3. The influence of water-table location with respect to the freezing zone,
4. The influence of freezing rate on frost heave and thaw weakening, and
5. The influence of a partially thawing or frozen layer on total heave and thaw weakening (although they are not part of the present study, we could also study frost buildup behind retaining walls or exposed culverts and/or frost action caused by below-freezing pipelines buried in thawed soils).

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Comparative Evaluation of Frost-Susceptibility Tests

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Methods of determining the frost susceptibility of soils are identified and presented. More than 100 criteria were found; the most common were based on particle-size characteristics. These particle-size criteria are frequently augmented by information such as grain-size distribution, uniformity coefficients, and Atterberg limits. Other types of information, such as permeability, mineralogy, and soil classification, have also been required. More complex methods that require tests based on pore-size distribution, moisture tension, hydraulic conductivity, heave stress, and frost heave have also been proposed. However, none have proved to be a universal test for determining the frost susceptibility of soils. Based on this survey, four methods are proposed for further study: the U.S. Army Corps of Engineers Frost-Susceptibility Classification System, the moisture-tension/hydraulic-conductivity test, a new frost-heave test, and the California bearing ratio after-thaw test.

The search for a reliable method to evaluate the frost susceptibility of soil has gone on for at least the past 50 years. More than 100 methods have been proposed since Taber's treatise on the mechanism of ice segregation in soils (1) and Casagrande's conclusion that "under natural freezing conditions and with sufficient water supply one should expect considerable ice segregation in nonuniform soils containing more than three percent of grains smaller than 0.02 mm, and in very uniform soils containing more than 10 percent smaller than 0.02 mm" (2). Even though there has been almost continuous research on frost heave since then, there has been little success in developing comprehensive criteria that more successfully predict the frost susceptibility of soil than does the Casagrande criterion. This has occurred in spite of the probability that Casagrande never intended that his grain-size criterion be universally applied.

Evidence of the lack of success in developing a comprehensive method to determine the frost susceptibility of soils is the plethora of methods reported in the literature. Obviously, each new method set forth has been developed because others have proved to be unsatisfactory for one reason or another. In many cases, the new criteria have been successful for specific but limited purposes. In most cases, however, there is little evidence as to the degree of success achieved.

This paper attempts to identify index tests for determining the frost susceptibility of soils and to select a few of these for further study. The period of time surveyed reaches back to the early work of Taber (1), Casagrande (2), Beskow (3), and Ducker (4) and includes methods reported through 1980. Although an attempt was made to identify all index test methods developed or reported during this period, some may have been missed. The most serious omissions may be from the Asian and Eastern European nations because of the difficulty in gaining access to their literature.

TYPES OF FROST-SUSCEPTIBILITY TESTS

This survey has identified five fundamentally different categories of tests for determining the frost susceptibility of soils and granular base materials. They include tests based on (a) particle-size characteristics, (b) pore-size characteristics, (c) soil-water interaction, (d) soil-water-ice interaction, and (e) frost heave. A brief description of each of the test methods follows.

Particle-Size Characteristics

Particle-size classification methods are by far the most extensively used tests for determining the frost susceptibility of soils. The most basic of these tests include only particle size as the determining factor. The most widely used, the Casagrande criterion (2), requires the determination of the percentage finer than 0.02 mm and the uniformity coefficient.

More complex classification systems, such as the U.S. Army Corps of Engineers criterion (5), are related to the Unified Soil Classification system (6), which requires information about the entire grain-size-distribution curve and the Atterberg limits. Others require information on capillary rise and hygroscopicity (3), permeability (7;8, p. 484;9), and mineralogy (10,11).

Not all of the particle-size tests can be universally applied. Some are limited to particular material types, such as granular base or subbase materials or fine-grained subgrade soils.

Two types of frost-susceptibility criteria were found: (a) pass-fail and (b) degree of frost susceptibility. The most common criteria are the pass-fail criteria, which are used in 61 of the 91 methods reviewed. The pass-fail criteria are usually based on the percentage finer than a certain particle size, most frequently 0.074 mm (39 methods) or 0.02 mm (17 methods). The 0.074-mm particle size is preferred, probably because it requires only a sieve analysis (determination based on the 0.02-mm particle size requires the addition of hydrometer and Atterberg limits tests). The tests that use degree of frost susceptibility as the criterion usually require the complete grain-size-distribution curve in combination with other soil factors.

Although all of the particle-size tests reviewed have published frost-susceptibility criteria, few have published evidence of efficiency. This problem appears to be a common thread with all frost-susceptibility testing, as will be seen throughout this paper.

Particle-size tests for determining frost susceptibility are given in Tables 1 and 2.

Pore-Size Characteristics

The basic importance of pore size in relation to frost action was recognized long ago by Taber (1). Penner (47) also recognized that pore size strongly affects the frost susceptibility of soils. However, Csathy and Townsend (48) and Townsend and Csathy (49) were the first to express this soil property quantitatively and to include it in a frost-susceptibility criterion. Since then, Gaskin and Raymond (50) and Reed and others (51) have also suggested using pore size as an index of frost susceptibility. Three laboratory methods for determining the pore-size distribution of soils have been used: the capillary rise method, the pressure-plate suction method, and the mercury intrusion method. In each of these methods, the pore-size-distribution curves are calculated from the test data, and characteristics of these curves are used as indicators of frost susceptibility. Only Csathy and Townsend (48) have attempted field validation. Authors and details of the pore-size-distribution methods proposed are given in Table 3.

