

# Erosion Mechanics of Soils with an Impermeable Subsurface Layer

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## ABSTRACT

More than 50% of annual soil loss in a number of temperate regions of the world occurs when frozen soils are thawing. Such losses occur as a consequence of relatively high surface soil water contents due to the presence of a subsurface impermeable layer. This laboratory study addressed the soil mechanical principles governing erosion of soils with an impermeable subsurface layer (frozen or compacted, etc.). We examined (i) the effect of a freeze-thaw cycle on soil cohesion and (ii) the effect of a subsurface impermeable layer on soil detachment during raindrop impact for two soils: a Galva loess (silty clay loam, mixed, mesic Typic Hapludoll) and a Nicollet glacial till (loam mixed, superactive mesic Aquic Hapludoll). A Mohr diagram was constructed, based on a series of triaxial tests at three matric potentials. Soil cohesion for each treatment was determined from the Mohr diagrams. Soil water content treatments of 0.15 and 0.25 g g<sup>-1</sup> were imposed before freezing and thawing. The freeze treatment was 90 min at -12°C, followed by a 30-min thaw period. Immediately thereafter, shear strength and detachment were measured. Soil cohesion values were <50 kg m<sup>-2</sup> and were not affected by freezing or by water content-at-freezing. The single-water-drop detachment values for soils with an impermeable layer vs. without an impermeable layer increased from 0.016 ± 0.0065 g to 0.054 ± 0.0265 g for loess and 0.036 ± 0.0071 g to 0.145 ± 0.0635 g for till. With an impermeable subsurface layer, soil matric potential is driven towards 0 Pa, resulting in extremely weakened soils prone to high soil-detachment values and quite likely high soil-erosion losses.

SOIL EROSION RATES vary throughout the season, with the most erodible soil conditions occurring when frozen soils are thawing. More than 50% of annual soil loss in a number of temperate regions of the world takes place during this relatively brief period (Kirby and Mehuys, 1987). Although extensive research has addressed the erosion processes occurring during the summer and winter months, little attention has been directed to the disproportionately high soil-loss rate exhibited by thawing soils.

Shear strength ( $\tau$ ) is a quantitative measure of a soil's internal resistance to externally applied forces before the soil fails. When raindrop-impact forces applied to the soil exceed the soil's  $\tau$  and cause a shear plane to develop, soil detachment occurs and the potential arises for soil erosion. Shear strength is calculated in Eq. [1] as

$$\tau = C + \sigma_n \tan\phi \quad [1]$$

where  $\tau$  = shear stress along the plane of failure (kg m<sup>-2</sup>),  $C$  = cohesion (kg m<sup>-2</sup>),  $\sigma_n$  = applied load normal

to the shear plane (kg m<sup>-2</sup>), and  $\phi$  = angle of internal friction. The  $\sigma_n$  is the sum of the external loads (compression and mass of soil) and internal loads (matric potential forces) (Eq. [2]):

$$\sigma_n = (s + M_s/A) - X\Psi_m \quad [2]$$

where  $s$  = mechanically added load (kg m<sup>-2</sup>),  $M_s$  = oven-dry mass of soil above the shear plane (kg),  $A$  = cross-sectional area of the soil sample at the shear plane (m<sup>2</sup>),  $X = f$  (degree of soil saturation: 1 at saturation, 0 at a volumetric water content of 0 g g<sup>-1</sup>), and  $\Psi_m$  = soil water matric potential at the shear plane (Pa, converted to kg m<sup>-2</sup>). At the surface of a field soil, mechanically added load ( $s$ ) and mass of soil above a shear plane ( $M_s$ ) approximates 0 kg m<sup>-2</sup>. Therefore, the strength of the surface soil (Eq. [1] and [2]) is solely a function of the cohesion parameter (which varies among soils and soil conditions), the angle of internal friction, and  $\Psi_m$ .

