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ADDITIVES FOR MODIFYING THE FROST SUSCEPTIBILITY OF SOILS

Part II

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and
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13. ABSTRACT

This report describes results of a search for additives to reduce the frost susceptibility of soil. The additives are divided into four primary function groups: 1) void fillers and cementing agents, 2) aggregants, 3) waterproofers, and 4) dispersants. Tests showed that a dispersant, tetrasodium pyrophosphate (TSPP), and an aggregant, ferric chloride, possess good frost-heave-modifying capabilities. A preliminary field test indicated that TSPP can reduce heave significantly under natural conditions. The long-term effectiveness under fiel conditions is still to be determined. Laboratory tests were conducted to determine the effect of prolonged water attack on the frost-heave-modifying capabilities of 0.3% treatments of TSPP and ferric chloride when used with two silty sandy gravels. The tests showed that in terms of percentage reduction of heave the effectiveness of TSPP was not mitigated by water attack while the effectiveness of ferric chloride was slightly lessened. Both additives reduced the frost susceptibility of the soils from classification of "medium to high" to "very low to low." Theory and experimental data are presented which help to explain the response of the soils to treatment and freezing.

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PREFACE

This report summarizes cooperative studies conducted over a three-year period (FY 1956-1958) by the former Arctic Construction and Frost Effects Laboratory (ACFEL) of the U.S. Army Engineer Division, New England, and Dr. T. William Lambe of the Department of Civil Engineering, Massachusetts Institute of Technology. Dr. Lambe's services were obtained under renewing contractual arrangements (Contracts DA-19-016-ENG-4006, -4657 and -6061).

ACFEL and the U.S. Army Snow, Ice and Permafrost Research Establishment were combined to form the U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL), Hanover, New Hampshire, in 1961.

The study was conducted for the Engineering Division, Directorate of Military Construction, Office, Chief of Engineers, and was administered by the Civil Engineering Branch (Mr. F.B. Hennion, Acting Chief), in connection with Military Construction Investigations, Engineering Criteria and Investigations and Studies; Studies of Construction in Areas of Seasonal Frost, Subproject 30, Additives to reduce frost susceptibility of soils. The Military Construction Investigations program is now conducted for the Office of Plans, Research and Systems (OPRS), Directorate of Military Construction, Office, Chief of Engineers.

Dr. Lambe was responsible for planning the scope of the investigation and assisted by furnishing the additives and preparing some soil admixtures. All soils except one were furnished by ACFEL. The freezing tests and preparation of data were performed by ACFEL personnel under the immediate supervision of Chester W. Kaplar, Project Engineer. The study was conducted under the general direction of Mr. Kenneth A. Linell, Chief, Experimental Engineering Division, USA CRREL (formerly Chief, ACFEL).

Lt. Col. Joseph F. Castro was Commanding Officer/Director of the U.S. Army Cold Regions Research and Engineering Laboratory during the publication of this report.

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ADDITIVES FOR MODIFYING THE FROST SUSCEPTIBILITY OF SOILS, PART II

by

T.W. Lambe, C.W. Kaplar and T.J. Lambie

INTRODUCTION

Background and purpose

The investigation described in this report was part of a joint program conducted by the Contractor (T. William Lambe) and the Arctic Construction and Frost Effects Laboratory over a period of several years having two complementary objectives: to investigate the correlation between the mineralogical composition and the frost heaving behavior of soils, and to find additives that would effectively reduce frost susceptibility. In this search for promising frost-heave modifiers particular attention was given to finding additives which are effective in trace amounts (1% or less of the dry soil weight) and which, by reducing the frost susceptibility of silty sands and gravels, might make these materials suitable for base course construction. This report presents the results of investigations aimed at the second objective stated above.

Previous reports

The findings of the mineralogical study phase of the program have been summarized in USA CRREL Technical Report 207 (Lambe et al., 1969).

The findings of the additive test program for the three-year period 1953-1955 have been summarized in USA CRREL Technical Report 123, Part I (Lambe and Kaplar, 1971). The theoretical considerations which served as a rationale for the test program as well as the testing procedures are fully described in that report.

Scope

The present report discusses the results of tests conducted in the three-year period 1956-1958. The following are the chief studies made during this period:

1. Laboratory freezing tests to evaluate the effectiveness of hitherto untried additives and to confirm the promising results previously obtained, especially with a dispersant, tetrasodium pyrophosphate (TSPP), and an aggregant, ferric chloride. A limited number of void pluggers and cementing agents, and waterproofers, were also tried on standard size specimens of several representative base courses.

2. A trial field test on several base course type soils to observe the effectiveness of TSPP under natural field conditions.

3. Laboratory freezing tests to evaluate the permanence of effectiveness of TSPP and ferric chloride in the face of water attack and leaching.

INVESTIGATIONAL PROGRAM

Additives and soils

Table I lists the additives evaluated as frost-heave modifiers in the period 1956-1958. The 35 additives are classified as follows: 1) void fillers and cementing agents, 2) aggregants, 3) metallic salts, 4) waterproofers, and 5) dispersants. With the exception of the metallic salts, the grouping is by primary function; metallic salts can interact with soil fines as both aggregants and waterproofers.

The same three basic fine-grained soils used in the screening tests reported in TR 123, Part I, were used in further screening tests: New Hampshire silt, Boston blue clay, and Ft. Belvoir sandy clay. Thirteen additional coarse-grained silty sands and silty (dirty) sandy gravels not previously used were selected for testing in standard-size cylinders with the more promising additives. The physical index properties of these soils are presented in Table II.

Presentation of results

The evaluation procedure involved the use of two sizes of specimens prepared in cylindrical Lucite containers. Small cylindrical molds (hereafter referred to as miniature), 1.25 in. in diameter and 3.108 in. long (see Fig. 1, TR 123, Part I) were used in trays of 25 each in screening tests with the three fine-grained soils. The coarser-grained base course type soil specimens were prepared in larger diameter (approximately 6 in.), 6-in.-high cylinders, slightly tapered inside with the larger diameter at the top to minimize friction. Except for the specimens in trays 56-1, 56-2 and 56-3, all miniature molds in this series were of improved design, i.e. slightly tapered inside to minimize heaving frictions. It can be noted on Table AI that the heave rates of untreated soils were considerably greater in the tapered miniature molds than in the straight-walled molds. It is believed, however, that these differences in heaving rates between trays have not affected the value or validity of the test results since comparisons of results have been made only between the specimens in each tray.

LABORATORY TESTS: EFFECT OF ADDITIVES ON FROST HEAVE OF MINIATURE SPECIMENS

Laboratory screening tests were run on fine-grained soils which were treated with various additives, compacted, and subsequently frozen in miniature molds, as described in TR 123, Part I. Appendix Tables AI and AII present the basic test data. Summary tables (Tables III-IX) compare the effectiveness of the various treatments in terms of *heave ratio* (the average rate of heave of the treated specimen divided by the average rate of heave of the untreated specimen). The results are discussed below.

Void fillers and cementing agents

When void fillers and cementing agents are used with fine-grained soils, the difficulty of incorporation and the required treatment levels increase with increasing plasticity. The levels of treatment used in the tests were lower than would usually be used in field practice. Normally, these agents require curing to be most effective; moreover, since their effectiveness depends upon their adequately coating the soil grains, mixing and pretreatment can be critical. Attempts were made to increase the effectiveness of some of the conventional stabilizers through the use of secondary additives.

Table I. Additives tried as frost heave modifiers.

Item	Additive	Registered trademark	Supplier	Approx. price $/lb. (1967)	Form
	Void fillers and cementing agents				
1	Portland cement			0.015	Powder
2	Sodium sulfite		Merck & Co., Inc., Rahway, N.J.	0.025	Granular
3	Sodium metasilicate		Allied Chemical & Dye Corp., New York	0.06	Crystalline
4	Gypsum (land plaster of approx. 95% purity)		U.S. Gypsum Co., Chicago, Ill.	0.021	Powder
5	Quicklime (chemically pure CaO)		J.J. Baker Chemical Co., Phillipsburg, N.J.	0.01	Powder
6	Hydrated lime (calcitic)		Fisher Scientific Co., New York	0.01	Powder
7	Fly ash		Detroit Edison Co., Detroit, Michigan		Powder
8	Phosphorus pentoxide		Howe & French Inc., Boston, Mass	0.15	Powder
9	Sodium silicofluoride		Fisher Scientific Co., New York	0.08	Powder
10	Benzene phosphonic acid		Victor Chemical Works, Chicago, Ill.		Crystal
11	Asphalt emulsion (68% solids)		American Oil Products Co., Somerville, Mass.	0.03	Liquid
12	Asphalt cutback (2 asphalt: 1 gasoline)		Standard Oil Co., Everett, Mass.	0.03	Liquid
13	AM-9 (grout gel)		American Cyanamid Co., 30 Rockefeller Plaza, N.Y., N.Y.	*	Powder
14	Sodium thiosulfate		Mallinckrodt Chemical Works, St. Louis, Mo.	0.08	Crystalline
15	Ammonium persulfate		Mallinckrodt Chemical Works, St. Louis, Mo.	0.20	Crystalline
	Aggregant				
16	Sodium polyacrylate	Agrilon	Borden Chemicals, Div. of Borden, Inc., New York, N.Y.	*	Solution, flakes
	Metallic salts (Aggregants and waterproofers)				
17	Thorium chloride		Fisher Scientific Co., St. Louis, Mo.	*	Crystalline
18	Aluminum chloride		Mallinckrodt Chemical Works, St. Louis, Mo.	0.12	Crystalline
19	Aluminum sulfate		Mallinckrodt Chemical Works, St. Louis, Mo.	0.02	Crystalline
20	Aluminum phosphate		Mallinckrodt Chemical Works, St. Louis, Mo.	*	Crystalline
21	Ferric chloride		Mallinckrodt Chemical Works, St. Louis, Mo.	0.08	Crystalline
22	Ferric sulfate		Mallinckrodt Chemical Works, St. Louis, Mo.	0.02	Crystalline
23	Zinc sulfate		Mallinckrodt Chemical Works, St. Louis, Mo.	0.07	Crystalline
24	Calcium chloride		Mallinckrodt Chemical Works, St. Louis, Mo.	0.02	Crystalline
25	Sodium chloride		Mallinckrodt Chemical Works, St. Louis, Mo.	0.01	Crystalline
26	Lithium chloride		Mallinckrodt Chemical Works, St. Louis, Mo.	0.80	Crystalline
27	Silver iodide		Allied Chemical & Dye Corp., New York	>2.00	Powder
	Waterproofers				
28	Dioctadecyl dimethyl ammonium chloride	Arquad 2HT	Armour Industrial Chemical Co., Chicago, Ill.	0.34	Solution
29	Methacrylato chromic chloride	Volan	E.I. duPont deNemours and Company, Grasseli Chemical Dept., Boston, Mass.	1.46	Liquid
30	Polyethylene glycol	Carbowax Peg 200	Union Carbide Corp., New York, N.Y.	0.32	Liquid
31	Octadecyl amine	Armeen 18D	Armour Industrial Chemical Co., Chicago, Ill.	0.64	Solution
32	Ethylene diamine dihydrochloride		Howe & French Inc., Boston, Mass.	<0.20 †	Solution
33	Alkyl dimethyl benzyl ammonium chloride		Howe & French Inc., Boston, Mass.	~0.25 †	Solution
	Dispersants				
34	Tetrasodium pyrophosphate (TSPP)		Westvaco Chemical Co., New York, N.Y.	0.12	Powder, granular
35	Sodium tetraphosphate	Quadrafos	Rumford Chemical Works, Rumford, R.I.	0.12	Powder, granular

* Data not available

† Estimated

Table II. Soils used in additive freezing tests.

				Material (Unified Soil Classification System)			Basic gradation % finer (U.S. standard sieve)					Compaction		Atterberg limits[2]			Permeability	
Item	Lab serial no.	Specimen designation[1]	Source	Description	Symbol	Max. size (in.)	#4 4.76 mm	#40 0.42 mm	#200 0.074 mm	0.02 mm	0.002 mm	Max dry unit wt. (lb/cu ft)	Opt water content %	LL %	PI %	Sp gr (total sample)	Void ratio	K × 10⁻⁴ cm/sec at 10° C
1	49-49	LSG	Loring AFB Limestone, Maine	Silty sandy gravel	GW-GM	3/8	47	17	9.5	6.8				Non-plastic		2.71	0.250 0.213	0.3 0.1
2	B-18	DFSB	Dow AFB Bangor, Maine	Silty sandy gravel	GW-GM	3/8	49	17	8.0	3.2	<1	138.8^4		Non-plastic		2.69	0.290 0.270	6.2 4.6
3	49-138-1	BPG	Bowley Pit Hampden, Maine	Silty sandy gravel	GW-GM	2½	47	13	7.5	4.3	1	137.9^5		Non-plastic		2.69		
4	49-139 &	CBG	Coldbrook Pit Hampden, Maine	Silty sandy gravel	GM	2½	55	28	15	6.3	<1	144.7^5		Non-plastic		2.72	0.200	0.4
	49-141					2	53	26	12.8	7.5	2.5						0.300	3.0
5	49-20	GF	Great Falls AFB Great Falls, Montana	Clayey sandy gravel	GC	1½	48	36	22	17	8.5			43	25	2.66	0.355 0.375	0.1 1.0
6	49-142	HDG	Hutchinson's Pit Pittsfield, Mass.	Silty gravelly sand	SW-SM	1½-2	55-60	18-21	8.0-9.5	4.7-5.3	1	143.3^4	5.3	Non-plastic		2.75		
7	49-18-2	TD	Truax AFB Madison, Wisconsin	Silty gravelly sand	SM	3/4	90	79	26	17	6.5			Non-plastic		2.73	0.464 0.570	1.0 10
8	MIT-I	MIT	Camosse Pit Auburn, Mass.	Silty gravelly sand	SM	1½	81	58	33	18.6	3			21	1	2.70		
9	MIT-II	MIT	Camosse Pit Auburn, Mass.	Silty gravelly sand	SM	2	76	49	17.3	7.8	1			Non-plastic		2.70		
10	MIT-III	MIT	Camosse Pit Auburn, Mass.	Silty gravelly sand	SM	2	84	47	13	7.5	2			Non-plastic		2.70		
11	MIT-IV	MIT	Concord, Mass.	Silty gravelly sand	SW-SM	1½	70	29	9.7	4.4	2			Non-plastic		2.70		
12	49-12	CA	Casper AFB Casper, Wyoming	Clayey silty sand	SM-SC	1½	91	48	23	15	7.5			22	5	2.64	0.400 0.580	1.0 30
13	49-14	PA	Pierre AFB Pierre, S. Dakota	Clayey gravelly sand	SC	1½	67	31	17	8.7	2			25	7	2.73	0.340 0.540	1.0
14	49-46 & 49-105	CM (miniature)	Goff's Falls, New Hampshire	Clayey silt (New Hampshire silt)	ML-CL		100	97-100	93-99	67-73	6-14	98.6^7	21.0	24-27	6	2.71- 2.74	1.000 0.800	0.8 0.3
15	49-66	CM (miniature)	Fort Belvoir, Virginia (minus 2.0 mm fraction used in miniature size specimens)	Sandy clay (Fort Belvoir sandy clay)	CL	3/4	95-97	88	62-64	43-46	25-28	107.6^7	18.5	41	19	2.73	0.551 1.000 0.500	0.1 2.0 0.2
16	49-42	CM (miniature)	North Cambridge, Mass.	Clay (Boston blue clay)	CH		100	100	100	94	67	100.2^7	20.2	53	26	2.78	0.917 (re-molded)	0.001

Notes
(1) Freezing test specimens standard size unless otherwise noted.
(2) Limits on material passing U.S. Standard No. 40 sieve.
(3) Minerals determined by differential thermal analysis and X-ray diffraction. Free iron extracted by Na_2SO_4 and expressed as Fe_2O_3. Organic matter determined by H_2SO_4-$K_2Cr_2O_7$ oxidation method. Ethylene glycol retention is a measure of surface area; 1 mg glycol covers area of approximately 3.2 sq m.
(4) Modified AASHO designation T 180-57 method C.
(5) Providence vibrated density test method.
(6) Modified AASHO designation T 180-57 method D.
(7) Harvard miniature compaction test: 1/454 cu ft cylinder, 3 layers, 25 tamps per layer, 40-lb prestressed spring tamper, minus 2.0-mm soil fraction.

Asphalt. The limited data on the two fine-grained soils in Table III suggest that, for the asphalt emulsion, treatment levels in excess of 3% and drying (or curing) after compaction were necessary to achieve any significant frost-heave modification. Of the specimens treated with asphalt cutback, only the silt was benefited significantly by the use of phosphorus pentoxide as a secondary additive followed by curing.

Cementing agents. Table IV summarizes the data on effect of cementing agents on two fine-grained soils.

The data show that for the clay, a 5% portland cement treatment reduced heave to zero, a reduction not effected by any other additive in this series. For the silt, the use of secondary additives produced significant improvement with 3% portland cement.

Lime and allied calcium compounds have long been used in soil stabilization for non-freezing conditions. The immediate effect of these additives upon a fine-grained soil is one of flocculating the particles. With time, and after chemical reaction with water, cementation takes place, perhaps through calcium silicate or aluminate bonding. The addition of a pozzolan such as fly ash causes additional cementation. The data in Table IV show that in terms of heave ratio (or percentage reduction in heave), the clay was benefited more than the silt by 3% treatments of lime, quicklime, and gypsum. On the other hand, the silt responded better than the clay to the lime - fly ash mixtures.

In some heavily industrialized areas, a mixture of furnace slag, lime and fly ash is being used to produce a cemented material as a substitute for the conventional sand and gravel base course material used in pavement construction. The mixture may set up in a period of several months to about 2000 psi compressive strength and 400 psi flexural strength (Hollon and Marks, 1962). Frost susceptibility tests on a mixture of 66% slag, 30% fly ash and 4% lime, by weight, have indicated negligible frost susceptibility when the material is cured properly before freezing (Kaplar, 1963).

The effectiveness of phosphorus pentoxide and benzene phosphonic acid depends upon curing of the treated soil.

Studies performed at MIT indicate that phosphorus pentoxide reacts with soil constituents to form a gradually hardening, irreversible gel (MIT, 1957). The action of benzene phosphonic acid is probably similar; in addition, it has a waterproofing effect because of the formation of benzene rings. Both additives require care in handling, compaction soon after incorporation, and curing. Table IV shows that the silt was improved by their use more than the clay. Of the two primary chemicals, the phosphorus pentoxide plus its secondary additive was the more effective for the treatment levels used.

AM-9 grout gel was used to see if it was possible to attain continuous gelation at the usual degrees of saturation reached in compaction of fine-grained soils. As a grout, the material offers promise in many uses. Its gelation time can be controlled between the limits of a few minutes to several hours. Its use as a compaction material is, of course, limited. In the tests summarized in Table IV the material was added with amounts of the mixing water approximately equal to optimum moisture content and optimum plus 2% for the two soils. The proportions of the mix were: 10 parts AM-9 powder, 1 part sodium thiosulfate and 80 parts of water; to this was added 10 parts of a solution containing 1 part of ammonium persulfate.

The quantity of this mixture used with a soil was 3% of dry soil weight. Table IV shows that both soils were significantly benefited by the treatment and that the improvement was largely insensitive to difference in molding water content at the treatment level of 3%. The main effect was probably due to a decrease in permeability.

Table III. Summary: Effect of asphalt on frost heave (heave ratios of miniature specimens).

		New Hampshire Silt				*Fort Belvoir Sandy Clay*			
		Not	*Dried*			*Not*	*Dried*		
Additive	*%*	*Dried*	*(1)*	*(2)*	*(3)*	*Dried*	*(1)*	*(2)*	*(3)*
Asphalt Emulsion	0.5								1.67
	1.0	0.83	1.02	1.02		0.58	0.52	4.42	0.50
	3.0	0.82	0.70	*		0.43	0.87	0	0.11
	5.0	0.47	0.76	*		0.23	1.14	0	
**Asphalt cutback	7.5				0.83				0.25
**Asphalt cutback plus 2% Phosphorus pentoxide	7.5				0.13				0.24

Notes:

(1) Oven-dried before compaction
(2) Oven-dried after compaction
(3) Cured 7 days at room temperature and 100% relative humidity
* Did not freeze during test.
** Added to wet soil

Table IV. Summary: Effect of cementing agents on frost heave (heave ratios of miniature specimens).