Soil-Water Interaction Tests

Included in the category of tests based on soil-water interaction are all of the frost-susceptibility tests that are principally based on the physical behavior of water in soil. The list of soil-water interaction methods includes (a) moisture retention, (b) capillary rise, (c) unsaturated permeability, and (d) centrifuge moisture content.

The moisture-retention test is used to determine moisture characteristic curves of soils. The test methods used include the pressure-plate apparatus (52) (also used to determine the pore-size-distribution curves) and an osmotic suction device (53). Whatever method is used, the frost-susceptibility criteria are based on some distinguishing feature(s) of the moisture characteristic curve.

The capillary-rise test (24) is also essentially the same as the test that is used to determine pore-size distribution. However, in this instance, the height of capillary rise is used directly in the frost-susceptibility criteria.

The critical permeability/suction test (54) is an extension of the pressure-plate test in which the hydraulic conductivity of water is determined over a range of moisture-tension values and the product of the air-intrusion value and the corresponding hydraulic conductivity are used as an index of frost susceptibility.

The centrifuge-moisture-content test (55, p. 275) is not in common use now, and few details are known. However, it appears that this test determines some critical factor on the moisture characteristic curve and that this factor is used as an indicator of frost susceptibility.

Although frost-susceptibility criteria are suggested for all of these tests, none have been field validated. Details of the soil-water interaction tests are given in Table 4.

Soil-Water-Ice Interaction Tests

Tests that fall into the category of soil-water-ice interaction are those that involve the freezing of soils but not the measurement of frost heave. Some other measured quantity is used to characterize frost-heave susceptibility. Tests of this type involve the measurement of (a) frost-heave stress, (b) pore-water suction, or (c) hydraulic conductivity.

The frost-heave stress test (56,57) requires that constant sample volume be maintained during freezing and that the stress required to maintain the constant volume be used as an indicator of frost susceptibility. The pore-water-suction test is conducted in a similar apparatus but, instead of heave stress, the reduction in pore-water pressure is measured and used as an index of frost susceptibility. The hydraulic conductivity test (59) involves the calculation of the permeability of the partly frozen zone beneath a growing ice lens in a frost-heave test.

For most frost-susceptibility tests, little field validation is in evidence for the soil-water-ice characteristic tests. Authors and details of these methods are given in Table 5.

Frost-Heave Tests

Frost-heave tests are perhaps the most direct laboratory methods of assessing the frost susceptibility of soils. Three basically different types of laboratory frost-heave tests were identified: One involves step changes in the cold-plate temperature and observations of frost heave with time as thermal equilibrium is established, another uses a steadily decreasing cold-plate temperature and a constant rate of frost penetration, and the third imposes a constant rate of heat removal at the cold plate. The step-change test in which the cold-plate temperature is maintained constant is by far the most commonly used (19 of the 22 tests reviewed). The test using constant rate of frost penetration was reported by only two authors (31,60), and that using constant rate of heat removal by one (34). The test using constant rate of heat removal, however, was suggested by two other authors (61,62), who suggested using the step-temperature-change method.

The frost-heave tests reviewed used a number of different methods to confine the test specimen while maintaining side friction at a minimum. The most commonly used method is the multiring device (9 of 22 tests). The tapered plexiglass cylinder is the next most frequently used (5 sources reported this method). Other methods used include wax paper, polyethylene film, cellulose foil, or rubber tubing. In two tests that use bottom-up freezing in straight-walled cylinders (34,62), the side friction is minimized because unfrozen rather than frozen material is heaved.

The time required to conduct the frost-heave tests ranges from 4 h (4) to 28 days (63). Most of the methods reviewed use a single freeze-thaw cycle, but five reported using three or more freeze-thaw cycles.

Whereas most of the tests can accommodate the

Table 1. Particle-size frost-susceptibility tests: countries other than United States.