Soil detachment is the initial phase of the water-erosion process (Farmer, 1973). Detachment due to raindrop impact increases as  $\Psi_m$  increases (Al-Durrah and Bradford, 1981 and 1982; Cruse and Larson, 1977) and as bulk density decreases (Al-Durrah and Bradford, 1981; Cruse and Larson, 1977), both resulting in lower  $\tau$ . In saturated or nearly saturated soils,  $\tau$  is inversely related to  $\Psi_m$  (Towner, 1961; Towner and Childs, 1972). The role of  $\Psi_m$  on soil strength and soil detachability is well documented; however, no study identifies the role of a subsurface impermeable layer on surface  $\Psi_m$ ,  $\tau$ , and erodibility.

A soil-surface seal develops as aggregates are broken into fragments or primary particles by raindrop impact. Bradford et al. (1987) noted that detachment varies greatly among soils and depends largely upon the degree of surface sealing. At least two reasons exist for this observation, both of them related to the surface-seal effect on soil strength. First, the surface-seal bulk density is higher than that for unsealed soil. Increasing bulk density increases soil  $\tau$  and concurrently reduces soil detachment from raindrop impact (Cruse and Larson, 1977). The second reason is less well documented, but evidence suggests it may play a significant role as well. Water flow through the high bulk-density layer is restricted. The hydraulic conductivity of this layer is reduced by seal development, whereas that of the subseal layer is not altered. Thus, water flow through the seal is impeded, whereas flow away from the seal base is unimpeded (Segeren and Trout, 1991). This combination of conditions results in a  $\Psi_m$  less than 0 at the base

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**Abbreviations:**  $A$ , cross-sectional area of the soil sample at the shear plane;  $C$ , cohesion;  $M_s$ , oven-dry mass of soil above the shear plane;  $s$ , load applied by the Instron at failure;  $s$ , mechanically added load;  $t$ , shear strength;  $X, f$  (degree of soil saturation);  $\sigma_1$ , major principal stress;  $\sigma_2$ , intermediate principal stress;  $\sigma_3$ , minor principal stress;  $\sigma_n$ , applied load normal to the shear plane;  $\tau$ , shear strength;  $\phi$ , angle of internal friction;  $\Psi_m$ , soil water matric potential.

**Table 1. Selected physical and chemical properties of surface soils used in this study.**

Series	Phase	Classification	Organic matter	Size fraction			Surface texture†	Cation-exchange capacity
				Sand	Silt	Clay		
			g kg <sup>-1</sup>	%				cmol kg <sup>-1</sup>
Galva	Loess	Mixed, mesic, Typic Hapludoll	56	3	61	36	SiCL	28.9
Nicollet	Till	Mixed, superactive, mesic Aquic Hapludoll	42	37	39	24	L	22.2

† SiCL, silty clay loam; L, loam.

of the seal, but at a few millimeters above this depth the surface  $\Psi_m$  may be very close, or equal, to 0 during rainfall (Edwards and Larson, 1969). A  $\Psi_m$  gradient through the seal results in the  $\Psi_m$  very near the surface, i.e., within the depth of the crater formed by raindrop impact, of less than 0 (Sharma et al., 1981) and, therefore, is influential in determining detachment zone  $\tau$  (Eq. [1]) and, in turn, soil detachment. Simulating surface crust formation in the laboratory, Sharma et al. (1981) found decreases in the  $\Psi_m$  gradient across the seal of up to 1.4 kPa during simulated rainfall. This is critical because  $\Psi_m$  changes between  $-0.5$  and  $0$  kPa seem to influence detachment (at least for individual aggregates) much more than comparable changes at lower  $\Psi_m$  (Francis and Cruse, 1983). In the Francis and Cruse (1983) study, detachment differences between  $\Psi_m$  of  $0$  and  $-0.5$  kPa were 31 times greater than those observed for  $\Psi_m$  changes between  $-0.5$  and  $-1.0$  kPa. Cohesion has also been found to increase 3.5-fold from  $\Psi_m$  values of  $0$  to  $-0.5$  kPa (Formanek et al., 1984). Thus, even a slight change in  $\Psi_m$  near the surface where  $\Psi_m$  is very close to  $0$  may significantly affect detachment.

Based on detachment rates, Moore and Singer (1990) suggested that the surface seal is more cohesive than the nonsealed soil and hence less erodible. Froese and Cruse (1997) hypothesized that surface-seal formation is impeded by the presence of an impermeable, frozen layer beneath the surface. The resulting restricted infiltration, high  $\Psi_m$ , and low soil  $\tau$ , a consequence of the subsurface impermeable layers, could conceivably increase detachment from impacting raindrops.

