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SMALL-SCALE TESTING OF SOILS FOR FROST ACTION AND WATER MIGRATI--ETC(U)
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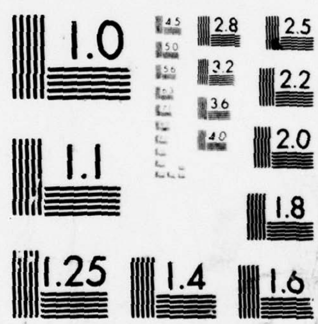

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May 1979

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SMALL-SCALE TESTING OF SOILS FOR FROST ACTION AND WATER MIGRATION

John M. Sayward

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A method is described by which frost action (soil heaving and needle ice) and the use of soil additives for its control can be studied. The apparatus and procedure are simple and convenient, requiring no extensive space or services and using only small quantities of materials. The procedure could be useful in developing a standard test for such purposes where small scale and convenience are requisite.

Also described are two simple, small-scale accessory tests that likewise relate to permeability of soils. These evaporation and wetting tests might also have

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similar use, particularly in the study of water migration-inhibiting additives.

PREFACE

This report was prepared by John M. Sayward, Research Chemist, of the Earth Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was provided by DA Project 1NO25001A130, Exploratory Development - Environmental, Task 01, Cold Regions Research.

Dr. Samuel Outcalt and Richard McGaw of CRREL technically reviewed the manuscript of this report.

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SMALL-SCALE TESTING OF SOILS FOR FROST ACTION AND WATER MIGRATION

John M. Sayward

Introduction

In cold climates, frost action or heaving is well-known for disrupting roads and building foundations. There are also disruptive effects in agriculture and forestry, as frost action can damage root systems or even uproot seedlings.

Though studied and reported on by a number of workers, the mechanism of frost action is neither widely nor completely understood. It is not caused merely by the 9% expansion in the volume of soil pore water when it changes to ice; the water/ice expansion could amount to only about 3% change in total volume, since pore volume is usually around 30-40% of soil volume. Actually, frost action can be demonstrated with organic liquids which contract rather than expand upon solidifying.

Water in bulk or in normal soil voids can readily nucleate and freeze; this is called "in-situ," "normal" or "bulk" freezing. In fine-grained soils, where 3% or more of the grains are smaller than 0.02 mm [the Casagrande (1932) criterion], frost action is likely, although some well-graded soils may tolerate up to 10% fines. In these soils, ice may segregate at the freezing interface (Beskow 1935). Many pores are so small that the thermodynamic requirements for nucleation and growth of crystals are not met, or freezing occurs only at much lower temperatures.

Less energy is required per unit volume to increase the mass of a homo-dimensional crystal than to form the extensive surface of a long, narrow crystal with a large area/volume ratio. Even more energy would be required in a thin capillary pore, where, in addition, pore wall surface forces resist the reorienting of water molecules into the crystalline order of the ice lattice. Such interfacial forces inhibit nucleation, and they apparently preserve a "liquid-like" layer at ice interfaces in general (Jellinek 1964, 1972), whether in large voids or capillaries of porous materials.

As cooling proceeds, adjacent water freezes to the initial crystal nucleus. More water is then drawn by capillarity from the surrounding finer pores and distributed via the liquid-like layer over the already-formed ice in a void or larger capillary. This new water likewise freezes, enlarging the original ice crystal to form a growing "lens." Such lenses may vary from subvisual and thickly distributed to a few centimeters or sometimes even decimeters in thickness and more widely separated in the soil.

Though often of clear ice, lenses may include scattered grains of soil that are lifted as ice continues to form on the underside of the lens. Lenses also contain tiny bubbles of water-dissolved air that is excluded upon freezing. Fine silky tubes or tiny bubble chains of air may give the ice a fibrous appearance. This is likely caused when soil particles excluded below the ice act as centers of nucleation, inducing transition of the excluded air to the gas phase (much as added stones nucleate vapor and prevent a boiling liquid from "bumping" due to the sudden relief of superheating).

The ice lens will continue to grow as long as the heat removed upward and the mass of ice formed are in balance with those of the water coming from below and freezing. The thermodynamics of this is not yet well understood; it has been considered, for example, by Radd and Oertle (1966, 1968), Hoekstra et al. (1965), Hoekstra (1969), Outcalt (1969), Neumann et al. (1973), Biermans et al. (1976), Vignes-Adler (1977) and Takagi (1978). When moisture migration slows due to depletion, or when a temperature drop increases the freezing rate beyond the rate of water migration, the freezing front jumps ahead to where there is water and a nucleatable void, starting a new lens.