Country	Reference	Allowable Percentage Passing 0.074 mm	Allowable Percentage Passing 0.020 mm	Allowable Percentage Passing Other	Other Factors	Type of Material	Type of Classification	Comments
Austria	Brandl (10)		3		Minerology	1	A	
	Brandl (11)		3		Minerology	1	A	
Canada	Alberta (12)		3, 10		Uniformity coefficient, Atterberg limits, soil classification	3	B	After Corps of Engineers (5)
	DOT (13)	15			Grain-size distribution	3	B	
	National Parks (13)	36			Atterberg limits	2	A	
	Manitoba (13)	60		x	Atterberg limits	3	A	
	New Brunswick (13)	50, 6-8			Minerology	3	A	
	Newfoundland (13)	6				1	B	
	Nova Scotia (13)	10				3	B	
	Ontario Department of Highways							
	(12)	8			Atterberg limits	3	A	
	(14)	40		x		3	B	
	Quebec							
	(12)	10		x		3	B	
	(13)	10		x		2	A	
	Saskatchewan (12)	10				1	A	
Denmark	Riis (15)		3, 10	x	Grain-size distribution	3	A	After Casagrande (2)
	Christensen and Palmqvist (16)	10				3	A	
England	Croney (17)	>70 or <20			Grain-size distribution	3	B	
East Germany	Klengel (18)			x		1	A	
Finland	Orama (19)		3, 10		Uniformity coefficient, grain-size distribution, capillarity	3	B	
Germany	Ducker (4)		3	x		1	A	
	Federal Transport Ministry (20)			x	Grain-size distribution, organic content	1	B	After Schaible (27)
	Federal Transport Ministry (20)			x	Uniformity coefficient, thaw CBR	1	B	Thaw weakening considered
	Floss (21)			x	Soil classification	3	B	Thaw weakening considered
	Jessberger and Hartel (22)				Uniformity coefficient, grain-size distribution	3	B	
	Jessberger (7)			x	Atterberg limits	3	B	Thaw weakening considered
	Kogeler and others (23)		3		Permeability	3	B	After Casagrande (2)
	Maag (24)			x	Capillarity, depth of water table	3	A	
	Schaible (25)		20		Permeability	3	A	
	Schaible (26)		10	x	Permeability	3	B	
	Schaible (27)		10	x		3	B	Thaw weakening considered
Greenland	Neilsen and Rauschenberger (28)		5, 35	x	Uniformity coefficient, grain-size distribution	3	A	
Japan	Jesserger (20)	6			Grain-size distribution	1	A	
Netherlands	von Moos (29)			x	Organic content	3		
Norway	Christensen and Palmqvist (16)			x		3	A	
	von Moos (29)			x		3	A	
Poland	Pietrzyk (30)				Grain-size distribution, surcharge	3	A	
Romania	Vlad (31)		10	x	Atterberg limits	3	B	After Schaible (27)
Sweden	Beskow (3)			x	Uniformity coefficient, capillarity, hygroscopicity	3	B	
	Beskow (32)	19, 40			Capillarity	3	A	
	Rengmark (33)				Soil type (general)	3	B	Thaw weakening considered
	Freden and Stenberg (34)				Capillarity	3	B	After Beskow (3)
Switzerland	Bonnard and Recordon (35)		3		Uniformity coefficient, Atterberg limits, soil classification	3	B	After Casagrande (2)
	Bonnard and Recordon (36)		3		Uniformity coefficient, coefficient of curvature	3	A	After Casagrande (2)
	Bonnard and Recordon (36)		3		Uniformity coefficient, Atterberg limits, thaw CBR, coefficient of curvature, frost heave	1	A	After Casagrande (2), thaw weakening considered
	Recordon and Rechsteiner (37)		3, 10		Uniformity coefficient, Atterberg limits, thaw CBR, coefficient of curvature, optimum water content	1	A	After Casagrande (2), thaw weakening considered
	Ruckli (38)	17			Permeability, depth of water table, soil type (general)	3	B	
	Jessberger (7)		1.5, 10		Uniformity coefficient	1	A	
	Jessberger (7)		3		Uniformity coefficient, Atterberg limits, soil classification	3	B	After Corps of Engineers (5), after Casagrande (2)
	Switzerland (39)		3, 3-10		Uniformity coefficient, Atterberg limits, thaw CBR, coefficient of curvature, optimum water content	3	A	After Corps of Engineers (5), after Casagrande (2), thaw weakening considered

Note: For material type, 1 = granular base and subbase materials, 2 = fine-grained subgrade soils, and 3 = all soils and granular materials; for type of classification, A = pass-fail and B = degree of frost susceptibility.

Table 2. Particle-size frost-susceptibility tests: United States.

Reference	Allowable Percentage Passing 0.074 mm	Allowable Percentage Passing 0.020 mm	Other Factors	Type of Material	Type of Classification	Comment
Alaska (12)		3	Uniformity coefficient, Atterberg limits, soil classification	3	B	After Corps of Engineers (5)
Alaska[a]	6			1	A	
Arizona (40)	8-12		Elevation above sea level	3	A	
Asphalt Institute (12)	7			3	B	
Bureau of Public Roads (41)			Uniformity coefficient, Atterberg limits, soil classification	3	B	
California (12)	5			2	A	
Casagrande (2)		3, 10	Uniformity coefficient	3	A	
Casagrande (42)			Uniformity coefficient, soil type (general)	3	B	
Colorado (12)	5-10			3	A	
Connecticut (12)	10	3, 10	Uniformity coefficient	3	A	
Delaware (43)	35			3	A	
Idaho (40)	36		Atterberg limits	2	A	
Idaho (12)	5		Sand equivalent	1	A	
Illinois (12)	36, 70		Atterberg limits	3	A	
Iowa (12)	15			3	A	
Kansas (12)	15			1	A	
Maine (12)	5, 7			1	A	
Maryland (12)	12			1	A	
Massachusetts (43)	15			3	A	
Massachusetts (12)	12			2	A	
Massachusetts Turnpike Authority (12)	10			1	A	
Michigan (12)			Fines lost by washing	1	A	
Minnesota (12)	10			3	A	
Montana (40)	12-35		Atterberg limits	1	A	
Nebraska (12)	8-12, 5-13		Atterberg limits	1	A	
New Hampshire (41)	10			2	A	
New Hampshire (12)		3, 8, 12		3	A	
New Jersey (44)	25		Atterberg limits	3	B	
New York (43)		3, 10	Uniformity coefficient, Atterberg limits	3	A	After Casagrande (2)
Ohio (12)	15			1	A	
Oregon (40)	10			3	A	
Oregon (12)	8		Atterberg limits, sand equivalent	3	A	
Texas (45)	16	8	Grain-size distribution	1	A	
Civil Aeronautics Administration (46)	15-25		Atterberg limits	1	A	
Corps of Engineers (6)		3	Atterberg limits, soil type (general)	3	B	After Casagrande (2), thaw weakening considered
Corps of Engineers (5)		1.5, 3, 10	Uniformity coefficient, Atterberg limits, soil classification, frost heave	3	B	After Casagrande (2), thaw weakening considered
Utah (40)	25			2	A	
Vermont (43)	10 or	3		3	A	
Vermont (12)	36			2	A	
Washington (12)	10			3	A	
Wisconsin (12)	5			1	A	
Wyoming (40)	20			1	A	

Note: Key for type of material and type of classification as given in Table 1.
[a]Paper by Esch and others in this Record.

range of material types encountered in road construction, a few (63,64,72) are designed for only a narrow range of material types.