This study focused on the soil mechanical principles that cause soils with an impermeable subsurface layer (or slowly permeable subsurface layer so as to influence surface layer matric potential during a rain event, such as is found under frozen or compacted conditions) to be highly erodible. The objectives were twofold: (i) identify the effect of one freeze–thaw cycle on soil cohesion (a  $\tau$  parameter) for two soil phases (loess and till) differing in texture and organic matter content and two soil water contents-at-freezing ( $0.15$  and  $0.25$  g g<sup>-1</sup>), and (ii) determine the effect of a subsurface impermeable layer on soil detachment during simulated raindrop impact.

## MATERIALS AND METHODS

### Soils

Two Iowa soils were examined in this laboratory study. Glacial-till and loess-derived soil materials were chosen for examination because of their differing parent materials and resultant contrasting physical characteristics (Table 1).

The soil cores used in this experiment represented the seal

commonly formed on the soil surface during rainfall. Therefore, the soil was ground and passed through a 0.5-mm sieve. The soil cores tested for  $\tau$  and detachment were constructed in a similar manner, yet some unique features were associated with each type of core. The  $\tau$  cores (from which  $\tau$  parameters were obtained) were 35 mm in height and 12 mm in diameter. For greater ease in measuring detachment, the detachment cores had a larger diameter (23.4 mm) and a reduced height (10 mm). Both the  $\tau$  and detachment cores had a target bulk density of  $1.18$  g cm<sup>-3</sup>. Cores were prepared by compacting a given amount of soil to a predetermined volume in a cylinder sectioned axially into quarters. These quartered sections were held in place by sliding them into a tight-fitting brass cylinder. When the desired bulk density was obtained, the sections were slid from the brass cylinder and removed, revealing the core.

### Matric Potential Establishment

Matric potential was established at the base of the cores using a tension table. (A schematic diagram of the tension table may be found in Cruse and Larson, 1977.) The tension table was constructed from a 0.4- by 0.5-m acrylic sheet with two outlet ports. Tygon<sup>1</sup> tubing connected these ports to a 0.46-m length of glass tubing marked in millimeters. The glass tubing (i.e., the end of the hanging water column) was positioned horizontally. Adjusting the height of the glass tubing with respect to the soil cores on the tension table changed the  $\Psi_m$  in the soil cores. The  $\Psi_m$  at a particular level in the cores was determined by Eq. [3]:

$$\Psi_m = H_{tt-c} + H_{t-tt} - H_c \quad [3]$$

where  $\Psi_m$  = matric potential acting at a particular level in the core (m, converted to Pa),  $H_{tt-c}$  = the height difference between the tension table and a particular level in the core (m of water),  $H_{t-tt}$  = the height difference between the middle of the glass tubing and tension table (m of water), and  $H_c$  = the potential resulting from capillary forces in the glass tubing (m of water). A T-connection and shut-off valve were placed in the Tygon tubing, allowing water to enter the system from a reservoir.

Filter paper was placed directly over the two ports and overlaid with blotter paper (the wetting medium). Six cores were placed 6 cm from each port in a circular pattern. To minimize evaporation from the system, a polyethylene sheet (with holes slightly greater than the diameter of the soil cores) covered the blotter paper.

Water was added to the system so that the blotter supported a continuous water column to the glass tubing. The water contained 0.001 L/L formaldehyde and methanol, which retards fungal growth in the soil cores and has a negligible effect on the surface tension of water at these low concentrations (Green, 1962). Equilibrium was reached when the water meniscus in the horizontal glass tubing ceased to move.

<sup>1</sup> Mention of a trademark or a product name is for information purposes only and does not imply an endorsement by Iowa State University or the University of Maryland.

