Modification of Frost-Heaving of Soils With Additives

T. WILLIAM LAMBE, Associate Professor of Soil Mechanics
Director, Soil Stabilization Laboratory, Massachusetts Institute of Technology

This paper describes a three-year search for additives to reduce the frost susceptibility of soil. Fifteen soils and about forty additives have been tested. A discussion of the theoretical considerations for the choice of additives is presented. The additives are divided into four groups: (1) void pluggers and cements, (2) aggregants, (3) dispersants, and (4) "waterproofers" — according to their action in soil.

Tests reported herein show a number of additives, especially dispersants and polyvalent cation salts, merit further laboratory evaluation. Other tests on soils treated with resins and "waterproofers" have also indicated promising results.

A small-scale field test showed a laboratory-proved dispersant to be effective under field conditions; measurements made during the second freezing cycle showed no reduction in the potency of the dispersant treatment. Four freeze-thaw cycles on four soils tested in the laboratory also had no adverse effects.

●WHEN a wet soil is subjected to a low enough temperature, the water within the soil freezes. If the soil moisture is "pore" water (i.e., water not under significant attractive forces from the soil particles) it freezes at essentially the same temperature as water in a large container. "Adsorbed" water — that water under significant attractive forces from the soil particles — freezes at a temperature lower than the freezing point of free water. Accompanying the water-to-ice phase transformation is a volume increase of approximately 10 percent. Upon freezing, therefore, saturated soil swells a minimum of 10 percent of the pore volume.

There is, unfortunately, a phenomenon which occurs in certain soils when frozen that results in a volume increase which far exceeds the minimum (e.g., see Figures 1a and 1b). This phenomenon is the movement of soil moisture to form ice lenses. Thus, freezing a soil can cause swelling, or heaving, many times greater than the amount attributable to volume change of pore water. While more heave occurs when the freezing soil has access to an outside source of water, considerable heave can occur by a redistribution of moisture within a soil. In a soil to which no moisture is added, the migrated moisture is either replaced by air, or the soil reduces in volume, or both.

Frost-heaving in soil causes two major engineering problems. The soil expansion moves structures in contact with the soil, such as building foundations, retaining walls, and pavements. Of much more importance to the construction and maintenance of highways and airfields is the loss of soil strength upon melting. Since melting occurs from the ground surface down, and the melt water cannot easily drain downward because of the underlying ice barrier, this melt water can make the soil sloppy wet and, thereby, very weak. Many base courses and subgrades lose a major portion of their strength during the spring thaw and thus cause pavement failure.

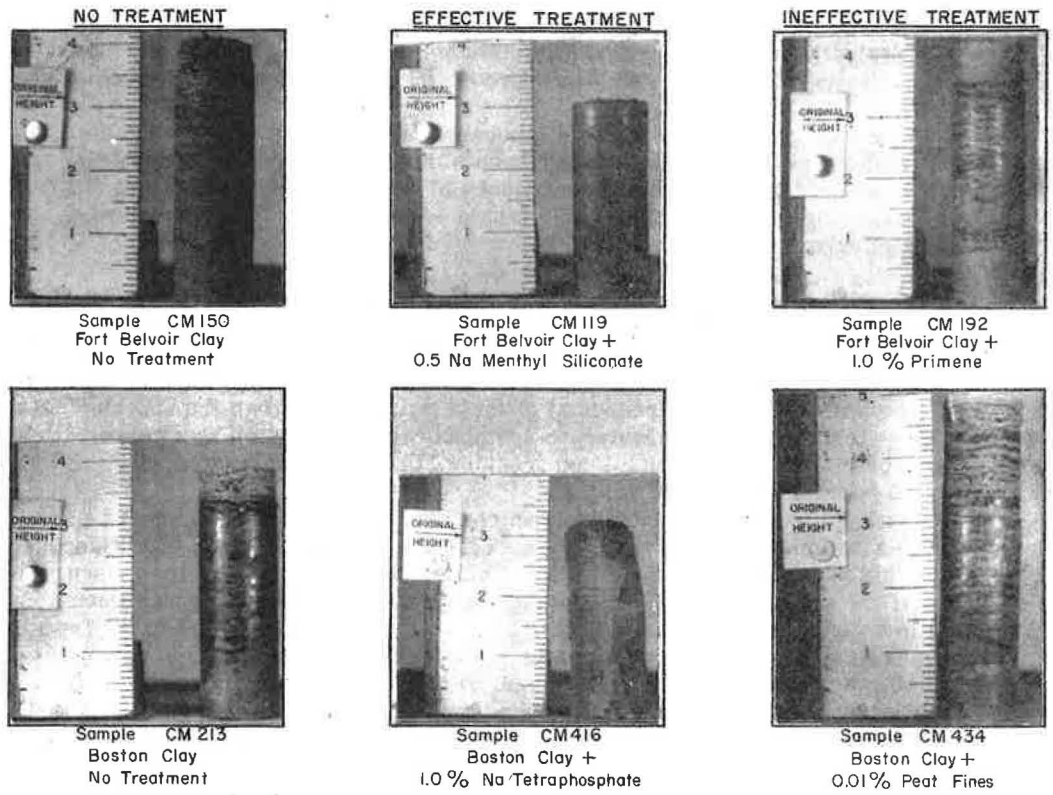
Three conditions must exist at a site for frost-heaving to occur — a frost-susceptible soil, a freezing temperature, and a water source. Since seasonal freezing and thawing of surface soils occur in more than one-half of the land area of the Northern Hemisphere, frost is a major concern to soil engineers. On an alarming number of highway and airfield projects, the pavement design is controlled by frost considerations (4). As the supply of select granular soils is being exhausted, the construction of frost-resistant pavement is becoming extremely expensive.

Researchers in many countries, especially in Sweden and the United States, have studied frost action in soils. The Artic Construction and Frost Effects Laboratory (ACFEL), Corps of Engineers, U.S. Army, has been conducting studies on many facets of construction in freezing climates. The author and personnel of ACFEL have collabo-

rated in a search for additives that will effectively reduce the frost susceptibility of soil. This report summarizes three years of experimentation on this continuing research.

MECHANISMS WHEREBY ADDITIVES CAN REDUCE FROST

Although the most obvious method of making a frost-susceptible soil non-frost-susceptible is to treat the soil so that moisture cannot migrate to form ice lenses; it is not easy to accomplish this since the principles of water migration are not fully understood. A coarse-grained soil (e.g., a clean sand or coarser) does not heave; a very plastic clay (e.g., sodium montmorillonite) does not heave appreciably under natural conditions. Some fines are needed to aid the movement of water by soil-water forces, probably of the type which cause capillarity. Too many fines or fines of certain mineralogical compositions can make the soil so impermeable that water for the formation of ice lenses



TYPICAL FROZEN SAMPLES

Figure 1A.

cannot move fast enough under normal freezing rates. Therefore, there is apparently a critical range of particle sizes necessary for ice lens formation. While particle size is probably not the fundamental characteristic, no precise relation between frost susceptibility and any other soil characteristic (such as permeability, density, capillarity, composition, and specific surface) has been found.

Two other ways of reducing frost heave are: (1) to prevent freezing of the soil pore water, and (2) to cement the soil particles together with a bond strong enough to resist the expansion forces from frost action.

Additives can reduce moisture migration, reduce the freezing temperature of pore water, and cement particles together. Some of the mechanisms whereby additives can perform these functions are described in the following.

Fill Soil Voids

Completely plugging the voids of a soil with a non-pervious material prevents, of course, the movement of water. Asphaltic concrete and portland cement concrete, having most of their voids filled, are not frost-susceptible even though they can contain frost-producing fines. The prevention of frost heaving in soils by this technique is uneconomical; the soil in question could more cheaply be replaced with a non-frost-susceptible gravel or crushed stone.

Cement Soil Particles

Closely related to the plugging of soil voids is the cementing of soil particles. The non-heaving of concrete is undoubtedly due to cementing in addition to low permeability. As with void-plugging, the prevention of heaving by cementing is usually uneconomical.

Alter Characteristics of Pore Fluid

The dissolution of additives in the soil water can result in a lowering of the freezing temperature. Sodium chloride and calcium chloride are used to reduce frost action by this mechanism. Lowering the freezing point reduces the depth of frost formation; it has little or no effect on the heave characteristics of freezing soil (13).

An understanding of the nature of forces involved in water migration for ice lens formation might suggest other beneficial treatments to the pore water.

The drawback to the treatment of pore fluid is its impermanence. A study (13) in Massachusetts, for example, showed the effectiveness of a calcium chloride treatment of a subgrade to be about 3 years. Since stability requirements necessitate that base course soils be free-draining, the pore fluid in these soils is probably soon leached out by the movement of ground water. The leaching of salts from fine-grained subgrade soils can take considerably more time.

Aggregate Soil

As already noted, a soil must have a minimum amount of fine particles to be frost-susceptible. Casagrande (5) set this minimum as 3 percent by weight finer than 0.02mm While soils have been encountered that possess less than this 3 percent but still are frost-susceptible, no better criterion other than one based on laboratory freezing tests has been found.

A frost-susceptible soil can be made non-frost-susceptible by removing the frost-producing fines. This principle has been employed by washing the fines out of "dirty" gravels. This washing can be a difficult and expensive operation for soils containing more than a small percentage of fines, especially where water is not readily available.

The amount of fines in a soil can be reduced with additives that cause small particles to aggregate into larger units. Either conventional cements (e.g., portland cement) or chemicals that cause flocculation by electro-chemical reactions can be used to reduce soil fines. Michaels (10) hypothesized on the various mechanisms by which aggregants, especially the synthetic polymers, flocculate soil fines. The polymers usually exist as long-chain molecules whose ends can attach themselves to the soil mineral surfaces; the particles are thus linked together by the polymer.

Synthetic polymers have been marketed as "soil conditioners" for the improvement of the agricultural properties (primarily increasing the porosity and the permeability) of soil. Even though the polymers are effective in trace quantities, in fact as low as 0.005 percent of the soil weight, their high unit cost (upward of $0.50 per pound) has greatly limited their use.

Soil aggregation can also be obtained by polyvalent cations such as Fe^{+++} and Al^{+++}. These cations act by shrinking the diffuse double layers around the soil colloids enough to permit the interparticle attractive forces to make the particles cohere. Another phenomenon, ion fixation, comes into play with certain ions to increase greatly their aggregating ability. The most notable example is ferric iron, Fe^{+++}. If Fe^{+++} is added to a fine-grained soil an ion exchange reaction can occur wherein the iron replaces some of the exchangeable cations on the soil. This reaction tends to produce flocculation

because of the reduction of the interparticle repulsive charges (11). If the exchanged soil is now dried, some of the iron ions link adjacent particles together with a very strong bond that is resistant to water attack. These ions become fixed and are no longer exchangeable. When the iron is added to the soil as a chloride salt ($FeCl_3$), the formation of iron hydroxide is possible; iron hydroxide can be a weak cement.