Primary additive	*%*	*Secondary additive*	*%*	*New Hampshire silt*	*Fort Belvoir sandy clay*
Portland cement (Type I)	3.0			0.16	0.49
	3.0	Sodium sulfite	0.5	0.02	0.48
	3.0	Sodium metasilicate	0.5	0.04	0.47
Portland cement (Type I)	5.0			0.17	0
	5.0	Sodium sulfite	1.0	0.03	0.03
	5.0	Sodium metasilicate	1.0	0.01	0
Lime ($Ca(OH)_2$)	1.0			1.06	0.70
	3.0			0.27	0.16
Quicklime (CaO)	1.0			0.93	1.74
	3.0			0.43	0.13
Gypsum ($CaSO_4$)	1.0			0.34	0.27
	3.0			0.32	0.08
1 lime: 1 fly ash	25			0.18	0.21
1 lime: 4 fly ash	25			0.09	0.14
1 lime: 9 fly ash	25			0.08	0.66
1 lime: 9 fly ash	25	Calcium chloride	1.0	0.01	0.44
Phosphorus pentoxide	2.0	Sodium silicofluoride	0.25	0.09	0.39
Benzene phosphonic acid	1.0			0.27	0.77
AM-9 grout gel mixture*	3			0.01	0.12
	3			0.01	0.08

All specimens except AM-9 grout gel cured 7 days at room temperature and 100% relative humidity prior to freezing.

*The proportions of mix were: 10 parts AM-9 powder, 1 part sodium thiosulfate and 80 parts water; to this was added 10 parts of a solution containing 1 part of ammonium persulfate.

Aggregants

Previous test results (Lambe and Kaplar, 1971) showed that the polymeric aggregants effected only modest, if any, improvement in the frost response of fine-grained soils. Limited tests were run to determine if drying of aggregant-treated soils was necessary. The data in Table V are consistent with previous results and suggest that polymeric aggregants as a group are unpromising additives for frost-effects modification of fine-grained soils.

A second class of aggregant comprises the polyvalent cations of metallic salts. This class is represented by the salts thorium chloride through calcium chloride listed in Table VI. The effects of the salts can be complex and are not completely understood. Some of the possible multiple effects are: depressing the freezing point; waterproofing soil particles by the attachment of non-hydratable cations such as lead and mercury; depressing or expanding double layers as a consequence of the high or low valency of the cations, i.e., flocculating (aggregating) or dispersing the soil fines; forming weak cements by reaction with soil and water constituents; and nucleating ice by supplying seeds for crystallization.

One of the objectives in performing the tests summarized in Table VI was to determine the need for drying soils treated with salts having polyvalent cations. The limited data in Table VI show that drying did, in some cases, cause a modest improvement over the heave ratios of the treated specimens which were not dried.

There cannot be any separation of the possible multiple effects of the salt treatments reported in Table VI. In some cases, a portion of any benefit is undoubtedly due to freezing point depression. But previously reported tests (in which the cations of salts were exchanged, the excess salt removed, and the soil specimen compacted and frozen) suggest that some of the salts, particularly ferric chloride, are promising frost-heave modifiers (Lambe and Kaplar, 1971). A later section of this report will discuss additional tests made using ferric chloride.

Table V. Summary: Effect of an aggregant on frost heave (heave ratios of miniature specimens).

		Boston Blue clay		*Fort Belvoir sandy clay*	
Additive	*%*	*Not Dried*	*Dried**	*Not Dried*	*Dried**
Agrilon	0.1	0.39	0.54	1.17	1.09
	1.0	0.35	0.30	0.53	

* Soil-chemical mixture air-dried before addition of molding water and compaction.

Waterproofers

Table VII presents the results of tests to evaluate six waterproofers as frost-heave modifiers. For the treatment levels used the waterproofers effected only modest reductions in frost heave. In some instances drying of specimens following incorporation impaired the frost-heave-modifying capabilities of the chemicals.

Table VI. Summary: Effect of metallic salts on frost heave (heave ratios of miniature specimens).

		Boston Blue Clay				*New Hampshire Silt*				*Ft. Belvoir Sandy Clay*			
		Not	*Dried*			*Not*	*Dried*			*Not*	*Dried*		
Additive	%	*dried*	*(1)*	*(2)*	*(3)*	*dried*	*(1)*	*(2)*	*(3)*	*dried*	*(1)*	*(2)*	*(3)*
Thorium chloride^{++++}	0.2					0.71				0.55			
	0.5					0.69				1.08			
	1.0					0.73				0.60			
Aluminium chloride^{+++}	0.2					0.83				0.44			
	0.5					0.19				0.14			
	1.0					0.11				0.06			
Aluminum sulfate	0.1	0.41	0.28			0.62	0.75			1.03	0.85		
Aluminum phosphate	0.1	0.38	0.36			0.74	0.54			0.57	3.43		
Ferric chloride^{+++}	0.1	0.40	0.46							0.88	0.61		
	0.2					0.51		0.20	0.61	0.26		0.15	0.56
	0.5					0.15,0.45		0.36	0.19	0.15,0		0	0
	1.0					0.06,0		0.20	*	0.03,0		0	0
Ferric sulfate	0.1	0.38	0.35							1.03	0.79		
Zinc sulfate^{++}	0.1	0.39	0.38							0.92	0.95		
Calcium chloride^{++}	0.5					0.56				0			
	1.0					0.19				0			
	3.0					*				0.03			
Sodium chloride^{+}	0.5					0.11				0			
	1.0					0.11				0			
Lithium chloride^{+}	0.5					0.05				0			
	1.0					0				0			
Silver iodide^{+}	0.1					1.12				0.94			

Notes:

(1) Air-dried before compaction
(2) Oven-dried before compaction
(3) Oven-dried after compaction
* Did not freeze during test

Table VII. Summary: Effect of waterproofers on frost heave (heave ratios of miniature specimens).

		Boston Blue Clay				*New Hampshire Silt*				*Ft. Belvoir Sandy Clay*			
		Not	*Dried*			*Not*	*Dried*			*Not*	*Dried*		
Additive	%	*dried*	*(1)*	*(2)*	*(3)*	*dried*	*(1)*	*(2)*	*(3)*	*dried*	*(1)*	*(2)*	*(3)*
Arquad 2 HT	0.05	0.49	0.29			1.04	0.63			0.41	0.66		
	0.1	0.44	0.39			0.84	0.92			0.39	0.70		
	0.2									0.36		0.72	1.08
Volan	1.0					0.36			0.91	0.09			1.30
Carbowax Peg 200	0.5					0.71			0.65	0.25			0.46
Armeen 18D	0.2					1.15				1.40		0.79	2.05
Ethyl diamine dihydrochloride	0.1	0.45	0.44			0.64	0.42			0.63	0.56		
Alkyl dimethyl benzyl	0.1	0.45	0.54			0.91	0.71			1.19	1.73		
Ammonium chloride	0.5	0.44	0.53			0.68	1.08			1.10	1.19		

Notes:

(1) Air-dried before compaction
(2) Oven-dried before compaction
(3) Oven-dried after compaction

Dispersants

Previously reported test results indicated that dispersants, especially the polyphosphates, appeared to be effective as frost-heave modifiers. Tables VIII and IX summarize the data on various polyphosphates used in laboratory screening tests on miniature specimens of three fine-grained soils. These tables contain data presented in a previous report (Lambe and Kaplar, 1971) as well as new data, in order to present a comprehensive summary of the test results. Data on ferric chloride are included in Table IX for comparison.

The polyphosphate dispersants and ferric chloride are promising as soil additives since they are effective in low concentrations, are relatively cheap, have beneficial effects on other soil properties, are comparatively easy to incorporate, react instantaneously, and apparently require no special pre- or post-treatment curing, although in the case of the ferric chloride the data suggest that drying after treatment can have a slight beneficial effect.

The following sections of this report will discuss the results of tests conducted to evaluate further the frost-heave-modifying capabilities of one of the polyphosphate dispersants, tetrasodium pyrophosphate (TSPP), and of ferric chloride. The primary aim of the tests was to assess, by leaching tests, how long these additives would remain effective when used with frost-susceptible silty sands and gravels.

As in all the previous testing, the effectiveness of additive treatment was measured in terms of reduction in the average rate of heave which is, admittedly, only an approximate indicator of overall benefit. Equally as important in field application would be the extent to which an additive improved the strength characteristics of a thawing soil. However, this aspect was not within the scope of these studies.

Table VIII. Summary: Heave ratios of three polyphosphate dispersants* in fine-grained soils (miniature specimens – not dried).

Additive %	*N.H. Clayey Silt*	*Ft. Belvoir Sandy Clay*	*Boston Blue Clay*
0.01	1.64, 0.79 (1.22)**	0.82, 0.65 (0.74)	1.77, 1.36 (1.56)
0.05	0.72, 0.60 (0.66)	0.96, 0.77 (0.87)	2.10, 1.50 (1.80)
0.10	1.17, 1.09, 0.85 0.68, 0.63, 0.50 0.44, 0.26 (0.70)	0.84, 0.83, 0.70 0.63, 0.57, 0.53 0.53, 0.51 (0.64)	1.43, 1.42, 1.37 1.22, 1.20, 1.07 0.80, 0.69 (1.15)
0.50	0.64, 0.58, 0.54 0.48, 0.39, 0.36 0.32, 0.31 (0.45)	0.42, 0.26, 0.22 0.18, 0.18, 0.11 0.09, 0.08 (0.19)	0.67, 0.66, 0.51 0.49, 0.47, 0.37 0.21, 0.10 (0.44)
1.00	0.46, 0.36, 0.29 (0.37)	0.06, 0.06, 0 (0.04)	0.40, 0.32, 0.25 0.16 (0.28)

* Dispersants: Sodium tetraphosphate, sodium hexametaphosphate, and sodium tripolyphosphate.

** ( ) denotes average heave ratios.

Table IX. Summary: Heave ratios of tetrasodium pyrophosphate and ferric chloride in fine-grained soils (miniature specimens).

Additive %	*N.H. Clayey Silt*	*Ft. Belvoir Sandy Clay*	*Boston Blue Clay*
TSPP 0.1	0.86, 0.57 (ADB) 0.53	0.68 (ADB), 0.65 0.26	0.36, 0.30 (ADB)
0.3	0.57	0.13	
FeCL$_3$0.1		0.38, 0.61 (ADB)	0.46 (ADB), 0.40
0.2	0.61 (ODA), 0.51 0.20 (ODB)	0.56, (ODA), 0.26 0.15, (ODB)	
0.5	0.45, 0.36 (ODB) 0.19 (ODA), 0.15	0.15, 0, (ODB) 0 (ODA), 0	
1.0	0.20 (ODB), 0.06 0 (ODA), 0	0.03, 0 (ODB) 0 (ODA), 0	
*	0.48	0.29	1.49, 0.20

* Fe^{+++} exchanged, soil washed and dried before compaction.

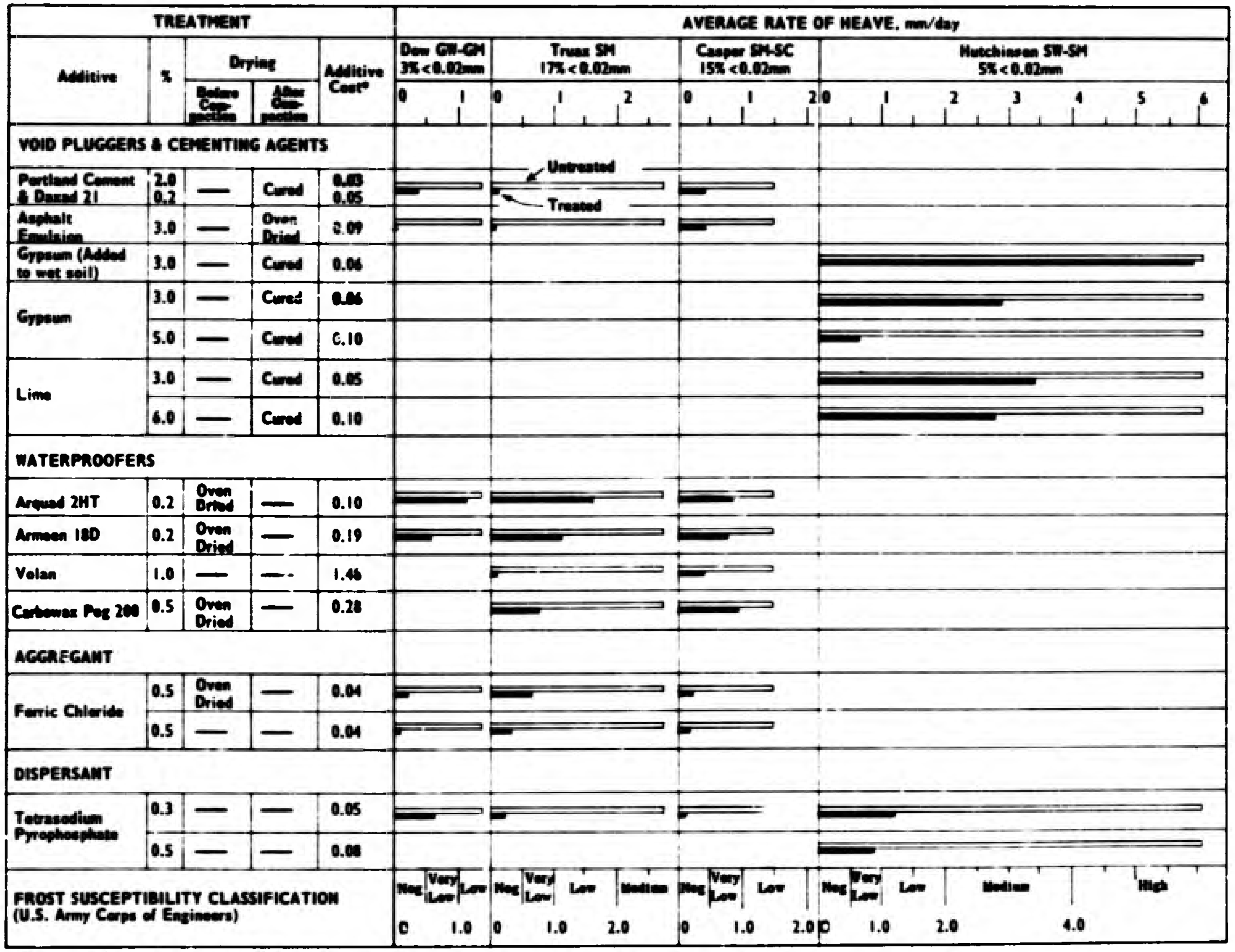
1. (ADB): air-dried before compaction; (ODB): oven-dried before compaction; (ODA): oven-dried after compaction; others not dried.

LABORATORY TESTS: EFFECT OF SELECTED ADDITIVES ON FROST HEAVE OF STANDARD SPECIMENS

In the screening studies performed with various additives on miniature specimens, a number of additives performed well enough to warrant a further examination using some typical "dirty" base course soils of standard size.

The additives (void pluggers and cementing agents) selected for additional trials were portland cement and Daxad 21, asphalt emulsion, gypsum and lime. From the waterproofers, Arquad 2HT, Armeen 18D, Volan and Carbowax Peg 200 were tested further. The soils selected were two base courses, Truax and Casper, that contained a relatively large quantity of fines (17% and 15% finer than 0.02 mm size, respectively) and two, Dow and Hutchinson Pit, containing 3% and 5% finer than the 0.02 mm size. The results are summarized in Figure 1. The detailed data from these tests are presented in Table AIII of Appendix A. The portland cement and Daxad 21 and the asphalt emulsion showed very good results in reducing heave in the base courses. So did gypsum at the 6% level of treatment. Some of the waterproofers showed remarkable effectiveness in one of the soils used (Casper). The biggest drawback to void pluggers and cementing agents, and to some waterproofers, is that oven drying of the soil or a controlled curing period is usually necessary. The most effective waterproofer, Volan, is too expensive (Table I) for ordinary consideration.

The results in Figure 1 are based on only one test and one freezing sequence; the effect of several freeze-thaw cycles could produce different results.



TREATMENT				
Additive	%	Drying: Before Compaction	Drying: After Compaction	Additive Cost*
VOID PLUGGERS & CEMENTING AGENTS				
Portland Cement & Daxad 21	2.0 0.2	—	Cured	0.03 0.05
Asphalt Emulsion	3.0	—	Oven Dried	0.09
Gypsum (Added to wet soil)	3.0	—	Cured	0.06
Gypsum	3.0	—	Cured	0.06
	5.0	—	Cured	0.10
Lime	3.0	—	Cured	0.05
	6.0	—	Cured	0.10
WATERPROOFERS				
Arquad 2HT	0.2	Oven Dried	—	0.10
Armeen 18D	0.2	Oven Dried	—	0.19
Volan	1.0	—	—	1.46
Carbowax Peg 200	0.5	Oven Dried	—	0.28
AGGREGANT				
Ferric Chloride	0.5	Oven Dried	—	0.04
	0.5	—	—	0.04
DISPERSANT				
Tetrasodium Pyrophosphate	0.3	—	—	0.05
	0.5	—	—	0.08
FROST SUSCEPTIBILITY CLASSIFICATION (U.S. Army Corps of Engineers)				

*Dollars/cu ft of soil assuming 100 lb/cu ft dry weight.

Figure 1. Effectiveness of additives in modifying frost heave of "dirty" gravels. (Standard size specimens, open system).

FIELD AND LABORATORY TESTS: EFFECT OF TETRASODIUM PYROPHOSPHATE AND FERRIC CHLORIDE ON FROST HEAVE

Theoretical considerations

Ferric chloride and TSPP both function through electrochemical reaction with the surfaces of soil fines. Logic suggests that it is this function which must be utilized if an additive is to be effective at very low treatment levels. The structural orientation of fine particles caused by the two chemicals takes different forms, but the end result, insofar as frost-heave modification is concerned, is the same in each case: an effective reduction in frost-heave producing capability.

Polyvalent cations such as Fe+++ cause small particles to aggregate into larger units by shrinking the diffuse double layer around soil colloids enough to permit the interparticle attractive forces to make the particles cohere. The subsequent drying of such an exchanged soil can cause the iron ions to link adjacent particles together with a very strong and water-resistant bond; such ions can become nonexchangeable. Another aggregating effect is possible when iron is added to the soil as a chloride salt ($FeCl_3$). This is the formation of iron hydroxide, which can act as a weak cement.

It is possible to break down natural agglomerations of soil fines through the use of chemical dispersants. Most of these compounds 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 mineral surfaces of the soil fines. The sodium ions become linked to the soil, replacing polyvalent exchangeable cations. Both the cation exchange (monovalent replacing polyvalent) and the anion absorption expand the diffuse double layers around the soil colloids, increasing interparticle repulsive forces which tend to disperse the aggregations of fines. Particles that do not cohere can be manipulated into a more ordered and dense structure by mechanical work or by moving water. Such a structural orientation of the soil fines can result in higher density, lower permeability, and higher stability to water. These effects are particularly pronounced in silts and clays. In silty sands and gravels in which the macrostructure is controlled by the coarse particles, dispersion has little effect on the overall density and, by permitting the fines to be packed into more intimate arrays (hence making the voids larger), or moved to other locations, can actually increase permeability.

Both these alterations in soil structure, i.e. dispersion and flocculation, can usually be effected because of the tendency of natural soil fines to exist in a state between the two extremes. Following alteration, the dispersed system tends to be less subject to reverse in the face of chemical or physical changes.