Only about half of the tests reviewed have established frost-susceptibility criteria, and few of these have been field validated. These criteria are mostly based on heave rate. A few use the heave ratio (ratio of frost heave to frost penetration). Other tests use the heave at a specific time. One includes the freezing index (64). While most of the frost-susceptibility criteria are based on frost heave, five require a California bearing ratio (CBR) test after thawing. One test requires only the thaw CBR test (22).

Common to most of the frost-heave tests is the nearly total lack of field validation. Several allude to being field validated (60), but none present any evidence.

Details and authors of the frost-heave tests reviewed are given in Table 6.

SELECTION OF FROST-HEAVE-SUSCEPTIBILITY TESTS FOR FURTHER ANALYSIS

The review of the literature related to frost-susceptibility testing has made it clear that no frost-susceptibility-index test emerges as the ultimate solution for selecting non-frost-susceptible materials or for determining frost heave or thaw weakening under field conditions.

Since we need reliable frost-susceptibility criteria, however, it is essential that we subject some of the more promising tests to further analysis. It seems appropriate that the choice should include tests of several different levels of complexity and sensitivity. The availability of an array of tests would allow project or design engineers to select a test that has the degree of reliability and complexity appropriate to their projects. I, therefore, propose to select prospective frost-susceptibility tests from four levels in the hierarchy of frost-susceptibility testing. The first and most basic type of test selected is one based on grain-size characteristics. The second test selected is one that is related to the more fundamental moisture-tension/hydraulic-conductivity aspects of frost heave. The third test selected is an actual frost-heave test, and the final method selected is the thaw CBR test.

Table 3. Pore-size frost-susceptibility tests.

Reference	Method	Criterion	Comment
Csathy and Townsend (48)	Capillary rise	NFS if $P_u = P_{90}/P_{70} < 6$	Pass-fail frost-susceptibility test, time consuming, good correlation with field tests
Gaskins and Raymond (50)	Pressure plate	NFS if $P_u < 6$ or $P_P < 5.5$ percent	Pass-fail frost-susceptibility test, time consuming, good correlation with field tests
	Mercury intrusion		Pass-fail frost-susceptibility test; quick; poor correlation with field tests; small sample, cannot accommodate gravels
	Capillary rise		Pass-fail frost-susceptibility test, time consuming, good correlation with field tests
Reed and others (51)	Mercury intrusion	$Y = 5.46 - 29.46(X_{3.0})/(X_0 - X_{0.4}) + 58.1(X_{3.0})$	DFS test; quick; small sample, cannot accommodate gravels; good correlation with laboratory tests; not field validated

Note: NFS = non-frost-susceptible, P_u = pore-size distribution, P_{90} = pore diameter such that 90 percent of pores are smaller, P_{70} = pore diameter such that 70 percent of pores are smaller, P_P = percentage of pores between 0.15 and 0.40 mm, Y = rate of frost heave in laboratory test (mm/day), $X_{3.0}$ = cumulative porosity for pores >3.0 μm but <30 μm, $X_{0.4}$ = cumulative porosity for pores >0.4 μm but <300 μm, and DFS = degree of frost susceptibility.

Table 4. Soil-water interaction frost-susceptibility tests.

Reference	Method	Criterion	Comment
Williams (52)	Moisture retention and air intrusion	NFS if $u_i = p_i - \sigma_{iw}/\sigma_{aw}(p_a - u_a) < u_w$	Pass-fail frost-susceptibility test, not field validated, well-defined air entry value limited to fine-grained soils
Jones and Hurt (53)	Moisture retention and osmotic suction	$FS = f(pF_{70})$	DFS test, no frost-susceptibility criteria established, can be used for all soils
Maag (24)	Capillary rise	FS = f(H, h, k, Q)	DFS test, few details available
Wissa and others (54)	Critical permeability and suction	$FS = f(k_c \times V_c)$	DFS test, not field validated, well-defined air entry value limited to fine-grained soils, poor correlation with frost susceptibility
Willis (55)	Centrifuge moisture content	NFS if $W_c < 12$	Pass-fail frost-susceptibility test, few details available, for non-plastic soils

Note: u_i = maximum suction during freezing; p_i = ice pressure or overburden pressure; σ_{iw}, σ_{aw} = surface tension ice-water and air-water, respectively; $(p_a - u_a)$ = air intrusion value from moisture retention curve; u_w = in situ moisture tension; FS = frost susceptibility; pF_{70} = osmotic suction at 70 percent saturation; H = height of capillary rise; h = depth to water table; k = permeability; Q = rate of water inflow; k_c = hydraulic conductivity at air intrusion pressure; V_c = air intrusion pressure; and W_c = centrifuge moisture content.