Considerable study (e.g., see ref. (9)) has shown that natural clays which contain iron and have been dried are considerably less plastic and have only a fraction of the fines that would be expected from the mineralogical composition of the clays. For example, a clay from Jamaica had 60 percent by weight of clay mineral matter, but had only 20 percent by weight of particles finer than 0.002 mm. The 2.3 percent iron oxide (Fe_2O_3) the clay contained, effectively made silt sizes out of most of the clay minerals.

Disperse Soil

Just as there are chemicals that can aggregate soil fines, so there are other chem-

TABLE 1

ADDITIVES TRIED AS FROST MODIFIERS

ITEM NO.	TRADE NAME	DESCRIPTION	SUPPLIER
1	-	Vegetable pitch	General Mills, Inc., Minneapolis, 13, Minn.
2	-	Tall oil	General Mills, Inc., Minneapolis, 13, Minn.
3	-	Vegetable residue	General Mills, Inc., Minneapolis, 13, Minn.
4	-	Asphalt emulsion	American Oil Products Co., Somerville 43, Mass.
5	-	Polyamide resin	General Mills, Inc., Minneapolis 13, Minn.
6	-	Portland cement	-
7	Pozzolith	A calcium lignosulfide	Master Building Co., Waltham, Mass.
8	Flocgel	A modified starch	W.A. Scholten's Chemische, Fabrieken, Netherlands
9	CRD-197	Sodium salt of a polymer	Monsanto, Everett Station 49, Boston, Mass.
10	Guartec	Polygaloctomannan	General Mills, Inc., Minneapolis 13, Minn.
11	Krilium	Maleic polymer	Mansanto, Everett Station 49, Boston, Mass.
12	Agrilon	Sodium polyacrylate	American Polymer Div., Peabody, Mass.
13	-	Copolymer of Styrene and methosulfate	Koppers Co., Inc., Pittsburgh 19, Penna.
14	P.V.A.	Polyvinyl alcohol	E.I. duPont deNemours & Co., Grasselli Chemicals Dept., Boston 10, Mass.
15	Quadrafos	Sodium tetraphosphate	Rumford Chemical Works, Rumford 16, R.I.
16	-	Sodium tripolyphosphate	West Vaco, New York 17, N.Y.
17	-	Sodium hexametaphosphate	West Vaco, New York 17, N.Y.
18	Versenate	Sodium salt of ethylene diamine tetra acetic acid	Bersworth Chemical Co., Framingham, Mass.
19	Tamol 731	A sodium salt of a carboxylic acid	Rohm & Haas, Wellesley Hills, Mass.
20	Daxad 11 and 21	Formaldehyde-condensed naphthalene sulfonates	Dewey & Almy, Cambridge 40, Mass.
21	Marasperse N and C	Lignosulfonate salts	Marathon Corp., Rothschild, Wis.
22	Lignosol	Lignosulfonate	Marathon Corp., Rothschild, Wis.
23	SC-50	Sodium methyl siliconate	General Electric Co., Pittsfield, Mass.
24	XS-1	Sodium methyl ethyl propyl siliconate	Dow Chemical Co., Midland, Mich.
25	-	Potassium phenyl siliconate	Mansanto, Everett Station 49, Boston, Mass.
26	Triton K-60	Stearyl dimethyl benzyl ammonium chloride	Rohm & Haas, Wellesley Hills, Mass.
27	Volan	Methacrylate chromic chloride	E.I. duPont deNemours & Co. Grasselli Chemicals Dept., Boston 10, Mass.
28	Quilon	Stearate and chromic chloride	E.I. duPont deNemours & Co. Grasselli Chemicals Dept., Boston 10, Mass.
29	Hyamine 1622 and 2389	Fatty quantenary ammonium salts	Rohm & Haas, Wellesley Hills, Mass.
30	-	Triethylene tetramine	Eastman Kodak Co., Rochester, N.Y. Distributor: Howe & French, Boston, Mass.
31	-	Hexamethylene diamine	Eastman Kodak Co., Rochester, N.Y. Distributor: Howe & French, Boston, Mass.
32	-	Di-N-butylamine	Olin Mathieson Chemical Corp., East Rutherford, N.J. Distributor: Howe & French, Boston, Mass.
33	Primene 81-R	Tertiary alkyl primary amine	Rohm & Haas, Wellesley Hills, Mass.
34	Carbowax 200 and 6000	Polyethylene glycol	Carbide & Carbon Chemical Co., New York 17, N.Y.
35	Arquad 2HT	Dioctadecyl dimethyl ammonium chloride	Armour Chemical Div., Chicago 9, Ill.
36	Armeen 18D	Octadecyl amine	Armour Chemical Div., Chicago 9, Ill.
37	-	Diethanol rosin amine D acetate	Hercules Powder Co., Wilmington 99, Del.
38	-	Monoethanol rosin amine D acetate	Hercules Powder Co., Wilmington 99, Del.
39	-	Peat fines	Northeastern Massachusetts

TABLE 2

SOILS USED IN COLD ROOM TESTS

LAB NO.	SPECIMEN IDENT. SYMBOL	SOURCE	CORPS OF ENGINEERS' UNIFIED SOIL CLASSIFICATION: DESCRIPTION	CORPS OF ENGINEERS' UNIFIED SOIL CLASSIFICATION: SYMBOL	GRAIN SIZE (PERCENT FINER THAN) U.S. STANDARD SIEVE: #4 (4.76 mm.)	#40 (0.42 mm.)	#200 (0.074 mm.)	– (0.02 mm.)	WEIGHT LOSS ON IGNITION (Percent)	SPECIFIC GRAVITY (Total Sample)	COMPACTION CHARACTERISTICS: MAXIMUM DRY DENSITY (pcf.)	COMPACTION CHARACTERISTICS: OPTIMUM WATER CONTENT (Percent)	ATTERBERG LIMITS[a]: LIQUID LIMIT (Percent)	ATTERBERG LIMITS[a]: PLASTICITY INDEX (Percent)
	PBJ	Greenland, TP-250	Sandy GRAVEL	GW	38	16	4	2.0	-	2.72	148[b]	-	Non-plastic	
	DFB	Dow AFB, Bangor, Maine, B-11	Sandy GRAVEL	GW-GM	42	12	5	2.4	-	2.73	139[b]	-	Non-plastic	
	DFSB	Dow AFB, Bangor, Maine, B-13	Sandy GRAVEL	GW-GF	49	18	8	3.2	-	2.69	136[b]	-	Non-plastic	
49-11	RC	Ellsworth AFB, Weaver, South Dakota	Silty Sandy GRAVEL	GM	56	30	12	8	-	2.76	-	-	19	2
49-8	CL	Clinton County AFB, Wilmington, Ohio	Silty Clayey GRAVEL	GM-OC	53	23	15	9	-	2.74	-	-	25	7
49-89	LST	Loring AFB, Limestone, Maine, subgrade frost test section	Clayey Sandy GRAVEL	GC	66	52	41	30	-	2.73	137[c]	7.5	22	8
49-21	SPK	Spokane AFB, Spokane, Washington	Gravelly SAND	SW-SM[d]	70	15	8	4.0	-	2.82	-	-	Non-plastic	
49-102	LIN	Lincoln AFB, Lincoln, Nebraska	Gravelly SAND	SW-SM[d]	67	24	6	4.7	-	2.65	132[c]	-	Non-plastic	
49-80	WWS	Fairchild AFB, Spokane, Washington	Silty Gravelly SAND	SM	88	33	19	16	-	2.77	142[b]	-	22	3
49-54	PAFB	Portsmouth AFB, Portsmouth, New Hampshire	Silty Gravelly SAND	GM-SM[d]	68	45	23	14	2.3	2.71	129[b]	-	Non-plastic	
49-17	ST	Sioux Falls Airfield, Sioux Falls, South Dakota	Silty Clayey Gravelly SAND	GC-SC[d]	72	28	15	6	-	2.74	-	-	24	6
49-9	PT	Patterson AFB, Fairfield, Ohio	Silty Clayey Gravelly SAND	GC-SC[d]	56	34	21	15	-	2.74	-	-	22	6
49-46	NH	Goffs Falls, New Hampshire (Lew Hampshire silt)	Clayey SILT	ML-CL	100	100	99	77	-	2.74	110[c]	14.7	24	6
49-46	FB	Fort Belvoir, Virginia	Sandy CLAY	CL	97	88	62	46	-	2.73	135[c]	16.1	41	19
49-42	BC	North Cambridge, Massachusetts (Boston blue clay)	CLAY	CH	100	100	100	94	-	2.78	105[c]	20.2	53	26

[a] On material passing the U.S. Standard No. 40 sieve.
[b] Providence Vibrated Density Test.
[c] Corps of Engineers' Modified AASHO Density Test is made by compacting soil in a 6-in. diameter cylinder, 1/30-cu ft in volume using 5 layers, 10-lb tamper and 18-in. drop, 55 blows per layer.
[d] Dual symbols used are not in strict accordance with unified classification system but are modified as a result of visual examination of material.
[e] The maximum dry density was obtained by compacting soil (minus No. 4 sieve material only) in a 4-in. diameter cylinder, 1/30-cu ft in volume, using 5 layers, 10-lb tamper and 18-in. drop, 25 blows per layer.

icals that can do the reverse; namely, disperse some of the natural aggregates of soil fines. Most of these chemical dispersants are made up of a polyanionic group (e.g., phosphate or sulfonate) and a monovalent cation, usually sodium. Some of the anionic groups can remove any polyvalent cations by forming insoluble products, and others can become attached to the soil mineral surface. The sodium ions become linked to the soil, replacing the removed polyvalent exchangeable cations.

Both the cation exchange – monovalent for polyvalent – and the anion adsorption expand the diffuse double layers around the soil colloids, thus increasing interparticle repulsion. This increase of interparticle repulsion tends to disperse the soil aggregates. Particles that do not stick together can be manipulated into a more orderly and denser structure. Attendant with improved structure are higher density, lower permeability, and higher stability to water. These and other alterations of soil properties that can be effected with trace quantities of chemical dispersants have been described (8).

Since dispersants can alter soil properties that are related to frost susceptibility, they should change frost susceptibility. By decreasing the sizes of soil voids, dispersants also tend to lower the freezing temperature of soil moisture.

ALTER CHARACTERISTICS OF THE SURFACES OF SOIL PARTICLES

If the characteristics of the soil surfaces that contribute to the migration of soil moisture were fully known, the alteration of these characteristics could possibly be effected. Mineral surfaces can be made hydrophobic with the proper additives. This treatment can be effected in two ways: (1) by treating the soil with a substance made up of molecules one end of which is first preferentially adsorbed on the soil surface and then undergoes an irreversible reaction with the surface, the other end of the molecule is hydrophobic and thus makes the soil non-wettable with water; and (2) by treating the soil with "non-hydratable" cations that are attracted to the negatively-charged soil particles. A soil can thereby be waterproofed so it will not be "wet"; such a soil has little or no adsorbed moisture.

Coating soil with additives that have highly polar groups exposed to the soil moisture can increase the amount of moisture adsorbed by the soil and thereby lessen area available for flow. Such a treatment might reduce the permeability of a fine-grained soil enough to make it non-frost-susceptible.