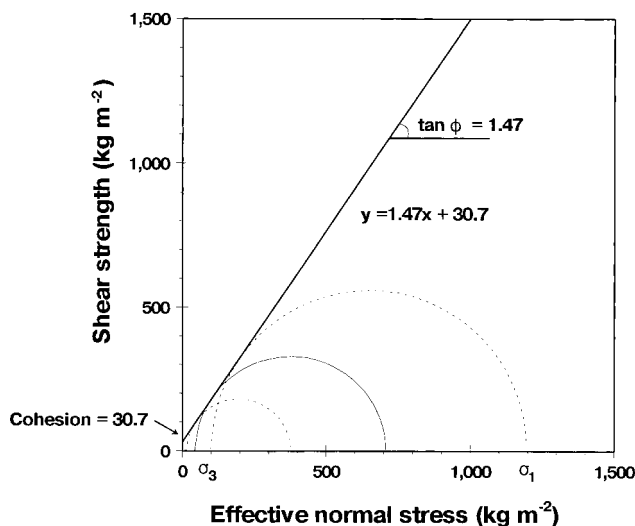


Fig. 1. Sample Mohr diagram.

To better simulate infiltration under rainfall, water equal to 20% of the soil core pore volume was gently added to the top of each core with a syringe 10 min before initiating either the  $\tau$  or detachment test. (Ten minutes was the time required for 20% of the pore volume, or 0.5 mL of water, to percolate through a core as determined by meniscus movement in the hanging water column.)

### Mohr Diagram

Effective normal stress,  $\sigma_n$ , has three components: the major ( $\sigma_1$ ), intermediate ( $\sigma_2$ ), and minor ( $\sigma_3$ ) principal stresses. The normal stress acting on a potential plane of failure may be determined by plotting a series of Mohr circles (Fig. 1). The abscissa and ordinate represent  $\sigma_n$  and  $\tau$ , respectively. Each circle is centered at the coordinates  $\tau = 0$  and  $\sigma_n = (\sigma_1 + \sigma_3)/2$ , where  $\sigma_1$  = applied load normal to the surface of the core and  $\sigma_3$  = the absolute value of  $\Psi_m$  (Das, 1994). Towner (1961) and Childs (1955) have shown that under saturated conditions, negative  $\Psi_m$  in a soil specimen is equivalent to an external load (that is, the minor principal stress,  $\sigma_3$ ) on the soil as it affects  $\tau$ . Thus  $\sigma_2$  (the intermediate principal stress) and  $\sigma_3$  (the minor principal stress) are assumed to be equal to each other and to the absolute value of soil  $\Psi_m$ . The effective intermediate principal stress,  $\sigma_2$ , has no influence on the  $\tau$  of the soil (Craig, 1983).

As illustrated in Fig. 1, when a number of states of stress are known (by varying  $\sigma_3$ ), a line of common tangency can be drawn to each Mohr circle representing a different state of stress. This line of common tangency is called the *failure envelope* of the soil. Any point lying within the envelope reflects a stable condition, whereas those outside the envelope indicate a stress at which failure will occur.

### Triaxial Test

An Instron Universal Testing Instrument (Model 1125, Instron Universal Testing Instrument, Canton, MA) was used to perform the unconfined, drained compression tests (Bishop and Henkel, 1962). The tension table (which ensured a constant  $\sigma_3$ ) was placed directly underneath the load cell and a slow rate of vertical strain,  $3.3 \times 10^{-6} \text{ m s}^{-1}$ , was applied to the cores. This slow rate of strain eliminated, or at least minimized,  $\Psi_m$  changes in the core from those imposed by the hanging water column. During load application, stress was plotted as a function of time on a strip chart recorder.

Major principal stress at failure (or applied load),  $\sigma_1$ , is given in  $\text{kg m}^{-2}$  and was determined by Eq. [4]:

$$\sigma_1 = (s + 2/3M_s/A) - X\Psi_m \quad [4]$$

where  $s$  = load applied by the Instron at failure ( $\text{kg m}^{-2}$ ),  $2/3M_s$  = mass of the soil in the soil core above the failure plane (kg), and  $A$  = cross-sectional area of the soil core ( $\text{m}^2$ ). The  $\Psi_m$  was assumed to be equal to the potential at the top of the soil core (Pa, converted to  $\text{kg m}^{-2}$ ). The  $X$  was assumed to be equal to 1. Compression tests for each  $\Psi_m$  were performed on three cores, thus obtaining three replicate measurements at each  $\Psi_m$ .

