

Effect of freezing and thawing processes on soil aggregate stability

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Abstract

The effect of freezing and thawing on wet aggregate stability of soils formed on different parent materials was determined for different aggregate size groups (0.0–1.0; 1.0–2.0; and 2.0–4.0 mm), different water contents and for various freezing and thawing cycles (three, six and nine times) and freezing temperatures (–4 and –18 °C). The initial wet aggregate stability decreased with freeze–thaw treatments by 28.6–51.7% depending on soil type, and was more pronounced with increased moisture contents at freezing. The percent decrease in wet aggregate stability for different aggregate size groups ranged from 13.8% to 57.7%. Wet aggregate stability generally increased when the number of freezing and thawing cycles increased from 3 to 6, but decreased after that point. The percentage of water-stable aggregates in all soils at –18 °C was less than that at –4 °C.

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1. Introduction

Aggregate stability is an important soil physical property that affects crop production indirectly through its effects on soil water, aeration, temperature and mechanical resistance (Letey, 1985). The abundance of water-stable aggregates at the soil surface determines the potential for sheet erosion and crust formation (Shouse et al., 1990).

One of the processes affecting soil aggregate stability is freezing and thawing. Lehrsch et al. (1991) found that the stability of field-moist aggregates usually increased with the first few freeze–thaw cycles. Mostaghimi et al. (1988) determined an inverse relationship

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between soil moisture content at the time of freezing and aggregate stability, and found little or no effect of the rate of freezing on aggregate stability. Staricka and Benoit (1995) found that freezing decreased wet aggregate stability in 85 of 96 soil cores.

Erzurum-Turkey (39°55' N, 41°61' E) suffers long, cold winters; on average, the soil freezes for 159 days, based on 60 years of meteorological data (Anonymous, 1997). This has a great influence on the soil's erodibility. In early spring, much soil loss occurs on thawed surfaces during snowmelt (Birhan, 2000). It represents a significant portion of the annual erosion loss of >500 million tons of productive soil, including large amounts of plant nutrients (Anonymous, 1994). Wischmeier and Smith (1978) emphasized that thawed surface layers over still frozen layers have great erosion potential. These layers may produce large amounts of runoff and sediment from snowmelt or low-intensity rainfall. Edwards and Burney (1989) reported that, where the soil was continuously frozen for 10 days, there was 178% greater sediment loss and 160% greater runoff than with daily freeze–thaw cycles over the same period. Chamberlain (1981) stated that soils are generally weaker after thawing than before freezing because their aggregates cannot reabsorb all the water immediately after thawing. Formanek et al. (1984) emphasized that the erosion resistance of Palouse silt loam in the state of Washington, USA, approaches a minimum value during thawing after freezing. Bullock et al. (1988) indicated that after thawing, little bonding remains between microaggregates.

The effects of freezing and thawing on soil aggregate stability, an important indicator for soil's erodibility, may vary with soil texture, organic matter content, initial aggregate size, soil water content at the time of freezing, the number of freezing and thawing cycles, and freezing temperature (Benoit, 1973; Mostaghimi et al., 1988; Lehrsch et al., 1991; Staricka and Benoit, 1995). The objective of this study was to determine the effects of freezing and thawing processes on the wet aggregate stability of Turkish soils formed from different parent materials, for different aggregate size groups, soil moisture contents at the time of freezing, number of freezing and thawing cycles and freezing temperatures.

2. Materials and methods

Surface samples (0–20-cm depth) of four soils commonly distributed in Erzurum Province, and formed from different parent materials were selected. Their physical and chemical properties are given in Table 1. All the soils had a neutral or slightly alkaline reaction, and their cation exchange capacities (CEC) ranged from 14 to 41 cmol kg⁻¹. The initial wet aggregate stability of different aggregate size groups of the study soils ranged from 31% to 87% with an overall mean of 34% and 82%. The Karasu soil has the largest clay content, organic matter content, CaCO₃ content, and exchangeable sodium percentage (ESP). This soil also had the greatest initial wet aggregate stability values.