The content of water (ice) in the lensed zone thus becomes much greater than it was initially, with consequent expansion (heaving) of the soil. The crystallization pressure generated may be on the order of several atmospheres (Hoekstra 1965, 1969; Yong and Osler 1971), or even 175 atm (17,500 kPa) (Radd and Oertle 1966), sufficient to heave roads and building foundations. Damage due to frost action also occurs upon thawing, when the abnormal soil water produces mud and consequent loss of bearing strength, as on back roads in springtime.

A similar phenomenon (Nakaya and Magono 1944) called "needle ice," "ice columns" or "pipkrake," can occur at or near the surface of uncompacted, frost-susceptible wet soil before ground freezing has set in. When conditions are right, freezing occurs at the surface and ensuing growth lifts the ice continually upward, forming columnar structures. These may be from 1 mm to 1 cm or more in diameter; they may be free-standing or associated in blocks, more or less fused together. While typically straight, they may also be twisted and curved. They are a surface manifestation of frost action. Conditions and observations regarding field needle ice have been recorded by several workers, including Fukuda (1936), Fujita et al. (1937, 1940), Konkô-Tatutarô et al. (1956, 1957), Outcalt (1969) and Satake (1977).

Like frost lenses, needle ice may have soil grains scattered through it. Often there is a cap of soil on the top, or a thin slab of soil may be lifted en masse by the collective action of columns growing together. Also like frost lenses, needle ice often has internal threads or chains of air bubbles, giving it a fibrous appearance.

Needle ice often appears in as yet unfrozen ground on a cool night with a clear (radiation heat-absorbing) sky. It can also grow in forests, under trees, in the open dirt cellar of an abandoned house near a spring, or under the snow, as well as in laboratory tests. Ice nucleates at or close to the soil surface; the soil cap or layer suggests in some cases a delay in nucleation, whereby supercooling and bulk in-situ freezing occur initially. This particularly damages small plants -- alfalfa or forest seedlings may be lifted "by the neck" by such layers and damaged or uprooted.

Test development

Experiments were carried out (Sayward 1966) to grow needle ice in the laboratory, and test soil additives (thickeners) for control of frost action in general. In the simple freezing test devised (Fig. 1) both needle ice and frost heaving of the soil developed, depending on the soils and conditions. The test setup had advantages in small scale and convenience, as have two related tests also noted below.

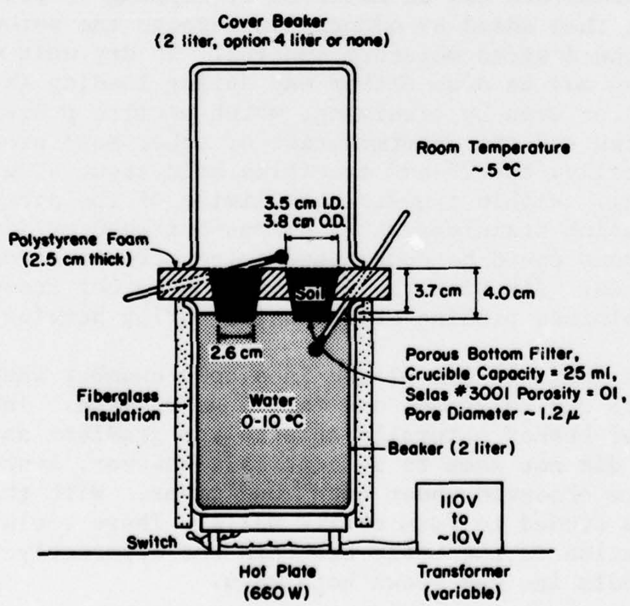

Figure 1. Small-scale soil freezing test.

Tests with the simple apparatus shown in Figure 1 produced frost heaving of soil, dirty ice, clear needle ice or no action. Appendix Figures A1-A10 show a few examples. Conditions for needle ice growth are rather critical not only as to temperature, but also as to thermal gradient, humidity, soil density and moisture content. Often the soil initially froze en masse at the surface, sometimes exhibiting fine cracks, and heaving followed. After thawing, a later freezing cycle was more likely to produce needle ice. This result is explainable by a lower bulk density and/or higher moisture content resulting from the initial freezing, heaving and thawing. As observed in nature, needle ice seems to occur where bulk density is low (little compaction) and moisture is plentiful. Fukuda (1936) found the optimum moisture content to be 60-90%. Some needle ice observed in the field was on soil of 60-70% moisture content and was next to a water-filled rut (Sayward 1966). Satake (1977) has described the intimate moisture exchange between a puddle and needle ice.