The use of chemicals, particularly salts such as ferric chloride, can reduce frost heave by lowering the freezing point of the soil moisture. This effect of freezing point depression by use of salts in low amounts is especially pronounced in sands and gravels which can be compacted to yield low saturated moisture contents. However, the Corps of Engineers method of evaluating frost susceptibility utilizes the application of a cold temperature in decremental steps periodically so that the salt-treated specimens are actually frozen. Furthermore, the method measures frost heaving not in terms of absolute amount but in terms of heaving rate (rate of ice formation in excess of void volume) which has been observed to be fairly constant with rate of freezing penetration in the range of ¼ to ½ in./day. This means that none of the beneficial effects of such additives, when noted in the present test results, can be attributed solely to a lowering of the freezing point of void water. In field applications, benefits resulting from freezing point depression may, of course, be of limited duration. Research has shown that salt concentrations in void water can be reduced to less than 20% of their original values by leaching of the soil with less than two void volumes of water (Gardner and Brooks, 1957). In some situations this may take several years or more depending upon the conditions.

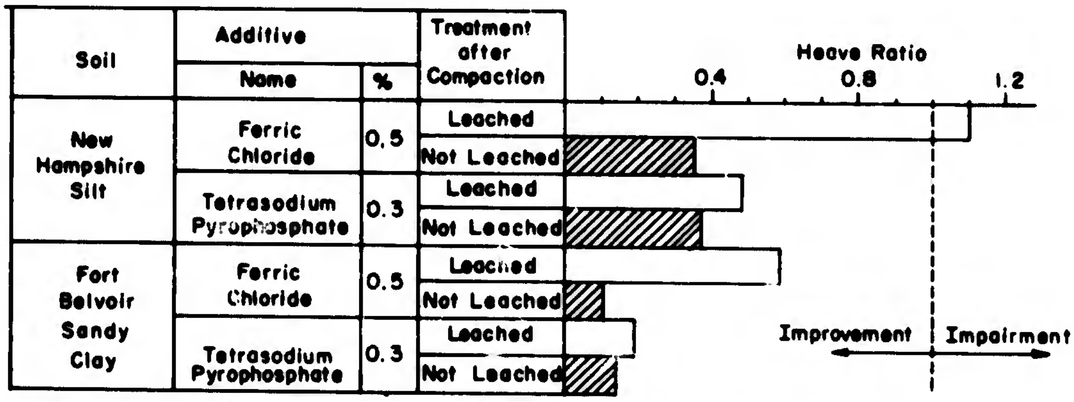
Preliminary leaching tests on miniature specimens

Since present theory can only imperfectly predict the consequences of water attack upon soils treated with TSPP or $FeCl_3$, a laboratory program was required in order to find the extent to which these additives met the important criterion of permanence. Compacted specimens of two fine-grained soils, New Hampshire silt and Fort Belvoir sandy clay, were treated with 0.5% ferric chloride and 0.3% TSPP to observe the effect of leaching tests on these soils with respect to effectiveness of treatment.

Figure 2 shows, in terms of heave ratios, a comparison between unleached specimens that have received similar chemical treatment. The following conclusions were made on the basis of the data in Figure 2 and Table AIV:

1. The apparently better response (with no leaching) of the clay to both additives has *not* been consistently observed in previous tests, and therefore no significance is attached to this circumstance.

2. Of most importance is the fact that for each soil, the heave ratios of the unleached specimens of both TSPP and ferric chloride are almost equal (Fig. 2) but the loss of effectiveness after leaching is much more pronounced for ferric chloride treatment than it is for TSPP treatment.



Untreated samples used as bases for heave ratios were not leached.

$$\text{Heave Ratio} = \frac{\text{Avg. heave rate of treated samples}}{\text{Avg. heave rate of untreated samples}}$$

Figure 2. Effect of leaching treated miniature specimens before freezing tests.

3. This implies that of the two, the TSPP treatment is more permanent in its effects. It suggests also that the effectiveness of ferric chloride as a modifier depends upon its being retained in the soil voids, that it is removable, and that any cementing action it develops is disrupted by permeating water.

An interesting speculation on the effect of leaching ferric chloride is this: Many researchers have called attention to the possibility that the channels for supplying water to growing ice lenses might exist in the double layer, which even silty sands can develop. Ferric chloride would depress a double layer and hence would constrict such channels. But with leaching, the pore concentration would be greatly diminished and a subsequent expansion of the double layer would occur, making the soil once again frost-prone. Indirect proof of this effect is seen in the response of the liquid limit to changes in pore water salinity (MIT; Bjerrum, Norw. Geo. Inst.). Two salt clays with the same void ratio and a void water salinity of 35 g/liter were compared. When the salinity of one was reduced by leaching to less than 5 g/liter, its liquid limit was lowered significantly, suggesting a double layer expansion. This condition is duplicated by the frost leaching tests described here. The initial concentration of ferric chloride is 25 g/liter and the final concentration after leaching is on the order of a few grams per liter.

The results of these few preliminary tests indicated a need for more testing, in the laboratory and field. Such additional tests are described in the following paragraphs.

Effectiveness of field mixing with a dispersant

The objective of the tests described below was to observe the difference in effectiveness between field-mixed and laboratory-mixed specimens of the same soil with the same treatment level of TSPP. Four different dirty gravels, designated MIT-I through IV (see Table II for physical properties) were used. Three large specimens of each soil were molded: one treated and field-mixed, one treated and laboratory-mixed, one untreated. The field-mixed soils were sampled in bulk and molded in the laboratory.

The nominal field treatment level was 0.3% TSPP. The actual amount of TSPP present after field-mixing was determined by analysis and the laboratory-mixed soil was prepared at this concentration. Table AV gives the pertinent test data and outlines the procedures followed in mixing and molding. A Roto-Tiller was used for field mixing.

Table AV shows that the rates of heave of the untreated soils increased with increasing percentages of material finer than 0.02 mm. It also shows that, with the one exception of sample MIT-12A, the use of TSPP increased dry density. Samples MIT-8A and -12A show very small rates of heave and final water contents less than initial ones, indicating either drainage or evaporation in excess of ice lens formation during freezing. Although some hairline ice lenses were noted, the percentages of heave could be accounted for by simple expansion of water upon freezing. Samples MIT-4 and -12A illustrate well the effect of TSPP in reducing permeability and hence frost heave; both are at the same void ratio but the untreated specimen heaved at a rate five times that of the treated specimen.

The most significant data from these tests are presented in Figure 3. Here it is seen that for equal treatment levels of the same soil, a field-mixed sample can heave at a rate twice that of a laboratory-mixed sample. This suggests that laboratory-mixed samples can be unconservative in their forecast of heave reduction, promising more than field practice can fulfill, especially when, as here, the laboratory mixing is done as a slurry and the field mixing as a powder.

Figure 3 also shows that the sequence of magnitudes of heave ratios is the same for both field- and laboratory-mixed specimens. The contractor interprets this as indicating that differences in rates of heave of any of these samples are due only to differences in mixing and distribution of additive.

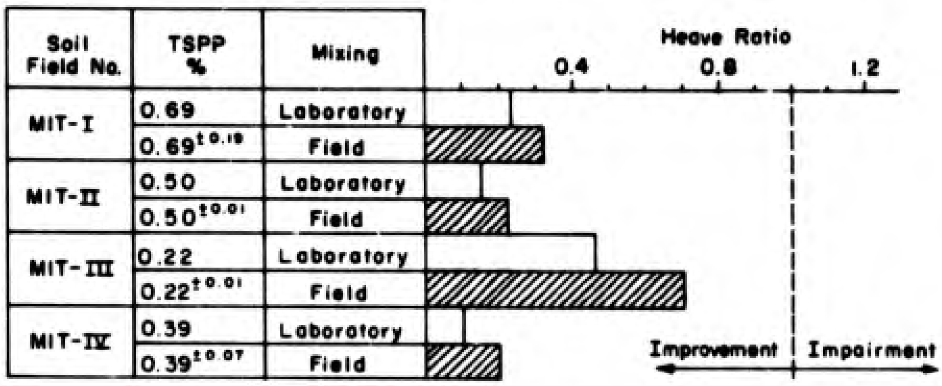


Figure 3. Comparative effectiveness of tetrasodium pyrophosphate (TSPP) in modifying frost heave of laboratory- and field-mixed "dirty" gravels (standard size specimens).

Brief review of previous results with TSPP and ferric chloride on base course type soils

Before proceeding with the discussion on leaching studies involving TSPP and ferric chloride a brief summary of prior results with these two chemicals on base course type soils is presented.

Tables X-XII and Figures 1-5 summarize results of freezing tests performed on silty sands and gravels treated with TSPP and ferric chloride and other additives. These tables and figures show the following:

1. TSPP and ferric chloride can be very effective frost-heave modifiers in concentrations as low as 0.3-0.5% of the dry soil weight (Fig. 1-5, and Appendix Table AIII). Figure 1 shows that in terms of heave reduction and unit cost, both TSPP and ferric chloride compare very favorably with other additives used in laboratory tests on dirty gravels.

2. The effectiveness of TSPP depends upon the degree of mixing before compaction. The extent of frost-heave modification accomplished by TSPP can be less in field-mixed soils than in laboratory-mixed soils (Fig. 3 and Table X).

3. The modification of frost heave in silty sands and gravels by 0.3% TSPP treatments has been demonstrated to be effective over four laboratory cycles of freezing and thawing (Table XI and Lambe and Kaplar, 1971).

4. The use of 0.3% TSPP treatment has reduced heave under field conditions by amounts which compare very well with laboratory test results on "dirty" base courses (Fig. 4). Results from an earlier field test (Lambe and Kaplar, 1971) have shown that 0.3% treatment of a similar polyphosphate dispersant reduced heave under field conditions by a factor of about two, even when the treatment depth was only 1 ft (Table XII).

Figure 2 (summarizing the data in Table AIV) shows the results of a pilot series of tests conducted on two fine-grained soils treated with trace amounts of TSPP and ferric chloride, compacted, leached with distilled water, and subsequently frozen. The data show that leaching impaired the effectiveness of ferric chloride but did not materially alter the effectiveness of TSPP.

Additional leaching and soaking tests

The generally favorable results obtained in prior tests suggested the desirability of further testing of TSPP and ferric chloride in order to evaluate the permanence of their effectiveness as frost-heave modifiers under severe conditions of water attack.

Table X. Summary: Effectiveness of laboratory vs field mixing.

Auburn sand treated with tetrasodium pyrophosphate, standard size specimens

	MIT-I (19% < 0.02 mm)			*MIT-II (8% < 0.02 mm)*			*MIT-III (8% < 0.02 mm)*			*MIT-IV (4% < 0.02 mm)*		
	L	*L*	*F*	*L*	*L*	*F*	*L*	*L*	*F*	*L*	*L*	*F*
TSPP, %	0	0.64	0.69±	0	0.5	0.5±	0	0.22	0.22±	0	0.39	0.39±
Rate of heave (mm/day)	1.9	0.45	0.6	1.83	0.28	0.43	1.66	0.77	1.17	1.23	0.12	0.25
Heave ratio		0.24	0.32		0.15	0.23		0.46	0.70		0.10	0.20

L = Manually mixed in laboratory
F = Mixed in field with Roto-Tiller

Table XI. Summary: Effect of four cycles of freezing and thawing on frost heave rate.

Standard-size specimens treated with 0.3% tetrasodium pyrophosphate.
Average rate of heave, mm/day

Freeze no.	*Dow sandy gravel (GW-GM) (3% < 0.02 mm)*		*Loring sandy gravel (GW-GM) (5% < 0.02 mm)*		*Lincoln sand (SP-SM) (5% < 0.02 mm)*		*Portsmouth sand (SM) (14% < 0.02 mm)*	
	U	*T*	*U*	*T*	*U*	*T*	*U*	*T*
1	1.2	0.2	3.1	0.3	1.2	0.1	5.6	0.5
2		0.2		0.2		0.1		0.8
3		0.1		0.2		0.1		0.5
4		0.2		0.2		0.1		0.7

U = Untreated
T = Treated

Table XII. Summary: Effectiveness of 0.3% sodium tetraphosphate in field test section, Limestone, Maine.

(Loring clayey sandy gravel (GC), 30% < 0.02 mm, LL 22%, PI 8%, treatment depth 1 ft, approximate depth to water table 20 ft.)

Section	*Undisturbed, untreated*	*Remolded, untreated*	*Chemically treated*
Penetration of 32°F isotherm (feet)			
16-19 March 1954	0.25	0.33	0.33
2-4 April 1955	1.67	1.00	1.42
Frost heave of surface (feet)			
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

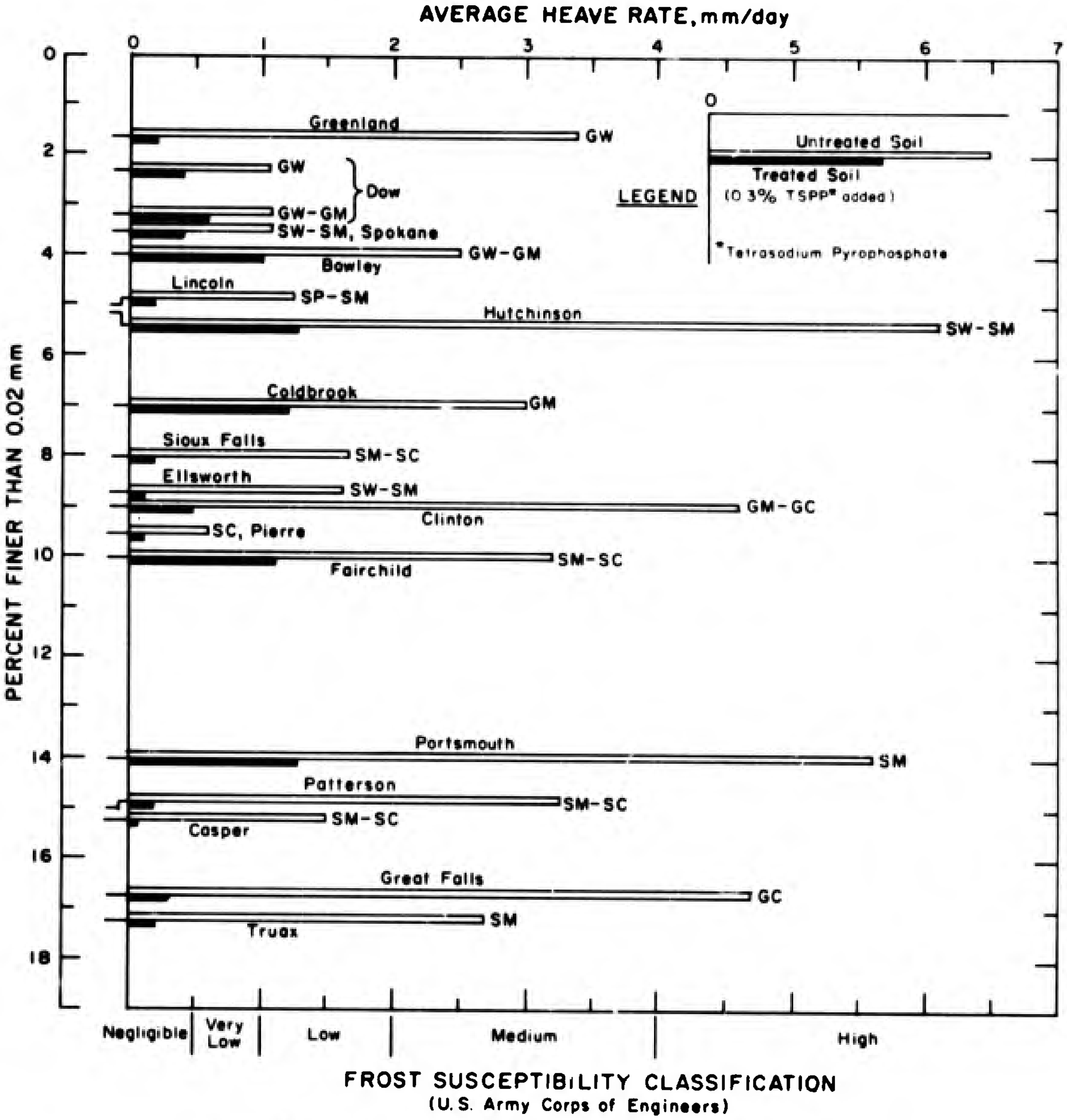


Figure 4. Freezing tests on 18 "dirty" gravels treated with 0.3% TSPP (standard size specimens, open system).

Soils. Two silty sandy gravels (Bowley and Coldbrook Pits, Hampden, Maine) with heave rates that varied from approximately 3 to 5 mm/day were used in the normal laboratory freezing tests. They were of medium to high frost susceptibility, according to the Corps of Engineers Frost Susceptibility Classification (see p. 22). The pertinent index data and engineering properties of these soils are included in Table XIII. Grain size distribution curves are shown in Figure A2, Appendix A. Data summarizing the mineralogical and chemical characteristics of the two soils are presented in Table XIV.

Chemicals. The chemicals used were chemically pure ferric chloride ($FeCl_3$) and tetrasodium pyrophosphate (TSPP). The ferric chloride was crystalline and the TSPP a powder. Both are highly soluble in water. The weight of the crystalline water was excluded in making up the desired concentrations.

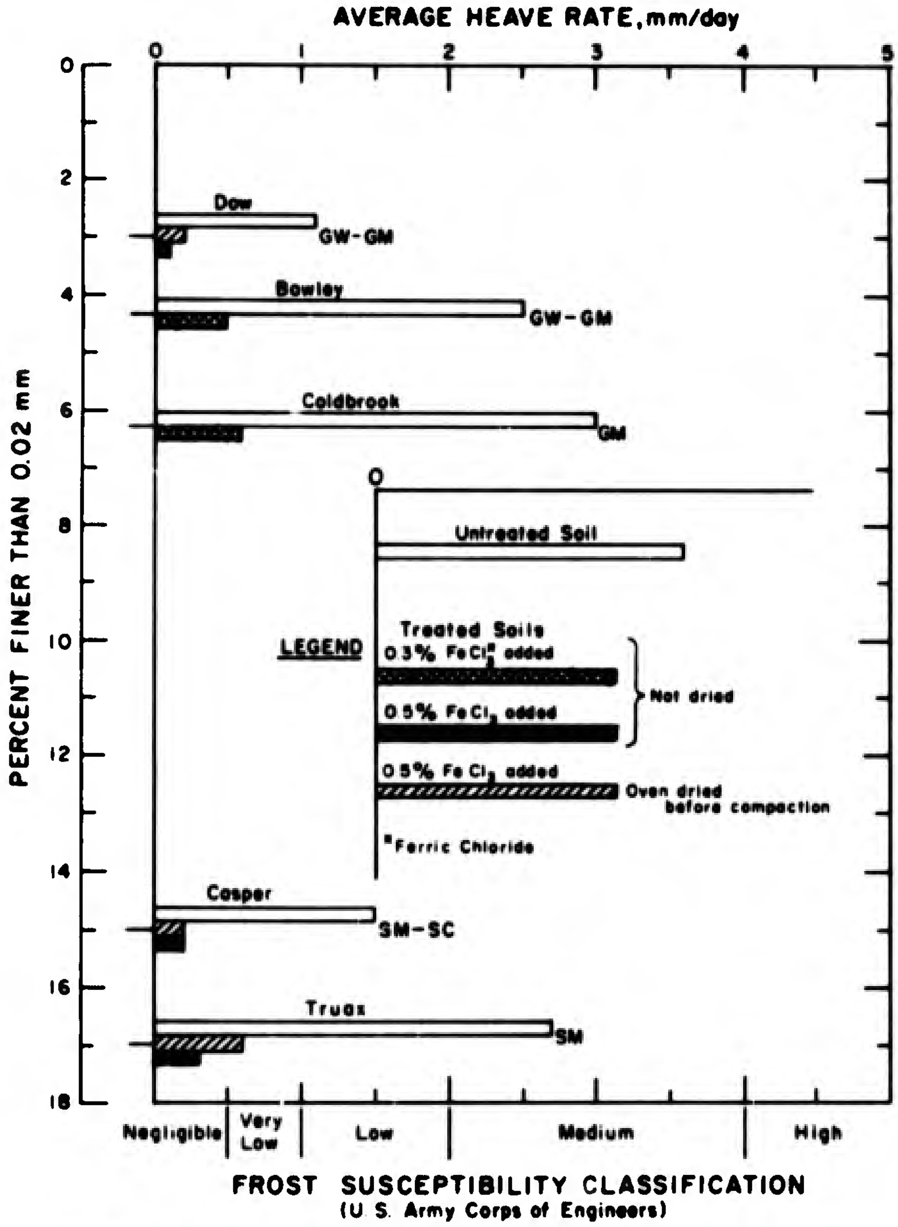


Figure 5. Freezing tests on "dirty" gravels treated with ferric chloride (standard size specimens, open system).