Additives Studied

The preceding theoretical considerations guided the selection of chemicals evaluated as frost modifiers (Table 1 lists those evaluated). Many, in fact most, of the chemicals employ more than one of the mechanisms described; for example, to be an effective dispersant, a chemical must alter the characteristics of the surfaces of soil particles. While all of the mechanisms should, under certain circumstances, alter the frost characteristics of soil, the potency of each must be determined by actual freezing tests.

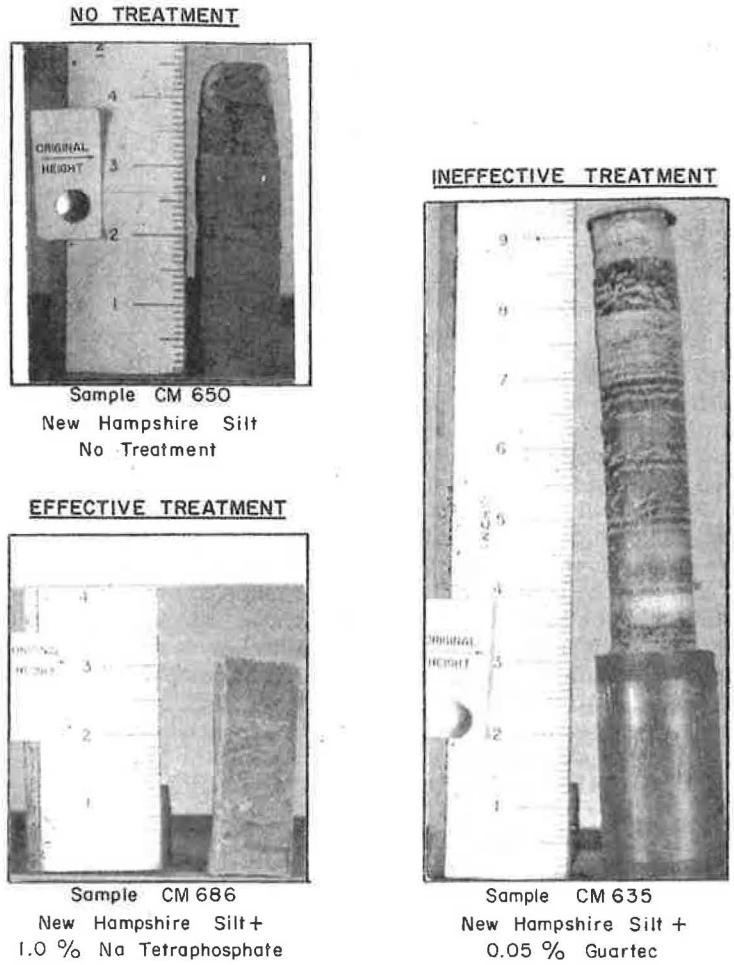


Figure 1B. Typical frozen samples.

FREEZING TEST PROCEDURE

The detailed freezing test procedures employed by the Arctic Construction and Frost Effects Laboratory (ACFEL) have been described in their official reports and in publications by personnel of the Laboratory (1, 2, 3, 6).

The soil and additive to be tested were thoroughly mixed and then compacted at a selected moisture content, usually optimum. In some instances, as noted in the results, the treated soil was dried prior to compaction. Two sample sizes were employed: a cylinder 1.25 inches in diameter and 3.108 inches long (Wilson miniature size sample), and a cylinder 5.91 inches in diameter and 6.0 inches long (standard size sample). Some of the compacted samples (i.e., those with portland cement) were cured at room temperature in a humid room for 7 days prior to freezing, but most were frozen with no curing.

The samples were saturated and then placed in a freezing chamber with a free water surface maintained approximately ⅛ inch above a porous stone at the bottom of each sample. After equilibrating for a day, the samples were frozen from the top by gradually decreasing the air temperature above the samples while the bottoms of the samples were maintained between 35 and 38F. The temperature in the test cabinet was lowered to obtain approximately ¼-inch penetration per day of the 32F isotherm into the sample,

a rate of penetration typical of severe field freezing. Each sample was examined at the end of the freezing period so that the results could be based on the frozen portion of the sample. Thus, none of the beneficial effects of the additives can be attributed to lowering the freezing temperature of the pore water.

The results of freezing tests are expressed as the average rate of sample heave in millimeters per day. Since alteration in frost characteristics is needed to evaluate an additive, the average rate of heave of a treated sample is divided by the average rate of heave of an untreated sample. The value obtained is termed "heave ratio" and is a measure of heave alteration, since a ratio below one indicates improvement and a ratio above one, impairment.

ACFEL studies have shown that frost heave varies with many test conditions, such as molding moisture, compacted density, sample surcharge, and rate of freezing (1, 2, 3). In the tests described herein an attempt was made to control these variables so as to permit the effects of the additives to be isolated and studied. Since 36 miniature samples were frozen in the same cold chamber, the rate of frost penetration could actually be controlled at ¼ inch per day on only one of the 36. To minimize the differences in penetration rates as much as possible, all samples in a given run were prepared from the same soil. With each run, at least one untreated sample was frozen.

The reproducibility of results within a given tray of 36 samples is good; for example, one tray had 5 samples of untreated Fort Belvoir sandy clay with heaves of 1.49, 1.46, 1.53, 1.59, and 1.84 mm per day. However, in another tray where the freezing rate was controlled from thermocouples in New Hampshire silt, untreated Fort Belvoir clay heaved 2.74 mm per day. Where different soils were frozen in the same tray, a blank for each soil was included; the rate of heave of this blank was used to compute the heave ratios of samples of that soil in the tray.

Because of the difficulties of controlling the many variables, especially freezing rate, the heave rates are probably no better than ± 15 percent. Since the miniature tests are used only to screen the many additives studied, this reproducibility is acceptable.

The question has fairly been raised: Can the results of a laboratory freezing test ac-

TABLE 3

EFFECT OF RESIN-TYPE ADDITIVES ON FROST HEAVE

(In Heave Ratios[a])

Additive	Percent	Boston Blue Clay	New Hampshire Silt	Fort Belvoir Sandy Clay
Vegetable pitch	0.50	0.29, 0.89	0.52, 0.82	0.76, 0.52
	1.00	0.58, 0.75	0.72, 1.01	0.84, 0.39
	3.00	0.70, 0.67	0.94, 1.27	0.33, 0.29
Tall oil	0.05	0.73	0.48	0.64
	1.00	0.73	0.24	0.47
	3.00	0.64	0.25	0.37
Vegetable residue	0.50	0.73	0.34	0.78
	1.00	0.69	0.50	0.74
	3.00	0.88	0.33	0.41
Asphalt emulsion	0.50	0.34	0.43	0.23
	1.00	0.62	0.60	0.24
	3.00	0.27	0.53	0.37
Polyamide resin	0.10			1.03
	1.00			0.98
	3.00			1.22

[a] Heave ratio = $\frac{\text{average rate of heave of treated soil}}{\text{average rate of heave of untreated soil}}$

curately indicate the frost behavior of a soil in the field, especially since the major problem is loss of strength upon melting? The answer is thought to be generally yes. Since the more the sample heaves, the greater is the water imbibed during freezing, and the greater is the quantity of water present upon thawing, the lower is the strength of melted soil. In other words, rate of heave does give an indication of strength of melted soil. As a matter of fact, the strength of melted soil can be (and sometimes is) measured with a cone penetrometer or California Bearing Ratio apparatus.

The use of amount of heave to predict strength loss of the soil upon thawing has limitations. All soils are not equally sensitive to moisture; a soil might heave only a mod-

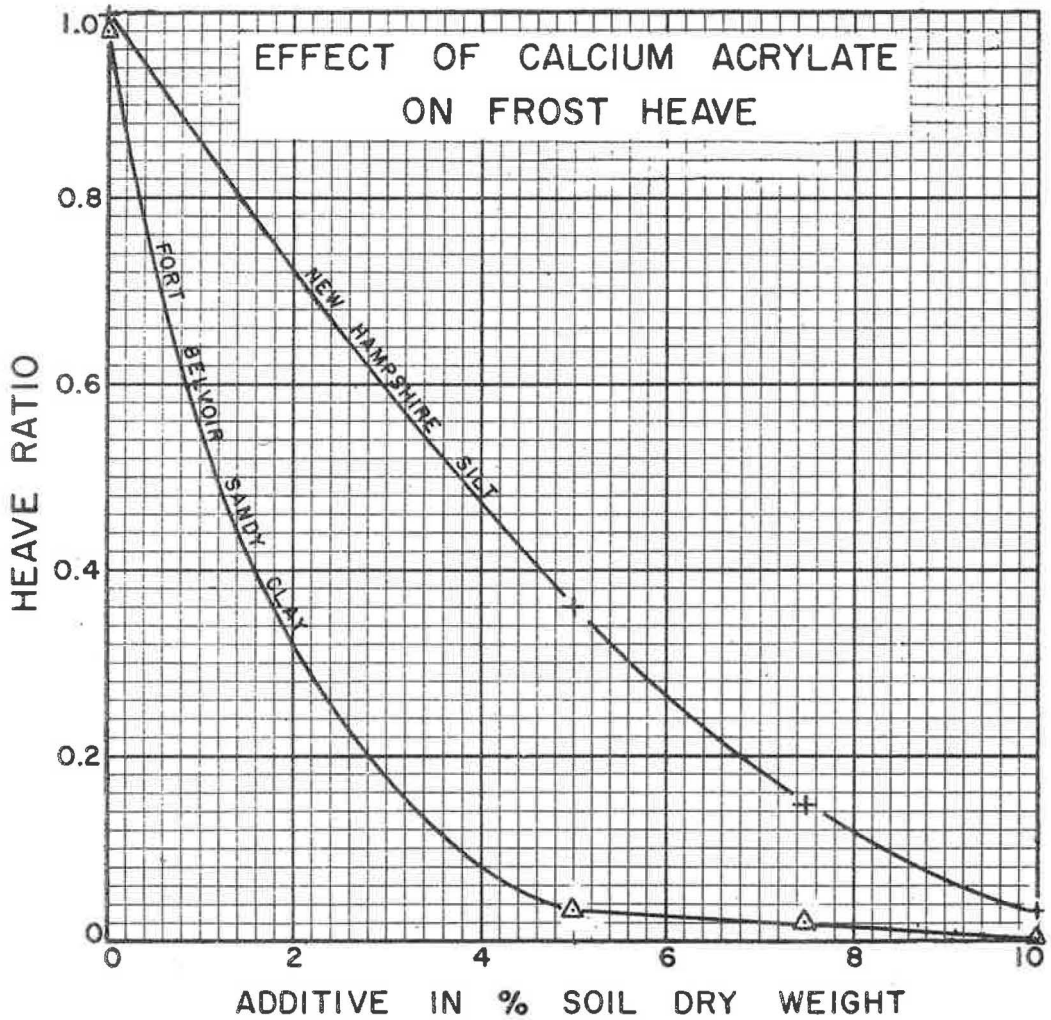


Figure 2. Effect of calcium acrylate on frost heave.

erate amount but lose considerable strength upon melting. The cumulative effects of several freeze-thaw cycles can be more serious on fine-grained soils than on coarse soils. A later section of this paper considers this point further.