Freezing test procedure

Porous-bottomed filter crucibles are first filled with soil. If the soil is dry, its dry unit weight and porosity may be calculated from the calibrated crucible volume and experimental soil specific gravity. These parameters can be modified by tapping or pressing during filling. Water is then added by adsorption through the porous bottom or by dropper to the desired moisture content. If dry unit weight is not needed, wetting may be done either way during loading (allowing better compaction) or even by premixing, which permits processing of identical replicates and the determination of other soil properties separately. Typically, the 25-cm^3 crucibles hold about 40 g of soil when full and level. Within the strength limits of the porcelain crucibles, or by using stainless steel porous-bottomed cylindrical containers, specimens could be compressed to construction density or other desired values. (As with the crucibles and other frost tests, a slight taper minimizes binding at the walls during heaving.)

The apparatus (Fig. 1) was placed in a cold chamber where temperatures and gradients may be chosen and varied as desired. The use or nonuse of the cover beaker naturally affects the gradient above the soil. The effect did not seem to be critical, however, since heaving and needle ice were observed under both conditions. With the cover on, hoarfrost crystals tended to form on its walls. These could fall off and provide nucleation of the soil, but this was apparently not a necessity, for needle ice was grown both ways.

Observations were made a few times a day in the preliminary work. They could also be made more regularly or instrumented in standard tests. Observations may include:

1. Temperatures of the room, water bath (near top), ambient air, and samples; sensors could even be placed in the soil.

2. Hot plate voltage.

3. General appearance (and hardness, i.e. frozen or not) of soil and ice growths.

4. Height of growth (estimate along curve if growth is bent).

5. Area of needle ice growth as a percentage of total area.

6. Water bath level (needs occasional adjustment; constant level could be arranged for standard test use).

7. Presence or absence of cover (large covers could be used for long duration tests or where large growth is expected; without cover, ice growths tend to sublime in time).

8. Photographs as desired (cover removed for clarity, but frost-free window might be feasible); time-lapse photography a possibility.

Growth rates may be calculated from successive height measurements. In our work, rates were observed of up to 1.2 mm/hr for soil heave and up to 3 or even 7 mm/hr for ice growth. Figure A7 is one example of change with time. Maximum heights or lengths of growth noted were up to 28 cm for soil heave and up to 22 cm for needle ice. These amounted to some 300-600% of the soil sample depth in the crucible. Under fixed conditions, growth rate, height and size should be indicative for comparing soils, densities, or additives. At an appropriate time, either when growth is significant or has stopped, or after a fixed time has elapsed, growths may be removed. Both needles and heaved soil are separated easily, since they rest on unfrozen soil. They may be photographed, weighed, melted to determine ice and solids content, or otherwise evaluated.

<u>Other tests</u>

As frost action involves water migration through the soil, two other small-scale simple tests were devised to supplement the freezing test. An evaporation test (Fig. 2), utilized air flow onto the surface of moist soil in a tube; the rate of water transfer from a contacting reservoir was noted. A wetting test (Fig. 3), measured the rate of capillary wetting when a small tube of dry soil was dipped into water. Photographs of the two set-ups appear in Figures 4 and 5.

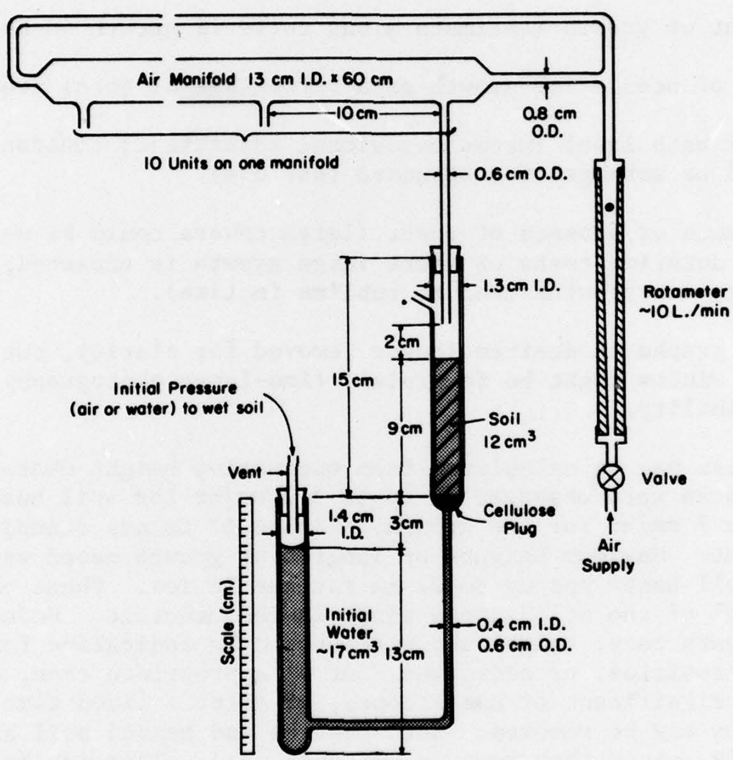

Figure 2. Small-scale evaporation test of soil permeation.