Mixing and molding. A total of 18 specimens were prepared, 9 for each of the two soils. The breakdown for each soil was as follows: three sets of three specimens of each soil were molded; in each set one specimen was not treated, one was treated with 0.3% ferric chloride, and one was treated with 0.3% TSPP. One set was frozen within a week after molding and saturation, one was leached, and the other was soaked, prior to freezing. The soil preparation and other data are shown in Table XV.

The specimens were molded in tapered 6-in.-high steel cylinders with inside diameters of 5.75 and 5.50 in. at the top and bottom respectively and then placed in similarly tapered Lucite cylinders for freezing. The cylinders were tapered on the inside to minimize the frictional side-restraint during heaving accompanying freezing.

Table XIII. Mineralogical composition and chemical data of soils.
Composition of minus 0.074 mm soil fraction.

	Mineral	%	*Organic matter* %	*Glycol retention mg/g of soil*
Loring silty sandy gravel	Kaolinite	40	1	14
	Illite	20		
	Limonite	5		
	Magnesite	5		
Dow silty sandy gravel				1 (est.)
Bowley Pit sandy gravel	Clay	5-10	0.3	4.9
	Quartz	40		
	Feldspar	40		
	Calcite	0		
	Free iron oxide	2-4		
Coldbrook silty sandy gravel	Clay	5-10	0.4	3.7
	Quartz	25		
	Feldspar	50		
	Calcite	15		
	Free iron oxide	2.6		
Great Falls clayey sandy gravel	Carbonates	8	1.8	49
Hutchinson's Pit silty gravelly sand	Clay	40-50	10	6.7
	Quartz	25		
	Feldspar	15		
	Calcite	6		
	Free iron oxide	1.4		
Truax silty gravelly sand	Carbonates	13	1.3	29
Casper silty gravelly sand	Carbonates	13	3.1	45
Pierre clayey gravelly sand	Carbonates	10	1	31
N.H. clayey silt	Illite	10	1	3
	Quartz	40		
	Feldspar	40		
	Mica	10		
	(no carbonates)			
Ft. Belvoir sandy clay	Kaolinite	25		26
	Quartz	40		
	Hydrous oxides of iron & aluminum			
Boston Blue clay	Illite	40-50	0	11
	Quartz	15-20		
	Limonite	5		
	Felspar & Mica	5		

The molding water contents varied between 5 and 6%. The additives were dissolved in the molding water which was added to the air-dried soil. The soils and molding water were thoroughly hand-mixed and allowed to equilibrate for a period of about one-half to one day before molding. The specimens were compacted in five layers with 55 blows per layer of a 10-lb tamper having a drop of 18 in. The gradations of the soils used are plotted in Figure A2, Appendix A; no fractions were deleted from the material as received. After compaction the molds were fitted top and bottom with porous stones having an average porosity of 35% and an average pore diameter of 0.20 mm. Filter paper separated the porous disk from the soil.

Table XIV. Additional mineralogical composition and chemical data on Bowley and Coldbrook soils.

Soil	*Coldbrook silty sandy gravel*	*Bowley sandy gravel*
Composition of 4.7 - 2.0 mm fraction, weight percent		
Slate (Phyllite and Mica. Siltstone)	60	85
Quartz and Feldspar	35	12
Other	5	3
Composition of minus 0.074 mm fraction, weight percent		
Clay (by composition)	5 to 10	5 to 10
Quartz	25	40
Feldspar	50	40
Calcite	15	Nil
Organic matter	0.4	0.3
Free iron oxide	2.6	2.4
Composition of minus 0.002 mm fraction, weight percent		
Illite	30 ± 10	35 ± 10
Chlorite	30 ± 10	35 ± 10
Vermiculite	15 ± 10	
Feldspar and Quartz	25 ± 10	25 ± 10
Free iron oxide	4.7	7.8
Water adsorption at 20°C and 100% R.H., mg H_2O/g soil		
4.7 mm to 2.0 mm	10.6	9.2
4.7 mm to 0.074 mm	11 (approx.)	9 (approx.)
Minus 0.074 mm	56	39
Cation exchange capacity, meq/100 g soil		
Minus 0.074 mm	2.0	6.0
Minus 0.002 mm	55	29
Glycol retention, mg/g soil		
Minus 0.074	3.7	4.9
Minus 0.02 mm	98	70

Leaching and soaking. The specimens designated for leaching were permeated with tap water under pressures varying from a few to about 30 psi until approximately 100 complete void volumes of flow had occurred. An additional 10-void volume flow was then provided by a constant head of 3 psi of distilled water. The time for this leaching was about 2 to 3 weeks. The specimens designated for soaking tests were submerged horizontally in distilled water for a period of about 4 months with the exposed ends protected by the porous disks. The water was periodically changed and sampled to obtain electrical conductivity measurements. These measurements indicated that outflow of ions from the samples had ceased within 3 months.

Freezing procedure. Following the various pretreatments, the specimens were frozen using the freezing method developed at ACFEL for frost susceptibility determinations (Kaplar, 1965). They were saturated for a period of 1 to 2 days, placed in sets of three in freezing cabinets with a free-water surface approximately ⅛ in. above the porous stones at the bottom of the specimens, placed under a load of 0.5 psi and allowed to equilibrate for about a day at ±37F. They were then frozen from the top down by a daily lowering of the air temperature above the specimens while the air temperature beneath them was kept at approximately 38F. The penetration of the 32F isotherm was manually controlled at a rate of about ¼ in./day. Thermocouples placed 1 in. apart along the vertical axis in one of the specimens in each set were used to measure the temperatures in the specimen. Daily measurements of heave were taken.

Table XV. Soil specimen preparation and freezing test data for effect of leaching and soaking studies (standard size specimens, tapered cylinders, open system).

ACFEL spec no	*Additive*	*% of dry soil wt*	*Molded dry unit wt (lb/cu ft)*	*Void ratio*	*% compaction*[1]	*% saturation*	*Avg water content, % before test*	*Avg water content, % after test*	*% increase in water content*	*% heave*[2]	*Avg rate of heave (mm/day)*	*Heave ratio*[3]
Coldbrook Pit silty sandy gravel (GM)[4]												
Specimens not leached or soaked after preparation – set 1												
CBG-1	None		139	0.218	96	96	7.6	20.9	175	40.0	3.0	
-2A	FeCl$_3$	0.3	142	0.196	98	100	7.4	10.4	41	6.2	0.6	0.20
-3A	TSPP	0.3	140	0.213	96	98	7.7	13.7	78	16.0	1.2	0.40
Specimens leached with 110 void volumes of water after preparation – set 2												
CBG-4	None		141	0.200	97	89	6.7	20.1	200	41.2	2.8	
5A	FeCl$_3$	0.3	140	0.213	96	95	7.5	12.5	67	14.9	0.8	0.29
6A	TSPP	0.3	140	0.206	96	100	7.6	15.1	99	19.9	1.1	0.39
Specimens soaked in water for 4 months after preparation – set 3												
CBG-7	None		146	0.164	101	92	5.5	26.5	382	68.0	4.6	
8A	FeCl$_3$	0.3	143	0.191	99	91	6.3	14.3	127	20.1	1.3	0.28
9A	TSPP	0.3	147	0.155	101	100	5.7	13.7	140	23.8	1.6	0.35
Bowley Pit silty sandy gravel (GW-GM)[5]												
Specimens not leached or soaked after preparation – set 4												
BPG-1	None		132	0.287	96	100	9.9	23.4	136	38.1	2.8	
3A	FeCl$_3$	0.3	131	0.284	95	98	10.3	11.4	10	4.7	0.5	0.18
2A	TSPP	0.3	131	0.281	95	98	10.3	12.2	18	7.9	1.0	0.36
Specimens leached with 110 void volumes of water after preparation – set 5												
BPG-4	None		136	0.235	99	80	6.8	34.7	410	76.0	4.5	
5A	FeCl$_3$	0.3	132	0.269	96	70	7.0	16.4	134	17.5	1.2	0.27
6A	TSPP	0.3	138	0.215	100	88	7.0	16.4	134	24.3	1.8	0.40
Specimens soaked in water for 4 months after preparation – set 6												
BPG-7	None		129	0.304	94	86	9.7	35.2	263	81.2	5.4	
8A	FeCl$_3$	0.3	132	0.276	96	99	10.2	18.8	85	18.8	2.2	0.41
9A	TSPP	0.3	132	0.275	96	75	7.7	18.0	134	18.0	1.8	0.33

Notes:

1. With reference to Providence Vibrated Density Test Method. (See Kenneth S. Lane, Providence Vibrated Density Test, *Proceedings of the Second International Conference on Soil Mechanics and Foundation Engineering*. Rotterdam, vol. 4, pp. 243-247, 1948).
2. Based on original height of frozen portion.
3. Heave ratio = ratio of rate of heave of treated specimen to average rate of heave of untreated specimens.
4. Ser. nos. 49-139 (A-D), specimens CBG-1 thru CBG-6A, and 49-141, specimens CBG-7 thru CBG-9A.
5. Ser. no. 49-138-1, all specimens.

Freezing test data. After the specimens were frozen to approximately their full depth (24-28 days) they were removed from the cabinets, measured, and cut into segments. Water content determinations were then made.

Appendix A contains a typical plot of water-content distribution after freezing (Fig. A2) and a heave and temperature plot (Fig. A3). Freezing test results are summarized in Table XV.

The average rate of heave of each specimen was computed from the daily heave records. This rate, expressed in millimeters per day, is determined from a portion of the plot of heave versus time in which the slope is relatively constant over a minimum period of five consecutive days, during which the penetration of the 32F isotherm is relatively linear and between ¼ in. and ½ in. per day. The following scale adopted by ACFEL was used for classification of frost susceptibility:

Average rate of heave (mm/day)	*Frost susceptibility classification*
0-0.5	Negligible
0.5-1.0	Very low
1.0-2.0	Low
2.0-4.0	Medium
4.0-8.0	High
8.0+	Very high

Percent heave was determined from the ratio of total amount of heave to the original height of the frozen portion. The rate of heave ratio* was used as a measure of the effectiveness of additive treatment: a heave ratio greater than one indicates impairment, a ratio of less than one shows improvement.

Subsequent laboratory tests. The grain size distributions of some of the soil specimens were obtained after freezing to determine the extent to which compaction might have caused a mechanical breakdown of particles and whether leaching caused a significant loss of soil fines. This is discussed further on p. 24 (1.). Test data are presented in Table XVI.

Summary of results. The data relating to this investigation are presented in Table XV. Figure 6 shows the variation in rate of heave with specimen treatment. This figure suggests the following summary:

1. The average rates of heave of the chemically untreated specimens vary over a considerable range. This variation appears to be a function of the duration of the period in which the specimens were subjected to water attack. The chemically treated specimens show a roughly similar variation. The soaking test was by far the most rigorous in its adverse effects.

2. The non-leached specimens of both the Bowley and Coldbrook soils were practically identical in their frost behavior, untreated and treated. However, with water attack, the Bowley specimens were significantly more frost susceptible than the Coldbrook specimens.

3. In terms of heave ratio (or percentage reduction in heave rate) the data show that the effectiveness of TSPP was not significantly changed by water attack while the effectiveness of ferric chloride was lessened. This response is in approximate agreement with what theory would predict and previous pilot tests have shown (Fig. 2).

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* In each set this was based on the chemically untreated soil specimen, which in all respects save that of chemical treatment had been subjected to the same test conditions as the two treated specimens. As previously defined, the heave ratio is the rate of heave (treated) divided by the rate of heave (untreated).

Table XVI. Grain size distribution of minus no. 4 sieve fractions of leached soils after freezing test.

Sieve no.	Size mm	Original gradation	Percent finer (by weight) Gradation after freezing test			
			Not leached untreated	Leached		
				Untreated	$FeCl_3$	TSPP
Coldbrook silty sandy gravel (49-189)						
4	4.76	100	100	100	100	100
40	0.42	51	51	49	49	52
200	0.074	27	25	25	25	26
	0.02	11.5	14.8	12.7	14.6	10.2
	0.005	2.5	6.9	4.5	3.0	3.5
Bowley Pit silty sandy gravel						
4	4.76	100	(not available)	100	100	100
40	0.42	28		37	31	36
200	0.074	16		19	15	19
	0.02	9.2		12.0	10.0	12.0
	0.0005	4.0		4.8	2.2	4.7

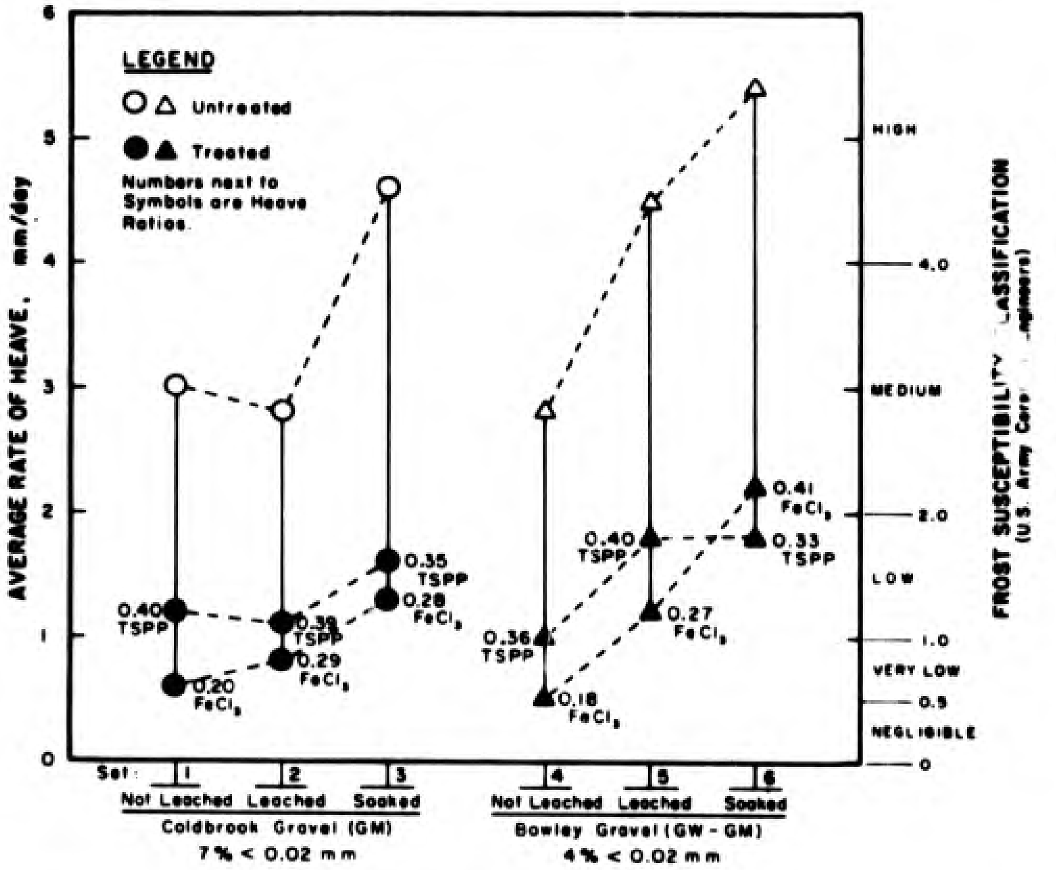

Figure 6. Effect of 0.3% treatments of TSPP and ferric chloride on frost heave.

4. In terms of heave ratio as well as in terms of absolute diminution of rate of heave, the ferric chloride was the more potent frost heave modifier in five of the six sets of specimens. This advantage was most pronounced in the non-leached specimens but, owing to the tendency of the ferric chloride to lose its effectiveness with water exposure, the differential of benefit was lessened.

From both the theoretical and practical standpoints the responses most worthy of note are believed to be two: first, the general increase in rate of heave with prolonged water attack; and second, the relatively low effectiveness of TSPP in reducing heave in these soils as compared with the benefits realized in the majority of TSPP-treated silty sands and gravels tested in previous years. Some of the reasons for the hypotheses concerning these responses will be discussed in the following sections.

Effects of water attack. An important fact revealed in the mineralogical analyses (Table XIV) of the soils is the high clay content of the coarse fraction and the low clay content of the fine fraction.* Two aspects of this fact are noteworthy:

1. Table XIV shows that in the 4.7-2.0 mm fractions of the soils, slate (clay, by composition) accounted for 60% of the fraction in the Coldbrook soil and 85% in the Bowley gravel. Furthermore, this fraction constituted about 12% of the total gradation in the Coldbrook soil and about 17% in the Bowley soil. This means that the Bowley soil exceeded the Coldbrook soil in this constituent in this fraction alone by a factor of two. Since this slate is easily fractured by mechanical impact such as is used in compaction, one would expect the gradations before and after compaction to be different, with this effect more pronounced in the Bowley soil. This expectation is approximately confirmed by the data in Table XVI which compares the gradations before compaction with those after for seven of the soil specimens. The non-leached, untreated specimen of the Bowley soil was not available for grain-size analysis, but the gradations of the leached Bowley specimens show the significant increase in fines after compaction, even after leaching. One would expect this effect to be even more apparent in the gradations of the non-leached Bowley specimens.

The data for the Coldbrook soil show the effect of leaching by the washing-out of fines (minus 0.02 mm) from a soil. The order of fines removal is approximately what would be expected from theoretical considerations: 1) TSPP, 2) untreated, 3) ferric chloride. However, this trend is not apparent in the Bowley data. The washing-out of fines can reduce the frost heave of soils. The fact that only a slight reduction in heave occurred in the leached, untreated Coldbrook soil and a significant increase in the untreated, leached Bowley soil is believed to be a further consequence of the high clay content of the coarse fractions of these soils (see par. above).

2. The data on water adsorption in Table XIV provide further evidence of the high surface reactivity and clay content of the coarse fractions of the Bowley and Coldbrook soils. The water adsorption of the 4.7-2.0 mm size fractions of these soils is more than 1000 times that of fine quartz sand. Moreover, since the coarse fractions are present in large amounts, they contribute significantly to the total water adsorption capacity. For example, the Coldbrook soil contains about 14% finer than 0.074 mm. Assuming a value of 11 mg H_2O per gram of soil for all material coarser than 0.074 mm, then the coarse material (greater than 0.074 mm) accounts for 55% of the total water adsorption. A similar estimate for the Bowley soil gives 75%. These estimates suggest that water transportation in the adsorbed phase in the coarse fractions could be significant in both soils and more pronounced in the Bowley. The effect of prolonged water exposure before freezing would be to permit the fulfillment of the adsorptive requirements of the coarse fraction and hence to provide continuous channels for water flow during freezing. The heave data in Figure 6 are fairly consistent with this physical picture, although more experimental data are required for confirmation.

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* In this discussion "coarse fraction" is defined as the greater than 0.074-mm fraction, "fine fraction" as the less than 0.074-mm fraction, unless otherwise stated.

Effectiveness of TSPP. As previously reasoned, the effect of TSPP treatment of frost-susceptible soils is thought to be one of dispersing the fines so that they can be mechanically manipulated into dense, well-ordered conglomerates – in effect "removing" the fines. Only fine particles respond to this joint action of dispersion-compaction. Coarse materials of high clay content and high surface reactivity would, with dispersant treatment, have their diffuse double layers expanded. This means that their ability to conduct water in the adsorbed phase would be increased.

