried, significant changes in cohesion did not occur during a 1-week period. However, initial air drying followed by remoistening has resulted in rapid and continued recovery of cohesion (e.g., Kemper et al., 1987).

Seasonal Changes in Soil Cohesion

Figures 5 and 6 show loss of cohesion during fall and winter with subsequent development of cohesion during the spring and summer of the Timpanogos soil from near Spanish Fork, UT, and of the Portneuf soil from near Twin Falls, ID, respectively. Daily minimum air temperatures were available from weather stations near both locations and are plotted for the Utah location in Fig. 5. At both locations, November and December were colder than normal and there were also times during January, February, and March when the soil was not frozen.

In the Timpanogos loam (Fig. 5), there was a rapid decline of soil aggregate stability as the minimum daily

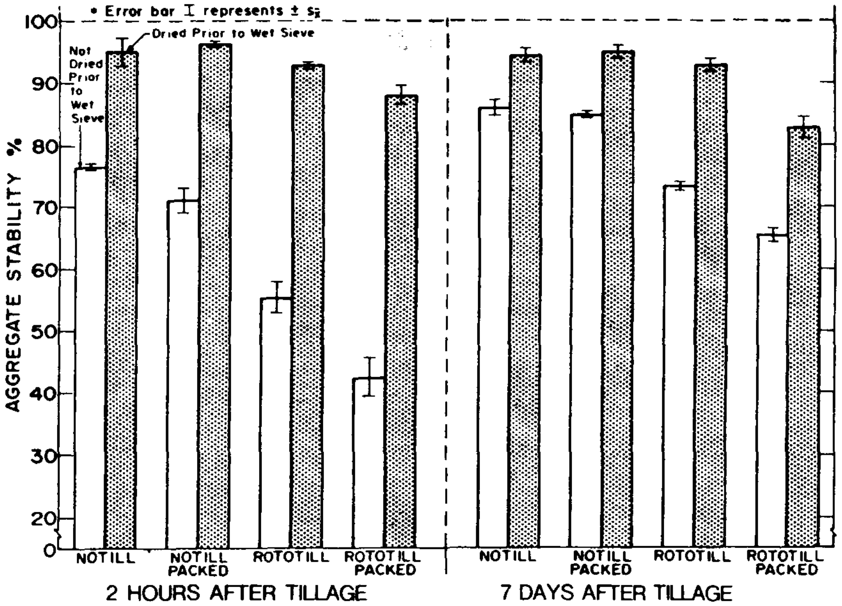


Fig. 4. Aggregate stability of Timpanogos loam 2 h after and 7 d after tillage. (Comparing air drying soil (0.02 kg kg $^{-1}$) vs. leaving soil at field moisture (0.15 kg kg $^{-1}$) before vapor wetting to 0.30 kg kg $^{-1}$ prior to wet sieving).

air temperatures dropped below 0 °C. During October, air temperatures dropped below 0 °C on only a few nights, but there was a large decrease in aggregate stability. This large decrease may result partially from air temperatures at the soil surface being considerably colder than the indicated weather station temperatures which are measured 1.5 m above the ground (R.A. Kohl, 1987, private communication). This tendency for surface soil temperature to be lower than air temperature may amount to several degrees when there is no wind at night. Most of the fluctuations of aggregate stability through the winter season are probably attributable to subsequent cohesion recovery during nonfreezing periods and disintegration when minimum soil temperatures dropped below 0 °C. For example, abnormally cold and freezing temperatures in late November preceded the December 6 sampling date when some of the lowest aggregate stabilities were measured.

The stability increase noted for 7 February followed a few days of nonfreezing temperatures in late January when cohesion recovery may have been occurring. However, on 7 February, the soil was near saturation and it was practically impossible to separate 1- to 2-mm aggregates for wet sieving. Consequently, larger wet masses of soil were used. The resulting stability measures were highly variable and the apparent increase in stability was of questionable significance. Several frost-free days preceded the 7 March sampling when a stability increase was recorded. The decrease in stability for the 4 April sample may have been a result of freezing surface soil temperatures which accompanied the 0 °C air temperatures on 2 April. The drop in average stability on this date of the 0 to 11 cm soil depth was primarily a result of a substantial drop in stability of aggregates from the 0 to 2 cm soil depth, which would be most vulnerable to slight freezing.

