FROST-SUSCEPTIBILITY CRITERIA

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•A SURVEY of frost-susceptibility criteria shows that those now in use can be divided into 3 groups based on the following characteristics:

1. Gradation curves and particle size,
2. Frost-heave rate, and
3. Phase-interface relation.

Groups 1 and 2 are empirical, and group 3 has a theoretical basis.

The existing frost-susceptibility criteria do not meet the demand of characterizing the soils with regard to frost action in the form of quantitative values. A more scientific approach encompassing complex variables is desired in order to define frost susceptibility. Manual testing procedures developed for rapidly detecting the frost susceptibility in situ are not described in this paper.

PARTICLE-SIZE CRITERIA

The most common method for determining the frost susceptibility is to plot the grain-size gradation curve and to compare the content of fines against some arbitrarily fixed values. Those values have been found by a series of field investigations at locations where frost damages occurred. The criteria formulated by Casagrande or by Schaible are typical examples of that procedure.

Table 1 (1) gives the limiting values of certain particle sizes listed according to different authors.

In the United States and several other countries, the Casagrande criterion is very often incorporated in the design of pavement (2, 3). However, soils conforming to the Casagrande criterion under certain conditions may show detrimental frost effects. On the other hand, any transgression of that criterion does not automatically lead to frost damages. Several of the United States have, therefore, established their own criteria based on experience and field investigations. Haley (4) reported that in Massachusetts soils with more than 15 percent passing the No. 200 sieve are considered frost susceptible, whereas in Delaware the limit is fixed at 35 percent.

Other authors (5, 6) have proposed to classify soils as having a tendency toward frost susceptibility rather than as being or not being frost susceptible.

The authors mentioned above have considered the particle-size distribution to be of paramount importance in influencing the frost susceptibility of a given soil. Other factors, such as soil minerals, chemical conditions, surcharge load, water table, and temperature gradients, have not been considered. For that reason, the particle-size criteria should not be used in geological formations and regions with climatic and hydrological conditions different from the conditions existing at the places where those criteria have been established and their validity confirmed.

The fact that the "bearing capacity" of a soil is lower after thaw than in the fall season suggests that the modulus of elasticity should be reduced accordingly in the design of pavements (7, 8). In other words, the bearing capacity after thaw has been given due consideration in addition to the grain-size distribution of a soil. Further advances in that direction show that the bearing capacity after thaw is controlled by

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the particle content <0.02 mm and the uniformity coefficient (9). The influence of other factors, such as soil minerals, chemical composition of the soil, climatic conditions, and water availability, on the test results are not yet known.

FROST-HEAVE RATE CRITERIA

Frequently the frost-heave rate serves as a gauge for the influence of various conditions, such as temperature, surcharge load, and water availability (tests in open or closed systems), on the frost susceptibility of a soil. Frost-heave rate is used especially in checking the efficiency of additives in stabilized soils because in stabilized soils the particle-size criterion has no validity.

Frost-heave tests have been made only with small-scale models that simulate the in situ conditions. The model laws, however, are not yet known. The few efforts made to detect them have not led to a definite conclusion, and controversy still exists concerning the influence of temperature gradient to heave rate (10, 11).

Therefore, a direct application of the results of heave-rate tests to road design against frost action is not recommended. That can be done only when the test procedure has been standardized in detail and a frost-susceptibility classification has been established by comparison of frost-heave rates found in laboratory tests with observations made at the site. The Road Research Laboratory (12) and the U.S. Corps of Engineers (3) have worked in that direction. The frost-susceptibility classification developed by the Corps of Engineers is as follows:

Avg Frost-Heave Rate (mm/day)	Frost Susceptibility
< 0.5	Negligible
0.5 to 1.0	Very low
1.0 to 2.0	Low
2.0 to 4.0	Medium
4.0 to 8.0	High
> 8.0	Very high

It is not known that the model law is linear; therefore, that classification can be used only if the conditions at a new construction site coincide with the general conditions at sites where comparisons between laboratory and field investigations have been made. Results of comparisons of untreated soils would, of course, not be applicable to stabilized soils.