Table 5. Soil-water-ice interaction frost-susceptibility tests.

Reference	Method	Criterion	Comment
Hoekstra and others (56)	Frost-heave stress	$FS = f(P_{max})$	DFS test; original unpublished, reported by Jessberger (7); not field validated
Martin and others (57)	Frost-heave stress	FS = f(R)	DFS test; not field validated, no frost-susceptibility criteria established, poor correlation with laboratory tests
Martin and others (52)	Pore-water-pressure drop during freezing/back pressure	$FS = f(\Delta p)$	DFS test, not field validated, no frost-susceptibility criteria established, poor correlation with laboratory tests, complex
Riddle (58)	Suction below freezing front	$FS = f(\Delta u)$	DFS test, good field correlation, limited to 1-bar moisture tension
Phukan and others (59)	Permeability of frozen fringe	$FS = f(k_f, p)$	DFS test; not field validated; permeability estimated from frost-heave test, not measured; proposed for chilled gas pipeline, not roads

Note: FS = frost susceptibility, P_{max} = maximum heave pressure, R = slope of heave stress versus log time, Δp = pore-water-pressure drop during freezing, Δu = matrix suction developed below freezing front, k_f = permeability of frozen fringe, and p = applied surcharge stress.

Grain-Size Classification

Three classification systems based on grain size emerge as candidates for further consideration here in the process of test selection. They are the frost-susceptibility classification systems of West Germany (20), Switzerland (29), and the U.S. Army Corps of Engineers (5). These have been selected from the long list of particle-size tests because they appear to be the most rigorously developed. The others have been excluded from further consideration because their data bases appear to be limited (as in the case of most of the states or provinces where only regional conditions are considered) or because they have evolved into more recent frost-susceptibility criteria, such as in the cases of Casagrande (2), Beskow (3,32), Ducker (4), and Schaible (25-27).

The West German classification system has evolved from the work of Schaible under the considerable influence of Jessberger of the Ruhr University, Bochum. In several reports (7,20,22,70,77,78), Jessberger has evaluated the problem of determining the frost susceptibility of soils and concluded that the reduced bearing capacity after thaw is the most important factor in any frost-susceptibility classification system. As a result, the standard now under consideration for adoption in West Germany (79) relates the frost susceptibility of soil to soil type on the basis of thawed CBR values.

The Swiss frost-susceptibility standards were originally developed from Casagrande's grain-size criterion (2) and the Corps of Engineers frost-susceptibility criterion (5). Recently, Bonnard and Recordon (36) proposed including the after-thaw CBR test. Recordon and Rechesteiner (37) then introduced further changes for granular materials to incorporate the coefficient of curvature and the optimum water content during compaction.

The current Swiss frost-susceptibility classification system (80) provides for three levels of screening. The first level is a grain-size criterion based essentially on Casagrande's criterion. This level allows separation of non-frost-susceptible soils from those of unknown frost susceptibility. The questionable soils can be subjected to a second level of screening based on soil classification. As with the first level of screening, the second level does not distinguish between frost-heaving and thaw-weakening potential.

Table 6. Direct frost-heave susceptibility tests.

Reference	Method of Minimizing Side Friction	Freezing Mode	Frost-Susceptibility Criterion	Time Required (h)	Comment
Aguirre-Puente and others (64)	Lubricated rubber tube	A	FS = f(p)	150-200	DFS test, not for gravels, excellent temperature control, multiple samples per test
Alekseeva (65)	Multiring	A	None	50	Few details available, fine-grained soils only, poor temperature control, little field experience
Balduzzi and Fetz (66)	Cellulose foil	A	FS = f(F, CBR_T)	50-70	DFS test, not for gravels, poor temperature control, thaw CBR test included, multiple samples per test, little field experience
Brandl (63)	Multiring	A	None	672	Gravels only, poor temperature control, freeze-thaw cycling, thaw CBR test included, multiple samples per test, little field experience
Brandl (67)	Multiring	A	FS = f(h, CBR_T)	384-504	All soils and granular materials, poor temperature control, freeze-thaw cycling, thaw weakening considered, thaw CBR test included, multiple samples per test, little field experience
Croney and Jacobs (68)	Waxed paper	A	FS = F(h_{250})	250	DFS test, all soils and granular materials, poor temperature control, multiple samples per test, considerable field experience, TRRL test
Ducker (4)	Waxed paper	A	NFS if F < 3 percent	4	Pass-fail frost-susceptibility test, not for gravels, poor temperature control, little field experience
Freden and Stenberg (34)	Bottom-up freezing	B	None	Unknown	Not for gravels, excellent temperature control, freeze-thaw cycling, little field experience
Esch and others[a]	Multiring	A	FS = f(h_r)	72	DFS test, not for gravels, poor temperature control, multiple samples per test, little field experience
Gorlé (69)	Multiring	A	None	24	All soils and granular materials, multiple samples per test, little field experience
Jessberger and Heitzer (70)	Tapered cylinder	A	FS = f(CBR_T)	168	DFS test, all soils and granular materials, poor temperature control, freeze-thaw cycling, thaw weakening considered, thaw CBR test included, multiple sample per test, little field experience
Jones and Dudek (71)	Waxed paper	A	None	96-240	DFS test, all soils and granular materials, excellent temperature control, multiple samples per test, little field experience
Kalchef and Nichols (72)	Polyethylene film	A	None	200	Gravels only, poor temperature control, multiple samples per test, little field experience
Kaplar (60)	Tapered cylinder	C	FS = f(h_r)	288	DFS test, all soils and granular materials, poor temperature control, thaw weakening considered, multiple samples per test, considerable field experience, CRREL test
Loch (61)	Multiring	A	None	48	Not for gravels, excellent temperature control, suggests using constant rate of heat removal, little field experience
Thomas and Jones (73)	Waxed paper	A	FS = f(h_{250} or h_{100})	100-250	DFS test, all soils and granular materials, excellent temperature control, multiple samples per test, improvement on TRRL test
Maine (74)	Tapered cylinder	A	None	7	DFS test, poor temperature control, multiple samples per test, little field experience
Penner and Veda (62)	Bottom-up freezing	A	None	72-96	Fine-grained soils only, excellent temperature control, suggests using constant rate of heat removal, little field experience
Sherif (75)	Tapered cylinder	A	None	432	All soils and granular materials, poor temperature control, freeze-thaw cycling, multiple samples per test, little field experience
Vasilyev (76)	Multiring	A	None	Unknown	DFS test, not for gravels, poor temperature control, freeze-thaw cycling, little field experience
Vlad (31)	Tapered cylinder	C	FS = f(h_r, CBR_T)	360	DFS test, not for gravels, poor temperature control, thaw weakening considered, thaw CBR test included, multiple samples per test, little field experience
Zoller (77)	Multiring	A	FS = f(h_r)	12	DFS test, all soils and granular materials, excellent temperature control, little field experience