The samples were air dried and dry sieved into three aggregate size groups (0.0–1.0, 1.0–2.0 and 2.0–4.0 mm). Thirty-six 500 g samples from each aggregate size group of each soil were put into 1 kg plastic pots with holes. One-third of each set was equilibrated at one of three different water contents [air dry, field capacity (–33 kPa) and 0.9 × saturation percentage]. All aggregate samples were then frozen at either –4 or –18 °C for 24 h in a temperature-controlled deep-freezer, and then thawed at a cool room

Table 1
Some physical and chemical properties of the soils studied

Soil series and surface texture	Classification	Texture (%)			OM ^a (%)	CEC ^b (cmol kg ⁻¹)	CaCO ₃ (%)	ESP ^c (%)	Wet aggregate stability (%)			
		Clay	Silt	Sand					Aggregate size groups (mm)			
									<1	1–2	2–4	Average
Pasinler clay loam	Typic	34.2	30.0	35.8	2.8	32	0.8	0.8	62	75	79	72
	Xerorthent											
Tuzcu sandy loam	Typic	11.0	20.8	68.2	0.9	14	1.6	2.9	31	34	37	34
	Xerochrept											
Karasu clay	Typic	57.5	27.5	15.0	6.8	41	8.4	8.9	76	87	84	82
	Cryaquect											
Nenehatun clay	Xerollic Camborthid	48.0	31.3	19.7	3.7	36	1.4	1.4	65	80	78	74

^a Organic matter.

^b Cation exchange capacity.

^c Exchangeable sodium percentage.

temperature (+5 °C) for another 24 h. This freezing and thawing procedure was repeated for three, six or nine cycles. The percentage of water-stable aggregates was then determined by a wet sieving procedure (Kemper and Rosenau, 1986).

The treatments were arranged factorially in two replications, and comprised soil types (4), aggregate size groups (3), soil moisture contents at the time of freezing (3), the number of freezing and thawing cycles (3), and freezing temperatures (2). Analysis of variance (ANOVA) was used to determine the treatment effects, and Duncan's multiple comparison test procedure was used for comparing means (SAS Institute, 1989).

3. Results and discussion

Freezing and thawing decreased the initial wet aggregate stabilities of all of the soils studied (Fig. 1). The percent decrease for different aggregate size groups ranged from 13.8% to 57.7%. The smallest percentage decrease in aggregate stability was for the 2–4-mm aggregates of the Tuzcu soil, and the largest was for the 0–1-mm aggregates of the Pasinler soil. Before the beginning of freezing and thawing, the mean percentage of water-stable aggregates of the Pasinler soil was 72.0%, but it decreased to 34.8% after nine freezing and thawing cycles. Nevertheless, the Pasinler soil still had greater aggregate stability values after freezing and thawing than the Tuzcu soil had initially.

After freezing and thawing, the mean values for all aggregate sizes decreased by 28.6%, 28.8%, 38.3% and 51.7% for the Nenehatun, Tuzcu, Karasu and Pasinler soils, respectively. The percent decrease for the poorly aggregated Tuzcu soil was almost the same as that for the Nenehatun soil, of which 74% of aggregates were initially water stable. This suggests that the effect of freezing and thawing on wet aggregate stability is less for poorly structured than well-structured soils. In other words, aggregates from

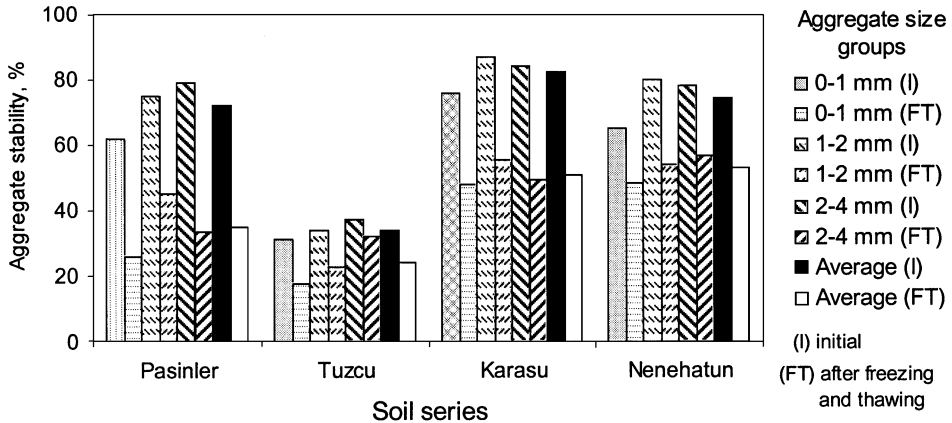


Fig. 1. Changes in aggregate stability values of different aggregate size groups after freezing and thawing.

poorly structured soils are more stable after freezing and thawing than aggregates from well-structured soils.