The frost-heave rate gives information on the soil behavior during freezing only and neglects the critical stage of thawing when the bearing capacity is at its lowest. The recently developed test method for recognizing the loss in bearing capacity (9) consists of subjecting soil samples to several freeze-thaw cycles. The frost-heave rates found during freeze periods are not identical with data obtained by using the method of the Corps of Engineers (3), but the tendency is the same. Table 2 gives the frost-heave rate of a few soils and CBR after the last thaw period (9). The index properties of the soils as well as their origin are described in another report (9). A direct relation between frost-heave rate and CBR after thaw does not exist. Here again consideration has been given to grain-size distribution. The data given in Table 2 show that the lesser the uniformity of the soil is, the smaller the bearing capacity is because the fine material is responsible for the frost effect and the coarse material is mainly responsible for the residual bearing capacity (compare soil 16 and soil 4, Table 3). Frost-heave rates alone give no information on that behavior.

The importance of incorporating the CBR value in the frost-susceptible criteria is shown in Figure 1. Although the heave rates during freezing and settlements during thawing are similar for the ETS and MSI soils, the CBR values are in the ratio of 14:1. The grain-size distribution curves of the ETS and MSI soils are shown in Figure 2.

Balduzzi (13) states that the bearing capacity is to be taken as a basis for pavement design. He considers the frost-heave rate test to be valuable in recognizing the "stability" of soils against frost effect. In other words, the "instability" of frost-susceptible

Table 1. Particle-size frost criteria according to content of fines.

Author	Fine Content	Percentage by Grain Size (mm)					
		<0.125	<0.1	<0.062	<0.05	<0.02	<0.002
Beskow	Uniform	22-35		15-25			
	Nonuniform			33-50			
Kögler-Scheidig[a]	Uniform					3	
	Nonuniform					10	
Morton[b]					10		
Casagrande[c]	Uniform					3	
	Nonuniform					10	
Schaible	Frost susceptible		20			10	1
	Highly frost susceptible		40			20	6

[a]If free water is available, the frost susceptivity is classed by means of the permeability: $k = 1.10^{-6}$ to 1.10^{-7} m/sec, highly frost susceptible; $k = 1.10^{-7}$ to 1.10^{-8} m/sec, frost susceptible; and $k < 1.10^{-8}$ m/sec, not frost susceptible.
[b]Valid only for soils with particle diameter between 0.001 and 2.0 mm.
[c]According to Dücker not applicable, for vulcanic soils and for very uniform soils.

Table 2. Frost-heave rate and CBR after thaw for 4 soils.

Soil	Frost-Heave Rate (mm/day)	CBR After Thaw (percent)	Particle Content <0.02 mm (percent)	Uniformity Coefficient d_{60}/d_{10}
16 ETS	42.4 (13.7)	11.7 (8.7)	9.0	54.5
1 MSI	32.1 (13.4)	0.63 (0.62)	65	3.0
1 HPG	21.0	31.7	5.5	29.3
4 HSS	19.1	7.3	7.1	6.3

Note: Numbers in parentheses are test results according to Figure 1.