It would seem reasonable, therefore, to expect that over a broad spectrum of frost-susceptible silty sands and gravels dispersant treatment would vary in effectiveness according to the amount (and nature) of fines and the amount (and nature) of coarse particles. Two major classes are visualized:

1. Sands and gravels rich in fines and having their coarse fractions made up of either inert or reactive minerals would have their frost heave reduced greatly by dispersant treatment. Moreover, the effects of varying concentrations of dispersant would be pronounced.

2. Sands and gravels low in fines would respond to treatment in one of two ways, depending upon the surface reactivity of their coarse fractions. Where this surface reactivity is low, dispersant treatment would be very beneficial: this response would be rather insensitive to concentration. Where this surface reactivity is high, dispersant treatment could be rather ineffective and might even increase frost susceptibility.

These expectations can be roughly illustrated with the compositional and frost-heave data available on 18 frost-susceptible sands and gravels tested in this and previous years. All were treated with 0.3% dispersant. Ethylene glycol retention data are used as a measure of the amount of surface area of the fine fraction. Table XVII shows the use of the data. Figure 7 shows the effectiveness of treatment. Compositional data on the coarse fractions of these soils are lacking, except for the two used in this investigation, and the corroboration of the preceding statements is admittedly imperfect. More work needs to be done on this.

This concept allows some insight into the reasons why a chemical like ferric chloride, which in addition to "removing" the fines can also decrease the water adsorption of a coarse fraction high in clay minerals, might be more effective than the TSPP in materials like the Coldbrook and Bowley soils.

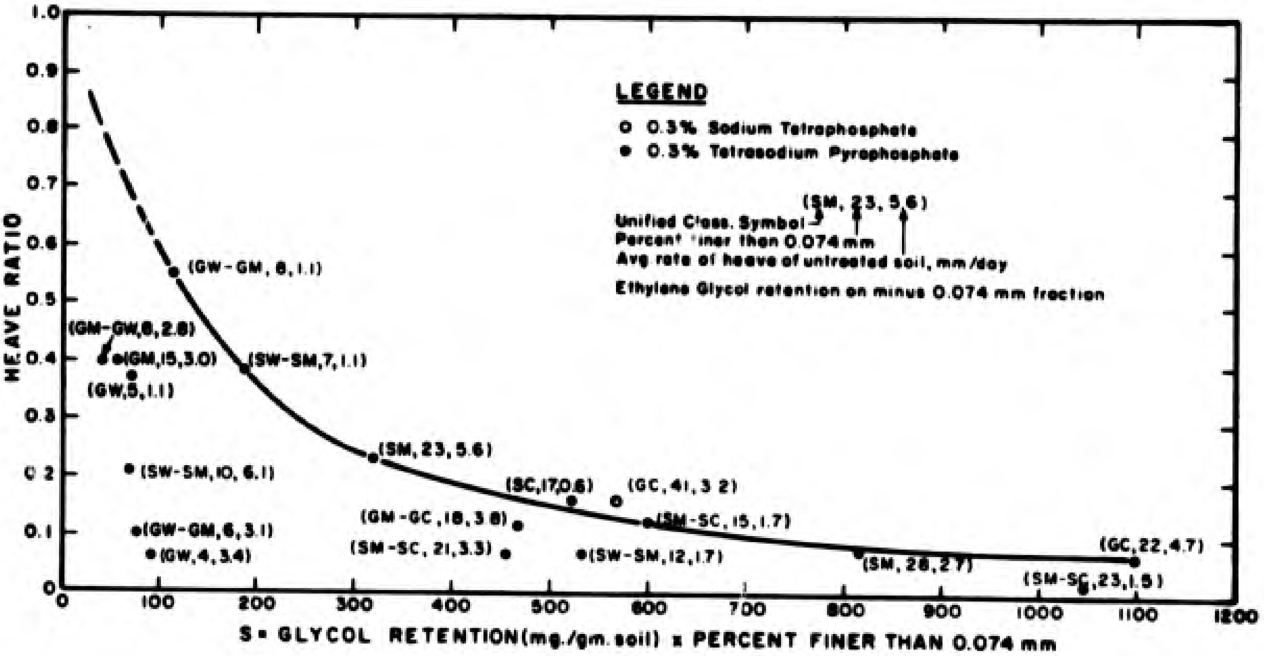

Figure 7. Effectiveness of 0.3% dispersant in modifying frost heave as a function of particle surface area.

Table XVII. Glycol retention data on sands and gravels treated with 0.3% TSPP.

	A	B		Avg. rate of heave mm/day		
Soil	% <0.074 mm	Glycol retention* mg/g soil	Product A×B	Untreated	Treated	Heave ratio
Great Falls (GC)	22	49	1100	4.7	0.3	0.06
Casper (SM-SC)	23	45	1050	1.5	0.03	0.02
Truax (SM)	28	29	810	2.7	0.2	0.07
Sioux Falls (SM-SC)	15	40	600	1.7	0.2	0.12
Loring (till, GC)	41	14	570	3.2	0.5**	0.16
Ellsworth (SW-SM)	12	44	530	1.7	0.1	0.06
Pierre (SC)	17	31	525	0.6	0.1	0.17
Clinton (GM-GC)	17.5	27	470	4.6	0.5	0.11
Patterson (SM-SC)	21	22	460	3.3	0.2	0.06
Portsmouth (SM)	23	14	320	5.6	1.3	0.23
Spokane (SW-SM)	7.0	27	189	1.1	0.4	0.36
Dow (GW-GM)	8.0	(14)	110	1.1	0.6	0.55
Greenland (GW)	4.0	24	96	3.4	0.2	0.06
Loring (GW-GM)	5.6	(14)	79	3.1	0.3	0.10
Dow (GW)	4.9	(14)	69	1.1	0.4	0.36
Coldbrook (GM)	15	3.7	56	3.0	1.2	0.40
Bowley (GW-GM)	7.5	4.9	37	2.5	1.0	0.40

* On minus 0.074 mm fraction.

** 0.3% Sodium Tetraphosphate

( ) estimated glycol retention based on data for similar Dow and Loring soils.

Table XVIII presents a summary of all of the heave ratios of additive treated standard size (large) specimens. The ratios are grouped by classifications of the soil involved, according to the Corps of Engineers Unified Soil Classification System. This permits a ready visual comparison of the soil types and various additives' effectiveness with various soil types. One can readily discern that the tetrasodium pyrophosphate is more generally effective in the clayey type soils than in the coarser soils, as theory would indicate. The asphalt emulsion appears to be more effective in the silty soils rather than with the clayey types. This may be due to slightly greater facility with which the emulsion may be mixed with the coarser soils. However it must be remembered that these results are based on very limited data from exploratory tests in this study. The permanence of treatments has not been established. Available data from literature and experience indicate that usually the effectiveness of most soluble salt treatments dissipates in a matter of a few years.

Table XVIII. Summary of heave ratio data versus Unified Soil Classification grouping.*

Soil group	*Additive*	*%*	*Heave ratio*
GW	TSPP	0.3	0.36, 0.06
GW-GM	TSPP	0.3	0.36, 0.40, 0.10, 0.55
	$FeCl_3$	0.3	0.18, 0.20
		0.5	0.14, 0
	P.C. + Daxad 21	2+0.2	0.02, 0.29
	Asphalt Emul.	3.0	0, 0
	Arquad 2HT	0.2	0.79
	Armeen 18D	0.2	0.21
GM	TSPP	0.3	0.40
	$FeCl_3$	0.3	0.20
GC	TSPP	0.3	0.16, 0.06
GM-GC	TSPP	0.3	0.11
SM	TSPP	0.22	0.46 (0.70 Field)
		0.3	0.23 0.07
		0.5	0.15 (0.23 Field)
		0.69	0.24 (0.32 Field)
	$FeCl_3$	0.5	0.22, 0.11
	P.C. + Daxad 21	2+0.2	0.04
	Asphalt Emul.	3.0	0
	Arquad 2HT	0.2	0.63
	Armeen 18D	0.2	0.44
	Volan	1.0	0.04
	Carbowax Peg 200	0.5	0.26
SW-SM	TSPP	0.3	0.36, 0.06, 0.21
		0.39	0.10 (0.20 Field)
		0.5	0.13
	Gypsum	3.0	0.48, 0.98
		5.0	0.10
	Lime	3.0	0.56
		6.0	0.46
SC	TSPP	0.3	0.17
SM-SC	TSPP	0.3	0.06, 0.12, 0.02, <0.1
	$FeCl_3$	0.5	0.13, 0.13
	P.C. + Daxad 21	2+0.2	0.27
	Asphalt Emul.	3.0	0.27
	Arquad 2HT	0.2	0.60
	Armeen 18D	0.2	0.53
	Volan	1.0	0.27
	Carbowax Peg 200	0.5	0.60

*Standard size specimens only, laboratory tested for frost susceptibility, not cycled, not leached; few data from field experiments are included for comparison as noted.

CONCLUSIONS

Several of the void fillers and cementing agents show promise, particularly for use with frost-susceptible sands and gravels. Some of the waterproofers show merit. Two trace chemicals which appear to be highly promising are TSPP, a dispersant, and ferric chloride, an aggregant.

Data are presented which suggest that the composition of the coarse fraction (plus No. 200 mesh sieve) of silty sands and gravels may be an important factor in soil frost susceptibility that needs to be taken into account in the modification of frost heave with additives.

Where the coarse fraction is high in clay minerals, water conduction in the adsorbed phase through and along the coarse particles can supply the moisture necessary for ice lens growth at the freezing front. In such a case, additives which react primarily with the soil fines, because of their larger specific surface area, may be less effective in modifying frost heaving.

Even in such a case, however, the laboratory leaching tests showed that TSPP can withstand severe conditions of water exposure, and still effect a reduction in heave of about 60%. In the soils tested ferric chloride was the more effective modifier, but the reduction in heave attained in specimens not subjected to water exposure (80%) was diminished to values ranging from 60 to 70% with prolonged water attack. The above percentage reductions are expressed in terms of the heave of the chemically untreated specimens. Nevertheless, according to the ACFEL Frost Susceptibility Classification, the TSPP and ferric chloride changed the soils' ratings from *medium – high* to *very low – low*.

Limited field test results indicate that TSPP can significantly diminish heave of a highly frost-susceptible gravel under natural conditions. The long-term effectiveness is still to be determined.

RECOMMENDATIONS

It is recommended that further laboratory evaluation be made of the effects of water exposure on the capabilities of TSPP and ferric chloride to modify frost heave in silty sands and gravels. The soils should be carefully selected to give a range of compositional types. Furthermore, to isolate the effects of mechanical manipulation on treated soils, an investigation should be made of the effects of leaching such soils with solutions containing TSPP and ferric chloride. The effect of field-mixing of TSPP and ferric chloride with specially selected soils warrants further investigation.

Available ACFEL data on the response to freezing of silty sands and gravels treated with TSPP and ferric chloride should be reexamined with particular attention paid to the possible effects of the mineralogical composition of the coarse fraction of those soils on frost heave.

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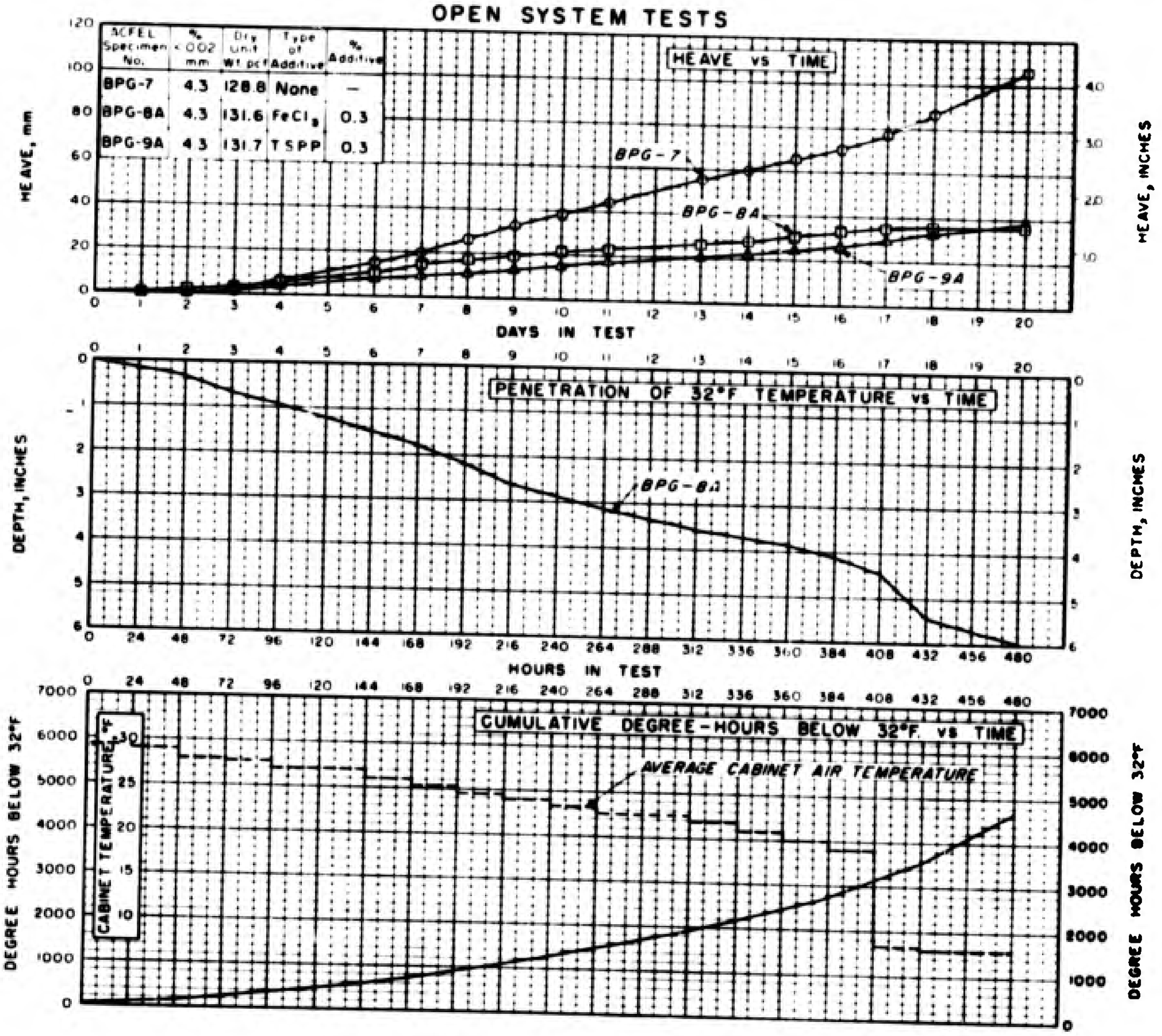
APPENDIX A: INVESTIGATIONAL DATA



SCFEL Specimen No.	% < 002 mm	Dry Unit Wt pcf	Type of Additive	% Additive
BPG-7	4.3	128.8	None	—
BPG-8A	4.3	131.6	$FeCl_3$	0.3
BPG-9A	4.3	131.7	TSPP	0.3

Figure A1. Typical temperature penetration and heave data for specimens from Bowley Pit, Hampden, Maine.

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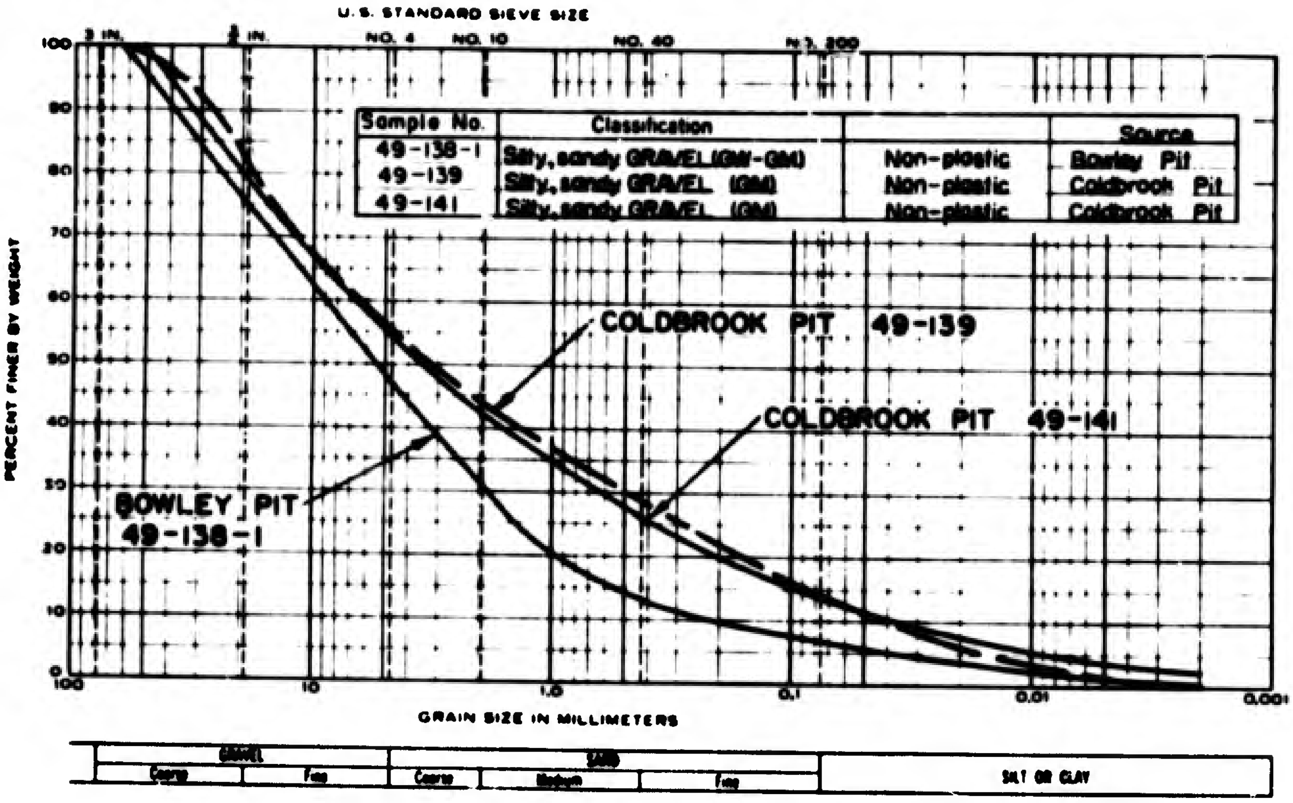

Figure A2. Grain size distribution, soils from Hampden, Maine.