### Detachment Measurements

A raindrop tower of 1.98 m was constructed so that single drops of 0.0037-m diam. ( $2.56 \times 10^{-5} \text{ kg}$ ) fell through a 0.075-m diam. acrylic cylinder. Based on drop diameter and height of fall, the velocity at impact was estimated at  $5.2 \text{ m s}^{-1}$  (Meyer, 1965). During the detachment test, the tension table was slid into position underneath the tower and one drop allowed to hit the target core. Modified aluminum cupcake tins (with holes slightly larger than the diameter of the cores cut into the base of the cupcake tin and the top edge of the tin curved inward) caught the raindrop splash. A tin was placed over each core before waterdrop impact.

### Water Content-at-Freezing

The soil water contents in the  $\tau$  and detachment cores were lowered before they were frozen. Following their initial wetting, the cores were removed from the tension table and dried under a heat lamp to the desired water contents (i.e., either 0.15 or 0.25  $\text{g g}^{-1}$ ). The cores were weighed periodically to determine when the desired water content had been reached.

### Soil State

After their soil water contents were lowered, those cores randomly designated to be frozen were then placed in a  $-12^\circ\text{C}$  freezer for 90 min. Immediately thereafter, the cores were withdrawn from the freezer and allowed to thaw at room temperature for 30 min. The cores appeared to be completely frozen after 90 min and completely thawed after 30 min. Cores not exposed to the freezing treatment remained in an enclosed chamber at room temperature.

A key element of this experiment was examining the effect of an impermeable subsurface layer on soil detachment. Impermeable conditions were created by placing thawed cores in a small, metal container. As a result, when the cores were placed on the tension table, matric equilibration was impeded by the impermeable layer (e.g., an ice lens in the field, compacted layer, or the metal container in this study).

### Matric Potential

Once the cores had undergone the freeze and thaw treatment, they were placed on the tension table and allowed to absorb water. Cores were wet to  $-65 \text{ Pa}$  and equilibrium was maintained for 30 min. Following this, the  $\Psi_m$  was adjusted to the desired level for the particular  $\tau$  (or detachment test) and once reached, allowed to equilibrate there for 45 min.

In the  $\tau$  portion of the experiment, cores at three levels of  $\Psi_m$  ( $-225$ ,  $-520$ , and  $-1010 \text{ Pa}$ ) were used to construct the Mohr-Coulomb failure envelope. The  $\Psi_m$  in the core at the level of shear plane development (the plane evidenced by a bulge located approximately one-third of the distance from the bottom of the core to the top) was assumed to be  $\sigma_3$ .

Detachment cores, however, were exposed to four  $\Psi_m$  (measured at the top of the core, where detachment occurs): 0, -65, -560, and -1045 Pa.

Considering that under field conditions, the water content of a soil above a subsurface impermeable layer (such as an ice lens) may reach saturation, special procedures were used for the detachment test in applying  $\Psi_m$  to the impermeable layer treatment (also referred to as the *partly thawed treatment*). To simulate this condition in the laboratory, after the core was frozen and thawed, it was placed inside a metal container on the tension table and the water level within the container was gently raised to the surface of the core. (In the absence of the metal container to confine the water, the core's surface  $\Psi_m$  would equal the height of the soil core and would be lower than that in the field with free water perched to the soil surface.)

### Statistical Design

The  $\tau$  experiment followed a completely randomized factorial design with three replications. The experimental unit was a soil core; the response variable was  $\tau$ ; and the treatments were soil phase (loess and till), soil state (never frozen, and frozen and thawed), and water content-at-freezing (0.15 and 0.25 g g<sup>-1</sup>). The detachment experiment was a completely randomized split-plot factorial design with three replications. The experimental unit was again a soil core, but the response variable was soil detachment, and the treatments were soil phase (loess and till), soil state (never frozen, frozen, and thawed, as well as frozen and partly thawed), and water content-at-freezing (0.15 and 0.25 g g<sup>-1</sup>). The factorial combination of phases, soil states, and water content-at-freezing were randomly placed on the tension table. The tension table was maintained at a given  $\Psi_m$  (0, -65, -560, and -1045 Pa) and the  $\Psi_m$  treatments (main plots) were randomized in time. Data were analyzed using an analysis of variance. Means for those factors identified as being significant ( $P \leq 0.05$ ) sources of variation were separated using an LSD<sub>0.05</sub>.