The ANOVA results indicated that all treatment effects were statistically significant at $p < 0.001$ (Table 2). Duncan's multiple comparison tests showed that the Nenehatun and Karasu soils were different from the Pasinler and Tuzcu soils (Table 3). The reason for the small wet aggregate stability mean values (Table 3) is that they include all 108 values in the combination of three aggregate sizes, three moisture contents, three freezing and thawing cycles, two freezing temperature and two replications. The smallest values of aggregate stability were obtained with the highest moisture contents at freezing. The samples frozen at the lower temperature had significantly smaller overall mean values than the samples frozen at the higher temperature.

The Nenehatun soil had the highest mean wet aggregate stability and was in the same Duncan group as the Karasu soil. In contrast, the Tuzcu soil had the lowest mean wet aggregate stability and was significantly different from the other three. At the end of the experiment, it was >30% less than the means of the Nenehatun, Karasu and Pasinler soils. Although, the Nenehatun soil has less organic matter and clay than the Karasu soil, it has the highest mean aggregate stability after freezing and thawing. This may be related to this soil's exchangeable sodium percentage and land use type. The Nenehatun soil is a rangeland soil in which intensive root development may help create more stable

Table 2
Results of ANOVA for the wet aggregate stability of soils

Source of variation	df	F	$P_t > F$
Soil type	3	237.9	0.0001
Initial aggregate size	2	40.6	0.0001
Moisture content at freezing	2	178.6	0.0001
Number of freezing–thawing cycles	2	8.3	0.0003
Freezing temperature	1	21.9	0.0001

Table 3
Results of Duncan's multiple comparison tests for the means

Treatments	Levels	Means of wet aggregate stability*
Soil type	Nenehatun	53.0a
	Karasu	50.8a
	Pasinler	34.8b
	Tuzcu	24.2c
Initial aggregate size (mm)	0.0–1.0	35.1b
	1.0–2.0	43.5a
	2.0–4.0	43.6a
Moisture content at freezing	air dry	51.4a
	field capacity	39.9b
	0.9 × saturation	30.9c
Number of freezing and thawing cycles	three times	40.2b
	six times	43.2a
	nine times	38.8b
Freezing temperature (°C)	– 4	42.8a
	– 18	38.7b

* Means shown by the same letter in each category are not different at $p < 0.05$ significance level.

aggregates. Haynes and Beare (1997) reported that a larger root mass increased aggregate stability by producing carbohydrate binding agents. However, the Karasu soil had the highest ESP (8.9%), which would cause greater dispersion of clay, resulting in weaker aggregate stability. In the Tuzcu soil, which was formed on colluvial material and is coarse-textured with only 0.9% organic matter, the percentage of water-stable aggregates decreased on average from 34.0% to 24.2% following freezing and thawing (Table 3).

The initial wet aggregate stability values of 0–1-mm aggregate sizes were significantly different from those of 1–2- and 2–4-mm aggregates. The percentage of initial water-stable aggregates >1 mm was nearly 20% more than those < 1 mm at the end of freezing and thawing (Table 3). After freeze–thaw treatment, there was no statistically significant difference in the wet aggregate stability values of the 1–2- and 2–4-mm size groups. This suggests that soils dominated by 1–2-mm aggregates can be as stable after freezing and thawing as those dominated by larger (>2 mm) aggregates. Benoit (1973) found that the greatest decrease in percentage of water-stable aggregates on freezing and thawing occurred within the largest aggregate sizes.

The moisture content of aggregate samples significantly influenced their stability on freezing (Fig. 2 and Table 3). The air-dried samples were less affected by freezing and thawing than those at field capacity or nearly saturated. This indicates that aggregates in soils having a moisture content near saturation on freezing will be easily dispersed after thawing. These results agree with others. Benoit (1973) reported that the largest decrease in aggregate stability occurred when soil was at the maximum water holding capacity, and Lehrsch et al. (1991) found that the aggregate stability of fine and medium textured soils decreased linearly with increasing initial moisture content.