Note: For freezing mode, A = constant cold-plate temperature, B = constant rate of heat removal, and C = constant rate of frost penetration.
[a]Paper elsewhere in this Record.

A third level of screening is provided for sand and gravel subbase and base-course materials of still questionable frost susceptibility. At this level, the Swiss separate coarse materials into two categories: gravel 1 and gravel 2. Gravel 1 is the material that passes the first two levels of screening. Gravel 2 materials must pass additional classification tests and must be submitted to CBR tests after soaking or one freeze-thaw cycle.

The Corps of Engineers frost-susceptibility classification system (5) has also evolved from the original work of Casagrande (2). In the 1930s, Casagrande further clarified his grain-size criterion (81) and then later proposed a frost-susceptibility classification system based on the Unified Soil Classification system (42). Numerous studies by the Corps of Engineers Arctic Construction and Frost Effects Laboratory led to the development of a frost-susceptibility classification system (82) based on three levels of screening: (a) the percentage of particles smaller than 0.02 mm, (b) soil classification, and (c) a frost-heave test. The first two levels of screening are similar to that used by the Swiss. The third level of screening in the Corps of Engineers criterion differs from that of the Swiss in that it calls for a frost-heave test rather than a CBR test after freezing and thawing.

The soil classification test that emerges as the candidate for further consideration is the Corps of Engineers Frost Design Soil Classification System (see Table 7). In concert with the Unified Soil Classification equivalent groupings and the tabulation of the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) standard frost-heave data, this method has probably the largest data base of any of the grain-size or soil classification methods reviewed. The great advantage of the Corps of Engineers method is that it does not require a higher-level test (CBR or frost heave) for soils of questionable frost susceptibility. The amount of frost heave, and thus the frost-susceptibility classification, can be estimated from the large tabulation of results of previous frost-heave tests. Another advantage of this method is that we at CRREL have ready access to the data, the soils, the CRREL frost-heave test, and the field sites on which this method was based.

The disadvantage in selecting the Corps of Engi-

Table 7. U.S. Army Corps of Engineers Frost Design Soil Classification System.

Frost-Susceptibility Classification[a]	Frost Group	Kind of Soil	Percentage Finer Than 0.02 mm by Weight	Typical Unified Soil Classification System Soil Types
NFS	None	Gravelly soils	0-1.5	GW, GP
		Sandy soils	0-3	SW, SP
Possibly frost susceptible[b]	?	Gravelly soils	1.5-3	GW, GP
		Sandy soils	3-10	SW, SP
Very low to high	F1	Gravelly soils	3-10	GW, GP, GW-GM, GP-GM
Medium to high	F2	Gravelly soils	10-20	GM, GM-GC, GW-GM, GP-GM
Negligible to high		Sands	3-15	SW, SP, SM, SW-SM, SP-SM
Medium to high	F3	Gravelly soils	>20	GM, GC
Low to high		Sands except very fine silty sands	>15	SM, SC
Very low to very high		Clays, PI > 12	-	CL, CH
Low to very high	F4	All silts	-	ML, MH
Very low to high		Very-fine silty sands	>15	SM
Low to very high		Clays, PI < 12	-	CL, CL-ML
Very low to very high		Varved clays and other fine-grained, banded sediments	-	CL and ML; CL, ML, and SM; CL, CH, and ML; CL, CH, ML, and SM

[a]Based on laboratory frost-heave tests. [b]Requires laboratory frost-heave test to determine frost susceptibility.

neers method is that it is principally based on frost heave although, according to Linell and Kaplar (82), thaw-weakening characteristics determined from field plate bearing tests also have been taken into account.