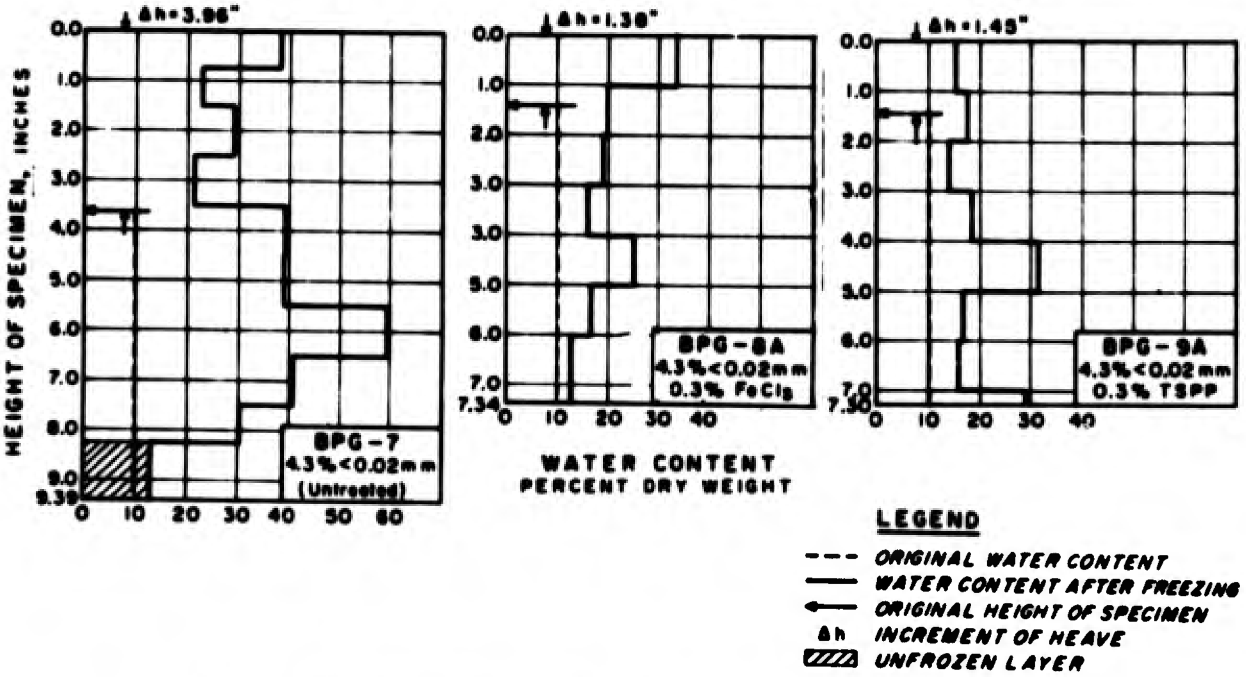

Figure A3. Typical water content distributions after freezing.

Table AI. Freezing tests on untreated soils made in conjunction with freezing tests on treated miniature specimens (open system).

Specimen no. CM-	Tray*	Soil†	Dry unit weight (lb/cu ft)	Void ratio	% saturation at start of test	Average water content (%)		% heave	Avg. rate of heave (mm/day)			No. of specimens
						Before freezing	After freezing		Specimen	Avg. for tray	Avg. for all tests	
1073	56-1	Boston blue clay	104.0	0.668	94.7	22.7	38.5	42.1	2.33	2.33		
1105	56-2		101.8	0.703	98.2	24.8	37.3	33.8	2.02	2.02		
1151	56-3		98.5	0.761	96.9	26.5	37.9	38.6	2.09	2.09	1.84 (not tapered)	26
1067	56-1	New Hampshire silt	101.8	0.679	94.0	23.3	45.5	49.8	4.32	4.32		
1127	56-8		96.5	0.735	91.5	24.5	56.0	71.0	6.67	6.67	3.60 (not tapered)	21
1232	56-5		100.7	0.696	92.9	23.6	147.4	312.5	13.11	14.92		
1233	56-5		93.5	0.830	80.9	24.5	179.5	350.0	16.73			
1235	58-1		99.3	0.723	83.3	22.0	152.4	227.6	16.89	16.89		
1271	58-2		101.3	0.688	92.6	23.3	104.0	165.8	8.59	8.59	13.83 (tapered)	4
1064	56-1	Fort Belvoir sandy clay	109.3	[illegible]41	96.7	19.4	25.6	29.2	1.48	1.48		
1116	56-2		110.6	0.523	96.4	18.7	29.0	30.2	1.21	1.21		
1138	56-3		108.0	0.559	99.6	20.6	29.2	26.4	1.50	1.50	2.05 (not tapered)	28
1197	56-4		113.8	0.481	96.5	17.2	30.4	34.0	2.99	3.27		
1198	56-4		114.4	0.473	93.3	16.3	32.4	51.7	3.55			
1253	58-1		107.1	0.574	97.2	20.7	91.4	146.6	7.43	7.43		
1281	58-2		106.6	0.580	92.0	19.8	30.2	30.6	2.48	2.48	4.11 (tapered)	4

* Miniature molds in trays 56-1 through 56-3 not tapered. Inside dimensions: Length 3.11 in., diameter 1.25 in. Miniature molds in all other trays tapered. Inside dimensions: Length 3.11 in., top diameter 1.38 in., bottom diameter 1.25 in.

† Identification of soils used:

Soils	Trays	Lab. serial no.
Boston blue clay	All	49-42
New Hampshire silt	56-	49-46
	58-	49-105
Fort Belvoir sandy clay	All	49-66

Table AII. Additive freezing tests miniature specimens (open system).

Specimen Number	Tray Number	Soil	Additive	Percent	Dry Unit Weight pcf (1)	Void Ratio (1)	Percent Saturation at Start of Test	Average Water Content, % (2)		Percent Heave (3)	Average Rate of Heave mm/day	Heave Ratio (4)	Notes on Specimen Preparation (5)		
								Before Freezing	After Freezing				Incorporation of Additive	Before Compaction	After Compaction
			ASPHALT												
1213	58-5	New Hampshire SILT	Asphalt Emulsion	1.0	101.1	0.680	87.3	21.8	121	244	17.3	0.83	a (mold water)	f (not dried)	i (not dried)
1218	58-5			1.0	101.2	0.671	88.3	21.9	140	294	15.3	1.07	a (mold.water)	e (oven dried)	i (not dried)
1221	58-5			1.0	101.8	0.668	64.5	15.8	141	363	15.3	1.32	a (mold.water)	f (not dried)	h (oven dried)
1214	58-5			3.0	101.7	0.657	87.3	21.3	136	275	17.3	0.87	a (mold.water)	f (not dried)	i (not dried)
1219	58-5			3.0	99.2	0.693	80.0	20.6	109	195	10.5	0.70	a (mold.water)	e (oven dried)	i (not dried)
1222	58-5			3.0	102.3	0.644	50.2	17.3	15.2	*	*	*	a (mold.water)	f (not dried)	h (oven dried)
1215	58-5			5.0	95.8	0.725	71.2	22.6	86.4	135	7.3	0.47	a (mold.water)	f (not dried)	i (not dried)
1220	58-5			5.0	100.1	0.653	80.9	20.0	111	229	11.3	0.76	a (mold.water)	e (oven dried)	i (not dried)
1212	58-5			5.0	107.6	0.537	40.6	8.2	11.8	*	*	*	a (mold.water)	f (not dried)	h (oven dried)
1247	58-1		Asphalt Cutback	7.5	103.6	0.524	82.1	17.6	195.1	219.2	13.94	0.83	c (wet soil)	f (not dried)	g (cured)
1248	58-1		Asphalt Cutback plus Phosphorus Pentoxide	7.5 2.0	107.1	0.419	97.9	16.8	31.9	30.5	2.17	0.13	c (wet soil) a (mold.water)	f (not dried)	g (cured)
1139	58-3	Fort Belvoir Sandy CLAY	Asphalt Emulsion	0.5	105.5	0.596	93.5	20.6	35.4	31.5	2.50	1.67	a (mold.water)	f (not dried)	g (cured)
1180	58-4			1.0	113.7	0.471	94.4	17.5	29.1	33.8	1.88	0.58	a (mold.water)	f (not dried)	i (not dried)
1182	58-4			1.0	106.3	0.603	77.3	17.4	31.8	36.4	1.71	0.57	a (mold.water)	e (oven dried)	i (not dried)
1185	58-4			1.0	112.5	0.486	87.8	15.9	94.8	173.0	14.46	4.47	a (mold.water)	f (not dried)	h (oven dried)
1140	58-3			1.0	106.4	0.571	82.2	17.5	23.3	12.9	0.75	0.50	a (mold.water)	f (not dried)	g (cured)
1179	58-4			3.0	111.2	0.487	93.3	17.2	23.2	20.6	1.41	0.43	a (mold.water)	f (not dried)	i (not dried)
1183	58-4			3.0	106.2	0.557	86.1	18.1	34.6	35.0	2.84	0.87	a (mold.water)	e (oven dried)	i (not dried)
1186	58-4			3.0	109.2	0.514	68.3	13.2	19.1	2.3	0.01	0	a (mold.water)	f (not dried)	h (oven dried)
1141	58-3			3.0	104.2	0.581	77.4	17.0	15.2	2.9	0.17	0.11	a (mold.water)	f (not dried)	g (cured)
1181	58-4			5.0	108.6	0.505	87.7	16.9	22.4	15.4	0.74	0.23	a (mold.water)	f (not dried)	i (not dried)
1184	58-4			5.0	107.2	0.525	80.5	16.1	40.6	51.8	3.73	1.44	a (mold.water)	e (oven dried)	i (not dried)
1187	58-4			5.0	108.7	0.504	40.5	8.9	12.2	3.0	0	0	a (mold.water)	f (not dried)	g (cured)
1265	58-1		Asphalt Cutback	7.5	107.4	0.470	56.3	17.9	26.3	25.1	1.05	0.25	c (wet soil)	f (not dried)	g (cured)
1266	58-1		Asphalt Cutback plus Phosphorus Pentoxide	7.5 2.0	107.7	0.461	90.5	16.6	34.9	54.3	1.77	0.24	c (wet soil) a (mold.water)	f (not dried)	g (cured)
			CEMENTING AGENTS												
1279	58-2	New Hampshire SILT	Portland Cement	3.0	102.0	0.682	90.9	22.5	28.3	16.3	1.39	0.16	b (dry soil)	f (not dried)	g (cured)
1278	58-2		Portland Cement plus Sodium Sulfite	3.0 0.5	103.0	0.666	90.3	21.8	21.1	0.7	0.15	0.02	b (dry soil) a (mold.water)	f (not dried)	g (cured)
1277	58-2		Portland Cement plus Sodium Metasilicate	3.0 0.5	102.0	0.682	88.3	21.9	22.4	1.0	0.34	0.04	b (dry soil) a (mold.water)	f (not dried)	g (cured)
1276	58-2		Portland Cement	5.0	100.5	0.714	88.7	22.9	25.4	19.8	1.49	0.17	b (dry soil)	f (not dried)	g (cured)
1275	58-2		Portland Cement plus Sodium Sulphite	5.0 1.0	104.9	0.642	90.7	21.1	18.2	1.0	0.26	0.03	b (dry soil) a (mold.water)	f (not dried)	g (cured)
1273	58-2		Portland Cement plus Sodium Metasilicate	5.0 1.0	102.2	0.683	87.3	21.7	19.0	2.9	0.08	0.01	b (dry soil) a (mold.water)	f (not dried)	g (cured)
1241	58-1		Lime	1.0	99.3	0.720	84.6	22.3	159.9	259.3	17.95	1.06	b (dry soil)	f (not dried)	g (cured)
1242	58-1			3.0	98.2	0.740	80.1	21.7	66.3	80.5	4.62	0.27	b (dry soil)	f (not dried)	g (cured)
1243	58-1		Quick Lime	1.0	97.9	0.766	83.6	23.1	139.3	213.7	15.63	0.93	b (dry soil)	f (not dried)	g (cured)
1244	58-1			3.0	98.5	0.757	79.6	21.6	73.6	101.0	7.18	0.43	b (dry soil)	f (not dried)	g (cured)
1245	58-1		Gypsum	1.0	100.4	0.700	88.4	22.6	75.3	94.5	5.81	0.34	b (dry soil)	f (not dried)	g (cured)
1246	58-1			3.0	100.5	0.693	90.2	22.9	72.9	94.8	5.46	0.32	b (dry soil)	f (not dried)	g (cured)
1249	58-1		1 Lime: 1 Flyash	25	95.3	0.762	82.2	23.3	38.6	20.3	3.[illegible]	0.18	b (dry soil)	f (not dried)	g (cured)
1250	58-1		1 Lime: 4 Flyash	25	91.9	0.835	84.2	24.0	34.2	13.8	1.43	0.09	b (dry soil)	f (not dried)	g (cured)
1251	58-1		1 Lime: 9 Flyash	25	97.7	0.816	84.6	25.6	48.9	20.3	1.30	0.08	b (dry soil)	f (not dried)	g (cured)
1252	58-1		1 Lime: 9 Flyash plus Calcium Chloride	25 1.0	93.4	0.808	86.4	26.4	27.2	1.5	0.16	0.01	b (dry soil) a (mold.water)	f (not dried)	g (cured)
1280	58-2		Phosphorus Pentoxide plus Sodium Silico-fluoride	2.0 0.25	105.9	0.608	91.7	20.4	21.4	1.6	0.81	0.09	a (mold.water) a (mold.water)	f (not dried) f (not dried)	g (cured) g (cured)
1285	58-2		Benzene Phosphonic Acid	1.0	103.4	0.670	90.4	22.1	38.5	34.2	2.29	0.27	a (mold.water)	f (not dried)	g (cured)
1283	58-2		AM-9 Grout Gel	3	103.9	0.593	83.6	16.7	20.4	-	0.08	0.01	a (mold.water)	f (not dried)	i (not dried)
1274	58-2			3	100.0	0.649	87.6	21.5	19.1	-	0.11	0.01	a (mold.water)	f (not dried)	i (not dried)
1291	58-2	Fort Belvoir Sandy CLAY	Portland Cement	3.0	111.5	0.517	96.8	18.9	21.0	7.3	1.21	0.49	b (dry soil)	f (not dried)	g (cured)
1290	58-2		Portland Cement plus Sodium Sulfite	3.0 0.5	113.4	0.491	100.0	18.1	23.3	[illegible]	1.19	0.48	b (dry soil) a (mold.water)	f (not dried)	g (cured)
1289	58-2		Portland Cement plus Sodium Metasilicate	3.0 0.5	110.4	0.530	94.8	19.0	25.1	12.2	1.17	0.47	b (dry soil) a (mold.water)	f (not dried)	g (cured)
1288	58-2		Portland Cement	5.0	112.2	0.577	90.6	18.4	17.9	1.0	0	0	b (dry soil)	f (not dried)	g (cured)
1287	58-2		Portland Cement plus Sodium Sulfite	5.0 1.0	112.0	0.515	96.7	18.3	17.2	0.3	0.07	0.03	b (dry soil) a (mold.water)	f (not dried)	g (cured)
1286	58-2		Portland Cement plus Sodium Metasilicate	5.0 1.0	111.4	0.529	96.8	18.6	19.3	1.6	0	0	b (dry soil) a (mold.water)	f (not dried)	g (cured)
1259	58-1		Lime	1.0	109.9	0.534	100.0	19.7	51.4	74.0	5.38	0.70	b (dry soil)	f (not dried)	g (cured)
1260	58-1			3.0	103.3	0.624	87.4	20.3	30.7	74.8	1.18	0.16	b (dry soil)	f (not dried)	g (cured)
1261	58-1		Quick Lime	1.0	100.9	0.674	85.8	21.4	108.3	186.4	17.96	1.74	b (dry soil)	f (not dried)	g (cured)
1262	58-1			3.0	101.4	0.674	81.9	20.3	28.8	14.6	1.00	0.13	b (dry soil)	f (not dried)	g (cured)
1263	58-1		Gypsum	1.0	106.0	0.588	90.4	19.7	31.4	28.3	1.98	0.27	b (dry soil)	f (not dried)	g (cured)
1264	58-1			3.0	106.2	0.580	72.7	15.7	23.3	12.2	0.61	0.08	b (dry soil)	f (not dried)	g (cured)
1267	58-1		1 Lime: 1 Flyash	25	100.7	0.642	89.4	21.7	36.0	38.7	1.59	0.21	b (dry soil)	f (not dried)	g (cured)
1268	58-1		1 Lime: 4 Flyash	25	101.8	0.636	88.2	21.0	40.2	37.6	1.05	0.14	b (dry soil)	f (not dried)	g (cured)
1269	58-1		1 Lime: 9 Flyash	25	102.8	0.623	88.3	20.6	60.5	78.8	4.90	0.66	b (dry soil)	f (not dried)	g (cured)
1270	58-1		1 Lime: 9 Flyash plus Calcium Chloride	25 1.0	105.0	0.534	96.9	20.1	26.7	13.7	3.30	0.44	b (dry soil) a (mold.water)	f (not dried)	g (cured)
1292	58-2		Phosphorus Pentoxide + Sodium Silicofluoride	2.0 0.25	111.9	0.494	100.0	18.7	24.5	14.9	0.97	0.39	a (mold.water) a (mold.water)	f (not dried)	g (cured)
1293	58-2		Benzene Phosphonic Acid	1.0	104.1	0.619	85.1	19.5	30.4	25.7	1.91	0.77	a (mold.water)	f (not dried)	g (cured)
1294	58-2		AM-9 Grout Gel	3	104.6	0.568	98.7	20.5	22.5	2.6	0.29	0.12	a (mold.water)	f (not dried)	i (not dried)
1298	58-2			3	112.3	0.459	100.0	17.4	21.8	4.1	0.20	0.08	a (mold.water)	f (not dried)	i (not dried)

* Specimen not frozen

SHEET 1 OF 3

Table AII. (Cont'd).