The laboratory test program was employed to select promising frost modifiers from the many materials that theory suggests might be effective. Those additives shown to have promise in miniature tests are subjected to evaluation employing different soils and the standard size test sample. Field testing is the next step for worthy additives. This sequence of testing is illustrated subsequently herein with the chemical dispersants.

DESCRIPTION OF SOILS EMPLOYED IN TESTS

Table 2 gives a description of the soils employed in the cold room tests. The great majority of the miniature tests were run on 3 soils — Fort Belvoir sandy clay, Boston blue clay, and New Hampshire silt — selected to give a wide range of frost-susceptible soil types.

EFFECT OF ADDITIVES THAT FILL SOIL VOIDS OR CEMENT SOIL PARTICLES

Under this category are included those additives whose primary function is either to plug soil voids or to cement soil particles. Most of them do both, as well as employ other mechanisms already described.

To plug completely the voids in a soil would require an inordinate amount of additive; for example, the void ratios of the compacted samples of soils studied herein varied from about 0.5 to 1. To fill these voids would require an additive volume of between one-half and the full volume of soil grains. Effective sealing may, of course, be accomplished at a lower level of treatment by plugging only the larger voids.

Because of the high treatments of pluggers and cementers required, only very cheap additives offer promise. Attempts were made to increase the effectiveness of cements with trace additives. The water-sensitive void pluggers were tried because they can employ pore water to help make up the volume needed to seal.

A disadvantage of most sealers and cements is that a reaction after addition to the soil is required (e.g., hydration of portland cement, breaking of asphalt emulsion, polymerization of calcium acrylate). The samples containing these materials were, therefore, cured before freezing.

Synthetic Polymer

Research at the Massachusetts Institute of Technology (7) sponsored by the Arctic Construction and Frost Effects Laboratory, indicated that the in situ polymerization of monomers, especially calcium acrylate, effected significant changes in soil properties. Figure 2 shows that 50 percent of calcium acrylate essentially prevented heave in Fort

TABLE 4

EFFECT OF PORTLAND CEMENT ON FROST HEAVE

(In Heave Ratios)

Additives	Percent	Boston Blue Clay	New Hampshire Silt	Fort Belvoir Sandy Clay
Portland cement	1	1.35	1.74	1.04
Portland cement	2	1.36	0.63	0.58
Portland cement	3	0.46	0.46	1.08
Portland cement + Pozzolith	1 0.1	1.35	0.59	0.67
Portland cement + Pozzolith	3 0.2	0.56		0.74
Portland cement + Daxad 21	1 0.1	1.41		0.82
Portland cement + Daxad 21	2 1.5	0.68	0.76	0.10
Portland cement + Daxad 21	3 0.2	0.61		1.10
Portland cement + Daxad 21	5.0 1.0	0.37	0.47	0.26

TABLE 5

EFFECT OF AGGREGANTS ON FROST HEAVE

(In Heave Ratios)

Additives	Percent	Boston Blue Clay	New Hampshire Silt	Fort Belvoir Sandy Clay
Flocgel	0.01	0.70	1.29	0.82
	0.05	1.12	0.58	0.60
	0.10	0.68	0.38	0.55
	0.50	0.59	0.36	0.55
CRD-197	0.01	-	0.74	0.46
	0.05	-	0.70	0.48
	0.10	1.31	0.35, 1.04	0.40, 0.56
	0.50	3.26	0.58	0.32, 0.71
	1.00	1.87	0.73	0.05
Guartec	0.05	1.11	6.15	0.56
	0.10	0.88	2.16	0.73
	0.50	0.66	0.31	0.60
	1.00	0.76	0.42	0.20
Krilium (maleic polymer)	0.01	1.26	1.35	0.69
	0.05	1.24	1.36	0.59
	0.10	1.16	0.96	0.53
	0.50	0.70	0.11	0.37
Agrilon	0.01	1.18	0.79	0.70
	0.05	1.35	0.83	0.69
	0.10	1.05	0.82	0.39
	0.50	0.52	0.45	0.32
Copolymer of styrene and methosulfate	0.10	0.61	0.06	0.76
	0.50	1.23	0.28	1.42
	1.00	1.53	0.61	0.87
P.V.A. (polyvinyl alcohol)	0.01	1.60	1.08	-
	0.05	1.54	0.78	0.70
	0.10	1.46	0.74	0.43
	0.50	0.76	1.40	0.56
	1.00	-	0.78	0.49

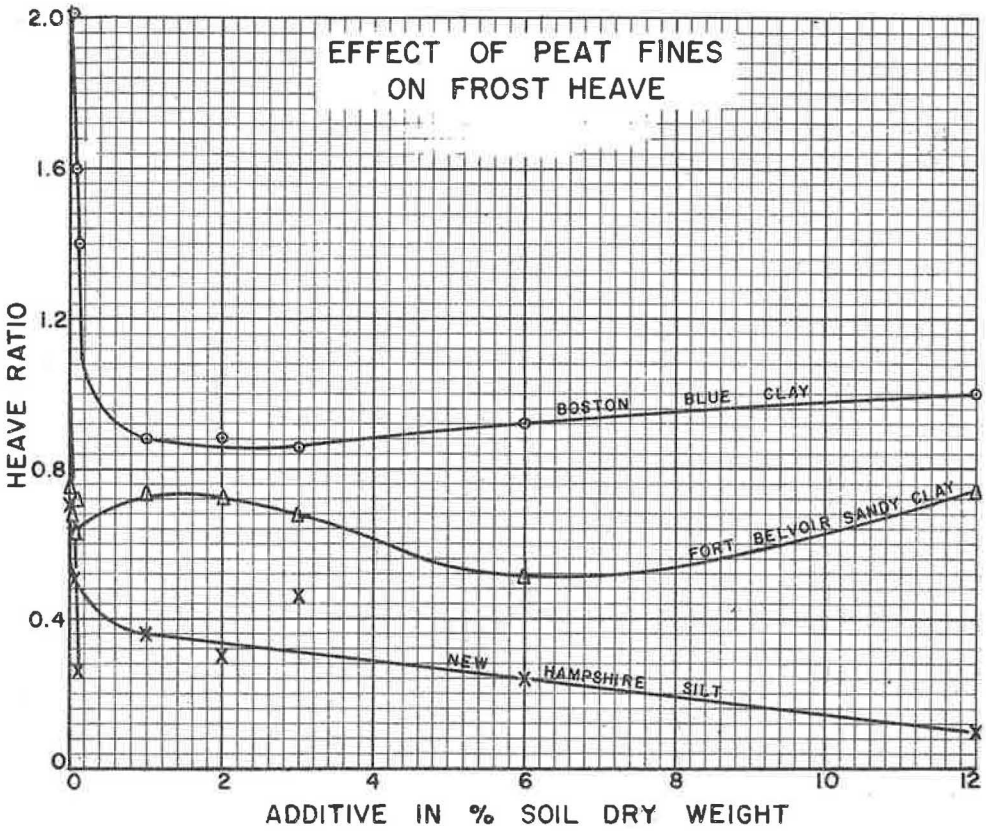
Belvoir sandy clay and that 10 percent prevented heave in New Hampshire silt.

Acrylate stabilization was developed for emergency military conditions; its cost is too great for large-scale non-emergency use at other than trace level treatments.

Resin-type Additives

Table 3 lists the heave ratios of soils treated with each of five resin-type additives. Since the four non-asphalt additives contain antistripping-type components, they do not need as much soil predrying to get good soil-additive bonding as does asphalt. This advantage does not show in Table 3, since all samples were dried before and after treatment.

The data show neither general significant reduction in frost susceptibility nor increase of effectiveness with increase in concentration. These facts suggest that the treatment was too low to obtain beneficial effects from plugging soil voids.



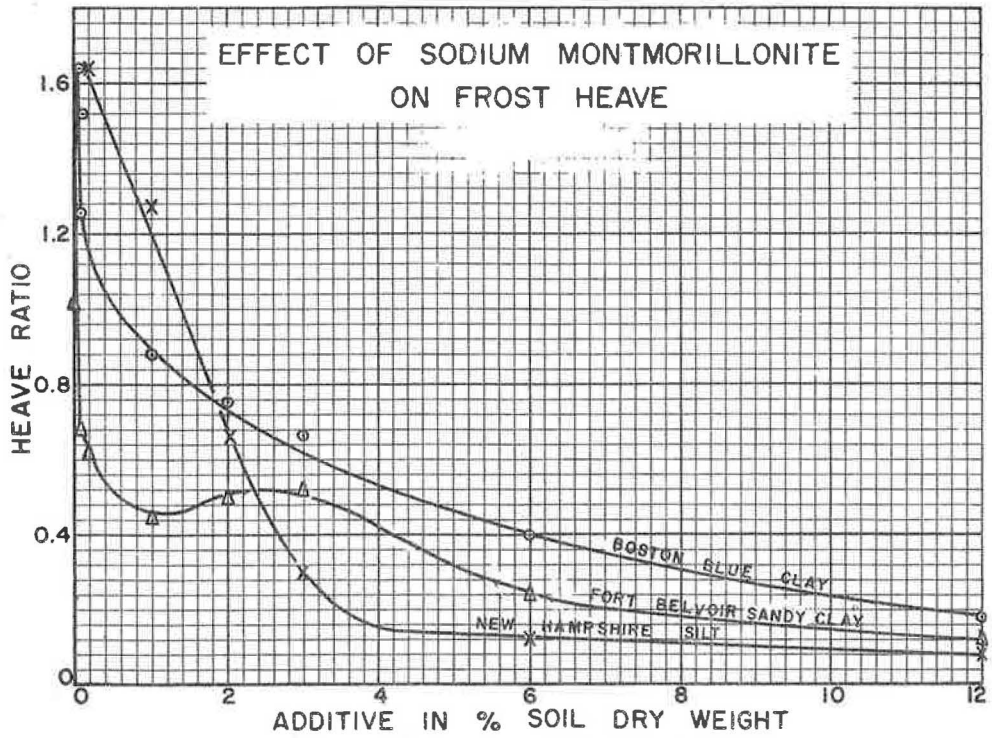


Figure 3 (above), and Figure 4 (below).

Portland Cement

Table 4, presenting results of tests on soils treated with portland cement, indicates cement is not a promising frost modifier. The data show that more than 5 percent cement is required to reduce the frost heave significantly, and that the dispersants made the cement more effective. However, a treatment of cement plus dispersant is not as effective as a treatment of dispersant without cement; for example, 1 percent dispersant reduced the heave ratio of Fort Belvoir sandy clay to 0.06 (see Table 7) compared to 0.26 for the sample with 5 percent cement plus 1 percent dispersant. The cement apparently had an adverse effect on the dispersant.