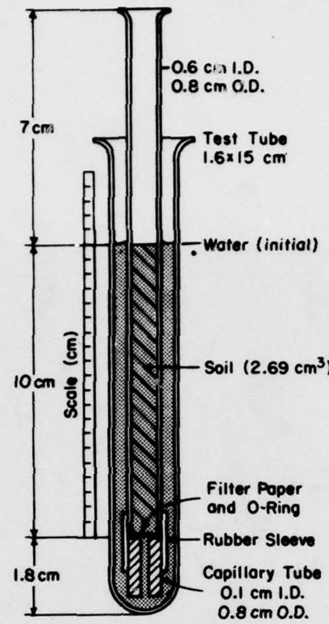

Figure 3. Small-scale wetting test for soil and additives.

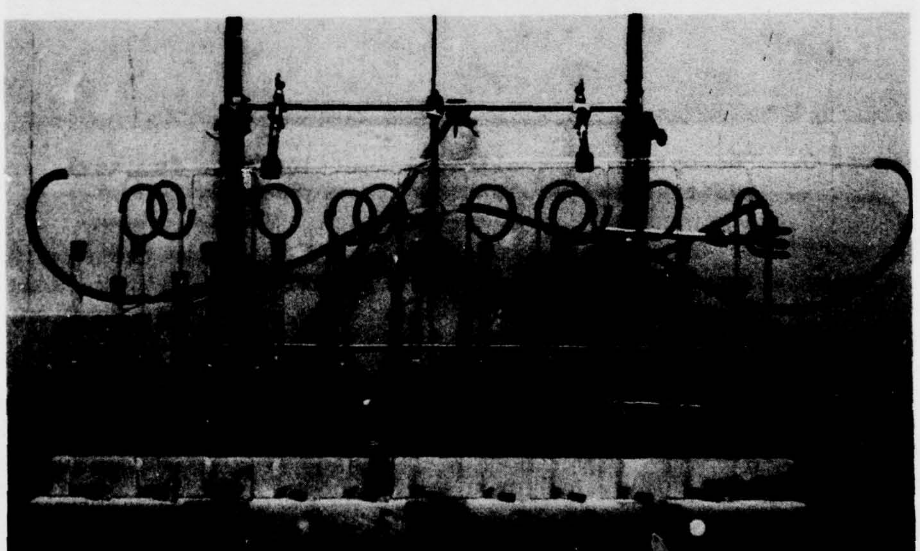

Figure 4. Photograph of small-scale evaporation test of soil permeation (x 1/10).

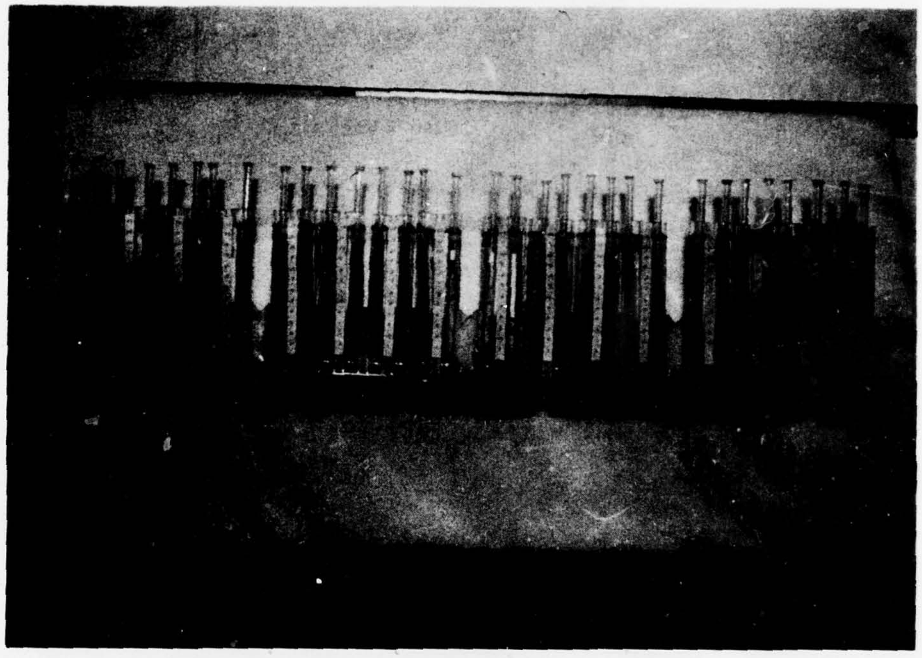

Figure 5. Photograph of small-scale wetting test for soils and additives (x 1/6).