Moisture Tension/Hydraulic Conductivity

A test based on moisture tension and hydraulic conductivity is a large step closer to the more fundamental aspects of frost heave. With test results characterizing these properties, one can address all but the thermal dynamics of frost heave. Of the index tests reviewed, only the critical permeability/suction test of Wissa and others (54) allows the determination of these factors. It is recommended, however, that neither their equipment nor their method of analysis be used. The equipment has proved to be unreliable (83). The problems appear to result from the close spacing of the piezometers (2.54 cm^2) and the high air-entry value (2 bar) of the piezometers, which together cause large uncertainties in head-loss determinations. The weakness of their method of analysis is that it assumes that the air-entry values on the continuous moisture-tension/hydraulic-conductivity curves are uniquely related to the frost-heave mechanism. This assumption is questionable, since moisture flow occurs over a range of suction values and hydraulic conductivities. Furthermore, many materials do not have well-defined air-intrusion values. Alternative methods of analysis that use more information from these curves must be developed.

I suggest that the pressure-cell permeameter now being used at CRREL (84) to determine moisture tension and hydraulic conductivity curves be used in this study. The porous piezometer cups for measuring the pressure gradient during the hydraulic-conductivity part of the test have considerably more surface area (1.27 cm^2) and low air-entry values (1 bar) than those used by Wissa and others (54). The distance between pressure sensors (6.4 cm) is also a large improvement over the spacing in the apparatus used by Wissa and others. All of these factors contribute to a more accurate determination of the pressure gradient and thus a more reliable test.

There are several other advantages to using this device rather than that of Wissa and others (54). First of all, the test is now being routinely conducted at CRREL in support of a number of research programs. Second, we are now establishing a data base of moisture-tension/hydraulic-conductivity curves for a large number of soils. Finally, many of the results are being used as input into a frost-heave model now under development. The same data on hydraulic conductivity and moisture tension can thus be useful in two approaches to the frost-susceptibility problem, one of which complements the other.

Frost Heave

Before selecting a frost-heave test, we must first set forth the important objectives for the test:

1. It should be as simple as possible so that highway and other test laboratories can readily conduct tests and obtain reliable and reproducible results.
2. It must be reliable.
3. It must relate to frost heave in the field.
4. It must be of short duration.
5. It must accommodate the complete range of material types; in particular, it must accommodate granular base and subbase materials as well as fine-grained subgrade soils.
6. It should be inexpensive to construct and operate.

There is one possible objective that is not so clear: Should the test replicate field conditions so that actual frost heaves can be predicted, or should it be only an index test that imposes the most severe conditions? My opinion is that a frost-heave test should be for the most severe conditions and that it should be easily modified so that actual field conditions can be simulated if desired.

We must also establish the test factors that are critical to these objectives. Precise temperature control at the top and bottom of the test sample must be maintained, and radial heat flow must be kept to a minimum. Side friction must also be minimized, and water must be freely available.

It is clear from the review that none of the methods surveyed fulfill all of these requirements. Thus, we have the choice of accepting an imperfect test or introducing desirable modifications. I am suggesting that a more perfect frost-heave test be developed and a new body of experience be established to support it.

I suggest that the new test include (a) a multi-ring freezing cell (MRFC), (b) circulating liquid-cooled cold and warm plates, (c) an air-cooled room or cabinet for multiple samples, (d) variable surcharge, and (e) adjustable moisture tension.

The multiring freezing cell was selected because it appears to be the best method for minimizing side friction while still accommodating the other important factors. The bottom-up freezing method is probably better for fine-grained materials, but compaction and side friction are problems for coarse-grained materials. The MRFC is not a new development in frost-heave testing, since it was used long ago by Taber (1) and Ruckli (38). Considerable experience with this method, however, has revealed certain drawbacks. For instance, it is difficult to completely saturate a specimen under vacuum (84) and, in the testing of noncohesive sandy soils, grains tend to fall through the joints between the ring segments. Placing a rubber membrane around the sample prior to insertion in the plastic rings, as in the Loch test (61), may eliminate both of these problems.

The MRFC is better than methods that use waxed paper, cellulose foil, polyethylene film, and foam rubber tubing because it appears to offer less heave resistance. No rigorous comparison testing of these alternatives has been published. However, Kaplar (60) reported that waxed cardboard cylinders were abandoned in favor of inside tapered plexiglass cylinders to reduce wall friction. In addition, Zoller (76) noted that, when the tape used to hold the multiple rings together during compaction was inadvertently left in place during freezing, frost heave was considerably suppressed. This leads me to conclude that all of the other freezing cells would offer more resistance to heave than the multiring cell and that the amount of the resistance is indeterminate, since it depends on the frictional characteristics between the soil and the sidewall material, the stiffness and strength of the sidewall material, and the amount of heave. However, since this choice has been made with some uncertainty, I suggest that some alternatives also be explored. These include, but are not restricted to, (a) lining the MRFC with a rubber membrane and (b) using polyethylene film or a rubber membrane alone.