Specimen Number CR-	Tray Number	Soil	Additive	Percent	Dry Unit Weight pcf (1)	Void Ratio (1)	Percent Saturation at Start of Test	Average Water Content, % (2)		Percent Heave (3)	Average Rate of Heave mm/day	Heave Ratio (4)	Notes on Specimen Preparation (5)		
								Before Freezing	After Freezing				Incorporation of Additive	Before Compaction	After Compaction
			AGGREGANTS												
1113	56-2	Boston Blue CLAY	Agrilon	0.1	98.2	0.765	99.3	27.3	34.6	20.5	0.78	0.39	a (mold.water)	f (not dried)	i (not dried)
1114	56-2			0.1	96.4	0.865	97.1	29.2	38.5	27.5	1.09	0.54	a (mold.water)	d (air dried)	i (not dried)
1115	56-2			1.0	96.7	0.831	100.0	29.9	33.5	17.4	0.70	0.38	a (mold.water)	f (not dried)	i (not dried)
1117	56-2			1.0	96.7	0.831	98.9	29.5	34.2	17.9	0.60	0.30	a (mold.water)	d (air dried)	i (not dried)
1126	56-2	Fort Belvoir Sandy CLAY	Agrilon	0.1	108.4	0.553	88.0	18.0	29.9	26.7	1.41	1.17	a (mold.water)	f (not dried)	i (not dried)
1125	56-2			0.1	110.6	0.577	90.7	17.5	27.7	26.0	1.32	1.09	a (mold.water)	f (not dried)	i (not dried)
1124	56-2			1.0	105.8	0.551	83.8	18.4	24.7	12.9	0.64	0.53	a (mold.water)	f (not dried)	i (not dried)
			METALLIC SALTS												
1154	56-3	Boston Blue CLAY	Aluminum Sulphate	0.1	99.6	0.741	96.0	25.6	26.3	8.7	0.86	0.41	a (mold.water)	f (not dried)	i (not dried)
1153	56-3			0.1	102.6	0.690	99.9	24.8	25.0	5.5	0.58	0.28	a (mold.water)	d (air dried)	i (not dried)
1158	56-3		Aluminum Phosphate	0.1	100.2	0.731	100.0	26.3	25.5	7.1	0.79	0.38	a (mold.water)	f (not dried)	i (not dried
1157	56-3			0.1	102.5	0.698	95.0	23.6	24.2	9.6	0.76	0.36	a (mold.water)	d (air dried)	i (not dried)
1107	56-2		Ferric Chloride	0.1	100.1	0.733	97.1	25.7	33.9	11.3	0.81	0.40	a (mold.water)	f (not dried)	i (not dried)
1106	56-2			0.1	109.4	0.694	96.9	24.2	28.7	14.5	0.92	0.46	a (mold.water)	d (air fried)	i (not dried)
1109	56-2		Ferric Sulphate	0.1	105.3	0.647	94.8	22.1	26.7	13.8	0.76	0.38	a (mold.water)	f (not dried)	i (not dried)
1108	56-2			0.1	105.4	0.644	99.8	23.1	27.4	12.5	0.70	0.35	a (mold.water)	d (air dried)	i (not dried)
1111	56-2		Zinc Sulphate	0.1	104.2	0.664	97.8	23.9	28.2	14.8	0.79	0.39	a (mold.wate	[illegible]	i (not dried)
1110	56-2			0.1	104.4	0.661	94.5	22.6	30.7	19.6	0.76	0.38	a (mold.water)		i (not dried)
1304	58-2	New Hampshire SILT	Thorium Chloride	0.2	101.0	0.693	91.5	23.1	69.8	91.5	6.12	0.71	a (mold.water)	f	ried)
1305	58-2			0.5	91.2	0.880	74.8	23.9	89.5	127.7	5.88	0.69	a (mold.water)	f (no	d)
1306	58-2			1.0	98.9	0.735	87.3	23.3	46.8	31.8	6.27	0.73	a (mold.water)	f (not dri	
1301	58-2		Aluminum Chloride	0.2	96.9	0.764	88.8	24.8	50.1	46.6	7.14	0.83	a (mold.water)	f (not dried)	
1302	58-2			0.5	99.3	0.771	87.7	23.1	73.1	7.3	1.47	0.19	a (mold.water)	f (not dried)	i (no
1303	58-2			1.0	99.0	0.727	91.4	24.2	71.3	-	0.91	0.11	a (mold.water)	f (not dried)	i (not dr
1129	56-3		Aluminum Sulphate	0.1	101.9	0.654	97.3	23.6	43.4	51.3	4.24	0.62	a (mold.water)	f (not dried)	i (not dried)
1128	56-3			0.1	101.9	0.677	91.4	22.6	44.7	48.6	4.99	0.75	a (mold.water)	d (air dried)	i (not dried)
1133	56-3		Aluminum Phosphate	0.1	102.1	0.674	99.0	24.4	48.2	61.4	4.95	0.74	a (mold.water)	f (not dried)	i (not dried)
1132	56-3			0.1	104.6	0.635	90.3	20.9	42.8	54.6	3.60	0.54	a (mold.water)	d (air dried)	i (not dried)
1205	56-5		Ferric Chloride	0.2	100.3	0.707	91.7	23.4	81.8	129.7	7.59	0.51	a (mold.water)	f (not dried)	i (not dried)
1199	56-5			0.2	98.9	0.730	91.5	23.7	66.2	103.0	3.08	0.20	a (mold.water)	e (oven dried)	i (not dried)
1202	56-5			0.2	99.9	0.720	75.9	19.7	53.8	71.5	9.17	0.61	a (mold.water)	f (not dried)	h (oven dried)
1239	58-1			0.5	101.1	0.699	87.0	22.0	29.4	14.3	2.49	0.15	a (mold.water)	f (not dried)	i (not dried)
1206	56-5			0.5	99.5	0.726	93.9	24.6	40.5	46.1	6.79	0.45	a (mold.water)	f (not dried)	i (not dried)
1200	56-5			0.5	101.4	0.688	95.7	24.0	45.7	57.8	5.40	0.36	a (mold.water)	e (oven dried)	i (not dried)
1203	56-5			0.5	101.5	0.686	95.1	23.8	30.5	20.6	2.90	0.19	a (mold.water)	e (oven dried)	i (not dried)
1240	58-1			1.0	99.5	0.720	83.8	22.0	23.2	2.3	1.08	0.06	a (mold.water)	f (not dried)	i (not dried)
1207	56-5			1.0	100.3	0.704	89.6	23.0	23.0	1.7	0.03	0	a (mold.water)	f (not dried)	i (not dried)
1201	56-5			1.0	97.7	0.750	78.7	21.5	32.0	19.3	3.03	0.20	a (mold.water)	e (oven dried)	i (not dried)
1204	56-5			1.0	101.2	0.698	12.8	3.2	4.6	0	-	*	a (mold.water)	e (oven dried)	i (not dried)
1228	56-5		Calcium Chloride	0.5	99.5	0.718	90.9	23.8	54.2	78.5	8.40	0.56	a (mold.water)	f (not dried)	i (not dried)
1229	56-5			1.0	98.2	0.740	86.4	23.3	25.6	-	2.78	0.19	a (mold.water)	f (not dried)	i (not dried)
1238	58-1			3.0	101.1	0.655	91.8	19.6	21.7	1.3	0.14	*	a (mold.water)	f (not dried)	i (not dried)
1216	56-5		Sodium Chloride	0.5	99.8	0.77	91.4	23.8	28.8	16.6	1.71	0.11	a (mold.water)	f (not dried)	i (not dried)
1217	56-5			1.0	99.5	0.7	90.7	23.8	25.2	-	1.72	0.11	a (mold.water)	f (not dried)	i (not dried)
1230	56-5		Lithium Chloride	0.5	97.9	0.74	90.5	23.6	26.6	7.4	0.76	0.05	a (mold.water)	f (not dried)	i (not dried)
1231	56-5			1.0	101.0	0.694	87.5	22.2	22.8	-	0.16	0	a (mold.water)	f (not dried)	i (not dried)
1272	58-2		Silver Iodide	0.1	98.7	0.732	93.5	25.0	99.2	140.7	9.58	1.12	a (mold.water)	f (not dried)	i (not dried)
1297	58-2	Fort Belvoir Sandy CLAY	Thorium Chloride	0.2	113.8	0.482	96.0	17.1	23.5	24.1	1.37	0.55	a (mold.water)	f (not dried)	i (not dried)
1299	58-2		Thorium Chloride	0.5	114.6	0.472	93.0	16.8	26.7	26.4	2.48	1.08	a (mold.water)	f (not dried)	i (not dried)
1300	58-2			1.0	116.7	0.464	93.2	15.7	22.3	19.9	1.48	0.60	a (mold.water)	f (not dried)	i (not dried)
1294	58-2		Aluminum Chloride	0.2	105.6	0.595	86.8	19.1	23.2	15.9	1.38	0.44	a (mold.water)	f (not dried)	i (not dried)
1295	58-2			0.5	114.5	0.465	90.5	14.9	15.3	1.6	0.36	0.14	a (mold.water)	f (not dried)	i (not dried)
1296	58-2			1.0	120.0	0.403	96.4	14.4	14.8	2.9	0.14	0.06	a (mold.water)	f (not dried)	i (not dried)
1143	56-2		Aluminum Sulphate	0.1	115.3	0.461	90.7	15.5	22.6	22.2	1.24	1.03	a (mold.water)	f (not dried)	i (not dried)
1142	56-3			0.1	104.3	0.615	100.0	27.7	25.6	22.8	1.27	0.86	a (mold.water)	d (air dried)	i (not dried)
1146	56-3		Aluminum Phosphate	0.1	[illegible].7	0.495	98.3	18.0	27.9	19.9	0.86	0.57	a (mold.water)	f (not dried)	i (not dried)
1145	56-3			0.1	[illegible]9.6	0.537	98.8	19.6	26.9	24.7	5.15	3.43	a (mold.water)	d (air dried)	i (not dried)
1118	56-2		Ferric Chloride	0.1	114.4	0.472	96.5	16.9	27.8	22.2	1.06	0.88	a (mold.water)	f (not dried)	i (not dried)
1117	56-2			0.1	116.5	0.465	97.0	16.0	19.6	17.4	0.74	0.61	a (mold.water)	d (air dried)	i (not dried)
1169	56-4			0.2	116.0	0.452	98.3	16.5	18.0	11.3	0.84	0.26	a (mold.water)	f (not dried)	i (not dried)
1163	56-4			0.2	113.4	0.486	96.9	17.4	16.8	4.9	0.50	0.15	a (mold.water)	e (oven dried)	i (not dried)
1166	56-4			0.2	116.5	0.446	93.5	15.9	20.4	15.8	1.93	0.56	a (mold.water)	f (not dried)	h (oven dried)
1257	58-1			0.5	114.5	0.471	87.7	15.3	16.6	7.1	1.14	0.15	a (mold.water)	f (not dried)	i (not dried)
1164	56-4			0.5	117.7	0.431	100.0	16.0	17.7	1.3	0	0	a (mold.water)	e (oven dried)	i (not dried)
1167	56-4			0.5	117.8	0.429	78.5	12.5	11.5	0.6	0	0	a (mold.water)	f (not dried)	h (oven dried)
1170	56-4			0.5	114.9	0.466	89.9	15.5	13.5	2.6	0	0	a (mold.water)	f (not dried)	i (not dried)
1258	58-1			1.0	116.2	0.451	94.1	15.7	15.8	2.6	0.21	0.03	a (mold.water)	f (not dried)	i (not dried)
1165	56-4			1.0	116.7	0.443	88.0	14.4	13.4	0	0	0	a (mold.water)	e (oven dried)	i (not dried)
1168	56-4			1.0	116.8	0.449	83.4	14.5	12.9	1.9	0	0	a (mold.water)	f (not dried)	h (oven dried)
1171	56-4			1.0	119.6	0.409	94.7	14.4	13.2	2.2	0	0	a (mold.water)	f (not dried)	i (oven dried)
1120	56-2		Ferric Sulphate	0.1	120.6	0.550	89.2	18.2	25.8	25.9	1.74	1.03	a (mold.water)	f (not dried)	i (not dried)
1119	56-2			0.1	114.9	0.486	99.6	17.2	24.1	24.4	0.95	0.79	a (mold.water)	d (air dried)	i (not dried)
1122	56-2		Zinc Sulphate	0.1	115.3	0.461	96.8	16.5	23.9	22.5	1.11	0.92	a (mold.water)	f (not dried)	i (not dried)
1121	56-2			0.1	113.4	0.484	86.6	15.5	21.5	20.6	1.15	0.95	a (mold.water)	d (air dried)	i (not dried)
1193	56-4		Calcium Chloride	0.5	121.1	0.391	100.0	14.5	12.6	1.0	0	0	a (mold.water)	f (not dried)	i (not dried)
1194	56-4			1.0	119.5	0.410	84.5	12.8	11.7	1.6	0	0	a (mold.water)	f (not dried)	i (not dried)
1256	58-1			3.0	115.4	0.458	90.9	15.4	14.0	1.6	0.25	0.03	a (mold.water)	f (not dried)	i (not dried)
1191	56-4		Sodium Chloride	0.5	113.7	0.484	88.9	15.9	13.9	1.3	0	0	a (mold.water)	f (not dried)	i (not dried)
1192	56-4			1.0	114.8	0.442	97.2	15.4	14.0	0.6	0	0	a (mold.water)	f (not dried)	i (not dried)
1195	56-4		Lithium Chloride	0.5	119.0	0.416	95.6	14.7	12.8	1.6	0	0	a (mold.water)	f (not dried)	i (not dried)
1196	56-4			1.0	121.1	0.391	91.8	13.3	11.6	1.3	0	0	a (mold.water)	f (not dried)	i (not dried)
1282	58-2		Silver Iodide	0.1	111.3	0.515	96.7	18.6	31.6	41.7	2.32	0.94	a (mold.water)	f (not dried)	i (not dried)
			WATERPROOFERS												
1077	56-1	Boston Blue CLAY	Arquad 2 HT	0.05	104.9	0.654	97.6	21.8	28.2	14.2	1.15	0.49	a (mold.water)	f (not dried)	i (not dried)
1074	56-1			0.05	99.8	0.737	83.9	22.2	26.5	10.6	0.67	0.29	a (mold.water)	d (air dried)	i (not dried)
1072	56-1			0.1	101.2	0.714	83.5	21.5	27.8	11.3	1.07	0.44	a (mold.water)	f (not dried)	i (not dried)
1076	56-1			0.1	100.9	0.718	88.4	22.8	26.5	10.0	0.90	0.39	a (mold.water)	d (air dried)	i (not dried)
1156	56-3		Ethyl Diamine Dihydrochloride	0.1	97.5	0.778	99.2	27.8	29.0	9.6	0.94	0.45	a (mold.water)	f (not dried)	i (not dried)
1155	56-3			0.1	101.3	0.715	88.5	22.8	30.2	10.6	0.91	0.44	a (mold.water)	d (air dried)	i (not dried)
1162	56-3		Alkyl Dimethyl Benzyl Ammonium Chloride	0.1	93.0	0.865	100.0	31.1	30.8	19.0	0.93	0.45	a (mold.water)	f (not dried)	i (not dried)
1161	56-3			0.1	94.3	0.844	99.6	30.2	34.3	13.8	1.13	0.54	a (mold.water)	d (air dried)	i (not dried)
1160	56-3			0.5	96.4	0.798	97.8	26.7	32.4	10.3	0.92	0.44	a (mold.water)	f (not dried)	i (not dried)
1159	56-3			0.5	100.0	0.733	94.4	24.9	28.7	10.3	1.10	0.53	a (mold.water)	d (air dried)	i (not dried)

* Specimen not frozen.

Table AII. (Cont'd).

Specimen Number CM-	Tray Number	Soil	Additive	Percent	Dry Unit Weight pcf (1)	Void Ratio (1)	Percent Saturation at Start of Test	Average Water Content, % (2)		Percent Heave (3)	Average Rate of Heave mm/day	Heave Ratio (4)	Notes on Specimen Preparation (5)		
								Before Freezing	After Freezing				Incorporation of Additive	Before Compaction	After Compaction
1062	56-1	New Hampshire SILT	Arquad 2 HT	0.05	101.0	0.687	86.9	21.9	54.6	57.2	4.51	1.04	a (mold.water)	f (not dried)	i (not dried)
1061	56-1			0.05	100.5	0.700	83.0	21.2	44.2	39.2	2.74	0.63	a (mold.water)	d (air dried)	i (not dried)
1064	56-1			0.1	99.9	0.711	83.8	21.7	45.4	45.6	3.64	0.84	a (mold.water)	f (not dried	i (not dried)
1063	56-1			0.1	101.4	0.687	80.5	20.2	44.8	47.6	3.97	0.92	a (mold.water)	d (air dried	i (not dried)
1208	56-5		Volan	1.0	101.7	0.682	89.8	22.3	40.2	54.0	5.46	0.36	a (mold.water)	f (not dried)	i (not dried)
1209	56-5			1.0	101.2	0.688	95.0	23.9	65.3	120.4	13.67	0.91	c (mold.water)	f (not dried)	h (oven dried)
1210	56-5		Carbowax Peg 800	0.5	100.4	0.702	91.0	23.3	110.7	201.9	10.61	0.71	a (mold.water)	f (not dried)	i (not dried)
1211	56-5			0.5	100.6	0.699	87.7	22.9	134.7	250.0	9.67	0.65	a (mold.water)	f (not dried)	h (oven dried)
1234	56-5		Armeen 18 D	0.2	102.5	0.666	93.6	22.8	176.0	327.4	17.26	1.15	a (mold.water)	f (not dried)	i (not dried)
1131	56-3		Ethyl Diamine Dihydrochloride	0.1	100.3	0.703	94.4	24.2	47.2	41.8	4.29	0.64	a (mold.water)	f (not dried)	i (not dried)
1130	56-3			0.1	101.0	0.692	93.6	23.7	37.2	43.1	2.79	0.42	a (mold.water)	d (air dried)	i (not dried)
1137	56-3		Alkyl Dimethyl Benzyl Ammonium Chloride	0.1	102.6	0.666	90.0	21.9	52.4	67.2	6.06	0.91	a (mold.water)	f (not dried)	i (not dried)
1136	56-3			0.1	101.1	0.690	97.2	23.2	52.0	67.2	4.72	0.71	a (mold.water)	d (air dried)	i (not dried)
1135	56-3			0.5	103.1	0.658	94.5	22.7	45.8	55.0	4.56	0.68	a (mold.water)	f (not dried)	i (not dried)
1134	56-3			0.5	102.4	0.669	93.0	22.7	53.3	72.0	7.29	1.08	a (mold.water)	d (air dried)	i (not dried)
1088	56-1	Fort Belvoir Sandy CLAY	Arquad 2 HT	0.05	107.3	0.570	63.5	13.4	22.4	12.5	0.60	0.41	a (mold.water)	f (not dried)	i (not dried)
1087	56-1			0.05	107.7	0.564	76.1	15.9	22.0	15.0	0.98	0.66	a (mold.water)	d (air dried)	i (not dried)
1090	56-1			0.1	106.3	0.583	67.8	14.6	19.4	8.7	0.58	0.39	a (mold.water)	f (not dried)	i (not dried)
1089	56-1			0.1	111.9	0.505	74.5	14.0	22.1	16.7	1.04	0.70	a (mold.water)	d (air dried)	i (not dried)
1176	56-4			0.2	118.2	0.425	100.0	15.8	24.6	23.4	1.17	0.36	a (mold.water)	f (not dried)	i (not dried)
1177	56-4			0.2	112.2	0.501	96.9	18.0	30.3	30.2	2.34	0.72	a (mold.water)	e (oven dried)	i (not dried)
1178	56-4			0.2	110.2	0.529	84.0	16.4	37.0	44.7	3.54	1.08	a (mold.water)	f (air dried)	h (oven dried)
1172	56-4	Fort Belvoir Sandy CLAY	Volan	1.0	115.2	0.463	94.0	16.1	16.3	3.5	0.31	0.09	a (mold.water)	f (not dried)	i (not dried)
1173	56-4			1.0	117.3	0.436	99.7	16.1	38.7	43.7	4.75	1.30	a (mold.water)	f (not dried)	h (oven dried)
1174	56-4		Carbowax Peg 800	0.5	118.0	0.504	97.4	18.2	21.8	17.5	0.82	0.25	a (mold.water)	f (not dried)	i (not dried)
1175	56-4			0.5	114.6	0.470	94.5	18.4	23.7	20.6	1.50	0.46	a (mold.water)	f (not dried)	h (oven dried)
1179	56-4		Armeen 18 D	0.2	113.2	0.488	100.0	18.1	39.3	55.0	4.59	1.40	a (mold.water)	f (not dried)	i (oven dried)
1180	56-4			0.2	115.9	0.454	88.3	14.8	30.1	40.5	2.59	0.79	a (mold.water)	e (oven dried)	i (not dried)
1181	56-4			0.2	114.3	0.474	19.6	3.4	55.0	91.7	6.70	2.05	a (mold.water)	f (not dried)	h (oven dried)
1144	56-3		Ethyl Diamine Dihydrochloride	0.1	110.5	0.523	100.0	19.4	22.1	16.7	0.95	0.63	a (mold.water)	f (not dried)	i (not dried)
1143	56-3			0.1	111.6	0.509	98.3	17.4	21.6	14.5	0.84	0.56	a (mold.water)	d (air dried)	i (not dried)
1150	56-3		Alkyl Dimethyl Benzyl Ammonium Chloride	0.1	110.9	0.519	93.8	18.0	29.2	28.0	1.78	1.19	a (mold.water)	f (not dried)	i (not dried)
1149	56-3			0.1	106.3	0.585	96.4	20.9	32.9	35.4	2.61	1.73	a (mold.water)	d (air dried)	i (not dried)
1148	56-3			0.5	108.9	0.546	100.0	20.2	30.2	30.2	1.65	1.10	a (mold.water)	f (not dried)	i (not dried)
1147	56-3			0.5	106.4	0.583	95.4	20.8	30.7	30.8	1.79	1.19	a (mold.water)	d (air dried)	i (not dried)
			DISPERSANTS												
1075	56-1	Boston Blue CLAY	Tetrasodium Pyrophosphate	0.1	101.8	0.703	99.2	25.0	27.0	9.3	0.83	0.36	a (mold.water)	f (not dried)	i (not dried)
1071	56-1			0.1	105.1	0.648	91.4	21.4	25.9	10.6	0.70	0.30	a (mold.water)	d (air dried)	i (not dried)
1152	56-3		Sodium Tetraphosphate	1.0	97.7	0.775	-	-	32.6	5.8	0.34	0.14	a (mold.water)	f (not dried)	i (not dried)
1080	56-1	New Hampshire SILT	Tetrasodium Pyrophosphate	0.1	103.2	0.656	89.5	21.4	35.7	23.3	2.27	0.53	a (mold.water)	f (not dried)	i (not dried)
1236	58-1			0.1	99.5	0.719	81.5	21.4	150.8	268.5	14.53	0.86	a (mold.water)	f (not dried)	i (not dried)
1059	56-1			0.1	106.1	0.612	93.5	20.1	33.4	30.2	2.44	0.57	a (mold.water)	e (air dried)	i (not dried)
1237	58-1			0.3	97.1	0.749	100.0	31.0	102.0	127.7	9.56	0.57	a (mold.water)	f (not dried)	i (not dried)
1086	56-1	Fort Belvoir Sandy CLAY	Tetrasodium Pyrophosphate	0.1	113.2	0.488	92.9	16.8	20.7	16.4	0.96	0.65	a (mold.water)	f (not dried)	i (not dried)
1254	58-1			0.1	12.4	0.500	80.2	14.9	25.0	16.7	1.90	0.26	a (mold.water)	f (not dried)	i (not dried)
1085	56-1			0.1	113.3	0.486	96.0	17.3	21.8	18.3	1.01	0.68	a (mold.water)	d (air dried)	i (not dried)
1255	58-1			0.3	114.9	0.466	92.5	16.0	20.0	9.6	.98	0.13	a (mold.water)	f (not dried)	i (not dried)

SHEET 3 OF 3

NOTES: (1) Dry unit weight and void ratio of compacted soil - plus - additive mixture after saturation. All miniature specimens prepared from - No. 10 sieve material. Compaction: 3 layers, 60 tamps/layer, with 40 lb. spring tamper.