The apparent lack of correlation of either of these tests with frost susceptibility is ascribed to the complex relationships among sample dry density or compaction, particle size, size distribution, geometry, chemistry, and organic contaminants that affect porosity, contact angle, wetting and air entrapment. Thus, evaporation test rates were lowest and wetting times longest for soils of intermediate frost susceptibility, depending on clay/silt/sand proportions or other factors. Wetting times varied from 1-2 minutes for a fine sand to an hour or so for silty soils, and even approached a full day for one clay.

Frost control additive tests

Since water migration is crucial in frost action, its control by additives that increase water viscosity (thickeners) was tried. At 1% solution, water viscosity is claimed to be increased ∿ 450 fold by Methocel 90HG (Dow Chemical Co., methyl cellulose) ∿ 2000-fold by Natrosol 250HR (Hercules Powder Co., cellulose hydroxyethyl ether) and ∿ 53,000-fold by Carbopol 960 (B.F. Goodrich Chemical Co., ammonium carboxyvinyl polymer).

Limited trials of these were made in all three tests.

1. Frost tests. Both a silty clay and a silty sand showed marked decrease of frost action with Methocel at 0.5% (1.1-1.9% in pore water). Trials of all three additives at lower levels, mostly 0.05%, were less definitive -- some decreased, some increased frost action.

2. Evaporation tests. With 0.5% Methocel, both a clay and a non-frost-susceptible fine sand showed rates decreased by 10 to 15-fold.

3. Wetting tests. Several clayey-silty-sandy soils with 0.5% Methocel showed increases of several hundred-fold (one clay only 11 to 150 fold, other soils even over 2000-fold). At only 0.05%, these and some other additives gave only minor increases, 2- to 5-fold, in a sandy silt. Several thickener additives as a mere 1-mm layer also increased wetting times greatly -- over 500-fold for Methocel, over 1500-fold for Natrosol and especially Carbopol.

As the few trials seem to indicate, the effectiveness of thickener additives in decreasing frost action and the associated migration of moisture may be affected not only by the nature and amount of the thickener itself but also by the soil. Some soils, particularly if clayey, may adsorb the additive, partially removing it from solution and lessening its effect. The marked effects noted in wetting, evaporation and frost tests may justify further exploration of this route to the control of frost action.

Proposed tests

Although these procedures were not aimed at soil testing at the time, their simplicity, convenience and small scale (which conserve space, services and materials) could well make them useful in standardized testing of soils for frost-susceptibility (and permeability), and for evaluation of anti-frost action additives. They might also be useful in basic study of frost action and needle-ice phenomena in relation to soil and climatic parameters. More sophisticated apparatus and instrumentation could be provided as required.

Its small scale (25 cm^3) may give the proposed freezing test advantages where materials, space, time or services are limited, or where surface needle ice is the prime interest. Conventional frost heat tests require more time and material: CRREL test -- soil volumes of 95 $in.^3$ (1540 cm^3) and 12 days time (Kaplar 1965, Haley and Kaplar 1952); TRRL test (British) -- 75 $in.^3$ (1230 cm^3) and 10 days (Sutherland and Gaskin 1973); UNH rapid test -- 137 $in.^3$ (2240 cm^3) and one-half day (Zoller 1973), all exclusive of preparation time. Similar advantages apply for the evaporation and wetting tests.

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APPENDIX A. EXAMPLES OF TEST RESULTS

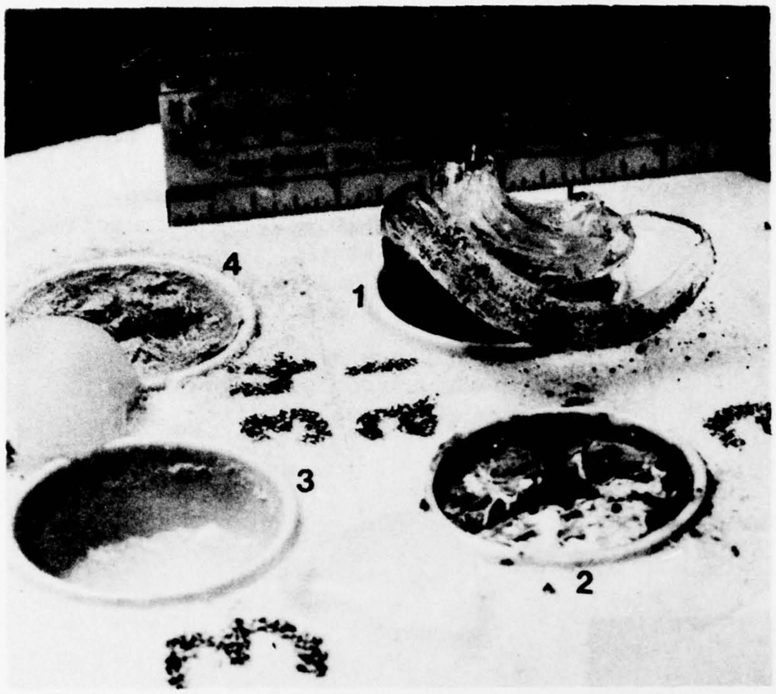

Figure A1.
1. Kanto loam #1: two weirdly contorted 8 x 100-mm ice columns, tips joined by 1 x 12-mm tongue (first successful needle ice grown in laboratory).
2. Bentonite: 14-mm expansion.
3. Cab-o-sil: 11-mm expansion.
4. Talc tailings (magnesite): 10-mm expansion.