## RESULTS AND DISCUSSION

### Shear Strength

Significant differences in cohesion were detected only between soil-phase treatment means (loess and till), but not between soil water content-at-freezing (0.15 and 0.25 g g<sup>-1</sup>) or soil state (never frozen vs. frozen and thawed) treatments (Table 2). No interactions between main effects were significant. Loess soil's higher cohesion is likely due to its greater clay fraction (Staricka and Benoit, 1995; Lehrsch, et al., 1991) and higher organic matter content (Lehrsch et al., 1991) than the till soil. Given the limited role that cohesion plays in the strength of sands (Yong and Warkentin, 1966) and the large percentage of sand in the till (Table 1), one would expect lower cohesion for the till than for the loess.

Lehrsch et al. (1991) reported that water content-at-freezing was the most consistent factor influencing aggregate stability (across a spectrum of textures and a number of freeze-thaw cycles). Bullock et al. (1988) also demonstrated that stability decreases substantially when aggregates of loam and silt loam soils at gravimetric water contents >20% are frozen and thawed once. The lack of significant difference in this study between the 0.15 and 0.25 g g<sup>-1</sup> water contents-at-freezing is

**Table 2. Mean cohesion values.**

Soil phase	Water content %	Cohesion	
		Never frozen	Frozen and thawed
		kg m <sup>-2</sup>	
Loess	15	45.4a <sup>†</sup>	53.4a
Loess	25	32.6a	39.8a
Till	15	24.8b	32.5b
Till	25	20.8b	16.0b

<sup>†</sup> Means not followed by a common letter are significantly different at  $P \leq 0.05$ .

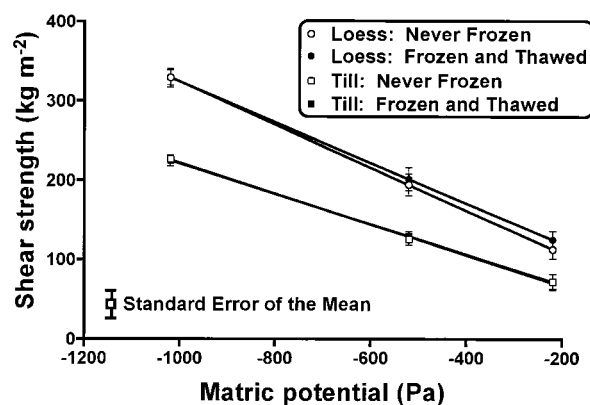
likely because cohesion was measured on remolded soil and not (as in the case of Bullock et al., 1988) on undisturbed aggregates.

There is disagreement in the literature regarding the effect of a small number of freeze-thaw cycles on aggregate stability. Lehrsch (1998) and Lehrsch et al. (1991) also found that stability of field-moist aggregates increased as the number of freeze-thaw cycles (from zero to three) increased. Dagesse et al. (1997), however, observed no significant difference between one and two freeze-thaw cycles. In the present study, cohesion was statistically unchanged after one freeze-thaw cycle. Differences in soils and technique (soil type, aggregate size, sample handling, pretreatment water content, etc.) likely account for these inconsistent results.

Shear strength was linearly related to  $\Psi_m$  between -1010 and -225 Pa (Fig. 2). Statistical analysis revealed that loess soils were more sensitive to changes in  $\Psi_m$  than till soils; however, no difference was observed between the never-frozen and frozen-and-thawed treatments or the 0.15 and 0.25 g g<sup>-1</sup> water contents-at-freezing.

### Detachment

A linear relationship between  $\Psi_m$  and detachment was anticipated, based on previous findings (Al-Durrah and Bradford, 1981; Cruse and Larson, 1977). But, this assumption did not seem to hold for  $\Psi_m$  approaching 0 Pa, particularly for the till soils (Fig. 3). Significant differences were noted in detachments between the two soil phases and the two  $\Psi_m$  ranges (-1045 to -65 Pa, and -65 to 0 Pa).