(2) Water content based on weight of soil and additive.

(3) Based on original height of frozen portion.

(4) Rate of heave ratio = $\frac{\text{average rate of heave of treated specimen}}{\text{average rate of heave of untreated specimen}}$
Unless otherwise noted heave ratios are based on the average rates of heave of untreated specimens in tray.
See Table A-1 for data on untreated basic soils.

(5) Explanation of specimen preparation:

<u>Incorporation of Additive</u>

a. Additive added to molding water.

b. Additive mixed with dry soil, water added.

c. Additive mixed with wet soil.

<u>Before Compaction</u>

d. Air-dried after mixing, water added, specimen compacted.

e. Oven-dried after mixing, water added, specimen compacted.

f. Not dried prior to compaction.

<u>After Compaction</u>

g. Cured 7 days at room temperature and 100% relative humidity before saturation.

h. Oven-dried before saturation.

i. Not dried or cured before saturation.

Miniature molds in trays 56-1 thru 56-3 not tapered. Inside dimensions: Length, 3.11 inches; diameter, 1.25 inches.
Miniature molds in all other trays tapered. Inside dimensions: Length, 3.11 inches; top diameter, 1.30 inches; bottom diameter, 1.25 inches.

Table AIII. Tests for effect of additives (open system, standard size specimens).[1]

Specimen no.	Symbol	Additive Name	%[2]	Atterberg limits (%)[3] LL	Atterberg limits (%)[3] PI	Dry unit wt (lb/cu ft)	Void ratio	% saturation at start of test	Avg. water content % Molding	Avg. water content % Before freezing	Avg. water content % After freezing	Freezing test results % heave[4]	Freezing test results Avg rate of heave[5] (mm/day)	Freezing test results Heave ratio[6]	Notes on specimen preparation[7] Incorporation of additive	Notes on specimen preparation[7] Before compaction	Notes on specimen preparation[7] After compaction
Casper clayey silty sand **Lab ser. no. 49-13**																	
CA-3	SM-SC	None		22	5	119.5	0.375	100	4.0	14.2	19.6	17.1	1.5	1.0		e (not dried)	h (not dried)
CA-10A		Portland cement plus Dazad 21	2.0 0.2			128.7	0.287	100	9.5	10.8	13.2	6.9	0.4	0.27	b (dry soil) a (mold water)	e (not dried)	f (cured)
CA-11A		Asphalt emulsion	3.0			125.3	0.319	83	9.5	9.3	11.3	4.8	0.4	0.27	c (wet soil)	e (not dried)	g (oven dried)
CA-6A		Ferric chloride	0.5			126.0	0.312	96	10.0	11.3	10.1	0	0.2	0.13	a (mold water)	d (oven dried)	h (not dried)
CA-7A		Ferric chloride	0.5			126.0	0.312	99	10.0	11.6	9.7	0	0.2	0.13	a (mold water)	e (not dried)	h (not dried)
CA-5A		Tetrasodium pyrophosphate	0.3			132.7	0.242	100	7.0	9.2	10.4	3.9	<0.1	<0.1	a (mold water)	e (not dried)	h (not dried)
CA-8A		Arquad 2 HT	0.2			125.8	0.314	93	10.0	11.0	16.0	15.6	0.9	0.60	a (mold water)	d (oven dried)	h (not dried)
CA-9A		Armeen 18 D	0.2			125.9	0.314	95	10.0	11.3	16.7	19.0	0.8	0.53	a (mold water)	d (oven dried)	h (not dried)
CA-12A		Volan	1.0			127.6	0.296	100	9.0	11.7	11.7	2.2	0.4	0.27	a (mold water)	e (not dried)	h (not dried)
CA-13A		Carbowax Peg 200	0.5			131.0	0.263	100	9.0	9.9	9.6	2.8	0.9	0.60	a (mold water)	d (oven dried)	h (not dried)
Loring silty sandy gravel **Lab ser. no. 49-49**																	
LSG-1A	GW-GM	None		17	17	137.0	0.250	100	6.0	9.1	30.0	61.1	4.2	1.0		e (not dried)	h (not dried)
LSG-14A		Portland cement plus Dazad 21	2.0 0.2			131.9	0.300	100	4.0	10.6	10.9	3.3	0.1	0.02	b (dry soil) a (mold water)	e (not dried)	f (cured)
LSG-15A		Asphalt emulsion	3.0			131.2	0.305	100	5.0	8.9	7.2	0.8	0	0	c (wet soil)	e (not dried)	g (oven dried)
Dow silty sandy gravel **test embankment B-18**																	
DFSB-2	GW-GM	None		Non-plastic		134.0	0.251	100		10.0	16.8	20.5	1.4	1.0		e (not dried)	h (not dried)
DFSB-10A		Portland cement plus Dazad 21	2.0 0.2			134.5	0.248	98	4.5	9.2	11.8	7.8	0.4	0.29	b (dry soil) a (mold water)	e (not dried)	f (cured)
DFSB-11A		Asphalt emulsion	3.0			129.9	0.291	90	4.5	8.9	5.2	1.0	0	0	c (wet soil)	e (not dried)	g (oven dried)
DFSB-9A		Ferric chloride	0.5			135.4	0.240	100	4.5	10.4	9.1	2.9	0.2	0.14	a (mold water)	d (oven dried)	h (not dried)
DFSB-6A		Ferric chloride	0.5			136.4	0.231	99	4.5	8.5	8.3	2.0	0	0	a (mold water)	e (not dried)	h (not dried)
DFSB-7A		Arquad 2 HT	0.2			136.9	0.226	100	4.5	8.4	19.5	31.4	1.1	0.79	a (mold water)	d (oven dried)	h (not dried)
DFSB-8A		Armeen 18 D	0.2			132.5	0.267	91	14.0	9.0	10.2	6.7	0.3	0.21	a (mold water)	d (oven dried)	h (not dried)
Truax silty gravelly sand **Lab. ser. no. 49-18-2**																	
TD-5	SM	None		Non-plastic		129.5	0.300	93		10.2	19.5	23.2	2.7	1.0		e (not dried)	h (not dried)
TD-43A		Portland cement plus Dazad 21	2.0 0.2	Non-plastic		132.6	0.270	100	5.3	10.1	10.1	1.4	0.1	0.04	b (dry soil)	e (not dried)	f (cured)
TD-44A		Asphalt emulsion	3.0			133.7	0.260	88	6.3	5.[illegible]	5.4	1.0	0	0	c (wet soil)	e (not dried)	g (oven dried)
TD-39A		Ferric chloride	0.5			133.4	0.261	100	5.3	9.7	10.1	2.3	0.6	0.22	a (mold water)	d (oven dried)	h (not dried)
TD-40A		Ferric chloride	0.5			134.4	0.250	100	6.0	9.4	9.1	0.5	0.3	0.11	a (mold water)	e (not dried)	h (not dried)
TD-38A		Tetrasodium pyrophosphate	0.3			138.8	0.212	96	7.0	7.5	8.1	3.5	0.2	0.07	a (mold water)	e (not dried)	h (not dried)
TD-41A		Arquad 2 HT	0.2			131.9	0.278	100	5.3	10.4	28.3	43.2	1.7	0.63	a (mold water)	d (oven dried)	h (not dried)
TD-42A		Armeen 18 D	0.2			132.8	0.269	100	5.3	9.9	20.9	25.8	1.2	0.44	a (mold water)	d (oven dried)	h (not dried)
TD-45A		Volan	1.0			136.7	0.233	100	5.3	8.6	8.4	2.5	0.1	0.04	a (mold water)	e (not dried)	h (not dried)
TD-46A		Carbowax Peg 200	0.5			136.8	0.232	100	5.3	8.6	12.2	11.5	0.7	0.26	a (mold water)	d (oven dried)	h (not dried)

Table AIII (Cont'd). Tests for effect of additives (open system, standard size specimens).[1]

Specimen no.	Symbol	Additive Name	Additive %[2]	Atterberg limits %[3] LL	Atterberg limits %[3] PI	Dry unit wt (lb/cu ft)	Void ratio	% saturation at start of test	Avg. water content % Molding	Avg. water content % Before freezing	Avg. water content % After freezing	Freezing test results % heave[4]	Freezing test results Avg rate of heave[5] (mm/day)	Freezing test results Heave ratio[6]	Notes on specimen preparation[7] Incorporation of additive	Notes on specimen preparation[7] Before compaction	Notes on specimen preparation[7] After compaction
Pierre clayey gravelly sand **Lab. Ser. no. 49-14**																	
PA-1	SC	None		25	7	123.0	0.380	100		14.0	16.5	9.7	0.6	1.0		e (not dried)	h (not dried)
PA-2A		Tetrasodium pyrophosphate	0.3			137.1	0.237	90	7.0	7.8	9.4	4.5	0.1	0.17	a (mold water)	e (not dried)	h (not dried)
Great Falls clayey sandy gravel **Lab. Ser. no. 49-20**																	
GF-1	GC	None		43	25	133.0	0.252	100	6.0	9.5	21.0	28.0	4.7	1.0		e (not dried)	h (not dried)
GF-3A		Tetrasodium pyrophosphate	0.3			132.0	0.261	100	5.0	9.7	15.9	10.5	0.3	0.06	a (mold water)	e (not dried)	h (not dried)
Hutchinson silty gravelly sand **Lab. Ser. no. 49-142-4**																	
HDG-6	SW-SM	None		Non-plastic		144.5	0.179	99	5.3	6.7	24.7	49.7	6.1	1.0		e (not dried)	h (not dried)
HDG-8A		Gypsum	3.0			145.5	0.175	100	5.3	6.4	17.7	31.7	2.9	0.48	b (dry soil)	e (not dried)	f (cured)
HDG-9A			3.0			144.6	0.182	100	5.3	6.6	23.1	46.7	6.0	0.98	c (wet soil)	e (not dried)	f (cured)
HDG-7A			5.0			145.3	0.172	100	5.3	6.3	10.8	12.4	0.6	0.10	b (dry soil)	e (not dried)	f (cured)
HDG-16A		Lime	3.0			143.3	0.194	100	5.3	7.1	16.6	28.7	3.4	0.56	b (dry soil)	e (not dried)	f (cured)
HDG-17A			6.0			141.9	0.200	100	5.3	7.3	14.8	22.8	2.8	0.46	b (dry soil)	e (not dried)	f (cured)
HDG-14A		Tetrasodium pyrophosphate	0.3			144.7	0.186	98	5.3	6.7	7.8	7.8	1.3	0.21	a (mold water)	e (not dried)	h (not dried)
HDG-15A			0.5			144.7	0.186	90	5.3	6.8	3.8	7.5	0.8	0.13	a (mold water)	e (not dried)	h (not dried)
Coldbrook silty sandy gravel **Lab. Ser. no. 49-139 (A-D)**																	
CBG-1	GM	None		Non-plastic		139	0.218	95	5.6	7.6	20.9	40.0	3.0	1.0		e (not dried)	h (not dried)
CBG-2A		Ferric chloride	0.3			142	0.196	100	5.6	7.4	10.4	6.2	0.6	0.20	a (mold water)	e (not dried)	h (not dried)
CBG-3A		Tetrasodium pyrophosphate	0.3			140	0.213	98	5.6	7.7	13.7	16.0	1.2	0.40	a (mold water)	e (not dried)	h (not dried)
Bowley silty sandy gravel **Lab. Ser. no. 49-138-1**																	
BPG-1	GW-GM	None		Non-plastic		132	0.267	100	5.6	9.9	23.4	38.1	2.5	1.0		e (not dried)	h (not dried)
BPG-2A		Ferric chloride	0.3			131	0.284	98	5.6	10.3	11.4	4.7	0.5	0.20	a (mold water)	e (not dried)	h (not dried)
BPG-3A		Tetrasodium pyrophosphate	0.3			131	0.281	98	5.6	10.3	12.2	7.9	1.0	0.40	a (mold water)	e (not dried)	h (not dried)

Notes:

1. Tapered molds used for all specimens except CA-3, LSG-1A, DFSB-2, TD-5, PA-1, and GF-1. Dimensions: 6 in. high, 5.75 in. top diam, 5.50 in. bottom diam. Straight-wall molds used for CA-3, LSG-1A, DFSB-2, TD-5, PA-1, and GF-1. Dimensions: 6 in. high, 5.91 in. diam. All specimens frozen under load pressure of 0.5 psi.
2. Percent of dry soil weight.
3. On material passing U.S. Standard Sieve no. 40.
4. Based on original height of frozen portion.
5. Heave rates of specimens in straight-wall molds are maximum rates, chosen to permit better comparison with heave rates of treated specimens frozen in tapered cylinders.
6. Ratio of rate of heave of treated soil to rate of heave of untreated soil.
7. Explanation of specimen preparation:

Incorporation of additive	*Before compaction*	*After compaction*
a. Additive added to molding water	d. Oven-dried after mixing water added, specimen compacted.	f. Cured 7 days at room temp.
b. Additive mixed with dry soil, water added.	e. Not dried prior to compaction.	g. Oven-dried before saturation.
c. Additive mixed with wet soil.		h. Not dried or cured before saturation

Table AIV. Effect of leaching on specimens treated with dispersants and aggregants (open system, miniature specimens).

Specimen no. CM-	Soil	Additive Name	%¹	Treatment after compaction²	Compaction Dry unit wt (lb/cu ft)³	Compaction Void ratio	Compaction Water content (%)	After leaching and/or saturation Dry unit wt (lb/cu ft)	After leaching and/or saturation Void ratio	After leaching and/or saturation Water content (%)	After leaching and/or saturation % saturation	Void volumes of flow	After freezing Water content (%)	After freezing % heave⁴	After freezing Avg. rate of heave (mm/day)	Heave ratio⁵
1307	New Hampshire silt	None		Not leached	95.1	0.798	19.2	92.5	0.848	27.7	90		61.1	57.4	6.88	
1308	(49-105)	Ferric chloride	0.5	Leached	104.0	0.643	19.9	107.8	0.586	20.1	94	8.7	86.3	122.1	7.54	1.09
1309		Ferric chloride	0.5	Not leached	96.1	0.777	19.6	93.9	0.820	26.8	90		35.2	17.5	2.44	0.35
1310		Tetrasodium pyrophosphate	0.3	Leached	105.2	0.627	19.0	113.6	0.505	18.4	100	3.9	26.7	37.0	3.28	0.48
1311		Tetrasodium pyrophosphate	0.3	Not leached	98.6	0.733	17.4	101.3	0.688	24.5	98		30.2	11.3	2.49	0.36
1312	Fort Belvoir sandy clay	None		Not leached	106.9	0.578	18.6	106.9	0.578	21.4	100		39.2	41.1	3.27	
1313	(49-66)	Ferric chloride	0.5	Leached	107.4	0.568	20.6	107.4	0.568	21.1	100	3.5	33.9	25.8	1.94	0.58
1314		Ferric chloride	0.5	Not leached	106.1	0.587	19.7	106.1	0.587	21.1	97		22.9	8.2	0.36	0.11
1315		Tetrasodium pyrophosphate	0.3	Leached	114.9	0.466	17.6	111.4	0.512	18.7	99	2.1	22.8	6.8	0.63	0.19
1316		Tetrasodium pyrophosphate	0.3	Not leached	112.9	0.492	16.6	112.9	0.492	18.2	100		19.[illegible]	5.5	0.45	0.14

Notes
1. Percent of dry soil weight.
2. Leached specimens permeated with distilled water for approximately 3 months under pressures varying between 0.5 and 20 psi.
3. Compaction: Minus no. 10 sieve material; 3 layers, 60 tamps/layer with 40-lb spring tamper. Tapered cylinders: 3.11 in. high, top diam 1.38 in.; bottom diam 1.25 in.
4. Based on original height of frozen portion.
5. Heave ratio = $\frac{\text{avg rate of heave of treated specimen}}{\text{avg rate of heave of untreated specimen}}$

Table AV. Effect of field and laboratory mixing on frost heave of specimens treated with tetrasodium pyrophosphate (standard size specimens, open system).

Specimen no.	Material (Auburn Sand) Description	Symbol	TSPP % of dry soil wt[1]	Mixing[2]	Compaction[3] Dry unit wt (lb/cu ft)	Void ratio	After saturation Water content (%)	Saturation (%)	Water content (%)	After freezing % heave[4]	Avg rate of heave (mm/day)	Heave ratio[5]
MIT-1	Silty gravelly sand	SM	None	Lab.	119.0	0.404	15.0	100	30.2	35.4	1.90	
MIT-5A	MIT-I, 18.6% < 0.02 mm		0.69	Lab.	128.3	0.314	11.6	100	12.9	4.0	0.45	0.24
MIT-9A			0.69 ± 0.19	Field	129.7	0.299	10.0	90	12.8	4.9	0.60	0.32
MIT-2	Silty gravelly sand	SM	None	Lab.	121.6	0.384	14.2	100	25.3	28.3	1.83	
MIT-6A	MIT-II, 7.8% < 0.02 mm		0.50	Lab.	126.0	0.335	12.1	97	12.5	3.2	0.28	0.15
MIT-10A			0.50 ± 0.01	Field	127.0	0.327	11.6	96	13.3	4.7	0.43	0.23
MIT-3	Silty gravelly sand	SM	None	Lab.	122.7	0.374	13.2	96	21.9	22.4	1.66	
MIT-7A	MIT-III, 7.5% < 0.02 mm		0.22	Lab.	125.5	0.343	12.4	98	14.1	5.5	0.77	0.46
MIT-11A			0.22 ± 0.01	Field	129.0	0.305	11.3	100	17.4	16.6	1.17	0.70
MIT-4	Silty gravelly sand	SW-SM	None	Lab.	131.1	0.285	10.2	97	20.7	21.9	1.23	
MIT-8A	MIT-IV, 4.4% < 0.02 mm		0.39	Lab.	134.2	0.254	9.4	100	8.4	0.7	0.12	0.10
MIT-12A			0.39 ± 0.07	Field	131.5	0.282	10.4	100	9.3	1.0	0.25	0.20

Notes:

1. Laboratory-mixed specimens treated with amount of TSPP equal to that in field-mixed specimens; amount of TSPP determined by optical density of extract.
2. Laboratory-mixing: TSPP dissolved in distilled water, applied to soil to form slurry, air-dried to water content approximately equal to field-mixed specimens. Field-mixing: Six passes to loosen soil (using Roto-Tiller, Model RT-1, 2¾ HP, 125 lb, 16-in. swath, 6-in. depth). 0.3% (nominal) TSPP spread. Six passes to mix.
3. Specimens molded in laboratory in tapered, standard-size cylinders: 6 in. high, top diam 5.75 in., bottom diam 5.50 in.
4. Based on original height of frozen portion.
5. Heave ratio = $\frac{\text{avg rate of heave of treated specimen}}{\text{avg rate of heave of untreated specimen}}$