Figure A2.
1. Randolph, Vt., silty sand: 11-mm expansion.
2. Kanto loam #2: 90-mm ice and soil heave.
3. Asbestos: 8-mm expansion.
4. Celite: 78-mm hollow ice column.

Figure A3.
1. N.H. silt: 62-mm heave.
2. N.H. silt + 0.05% methyl cellulose: 50-mm heave.
3. N.H. silt + 0.05% Natrosol: 63-mm heave.
4. N.H. silt + 0.05% Carbopol: 73-mm heave.

(additives are thickeners, perhaps too low strength to be effective)

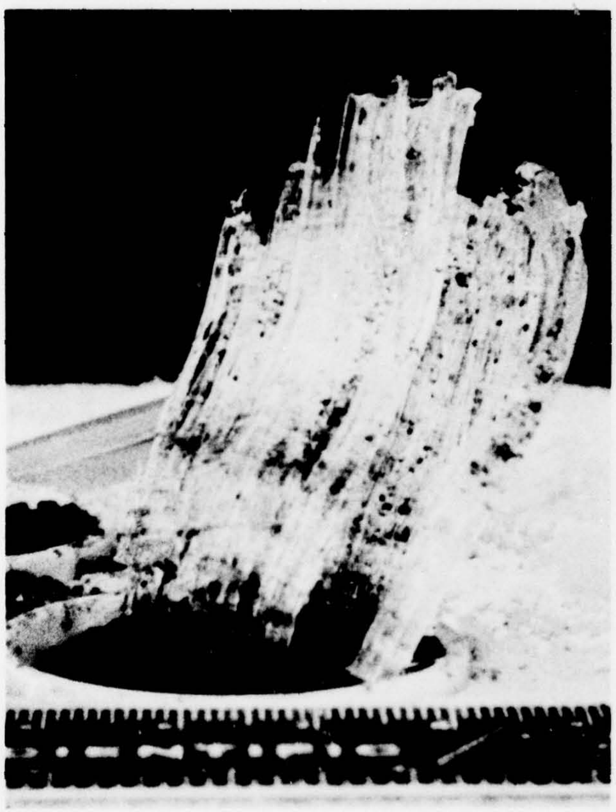

Figure A4.
1. Kanto loam #1: 44-mm columnar ice.

Figure A5. 1. Kanto loam #1: 100-mm multiple ice columns (older piece dangling at right).
2. Kento loam #1 + 0.15% Natrosol: 30 -mm heave (behind #1).
3. Celite: 58-mm multiple ice columns.
4. Celite + 0.25% Natrosol: 60-mm multiple ice columns.

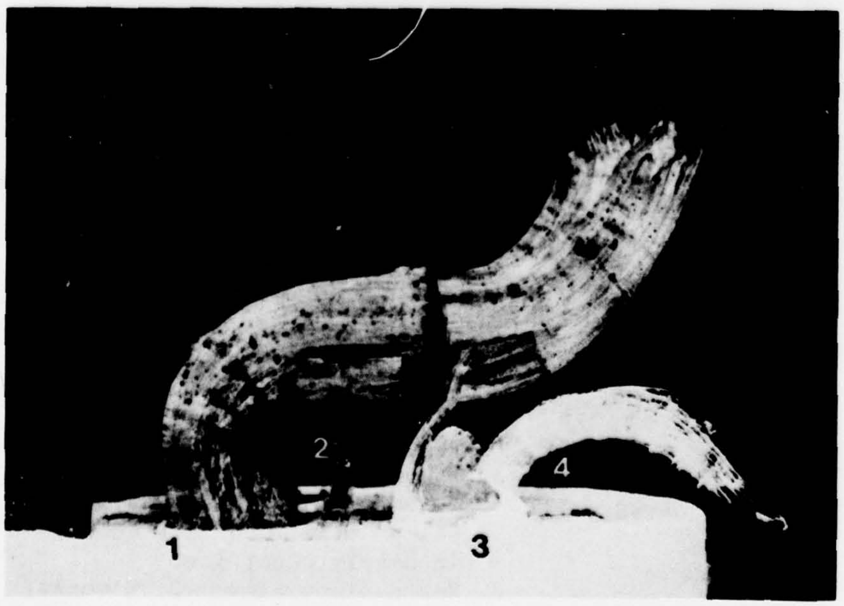

Figure A6.
1. Kanto loam #1: 190-mm ice column (growth "arrest" after first 90 mm).
2. Kanto loam #1 + 0.15% Natrosol: 55-mm heave (behind #1).
3. Celite: 130-mm tapered ice column (behind #4).
4. Celite + 0.25% Natrosol: 70-mm ice column.