The effect of the number of freezing and thawing cycles on wet aggregate stability was not consistent (Fig. 2). Generally, it increased as the number of cycles was increased from 3 to 6, but, thereafter the wet aggregate stability decreased. Similar results were obtained

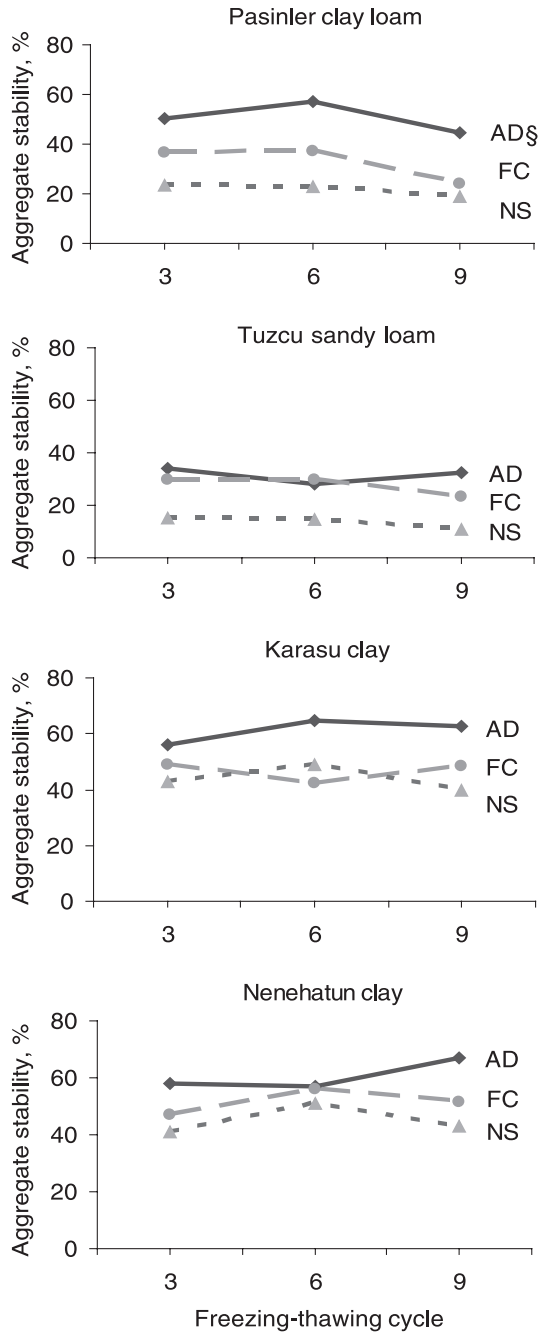


Fig. 2. Effects of soil moisture content at freezing and the number of freezing and thawing cycles on aggregate stability in different types of soils (§: AD=air dry; FC=field capacity; NS=near saturation).

by [Lehrsch et al. \(1991\)](#). They found that aggregate stability usually increased only with the first few freeze–thaw cycles.

The temperature of freezing had a significant effect on wet aggregate stability ([Table 3](#)). At the lower temperature ($-18\text{ }^{\circ}\text{C}$), it was less than that at the higher freezing temperature ($-4\text{ }^{\circ}\text{C}$).

4. Conclusions

Our results show that freezing and thawing decreases aggregate stability. The percent decrease in aggregate stability was dependent on soil type, the initial aggregate size and stability, soil moisture content at freezing, the number of freezing and thawing cycles and the freezing temperature.

Based on our results, we emphasize the importance of protecting soil structure from the disruptive effects of freezing and thawing in regions where consecutive freeze–thaw cycles occur during early spring. A cover of crop residues should be maintained on the soil surface to insulate it from freezing. In addition, soil organic matter content should be increased by the incorporation of farmyard manure or green manure to improve soil aggregation. In Oregon, USA, [Pikul and Almaras \(1985\)](#) reported that careful crop residue management and maintenance of soil organic matter can decrease the effect of freezing on soil structural degradation. They found that freezing did not occur under standing stubble during seven consecutive freeze–thaw cycles, but that a bare soil surface froze to about 1.5-cm depth during each nocturnal cycle.

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