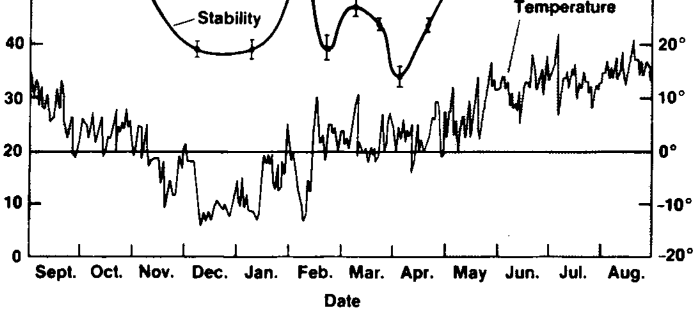


Fig. 5. Seasonal variation (1985–86) of aggregate stability of Timpanogos loam (Average for 11-cm profile of stabilities determined by leaving aggregates at field moisture prior to vapor wetting to 0.30 kg kg $^{-1}$ and wet sieving).

Thawing aggregates stay wet during cool spring weather. Under these conditions, molecular layers of water between particles persist and prevent particle-to-particle contact that is essential to initiation of bonding. Kemper et al. (1987) also showed that cool soils regain cohesion much more slowly than warm soils. Recently frozen moist, cool soils are highly vulnerable to water erosion (Zuzel et al., 1982; Imeson and Vis, 1984).

Following the last freeze on 28 April, warm weather increased evaporation while also initiating plant growth and transpiration. Resultant drying increased pore water tension and increased particle-to-particle contacts. Subsequent rains provided water which probably solubilized cementing agents from slightly soluble minerals and facilitated their diffusion to contact points where they bonded between adjacent soil particles and increased cohesion (e.g., Kemper et al., 1987). This increase in stability was particularly rapid during the 50 d following the last freeze.

Aggregates of Timpanogos loam used in the seasonal stability determinations (Fig. 5) were not allowed to air dry prior to vapor wetting and wet sieving because drying strengthens bonds and tends to overshadow stability differences due to treatments (i.e., Fig. 4). Since water contents of the samples fluctuated with the seasons, aggregates were brought to water contents of at least 0.30 kg kg^{-1} by exposing them to an air stream carrying water vapor to make the measured stabilities comparable.

The lines in Fig. 6 indicate that substantial seasonal variation in aggregate stability also occurred in the Portneuf silt loam. This soil was dried quickly and

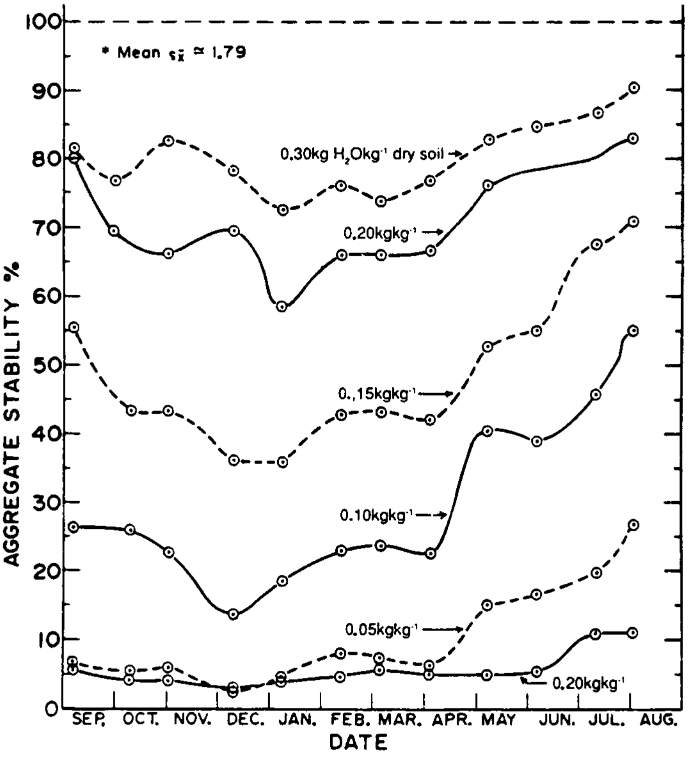


Fig. 6. Seasonal variation (1985–86) of aggregate stability of Portneuf silt loam which had been air dried and then wetted to the indicated water contents prior to wet sieving.