Natural Fines

Freezing tests were run on soils treated with two natural fines, sodium montmorillonite and a local peat, both of which are highly water sensitive. The peat, obtained at a depth of 4 feet below an athletic field in northwest Massachusetts, was a black fibrous material with some sand and gravel mineral particles. The portion coarser than a No. 200 sieve was removed and that portion passing through was used in the freezing tests. The organic content of the fines was measured to be 77 percent by the H_2SO_4 - $K_2Cr_2O_7$ digestion method (adapted from reference (12)). It had a specific gravity of 1.61, liquid limit of 375, and plastic limit of 260. The tests were performed both to evaluate the benefits of these materials as additives and to permit prediction of frost susceptibility of soils naturally containing either of these materials.

Figures 3 and 4 show that very low-level treatments of both additives caused an increase in heave, but that treatments usually greater than 0.1 percent and always greater than 1 percent reduced the heave. Sodium montmorillonite was more effective than peat fines.

Because both of these naturally occurring materials are water-sensitive, they are likely to have detrimental effects on soil; i.e., decrease strength and increase compressibility. Their water sensitivity would also cause problems in their field incorporation with soil.

EFFECT OF AGGREGANTS ON FROST HEAVE

Two types of aggregants — polymers and polyvalent cations — were studied. Table 5 presents the results on six widely different polymers. From this table the following observations can be made:

1. The polymers are generally not very effective.
2. The effect of concentration of polymer can be large and unpredictable.
3. The polymers can be detrimental

TABLE 6

EFFECT OF CATIONS ON FROST HEAVE

(In Heave Ratios)

Soil	Iron, $FeCl_3$	Iron, $Fe_2(SO_4)_3$	Lead, $PbAc_2$ [a]	Barium, $BaAc_2$ [b]	Potassium, KCl	Mercury, $HgCl_3$
Fort Belvoir Sandy Clay	0.28	0.64	0.12	-	-	0.48
	-	0.84	-	-	-	-
Boston Blue Clay	1.35	0.56	1.41	1.08	1.09	0.63
	0.20	0.35	-	-	-	-
	0.45	0.38	-	-	-	-
	0.40	-	-	-	-	-
New Hampshire Silt	0.48	-	0.37	-	-	0.77
Fairbanks silt	0.88	0.88	-	1.93	0.65	-
Niagara Falls Clay	0.03	-	-	0.98	2.09	-
Portsmouth sand	0.29	2.55	-	3.22	2.13	-
Loring till	0.05	0.44	-	1.20	0.52	-
Fargo clay	1.05	0.29	-	4.62	1.35	-
WASHO clay	0.12	1.32	-	0.97	0.62	-

[a] Lead Acetate
[b] Barium Acetate

TABLE 7

EFFECT OF DISPERSANTS ON FROST HEAVE

(In Heave Ratios)

Additives	Percent	Boston Blue Clay	New Hampshire Silt	Fort Belvoir Sandy Clay
Quadrafos	0.01	1.71	0.63	0.64
	0.05	2.03	0.48	0.76
		0.42, 0.74, 0.87	0.36, 1.17, 0.26	0.84, 0.83, 0.57
	0.10	0.65, 1.37, 0.48	0.85, 0.68, 1.09	0.62, 0.53, 0.53
		0.22, 0.30, 0.06	0.43, 0.36, 0.39	0.08, 0.18, 0.26
	0.50	0.29, 0.40, 0.31	0.64, 0.31, 0.32	0.18, 0.11, 0.22
	1.00	0.39	0.29	0.06
Sodium hexa-metaphosphate	0.01	1.31	1.32	0.81
	0.05	1.44	0.58	0.95
	0.10	1.32	0.40	0.69
	0.50	0.35	0.47	0.41
	1.00	0.25	0.23	0.06
Sodium tri-ployphosphate	0.10	1.20	0.50	0.50
	0.50	0.47	0.38	0.09
	1.00	0.32	0.36	0.00
Versenate	0.05	0.85	0.75	0.71
	0.10	0.69	0.71	0.18
	0.50	0.46	0.63	0.49
Tamol 731	0.01	1.13	0.98	0.71
	0.05	1.14	0.97	0.53
	0.10	0.94	0.54	0.39
	0.50	0.31	0.44	0.11
	1.00	0.26	0.38	0.00
Daxad 11	0.01	-	1.11	0.69
	0.05	-	0.83	0.68
	0.10	-	0.74	0.62
	0.50	-	0.15	0.20
	1.00	-	0.33	0.05, 0.09
Daxad 21	0.01	1.10	-	-
	0.05	0.98, 1.00	3.38	0.70
	0.10	1.06, 0.82	0.86	0.60
	0.50	0.63, 1.05	0.91	0.30
	1.00	0.44, 0.92	0.41	0.10
Marasperse N	0.05	1.57	0.40	0.78
	0.10	1.11	0.34	-
	0.50	1.36	0.43	-
Marasperse C	0.05	1.11	0.41	0.39
	0.10	1.41	2.46	0.64
	0.50	0.85	0.22	1.06
Lignosol	0.05	0.82	0.98	0.70
	0.10	0.64	1.18	0.40
	0.50	0.41	1.55	0.17
	1.00	0.51	0.57	0.17

4. The effectiveness of the polymers depends considerably on the soil treated. The unpredictable behavior of polymeric aggregants, especially the influence of aggregant concentration, is a discouraging fact which has been observed in other studies.

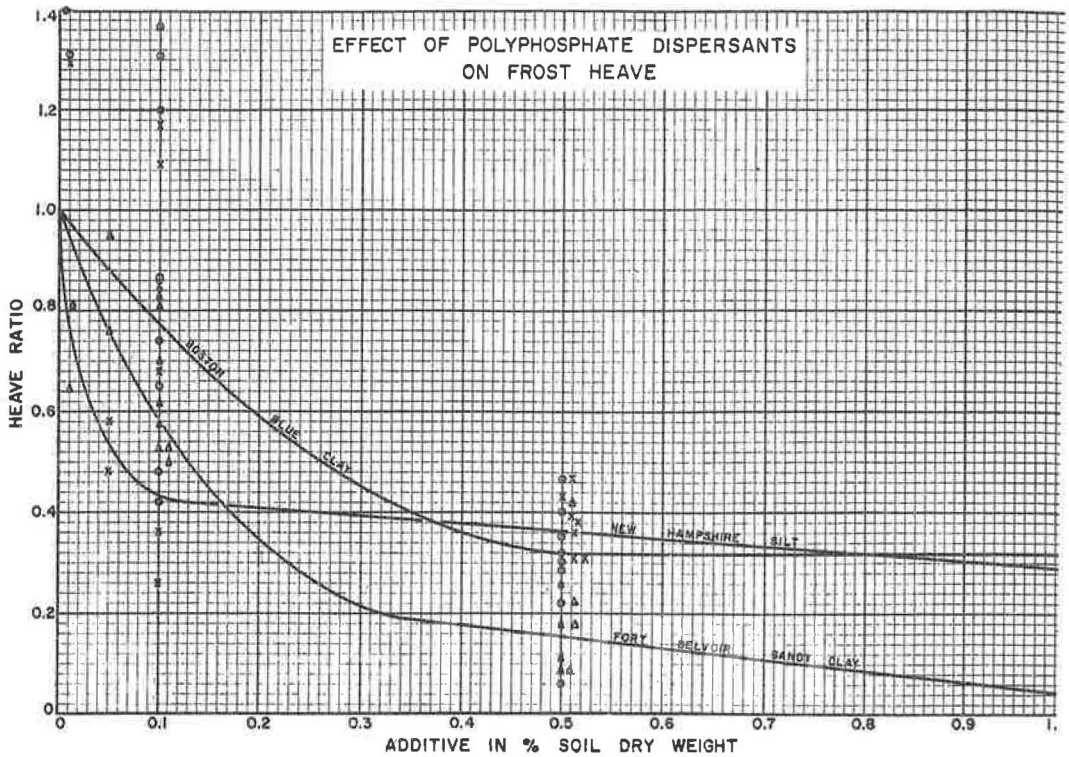


Figure 5. Effect of polyphosphate dispersants on frost heave.

As a matter of fact, many of these aggregants behave as dispersants at high-treatment levels. The modest effectiveness, importance of concentration, and high (chemical) cost combine to make the polymer aggregants unpromising as a group of additives for frost susceptibility modification.

Table 6 presents the effects of six cations on the frost heave of nine soils. Lead an mercury ions were investigated, not so much as aggregants but as "waterproofers" since they are non-hydratable ions. No treatment levels are given in Table 6; enough of each salt was added to saturate the ion exchange capacity of the soil with the salt's cations. Since all of the soils listed in Table 6 have low exchange capacities, the required treatments were low, always less than 0.5 percent. After treatment the soils were washed and dried.

The results show that some reaction in addition to ion exchange and ion fixation tool place, since ferric sulfate was inferior to ferric chloride. The reasons for this difference were suggested previously where it was noted that ferric hydroxide, a potentia cementing agent, could be formed from ferric chloride. Future tests on cations shoul consider the accompanying anions and the amount of salt used.

The main disadvantage to the use of cations, such as ferric iron, is the probable ne for drying the treated soil. The importance of drying will be investigated. Certainly, the results on one-half of the soils treated with ferric chloride are most encouraging. Other studies (Massachusetts Institute of Technology Soil Stabilization Laboratory) hav demonstrated the additional encouraging fact that ferric chloride has a beneficial effec on the strength characteristics of soil.

EFFECT OF DISPERSANTS ON FROST HEAVE

Table 7, presenting the results of freezing tests on miniature samples treated with various dispersants, indicates dispersants can be very effective as frost-heave reduce The data show several important and favorable facts, as follows:

TABLE 8

EFFECT OF "WATERPROOFERS" ON FROST HEAVE

(In Heave Ratios)