Temperature control is probably best accomplished by circulating a nonfreezing liquid from controlled temperature baths through plates placed in good thermal contact with the upper and lower surfaces of the test sample. The heat-extraction rate imposed should represent a severe condition or simulate the actual field conditions. The user of the test should have the option to impose either rate. According to Horiguchi (86) and Louch (87), the optimum heat-extraction rate for silts and clays is near 150 W/m² (no data are available for sands and gravels). Loch (88) determined that the heat-extraction rate immediately beneath asphalt concrete pavements in southern Norway ranges between 20 and 120 W/m² and chose a rate of 140 W/m² for his test. Freden and Stenberg (34), however, suggested that 490 W/m² be used in the Swedish test. According to Loch's data (88), a heat-extraction rate that high would preclude frost heave for undisturbed silts and clays. Thus, I have concluded that a standardized heat-extraction rate more nearly like that selected by Loch should be used in the new test being proposed. This would require that heat-flow sensors be placed on the warm and cold ends of the test sample and that manual or automated changes in the cold-plate temperature be made. Because this would cause both the test apparatus and procedures to be very complicated, I suggest a compromise in which a constant cold-plate temperature be used that will cause a rate of heat removal of approximately 100 W/m² when temperature equilibrium is reached.

The temperature gradient used should also represent a severe condition or simulate actual field conditions. Gorlé (69) showed clearly that this is an important factor, especially for coarser materials. He observed that the rate of heave increased significantly with increasing temperature gradient over a range of 0.1°-2.5°C/cm. I have observed that temperature gradients near 0.05°C/cm in the region immediately beneath the freezing front naturally occur over much of the freezing season in test sections near CRREL. I suggest, then, that a standard 0.25°C/cm on the low end of Gorlé's scale be adopted to make freezing conditions more severe than what normally occurs but not so severe as to be experimentally unrealistic.

At least two freeze-thaw cycles should be used to account for physical changes imposed under natural freezing conditions. This is an important consideration in determining the frost susceptibility of soils, because repeated freeze-thaw cycling is always a factor in freezing soils, whether the cycles are generated during a single season or during several successive seasons.

To limit the test to one-week duration and still get at least two freeze-thaw cycles completed will require careful design of the freezing conditions. I propose that the first freeze be accomplished at a relatively high rate of heat removal so that the full length of the test sample is frozen and thawed within two days. The second cycle should be designed so that only the upper 5-7 cm of the sample is frozen (at a rate of heat removal of approximately 100 W/m²) on the third day. Additional freeze-thaw cycles will have to be performed to validate this procedure.

The MRFC should be insulated radially with foam insulation, and this insulation should extend sufficiently above the cooling plate to ensure that no ring is exposed to the ambient temperature as heaving occurs. The insulated MRFCs should be placed in a cold box or cold room where the ambient temperature is maintained near but above freezing. An alternative is to provide sufficient insulation so that radial heat flow is not a problem. This detail must yet be worked out. Obviously, if the cold box or room can be eliminated, the test will be simpler and much less expensive.

The surcharge should be variable to simulate field conditions. Perhaps the 3.5-kPa value used in the CRREL test should be used as a standard. Air loading devices, which have been built at CRREL and are very simple and reliable in operation, are suggested.

Moisture tension is probably best varied by adjusting the elevation of the water reservoir or by applying a vacuum to the reservoir. With these methods, the tension is limited to 1 atmosphere by the cavitation pressure of water. This is probably sufficient for most materials, particularly for the dirty gravels, which are of much concern. For finer-grained clayey soils, a longer soil column may have to be used to maintain the desired moisture-tension condition. For a standard test, the water table should be maintained at the sample base.

Thaw CBR

The literature revealed few laboratory index tests for thaw weakening. The CBR tests after thawing previously reported as being included in the standards in Romania (31), Switzerland (66), Austria (67), and West Germany (70) are the only laboratory index tests found that are specifically used for determining thaw-weakening susceptibility. Others, such as the Corps of Engineers soil classification system (5), have indirectly considered thaw weakening by making correlations with field tests.

The repeated-load triaxial test now being conducted at CRREL (89) may also be considered a thaw-weakening test. Its current use, however, requires a commitment to some procedure of elastic layer analysis for pavement design. It is not an index test, since it provides specific values for the resilient modulus and resilient Poisson's ratio for the entire freeze, thaw, and recovery period.

Using the CBR test for thaw weakening is a rational approach, particularly where the CBR test is used in the design of pavement systems. It is a standard test conducted by many departments of transportation and geotechnical engineering firms and is relatively simple to conduct, particularly in comparison with the repeated-load triaxial test. It is also readily adapted to a frost-heave test.

SUMMARY AND CONCLUSIONS

Four methods of determining frost susceptibility have emerged as candidates for further study. The most basic of these methods is the Corps of Engineers frost-susceptibility classification system. This system provides for three levels of screening: (a) percentage of particles smaller than 0.02 mm, (b) soil classification, and (c) frost heave. The first two levels relate soil factors to frost susceptibility, and the third level considers the interaction of soil, moisture stress, and temperature factors. Because of the large data base available, it is not necessary to conduct the frost-heave test. All one needs to do is to make comparisons with the data base.

The second of the methods suggested is a test for moisture tension and hydraulic conductivity. Although the test is currently being routinely conducted at CRREL, a method of analysis needs to be developed.

The third of the methods selected is a frost-heave test. A new test is suggested because none of those reviewed fulfills all of the requirements of simplicity, reliability, and efficiency while accommodating the complete range of soil types in a short time at a low cost. It is suggested that a new frost-heave test be designed so that all soil, moisture, stress, and temperature factors can be addressed if desired.

The last method selected is the CBR test after thaw. This is the only method that directly addresses the thaw-weakening problem. I recommend that the CBR test after freezing and thawing be considered as one additional procedure in the frost-heave test for use with specific soil types, particularly sands and gravels. Procedures should be developed to include both frost heave and thaw weakening in the frost-susceptibility criteria.

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