**Fig. 2. Effect of matric potential on shear strength.**

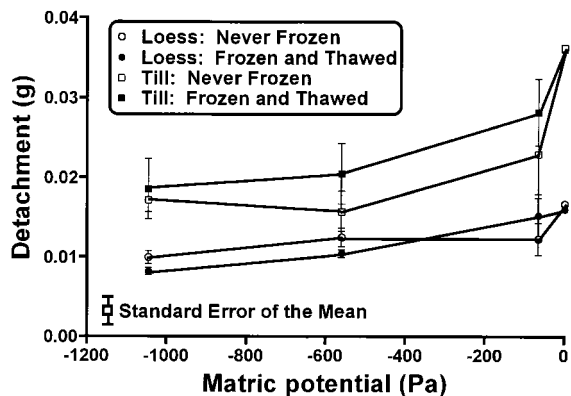


Fig. 3. Effect of matric potential on detachment.

### Impermeable Layer Effects

Statistical analysis was conducted to determine if the detachment influence of the impermeable layer was significant. In all instances, there was overwhelming evidence that the mean soil detachment of 0.10342 g resulting from the impermeable layer differed significantly with the detachment mean of 0.02625 g for never-frozen and frozen-and-thawed conditions (LSD = 0.3771).

### CONCLUSIONS

An impermeable layer (or slowly permeable layer as is found under frozen or compacted conditions) serves as a barrier to water movement during rainstorms, driving  $\Psi_m$  towards 0 Pa. In contrast, water infiltration is less impeded under permeable (unfrozen) conditions. Examining the  $\tau$  equation,  $\tau = C + [s + M_s/A - X\Psi_m] \tan \phi$  (Eq. [1] and [2]), one sees that it is the  $\Psi_m$  component that causes such an impact on  $\tau$ . Considering the soil surface during a rainstorm in which a seal has developed and under conditions of a subsurface impermeable layer, components  $s$  and  $M_s$  are 0, and the  $\Psi_m$  rises to 0 Pa. Based on this study, typical cohesion values for soils under conditions of a surface seal are  $<50 \text{ kg m}^{-2}$  and do not change because of freeze treatment or water content-at-freezing (Table 2). Surface  $\Psi_m$ , however, changes dramatically and can easily rise to 0 Pa or possibly change to positive potential during raindrop impact. Under these circumstances,  $\tau$  becomes a function solely of cohesion. As a result, detachment rates remain high and do not decline as they do when, for example, the soil is permeable and the surface layer bulk density can increase.

An important observation in this study was the rapid escalation of detachment as  $\Psi_m$  approaches 0 Pa (Fig. 3). The relationship between detachment and  $\Psi_m$  near 0 Pa needs to be defined. Furthermore, this elevated detachment is not explained by the relationships defined in the Mohr-Coulomb equation (Eq. [1] and [2]). Therefore, some other factor must be affecting detachment. One possible explanation considers the role of a raindrop as both a wetting source and a source of impact energy. When a drop impacts the soil surface, part of its energy goes to wetting the soil (increasing  $\Psi_m$ ) and part to detaching soil particles. If the existing soil  $\Psi_m$  is

0 Pa, then the raindrop's energy may be directed only toward soil detachment. If true, this may explain the escalation in detachment from soils at  $\Psi_m$  approaching 0 Pa and, therefore, the highly erodible conditions that precipitate the disproportionate losses of soil during the thawing period. Another possible explanation of the radically high detachment values between 0 and  $-65$  Pa in this study involves  $\Psi_m$  dynamics in the impact zone. With negative  $\Psi_m$  and permeable soil conditions, the impacting waterdrop may have a relatively small effect on  $\Psi_m$  in the impact zone. That is, equilibration with water potential in the surrounding soil may be very rapid. As  $\Psi_m$  increases to 0 Pa and impermeable conditions hold  $\Psi_m$  at or near 0 Pa in the impact zone, a potential that exceeds 0 Pa in the impact zone may result from waterdrop impact pressures. The resulting impact potentials greater than those imposed as treatments would lead to higher-than-expected detachment.