Additive	Percent	Boston Blue Clay	New Hampshire Silt	Fort Belvoir Sandy Clay
SC-50	0.01	1.03	0.85	0.48
	0.05	0.96	0.51	0.36
	0.10	0.29, 0.43	0.82, 0.60	0.37, 0.47
	0.50	0.06, 0.06	0.87	0.06, 0.26
	1.00	0.05, 0.13	0.55	0.05, 0.01
XS-1	0.01	-	-	0.73
	0.05	0.63	0.78	0.65
	0.10	0.56	0.66	0.39
	0.50	0.13	0.53	0.12
	1.00	0.12	0.23	
Potassium phenyl siliconate	0.01	-	-	0.69
	0.05	0.48	1.20	0.72
	0.10	0.81	1.58	0.70
	0.50	0.33	0.45	0.60
	1.00	0.23	0.76	0.74
Triton K-60	0.10	0.87	0.86	0.74
	0.50	1.16	1.11	0.53
	1.00	1.02	0.58	0.71
Volan	0.01	0.77	0.40	0.58
	0.05	0.73	-	-
	0.10	0.58, 0.64	0.63, 1.36	0.27, 0.63
	0.50	0.00, 0.37	0.43	0.24, 0.22
	1.00	0.17, 0.08	0.13	0.11, 0.10
Quilon	0.01	-	1.31	0.53
	0.10	0.83, 0.89	0.66, 1.08	0.40, 0.65
	0.50	0.48, 0.88	0.98	0.38, 0.34
	1.00	0.55	0.04, 0.86	0.18, 0.14
Hyamine 1622	0.10	1.02	1.40	0.92
	0.50	1.31	0.84	0.42
	1.00	1.26	0.74	0.60
Hyamine 2389	0.10	1.06	1.86	0.59
	0.50	1.20	0.80	0.41
	1.00	1.24	0.56	0.42
Triethylene Tetramine	0.10	0.94	1.29	0.41
	0.50	1.16	0.57	0.42
	1.00	1.05	0.40	0.51
Hexamethylene Diamine	0.01	-	0.55	-
	0.05	-	0.78	-
	0.10	1.01	0.04, 0.96	0.49, 1.07
	0.50	2.04	0.74	0.38, 0.73
	1.00	1.99	0.66	0.16, 0.49
Di-N-butylamine	0.05	-	-	0.54
	0.10	1.83	-	0.44
	0.50	0.61	-	0.31, 0.69
	1.00	0.69	0.80	0.12, 0.25
Primene 81-R	0.01	-	0.95	-
	0.05	-	0.57	-
	0.10	2.51	0.10, 0.67	0.99
	0.50	3.54	0.50, 0.38, 0.04	0.75
	1.00	3.91	0.30, 0.05	0.81
Carbowax 200	0.01	-	-	0.55
	0.05	-	-	0.99
	0.10	1.59	1.11	0.50, 0.91
	0.50	0.70	0.65	0.12, 0.21
	1.00	0.62	0.76	0.20
Carbowax 6000	0.01	-	-	0.56
	0.05	-	-	0.61
	0.10	1.34, 0.86	1.00	0.57, 0.88
	0.50	1.23, 0.82	1.07	0.18
	1.00	0.31, 0.36	0.42	0.26
Arquad 2HT	0.05	0.29[a], 0.49	0.63[a], 1.05	0.66[a], 0.41
	0.10	(1.56, 0.39[a], 0.44)	(0.84, 0.92[a], 0.84)	0.76, 0.70[a], 0.39
Arneen 18D	0.10	1.61	1.10	0.89
Diethanol rosin amine D acetate	0.10	0.87	-	-
	0.50	1.12	-	-
	1.00	1.27	-	-
Monethanol rosin amine D acetate	0.10	0.65	-	-
	0.50	1.23	-	-

[a] Sample air-dried after chemical treatment.

1. All dispersants studied were effective.
2. There was no one dispersant significantly superior to the others.
3. The higher the treatment, the better the results, but improvement past 0.5 percent is slight

Figure 5 is a plot of heave ratio and concentration for the three polyphosphates tested. The sample molding conditions were intentionally varied for these tests from very dry to very wet optimum moisture. No trend of effectiveness varying with molding moisture could be detected; in fact, Figure 5 shows little variation in heave at any given additive concentration.

Dispersants are particularly promising as soil additives since they are effective in low concentrations, are relatively cheap, have beneficial effects on other soil prop-

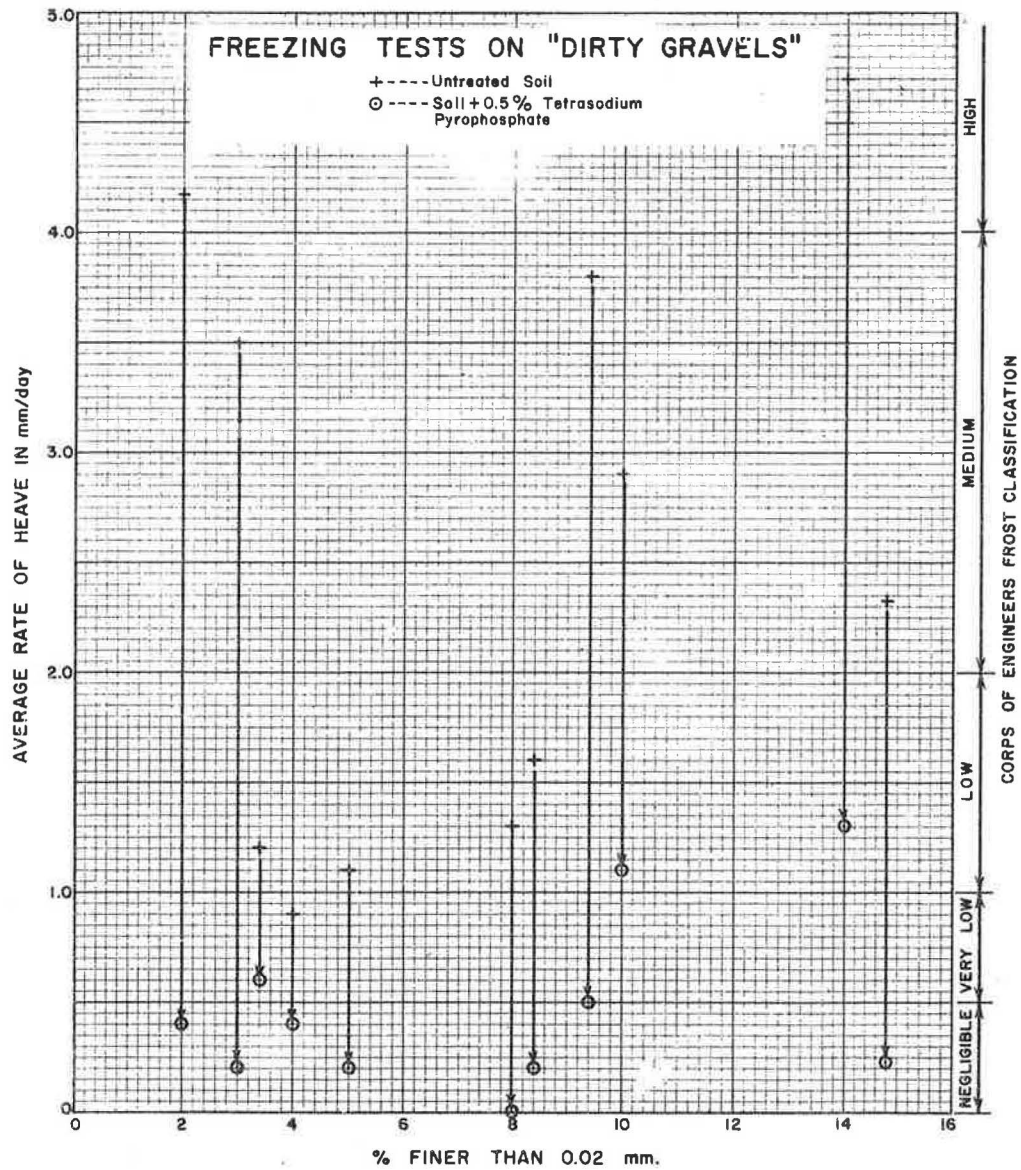


Figure 6. Freezing tests on ''Dirty Gravels.''

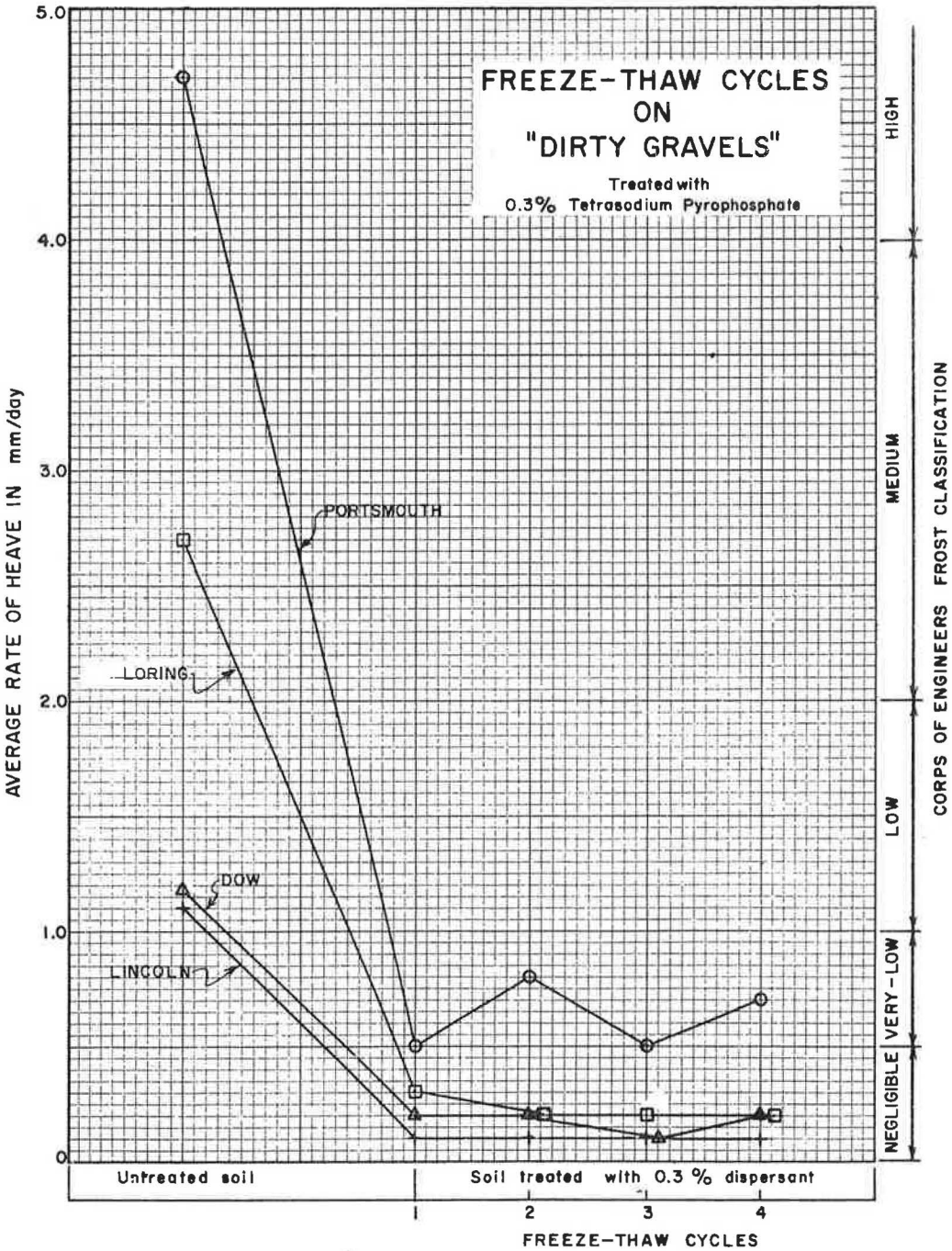


Figure 7. Freeze thaw cycles on ''Dirty Gravels.''

erties, are comparatively easy to incorporate, react instantaneously, and require no pre- or post-treatment curing (8). Based on the very favorable results obtained (Table 7), the tests described in the last part of this paper were conducted.