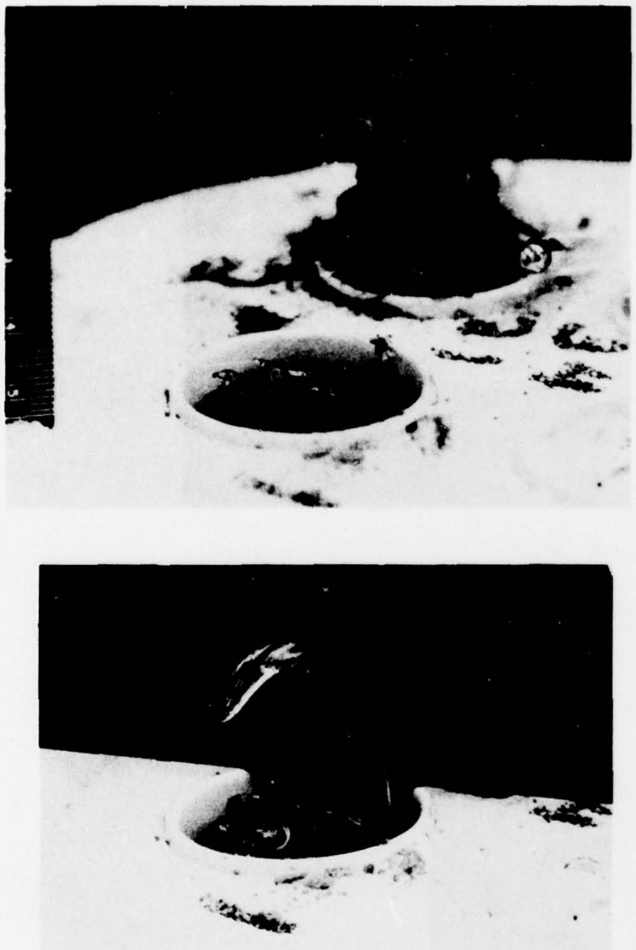

Figure A7.
1. Kanto loam #1.
   a. New tiny ice needles 40 min. after removal of larger ice pyramid.
   b. 16 hrs later: 55-mm tapered curved ice column and several smaller (7-30 mm) columns.