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## DIVISION S-6—NOTES

### LIME-INDUCED LOSS OF SOIL ORGANIC CARBON AND EFFECT ON AGGREGATE STABILITY

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#### Abstract

We investigated the decline in soil organic C on an Oxlic Paleustalf (red earth) as a result of lime application (1.5 t CaCO<sub>3</sub> ha<sup>-1</sup>) in New South Wales, Australia and determined how loss of organic C was related to soil aggregate stability changes. Organic C lost as a result of liming was mainly (up to 84% of total loss) in the form of light fraction (specific gravity <1.8) bound to macroaggregates. With liming, a given level of aggregate stability was achieved at a lower soil organic C level in limed soil (e.g., total C level for a 50% aggregate stability was 13.0 and 17.8 g kg<sup>-1</sup> for limed and unlimed soils, respectively). Increased aggregate stability in limed soils suggested formation of new bonding involved Ca bridges.

LIME (CaCO<sub>3</sub>) has been used extensively to overcome soil acidity problems. However, liming can also affect soil structural stability, and both beneficial (Gardner and Gardner, 1953; Muneer and Oades, 1989; Baldock et al., 1994) and deleterious (Ghani et al., 1955; Roth, 1991; Roth and Pavan, 1991) effects have been reported. Mechanisms responsible for improvements in soil physical and mechanical properties are still not fully understood (Davies and Paynes, 1988). Observed declines in permeability resulting from lime application in soils dominated by variable charges were associated with clay dispersion caused by a reduction in positive charges (Roth and Pavan, 1991). It is anticipated that the exact changes in soil physical properties due to liming depend on soil type. Recently, we reported a gradual increase in soil aggregate stability after an initial decline as a result of liming an Australian Oxlic Paleustalf (Chan and Heenan, 1998). Increase in soil structural stability was detectable 3 yr after lime application in the limed soils that also had lost soil organic C. It is well recognized that soil organic C exists in soils in forms with different

turnover rates (lability) due to different degrees of physical and chemical protection (Stevenson and Elliott, 1989). The fraction of organic matter which can be isolated densitometrically, the LF, is labile and tends to be lost preferentially when disturbed, for example under cropping (Janzen et al., 1992). In this study, we investigated (i) whether liming had resulted in changes in composition of soil organic C (particularly the light fraction), in addition to changes in quantity of soil organic C, and (ii) resulting changes in aggregate stability.

#### Materials and Methods

##### Site History

The liming treatment was imposed on a long-term rotation and tillage experiment at the Agricultural Research Institute, Wagga Wagga (35°05'S, 147°20'E), New South Wales, Australia. Lime was applied in June, 1991 at a rate of 1.5 t ha<sup>-1</sup> on half of each plot. For cultivated soils, lime was applied over the surface of the area and incorporated by scarifying to the 10-cm depth. In the case of direct-drilled soil, lime was spread onto the surface without any cultivation or mixing.

The soil was an Oxlic Paleustalf, a red earth (Gn2.12; Northcote, 1979). The soil profile was characterized by gradual transition in texture with depth. The surface A horizon (0–0.2 m) was brown to greyish brown clay loam (27% clay) that gradually changed to light to medium reddish brown clay at ≈0.2 m.

Stubble treatments included retention and burning. Tillage treatments were direct drilling (no cultivation prior to sowing) and conventional tillage (three cultivations). Cultivation was carried out to ≈0.1 m following local farmers' practices, namely using offset tandem disc harrows in the stubble-retained treatments and scarifiers in the burning treatments. Tillage, rotation, and stubble treatments were arranged in a randomized block design with six blocks, with liming as subplots. Plots were 50 by 4.3 m.

In this study, we were only concerned with four tillage by rotation treatments in three blocks, namely: (i) direct-drilled and stubble-retained treatment under wheat (*Triticum aestivum* L.) and lupin (*Lupinus angustifolius* L.) rotation (DD); (ii) conventional-cultivation and burned-stubble treatment under wheat and lupin (CC1); (iii) conventional-cultivation and burned-stubble treatment under continuous wheat cropping (CC2); (iv) conventional-cultivation and burned-stubble treatment under continuous wheat cropping with annual application of 120 kg ha<sup>-1</sup> of N fertilizer (CC3).

**Abbreviations:** IOC, incorporated organic C; LF1, light fraction present freely between soil aggregates; LF2, light fraction bound to soil aggregates; TOC, total organic C. \*, \*\*, \*\*\* Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

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