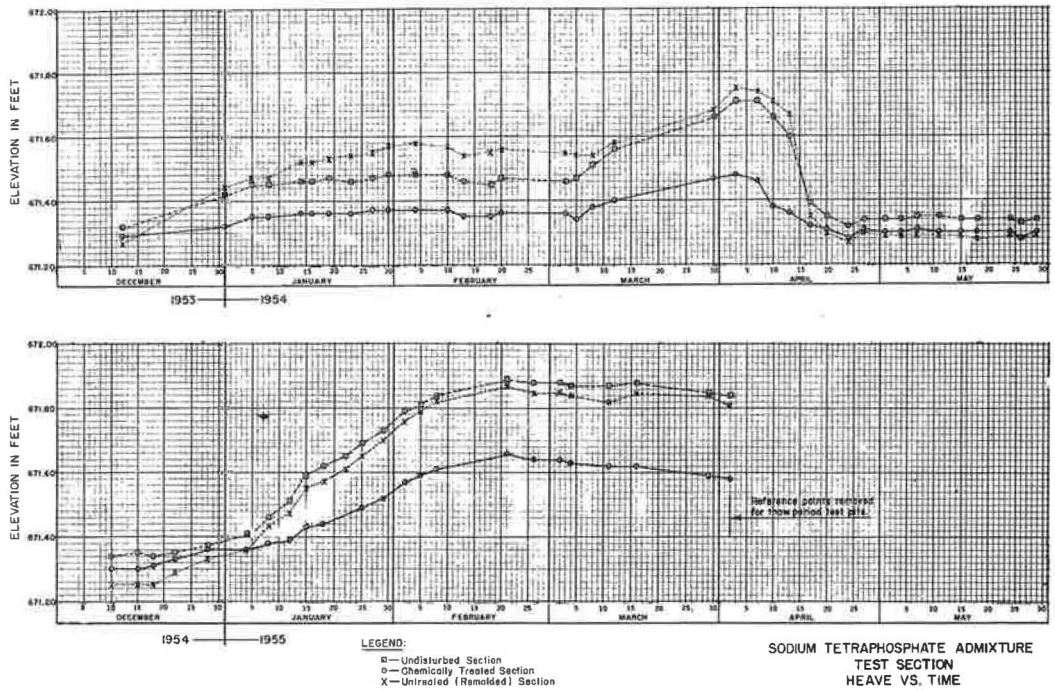


Figure 8. Sodium tetraphosphate admixture test section heave vs. time.

EFFECT OF "WATERPROOFERS" ON FROST HEAVE

Table 8 presents the results of tests to evaluate 18 "waterproofers" as frost modifiers. In all instances, the soils were dried after treatment; in some instances they were dried before the chemical was added. These necessary preparations and cure conditions are, of course, an undesirable feature of "waterproofers".

The results in Table 8 show that the effects varied from very beneficial to detrimental, with the majority being beneficial. As with polymeric aggregants, the effects of the "waterproofers" are not predictable; e.g., Primene was very beneficial with New Hampshire silt but most detrimental with Boston blue clay. As would be expected, the more "waterproofers" used, the better the results; generally, marked benefits were obtained only at treatments 0.5 percent and greater.

The high unit cost of "waterproofers" and the necessity of drying treated soils dim

TABLE 9

FREEZING TESTS ON "DIRTY" GRAVELS

Lab. No.	Source	Untreated Gravels			Gravels + 0.3 Tetrasodium Pyrophosphate			Heave Ratio
		Molding Water	Dry Unit Weight	Average Rate of Heave	Molding Water	Dry Unit Weight	Average Rate of Heave	
		Percent	pcf	mm/day	Percent	pcf	mm/day	
-	Greenland, TP-250	5.0	140.1	3.5	3.0	143.3	0.2	0.06
-	Dow AFB, Bangor, Maine, B-11	5.0	131.4	1.0	5.0	131.4	0.4	0.40
-	Dow AFB, Bangor, Maine, B-18	5.0	132.2	1.2	5.0	133.0	0.6	0.50
49-11	Ellsworth AFB, Weaver, South Dakota	6.0	137.0	1.3	5.0	137.0	0.0	0
49-8	Clinton County AFB, Wilmington, Ohio	9.0	129.0	3.8	5.0	129.4	0.5	0.13
49-21	Spokane AFB, Spokane, Washington	6.0	128.0	0.9	5.0	128.2	0.4	0.44
49-102	Lincoln AFB, Lincoln, Nebraska	7.0	132.2	1.1	4.8	134.4	0.2	0.18
49-60	Fairchild AFB, Spokane, Washington	4.5	131.3	2.9	6.3	131.3	1.1	0.38
49-54	Portsmouth AFB, Portsmouth, New Hampshire	8.5	127.0	4.7	5.0	129.8	1.3	0.27
49-17	Sioux Falls Airfield, Sioux Falls, South Dakota	4.0	131.0	1.6	11.1	128.5	0.2	0.12
49-9	Patterson AFB, Fairfield, Ohio	5.0	134.9	2.3	4.7	137.3	0.2	0.09

the prospects of these materials as frost modifiers even though they can be extremely effective.

FREEZING TESTS ON "DIRTY" GRAVELS TREATED WITH DISPERSANTS

Large percentages of the granular soils are unacceptable for fill material in the frost zone, not because of their strength characteristics under normal conditions, but because of their frost behavior. Even though a gravel with more than 3 percent by weight finer than 0.02 mm ("dirty" gravel) may have a very high California Bearing Ratio after soaking, it should not be used as a pavement base or foundation fill in the freezing zone because of frost-heaving and resultant weakening. A treatment that could make these otherwise excellent gravels non-frost-susceptible would be most useful.

To test the effectiveness of a chemical dispersant as a modifier of the frost characteristics of "dirty" gravels, 11 gravels were treated with 0.3 percent tetrasodium pyrophosphate and subjected to controlled laboratory freezing tests. The results of these tests are listed in Table 9 and plotted in Figure 6. They show that the polyphosphate reduced the rate of frost heave on all 11 gravels. The minimum reduction was to one-half of the untreated value, the maximum to essentially zero, and the average reduction was to one-fifth of the untreated value. Figure 6 shows that 75 percent of the gravels were made to fall within the Corps of Engineers' Relative Frost Susceptibility Classification lowest category, negligible (3).

In Figure 6, the results of freezing tests were plotted as a function of "percent finer than 0.02 mm" to see if the effectiveness of the dispersant was a function of fines content. The main relationship apparent is that the greater the rate of heave of the natural soil, the greater is the reduction caused by the dispersant; no relation between fines content and chemical performance is apparent.

The reason why dispersion is so potent in "dirty" gravels is not definitely known, but it may be the following: Since the overall structure of these soils is controlled by the gravel size particles, dispersion has little effect on the density (this fact can be observed from a comparison of the densities of untreated and treated samples, Table 9). Disaggregating the fines permits them to pack into a smaller space, thereby making the voids among gravel particles larger. In fact, the dispersed fines can be moved by pore water. Unpublished tests by Olsen at Massachusetts Institute of Technology which showed considerable removal of soil fines by leaching with a dispersant support this thought of "cleaning" the soil.

FREEZE-THAW CYCLES ON TREATED SOILS

For an additive to be of practical value, it must not only be an effective frost modifier, but it must also have reasonable permanence. The temporary effectiveness of salt to reduce the freezing point of pore water is, for example, a major drawback, as has already been mentioned. How permanent then are the other treatments, especially the very promising dispersants, described here?

Theoretical considerations suggest that when dispersants alter the structure of the entire soil mass, cycles of freezing and thawing may undo some of the improvements in structure. The effectiveness of a dispersant on a clay may well be gradually decreased over a number of years. On the other hand, where the structure benefits are limited to a small portion of the particles, freeze-thaw cycles probably have little, if any, influence.

A series of tests was conducted on standard-size samples (5.91 inches in diameter by 6.0 inches high) of four treated "dirty" gravels to ascertain the effect of freeze-thaw cycles. The results, presented in Figure 7, show no loss of dispersant effectiveness, during four cycles of freeze-thaw (i.e., the duration of the tests). Figure 7 also dramatically illustrates the pronounced reduction of frost action that can be obtained from dispersants.

The indicated permanence of dispersant treatment (Figure 7) is substantiated by the following field test.

FIELD TEST

To see if the laboratory tests indeed reflect field conditions, a small-scale test was

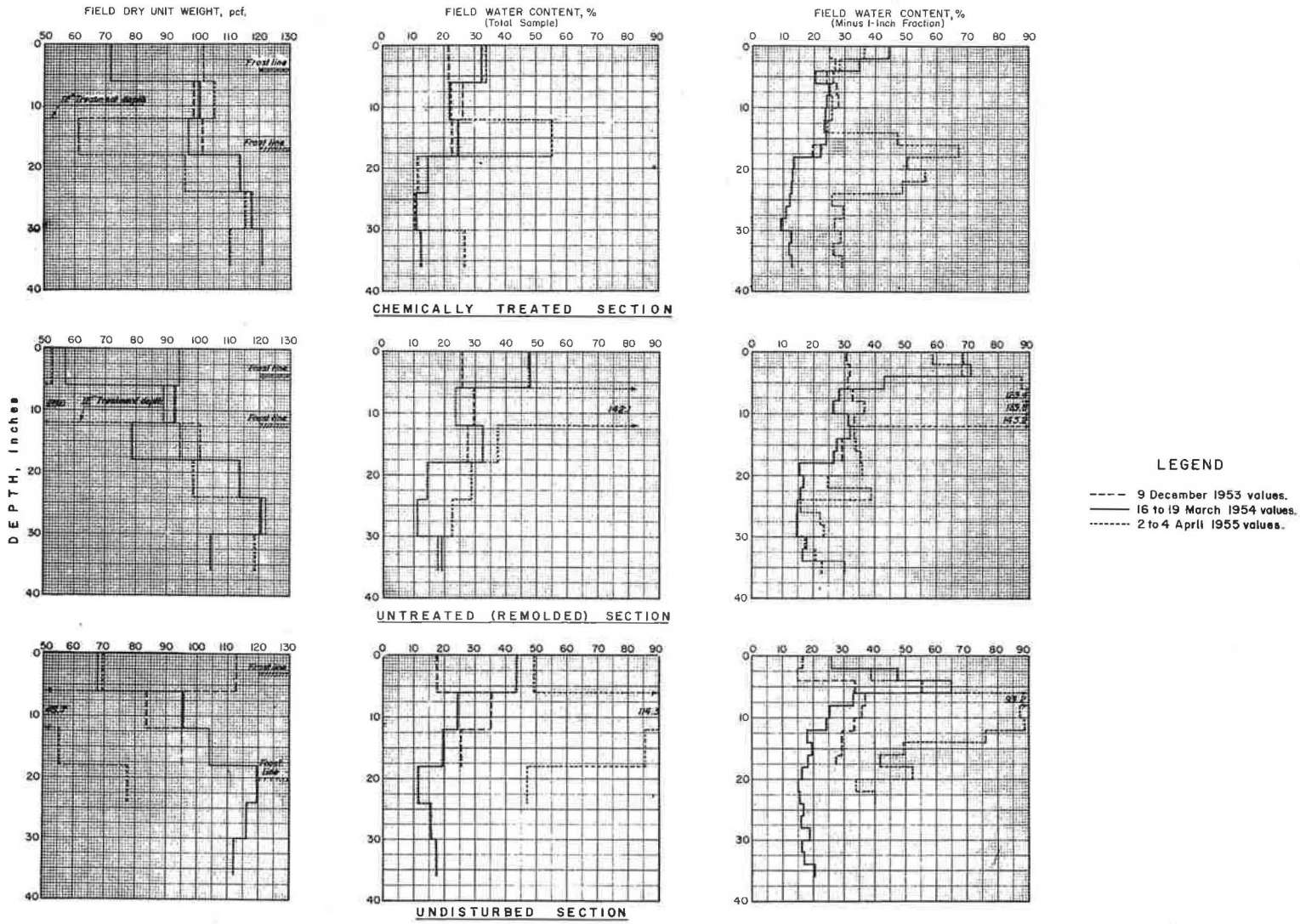


Figure 9. Sodium tetraphosphate admixture test section density and

conducted (and is still in progress) at Loring Air Force Base, Limestone, Maine. Three test sections, 4 feet by 4 feet by 1 foot deep, were prepared at a site where the water table is about 20 feet below ground surface. One section is of undisturbed soil; another of soil which had been remolded but given no chemical treatment; and a third section of soil which was hand-mixed with 0.3 percent sodium tetraphosphate, a dispersant. The soil is a clayey sandy gravel (i. e., glacial till) with a liquid limit of 22, a plasticity index of 8, and about 40 percent of its particles finer by weight than 0.02 mm.