vapor wetted to the indicated water contents before aggregate stabilities were measured. As previously mentioned, quick drying restores some stability to disrupted aggregates and tends to cloud treatment effects. Drying the soil, however, avoids the necessity of dealing with the wet masses of soil from which identification and separation of aggregates are difficult. Increasing the disruptive forces involved in the aggregate stability procedure can help differentiate between stronger inherent bonds and weaker bonds formed during quick drying. Bringing soil water contents to 0.30 kg kg^{-1} prior to immersion and wet sieving provided relatively mild disruptive forces and most aggregates remained stable (i.e., 0.30 kg kg^{-1} curve in Fig. 6). Equilibration at lower water contents prior to immersion caused an increase in disruptive force, because more air was entrapped within the aggregates during immersion. Immersion of air dried aggregates (0.02 kg H_2O kg^{-1} soil) caused so much air entrapment and subsequent strong disrupting force that almost all the aggregates were destroyed (bottom line of Fig. 6).

Providing moderate disruptive forces by bringing water contents to 0.15 kg kg^{-1} resulted in better differentiation of the changes in stability throughout the season as shown in Fig. 6. When the minimum daily air temperatures dropped below 0 °C in late September and the surface soil froze, substantial decreases in stability of the soil were noted (i.e., Fig. 6, samples taken early in October and vapor wetted to 0.20 and 0.15 kg kg^{-1}). The field was roller-harrowed 5 d prior to taking the April samples which may account for their relatively low stability. The samples which were brought to 0.15 kg kg^{-1} had stabilities ranging from 35% during the winter to over 70% during the summer months. The minimum and maximum stabilities for the Timpanogos loam were 35% and 90%, respectively (Fig. 5) where the soil was not dried and then vapor wetted to at least 0.30 kg kg^{-1} prior to wet sieving.

These seasonal cycles in cohesion of soils play a major role in fluctuations of their erodibility. For instance Mutchler and Carter (1983) found that erodibilities of bare soils from Mississippi and Minnesota were several times as great during late winter months as during the following summer months. One of the improvements being incorporated in the current refinement of the Universal Soil Loss Equation (USLE) is a factor which accounts for seasonal variations of this type.

CONCLUSIONS

Freezing disintegrated soil aggregates when their water contents were greater than 0.20 kg kg^{-1}. Less disintegration takes place in unconfined than in confined soil units where the growing ice crystals crush the soil aggregates against adjacent confined aggregates.

In these soils, cooling temperatures in the fall increased the water contents of the surface and subsequent freezing destroyed enough of their bonds to allow disintegration of the aggregates into microaggregates. Little bonding between microaggregates existed following thawing in the later winter or early spring. As the nonfreezing season progressed, bonds reformed between adjacent microaggregates. By the end of the summer, stabilities of the aggregates were at their maximum.

While rototilling and subsequent compaction caused decreases in aggregate stability almost as great as freezing, freezing was generally much more disruptive than single passes of more common types of tillage implements such as plows and disks.

Seasonal changes in stability of these soils were much larger than the differences between soils or differences caused by residue treatments ranging from burning off the stubble to adding 22 t ha^{-1} of manure per growing season for 50 yr.

REFERENCES

Alderfer, R.B. 1946. Seasonal variability in the aggregation of Hagerstown silt loam. Soil Sci. 62:151–169.

Benoit, G.R. 1973. Effect of freeze-thaw cycles on aggregate stability and hydraulic conductivity of three soil aggregate sizes. Soil Sci. Soc. Am. Proc. 37:3–5.

Benoit, G.R., and J. Bornstein. 1970. Freezing and thawing effects on drainage. Soil Sci. Soc. Am. Proc. 34:551–557.

Bisal, F., and K.F. Nielsen. 1964. Soil aggregates do not necessarily breakdown over winter. Soil Sci. 98:345–346.