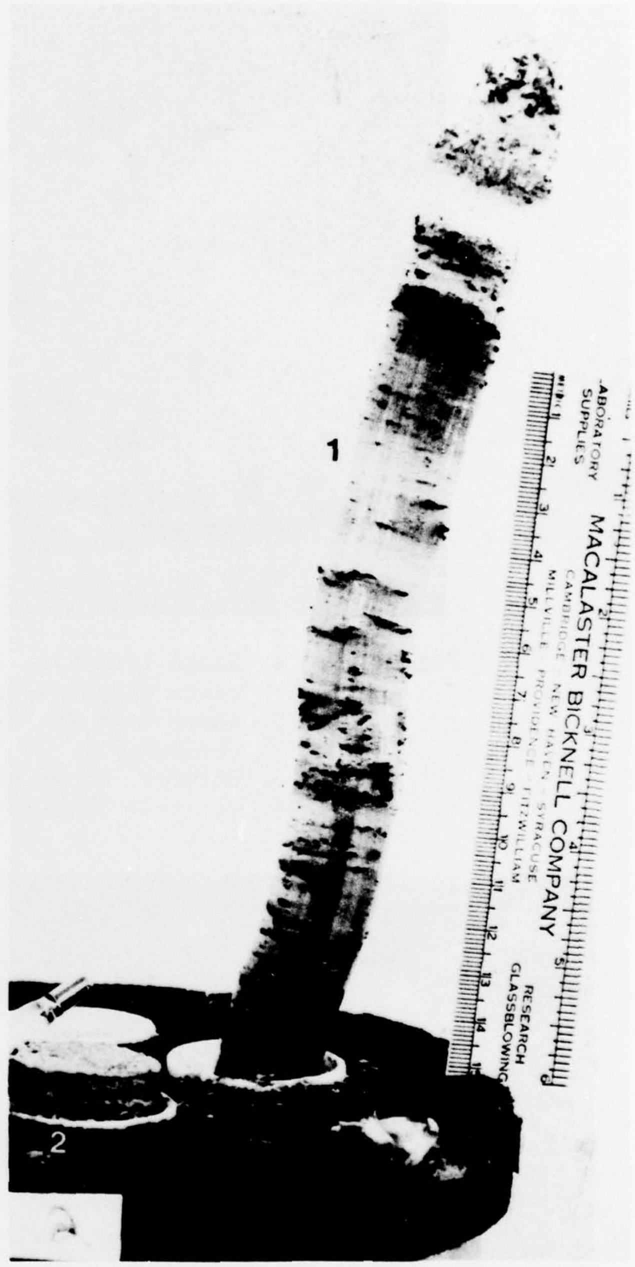

Figure A8.
1. Yukon silty clay: 258-mm ice column, note soil bands and silky striations (air tubes) in nearly clear ice.
2. Yukon silty clay + 0.5% methyl cellulose: 7-mm soil heave (inactive for two weeks).

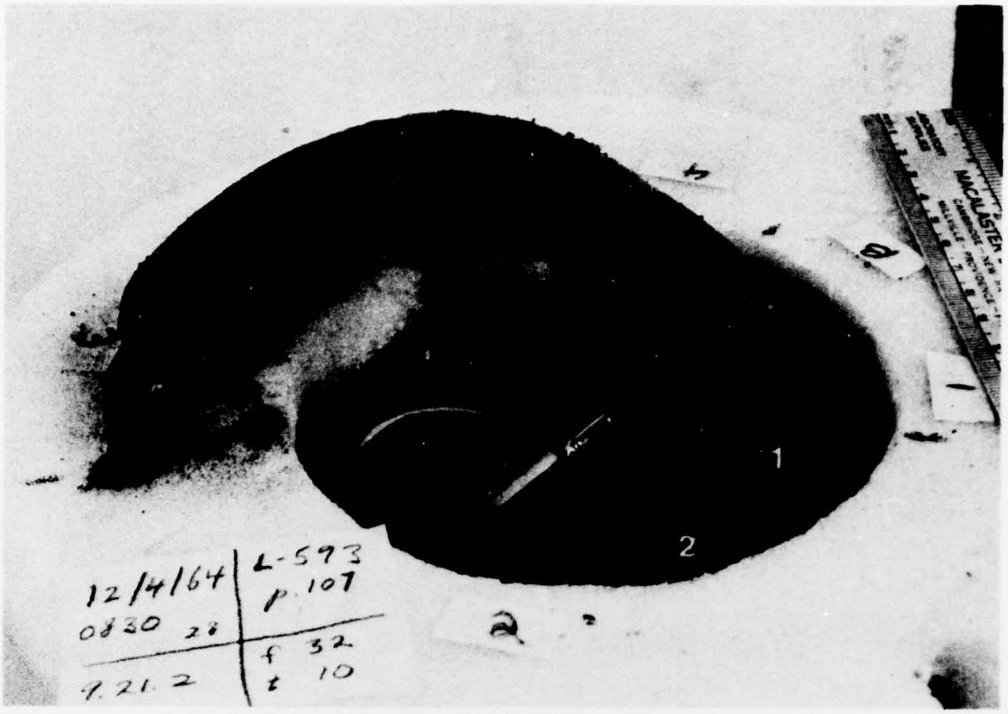

Figure A9.
1. Randolph, Vt., silty sand: 259-mm heave, banded and bent.

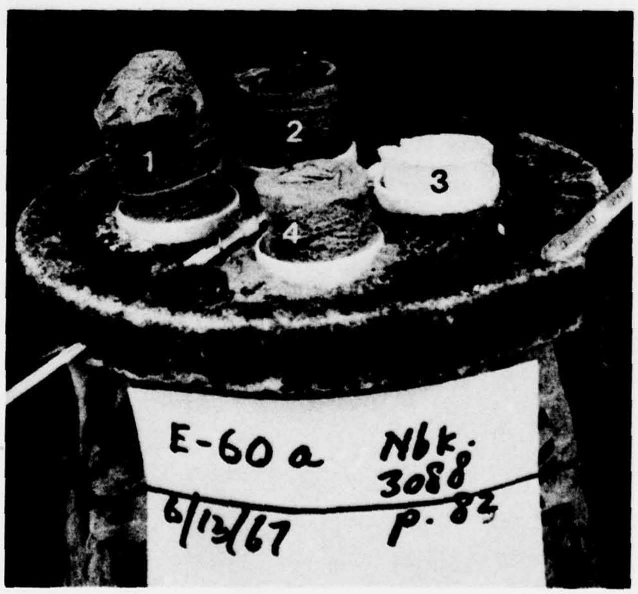

Figure A10. 1. N.H. silt (ether extracted): 45-mm heave.
2. N.H. silt (H_2O_2 oxidized): 25-mm heave.
3. #3200 glass microbeads (44 <10μm): 9-mm expansion.
4. N.H. silt (alcohol-extracted): 10-mm heave.

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