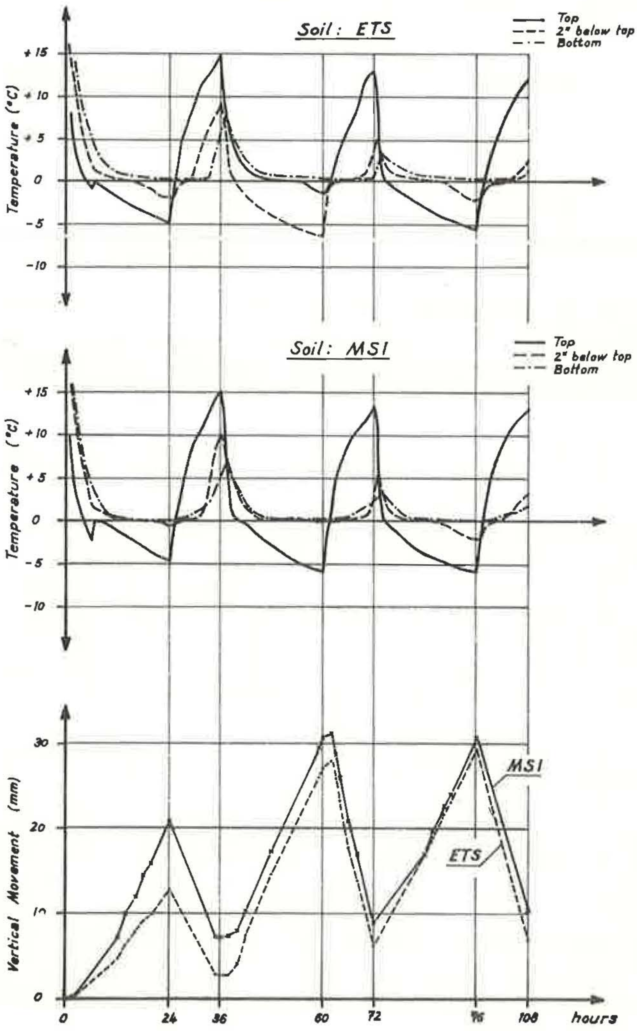

Figure 1. Temperature and vertical movement during freeze-thaw cycles.

soils can cause frost heaves and detrimental consequences to the pavement and traffic. It is to be noted, however, that the correlation between the instability (alteration of soil structure due to frost action) and the bearing capacity after thawing is not yet known.

Klengel (1) has proposed to characterize the frost effects of soils not only by the frost heave but also by the consistency index [defined as $(w_e - w)/I_p$] of the frozen and thawed soil. The index indirectly gives an indication of the bearing capacity of fine-grained soils. The method is, however, not applicable for the important group of dirty sands and gravels.

The greatest drawback in the case of heave-rate criteria lies in the reproducibility of results. It is indeed a difficult task to prepare samples having water content and density the same as those existing in the field. Relatively small differences of water content can be responsible for different heave rates and soil structure (14). In addition, as a result of unavoidable inhomogeneities in the sample and slight inconsistencies of frost-chamber temperatures, the heave-time relation may lead to curved lines so that a constant heave rate cannot be determined (Fig. 3, 15).

PHASE-INTERFACE CRITERIA

The fundamental investigations on the soil behavior during frost action comprise the thermodynamic equilibrium at the water-ice and water-air interface in connection with the pore diameter. Everett (16) considers the growth of a small crystal immersed in and in equilibrium with a fluid. The difference between the pressure of the solid crystal p_s and the pressure of the liquid p_l is proportional to the surface tension σ and conversely proportional to the crystal radius r.

$$p_s - p_l = \Delta p = \frac{2 \cdot \sigma_{sl}}{r}$$

Hoekstra, Chamberlain, and Frate (17) interpret the pressure difference Δp to be the frost-heaving pressure compared to an atmospheric soil-water pressure. According to their findings, every soil characterized by its pore structure and an effective pore radius r is associated with a certain maximum frost-heaving pressure. A comparison of that maximum frost-heaving pressure with the soil-water tension and the particle content smaller than 0.02 mm shows that the soil-water tension determined by the pore structure is more reliable in predicting frost susceptibility than a single point of the grain-size distribution.

That way, the maximum frost-heaving pressure could be chosen to classify frost susceptibility. Table 3 gives a few test results. (Because not enough data are available, it may be assumed that Augrey sand and Hanover silty sand, having approximately similar gradation curves, will behave in a similar manner when subjected to frost temperatures.) Although frost-heave rates and maximum frost-heave pressures for both the soils are about the same, a vast difference exists in the values of CBR after thaw.

The drawback in using the maximum frost-heaving pressure is that, although 2 soils may be frost susceptible to the same degree, it is possible that the pavement performance of one soil may be satisfactory while that of the other may be entirely unsatisfactory. The reason is that the criteria give no information about the bearing capacity after thaw.

Following another line of thought, Williams (18) compared the penetration of ice surface into the soil pores with the intrusion of air into the pores of the same soil system. He measured the air-intrusion value into the unfrozen sample and, by using the ratio of surface tension ice-water to surface tension air-water, he calculated "ice-penetration value." That value is governed not by the largest pore space but by the largest continuing pore diameter. In the application of that method to road design, the surcharge load on the soil layer and the soil-moisture tension are compared with the ice-penetration value: No frost susceptibility exists if the surcharge load and the pore-water tension exceed the ice-penetration value. Although his method has merit in that

Figure 2. Grain-size distribution of soils.