The sections were prepared on 8 December 1953, and thus data from two freeze-thaw cycles are available. During the two frost-melting periods, the frost lines as located in test pits were as follows:

	Penetration of 32°F Isotherm (inches)		
Date	Undisturbed Untreated Section	Remolded Untreated Section	Chemically Treated Section
16-19 March 1954	3	4	4
2-4 April 1955	20	12	17

Some of the results to date are shown in Figures 8 and 9. Figure 8 presents ground surface elevation as a function of time; it shows the following:

	Heave (feet)		
Date	Undisturbed Untreated Section	Remolded Untreated Section	Chemically Treated Section
19 March 1954	0.28	0.35	0.14
5 April 1954	0.39	0.47	0.18
2 April 1955	0.50	0.56	0.28

In comparison with either of the untreated sections, the dispersant caused a significant reduction in heave. Most important is the fact that the dispersant was effective the second year; i. e., during the second freeze-thaw cycle. The heave ratios in the field test, approximately ½, compare well with those from the laboratory tests, ⅕ to ⅓.

An explanation of why the results of chemical treatment did not show up better in the field test is furnished by Figure 9. This figure shows two things: (1) the treated and untreated (remolded) soil sections were placed at very low dry unit weights of 100 and 92 pcf, respectively, caused by rain during construction (the Corps of Engineers' Modified AASHO Density Test[1] maximum is 137 pcf); and (2) most of the dry unit weight loss and moisture increase in the treated section occurred below the treated zone. In other words, a large percentage of the heave in the treated section occurred in the untreated soil underlying the treated soil. In fact, most of the 1955 heave in the treated section came from the untreated soil. Figure 9 shows that the dry unit weight loss during the 1955 thaw for the treated section was 22 pcf or 22 percent for the top 6 inches of treatment, while for the underlying untreated 6 inches of soil in the frost zone the dry unit weight loss was 40 pcf or 40 percent. These values suggest a heave ratio (0.55) which compares favorably with that obtained from the elevation observations (0.6).

This limited field test shows these encouraging results:

1. The laboratory test is indicative of field performance.
2. The chemical dispersant was effective in reducing frost heave, density loss, and moisture gain in the frost zone.
3. The effectiveness of the chemical was not adversely changed by a freeze-thaw cycle.

In future field tests, a site with a higher water table will be selected and the treatments will be extended below the frost zone.

[1] Corps of Engineers' Modified AASHO Density Test is made by compacting soil in a 6-in. diameter cylinder, 1/10 cu ft in volume, using five layers, 10-lb tamper and 18-in. drop, 55 flows per layer.

TABLE 10

OVERALL EVALUATION OF ADDITIVES AS FROST MODIFIERS

Additive	Effectiveness[a] As Indicated By Laboratory Test	Requirements for Soil-Additive Reaction	Required Additive Concentration	Additive Cost Per Pound	Effect on Soil Properties Other Than Frost Action	Field Use	Comments	Evaluation[a] As Frost Modifier
			Percent					
Void Pluggers and Cement								
a. In situ polymerization (calcium acrylate)	Excellent	Polymerization marked function of temperature	> 5	> 50¢	Beneficial increase strength, density and decrease permeability	Difficult to control polymerization	Intended for emergency use	Poor
b. Resins	Interesting	Drying after treatment—some require soil be predried	> 1	1 to 15¢	Beneficial	Other than cure requirements, no special problems		Promising
c. Portland cement	Interesting (with additives to cement)	Cure period for cement hydration	> 4	1 to 2¢ (cement) 6 to 12¢ (additives)	Beneficial	No special problems		Interesting to Poor
d. Natural fines	Excellent	None	> 6	0 to 2¢	Probably detrimental to strength and permeability	Probably unusual mixing and processing problems		Interesting
Aggregants								
a. Polymers	Interesting to poor	None	< 1	12¢ to $1.00	Beneficial	Moderate mixing and processing problems expected	Effectiveness unpredictable and function of concentration	Interesting to Poor
b. Cations	Excellent	None for some, drying after treatment for others	< 0.5	2¢ and up	Beneficial	No special problems expected		Very Promising
Dispersants	Excellent	None	< 1	5¢ to $1.00	Beneficial	No special problems		Very Promising
"Waterproofers"	Excellent	Drying after treatment	> 0.5	25¢ to $2.00	Beneficial	Need for high degree of drying		Promising

[a]ADJECTIVE RATING SCALE: poor, interesting, promising, very promising, excellent.

SUMMARY AND CONCLUSIONS

This report describes a search for additives to reduce the frost susceptibility of soil the three-year search involved more than 1,000 freezing tests, using approximately 15 soils and 40 additives. The additives tried were chosen because of various theoretical reasons as to why each might reduce the moisture migration necessary for ice lens formation. The additives were divided into four groups — (1) void pluggers and cements, (2) aggregants, (3) dispersants, and (4) "waterproofers"— according to their action in soil.

Table 10 gives an overall evaluation of the additives studied. This evaluation considers effectiveness as a frost modifier as indicated by the freezing tests described herein, cost, and difficulty of field use. Any evaluation of the additives must consider the latter two practical items, even though the tests reported primarily measured additive effectiveness as a frost modifier. The evaluation in Table 10 is based on judgment as well as on quantitative test results.

The salts of polyvalent cations, especially ferric chloride, and the dispersants appear to be very promising as additives for reduction of the frost susceptibility of soil at low cost. Some of the resins and "waterproofers" show enough promise to warrant further laboratory testing.

A small-scale field test showed a laboratory-proved dispersant to be effective under field conditions; measurements made during the second freezing cycle showed no reduction in the potency of the dispersant treatment. Four freeze-thaw cycles on four soils tested in the laboratory also had no adverse effects.

While the primary objective of the test program was to screen additives, enough different soils were used to permit some important, if tentative, observations concerning effect of soil type. Well-graded soils with some coarse particles (gravel or large sand size) respond to treatment best. Uniform silts and moderately plastic clays are the least responsive. The most promising use of additives in in treatment of soils — well-graded ones with coarse particles — whose mass structure is determined by the large particles. Such "dirty" gravels, sandy clays, and silty sands can often be made essentially non-frost-heaving with additives at an economical cost; that is, at an additive cost of less than $1.00 per cubic yard of soil treated. The incorporation of additives with base and subbase soils may not necessarily be difficult, since they are usually obtained from borrow areas, placed in layers, and worked before compaction. These soils could be treated with little additional processing.

More field testing is required before the dispersants and other additives can be completely evaluated. Even though the dispersants appear to be effective in nearly all frost-susceptible soils, the characteristics of treated samples of the soil in question should be checked by laboratory freezing tests before dispersants are used in the field.

ACKNOWLEDGMENTS

The study described in this paper was sponsored by ACFEL, Corps of Engineers. Testing was performed at ACFEL under the direction of Kenneth A. Linell and James F. Haley, Chief and Deputy Chief of ACFEL, respectively. The author selected the additives to be tested and analyzed the test data; his assistants at the MIT Soil Stabilization Laboratory, James K. Mitchell and Thomas J. Lambie, prepared the treated soil samples. The laboratory freezing tests were supervised by Edward F. Lobacz and Chester W. Kaplar, soil engineers on the ACFEL staff. William C. Sayman, ACFEL general engineer, and Lobacz were responsible for the conduct of the Maine field tests.

Hanley, Kaplar, and Lobacz, and Ronald Scott of the ACFEL staff, reviewed this paper and made helpful suggestions for its improvement.

The author gratefully acknowledges all of the considerable aid by the ACFEL staff to the frost additive research, including the preparation of the figures, and for permission to publish this paper.

REFERENCES

1. Arctic Construction and Frost Effects Laboratory. Interim report of cold room studies (1949-50). New England Division, Corps of Engineers, U.S. Army, Boston, July 1950.

2. _____ Cold room studies, second interim report of investigations (FY 1950-1). 2 vol. Ibid. Boston, June 1951.

3. _____ Cold room studies, third interim report of investigations (FY 1952-3), with appendix by T.W. Lambe, 2 vol. Ibid. Boston, June 1953.

4. Army, Department of the. Engineering manual for military construction. Pt. XII. Airfield pavement design. Ch. 4. Frost conditions. Office of the Chief of Engineers. Washington, October 1954.

5. Casagrande, A., Discussion of frost heaving. Highway Research Board, Proc. 11, pt. 1, 168-72 (1932).

6. Haley, J.F., Cold-room studies of frost action in soils, a progress report. Highway Research Board, Bull. 71, 1-18 (1953).

7. Lambe, T.W., Stabilization of soils with calcium acrylate. Journal, Boston Soc. Civil Engrs. 38, No. 2, 127-54 (1951).

8. Lambe, T.W., Improvement of soil properties with dispersants. J. Boston Soc. Civil Engrs. 41, No. 2, 184-207 (1954).

9. Lambe, T.W., and Martin, R.T., Composition and engineering properties of soil (II). Highway Research Board, Proc. 33, 515-32 (1954).

10. Michaels, A.S., Altering Soil-water relationships by chemical means. Proc. Conf. Soil Stabilization, Massachusetts Institute of Technology, p. 59. Cambridge, June 1952.

11. Michaels, A.S., and Lambe, T.W. Laboratory evaluation of polyelectrolytes as soil flocculants and aggregate stabilizers. Agri. Food Chem. 1, No. 13, 835-43 (1953).

12. Peech, M., et al., Methods of soil analysis for soil fertility investigations. U.S. Dept. Agr. Circ. 757, 5-7 (1947).

13. Yoder, E.J., Freezing-and-Thawing tests on mixtures of soil and calcium chloride. Highway Research Board, Bull. 100, 1-11 (1955). Discussion by R.E. Pine. Ibid. 100, 11-16, (1955).