Blake, G.R., and R.D. Gilman. 1970. Thixotropic changes with aging of synthetic aggregates. Soil Sci. Soc. Am. Proc. 34:561–564.

Briggs, L.J. 1950. Limiting negative pressure of water. J. Appl. Phys. 21:721–722.

Brady, N.C. 1984. The nature and properties of soils. Macmillan Pub. Co., New York.

Chamberlain, E.J., and A.J. Gow. 1979. Effect of freezing and thawing on the permeability and structure of soils. Eng. Geol. 13:73–92.

Domby, C.W., and H. Kohnke. 1955. The effect of freezing and thawing of the structure of the soil surface. Agron. J. 47:175–177.

Ferguson, H., P.L. Brown, and D.D. Dickey. 1964. Water movement and loss under frozen soil conditions. Soil Sci. Soc. Am. Proc. 28:700–703.

Formanek, G.E., and D.K. McCool, and R.I. Papendick. 1984. Freeze-thaw and consolidation effects on strength of a wet silt loam. Trans. ASAE 27:1749–1752.

Gish, R.E., and Browning, G.M. 1948. Factors affecting stability of soil aggregates. Soil Sci. Soc. Am. Proc. 13:51–55.

Imeson, A.C., and M. Vis. 1984. Seasonal variations in soil erodibility under different land-use types in Luxembourg. J. Soil Sci. 35:323–331.

Kay, B.D., C.D. Grant, and P.H. Groenevelt. 1985. Significance of ground freezing on soil bulk density under zero tillage. Soil Sci. Soc. Am. J. 49:973–978.

Kemper, W.D., and R.C. Rosenau. 1984. Soil cohesion as affected by time and water content. Soil Sci. Soc. Am. J. 48:1001–1006.

Kemper, W.D., and R.C. Rosenau. 1986. Aggregate stability and size distribution. *In* A. Klute (ed.) Methods of soil analysis, Part I. 2nd ed. Agronomy 9:425–442.

Kemper, W.D., R.C. Rosenau, and A.R. Dexter. 1987. Cohesion development in disrupted soils as affected by clay and organic matter content and temperature. Soil Sci. Soc. Am. J. 51:860–867.

Kemper, W.D., R.C. Rosenau, and S.D. Nelson. 1985. Gas displacement and aggregate stability of soils. Soil Sci. Soc. Am. J. 49:25–28.

Krumbach, A.W., Jr., and D.P. White. 1964. Moisture, pore space, and bulk density changes in frozen soil. Soil Sci. Soc. Am. Proc. 28:422–425.

Logsdail, D.E., and L.R. Webber. 1959. Effect of frost action on structure of Haldimand clay. Can. J. Soil Sci. 39:103–106.

Mutchler, C.D., and C.E. Carter. 1983. Soil erodibility variation during the year. Trans. ASAE 26:1102–1108.

Pikul, J.L. Jr., and R.R. Allmaras. 1985. Hydraulic potential in unfrozen soil in response in diurnal freezing and thawing of the soil surface. Trans. ASAE 28:164–168.

Pikul, J.L., and R.R. Allmaras. 1986. Physical and chemical properties of a Haploxeroll after 50 years of several residue management treatments. Soil Sci. Soc. Am. J. 50:214–219.

Slater, C.S., and H. Hopp. 1949. The action of frost on the water-stability of soils. J. Agric. Res. (Washington, DC) 78:341–346.

Stoeckeler, J.H., and S. Weitzman. 1960. Infiltration rates in frozen soils of northern Minnesota. Soil Sci. Soc. Am. Proc. 24:137–139.

Uehara, G., and R.C. Jones. 1976. Mineral surfaces and cementing agents. *In* J.W. Cary and D.D. Evans (ed.) Soil crusts. Univ. of Arizona Agric. Exp. Stn. Bull. 214.

Utomo, W.H., and A.R. Dexter. 1981. Soil friability. J. Soil Sci. 32:203–213.

Zuzel, J.F., R.R. Allmaras, and R. Greenwalt. 1982. Runoff and soil erosion on frozen soils in northeast Oregon. J. Soil Water Conserv. 37:351–354.