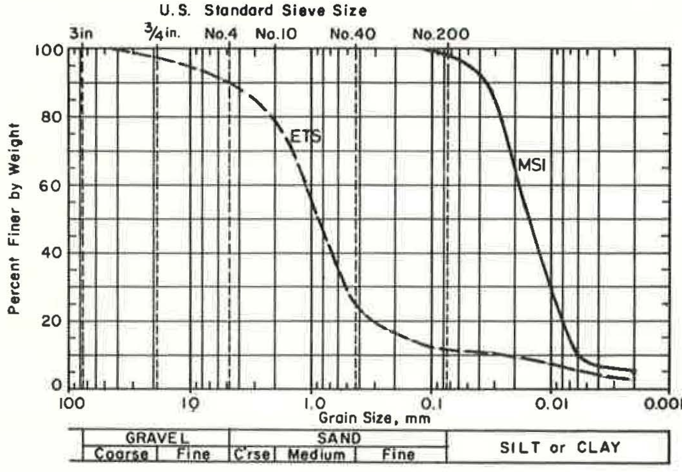

Figure 3. Frost heave of clay-sand mixtures.

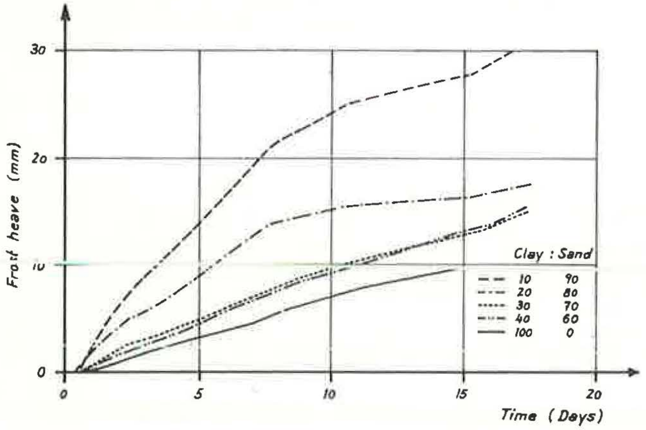

Table 3. Frost-heave rate and maximum frost-heave pressure for sands.

Soil	Frost-Heave Rate (9) (mm/day)	Maximum Frost-Heave Pressure (kp/cm^2)	CBR After Thaw (17) (percent)	Particle Content < 0.02 mm (percent)	Uniformity Coefficient d_{60}/d_{10}
1 Dirty sand					
AS	—	1.3	—	9	8
HSS	19	—	7.3	7	6
2 Dirty gravelly sand					
HPG	21	1.6	31.7	5.5	29
(2 - 1)/1	0.1	0.19	3.3	-0.31	3.1

it is to be applied to the calculation of the total design thickness, it has the following weaknesses:

1. The data of the example given (18) are not convincing;
2. There is no relation to the actual freezing temperature and the duration of the frost period;
3. The method seems to be unsuitable for dirty sands and dirty gravels; and
4. No information is given as to the remaining bearing capacity after thawing.

SUMMARY

The frost-susceptibility criteria in use can be divided into 3 groups: (a) particle size, (b) frost heave rate, and (c) phase interface.

To meet the practical requirements requires that frost susceptibility be correlated to the bearing capacity of thawed soil. The influence of the freezing process and other external conditions on the bearing capacity of thawed soils ought to be examined.

The survey shows that the term "frost susceptibility" does not fully meet the demands expected of a criterion. It is unfortunate that such a term has taken root in the literature. The term is as vague as that of "slide susceptibility" applied to embankment soils. Although the latter term gives a qualitative picture of the soil, the safety of the embankment can be ascertained only when the stability analysis is made.

It is time that the frost-susceptibility problem be similarly treated as an engineering problem demanding full analyses in terms of the type of soil and the stresses imposed on it by all factors connected with the frost action.

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