Freezing Tests of Granular Materials

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The purpose of this study was to develop procedures for simple and rapid evaluation of frost susceptibility of granular materials used for base courses. Granular materials are judged with respect to frost almost entirely on the basis of empirical grain-size criteria. It is believed that many materials rejected by current specifications would serve satisfactorily or might be readily beneficiated. Conversely, a number of materials acceptable under current standards have given poor service when subjected to frost action.

To meet the needs for improved techniques, a laboratory freezing test has been developed using a Peltier battery heat sink, cylindrical specimens in a ring-type mold with a continuous supply of water to the specimen, and determining rate of heave of the specimen during freezing. Preparation and freezing of a specimen can be accomplished in approximately 48 hours. Data are presented indicating the heave rate of materials of various grain-size distributions and void ratios. The ability of the test to distinguish degrees of frost susceptibility, on the basis of heave rate, among apparently similar materials is demonstrated. A statistical estimate of error of the test is presented.

•ROUGH pavement surfaces, loss of pavement strength, and cracking are major detrimental effects associated with frost action in pavements (12). The prevention or control of these effects is a primary function of the design and maintenance of highways in areas where a frost-susceptible soil, freezing temperatures, and an available water supply are encountered simultaneously (7, 11). Frost penetration under New Hampshire highways reaches a depth of 4 to 5 ft, sometimes resulting in frost heaves of as much as 6 to 8 in. (11). In order to surmount this problem in the past, a base course of non-frost-susceptible material has been placed to a depth equal to or greater than that of the anticipated frost penetration. However, the location and transportation of high-quality granular base material have become increasingly difficult and expensive. If the techniques for determining the frost-heaving characteristics of a base material could be improved, more accurate frost-susceptibility criteria could be established. This could result both in the satisfactory use of some materials now being rejected and in identification of unsuitable materials that are not otherwise recognized as frost susceptible.

To define better what materials are satisfactory for use in pavements, a research program was initiated in 1965 by the University of New Hampshire in cooperation with the U. S. Army Cold Regions Research and Engineering Laboratory (CRREL). The study was supported by a research grant established by the New Hampshire Department of Public Works and Highways (NHDPW&H), in which the U. S. Bureau of Public Roads (BPR) participated as a part of the HPR program. CRREL personnel provided guidance and technical assistance. In addition, CRREL made freezing and measuring equipment and cold-room space available to the project during the summers of 1965 and 1966.

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PURPOSE AND SCOPE

The primary objective of the project was to define the frost susceptibility of base course materials used in pavements and subsequently to relate that susceptibility to performance of pavements under service conditions. In order to distinguish between satisfactory and unsatisfactory soils for base courses, it was necessary to predict reliably the potential heave experience of a soil from easily measured characteristics, or to establish a reliable, quick, and economical test of heave potential. The application of heave potential as a criterion for acceptance or rejection of materials depended on the determination of acceptable limits of frost action in the field and corresponding values of parameters measured in the laboratory evaluation or test.

Following a review of theoretical considerations and currently available techniques for estimating the frost susceptibility of soils, the study was directed toward the development of a relatively rapid and inexpensive laboratory freezing test for evaluating frost susceptibility of granular materials. Large specimens were used to permit fairly coarse aggregates to be included in the study, and new techniques involving comparatively simple and compact apparatus were introduced.

Preliminary work on correlation of laboratory results to field performance is under way and an extensive field study is planned. This paper, however, is concerned only with the laboratory tests.

REVIEW OF PREVIOUS WORK

When water is converted to ice at atmospheric pressure it expands approximately 9 percent. The actual expansion of a natural soil upon freezing has been observed to be much greater than is possible simply by the expansion of the water within the voids of the soil.

The phenomenon of frost heaving is understood to the extent that heave is associated with the growth of ice lenses in soil (2). This lensing requires freezing temperatures in the soil and a supply of water available to the freezing zone. It also depends on certain properties of the soil, as it has been observed that some soils exhibit considerable lensing (and heaving) while others exhibit much less or none at all under identical conditions. It is not known completely what characteristics of the soil contribute to this behavior, although certain grain-size characteristics, such as consistency, permeability, and capillarity, have been observed to influence the degree and rate of heave (3, 4, 5, 8, 10, 17).

Studies by Taber (13), Beskow (2), Linell and Kaplar (10), and others show that the frost-heave potential of a soil increases as the percentage of grains finer than 0.02-mm diameter increases. Casagrande (3) states that considerable ice segregation should be expected in nonuniform soils with more than 3 percent by weight finer than 0.02-mm size, and in uniform soils with more than 10 percent finer than 0.02-mm size.

The U. S. Army Corps of Engineers (15) has classified frost-susceptible soils in the following manner: F1 materials, the least frost susceptible, are gravelly soils containing between 3 and 20 percent by weight finer than the 0.02-mm size; F2 materials include sands with 3 to 15 percent by weight finer than the 0.02-mm size; F3 materials include gravelly and sandy soils not in the F1 and F2 groups; and F4 materials are the most frost susceptible of all soils and include all silts, silty sands, lean clays with a plasticity index of less than 12 percent, and most varved clays.

The U. S. Army CRREL classifies quantitatively in terms of rate of heave of a specimen that has been prepared and frozen under standard test conditions (9). According to this criterion, the frost susceptibility of a soil is classified as negligible, very low, low, medium, high, or very high as the rate of heave varies on a scale from 0 to more than 8.0 mm per day (Table 1).

Permeability and Capillarity

The nature and importance of soil permeability and capillarity are discussed in numerous texts on soil mechanics. These parameters, while readily measured on a macroscopic scale by laboratory tests, are not simply related to particle shape and

TABLE 1

FROST SUSCEPTIBILITY CLASSIFICATION

Average Rate of Heave (mm/day)	Frost Susceptibility
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

size, although it can be stated in general that permeability decreases and capillarity increases with increasing proportions of fine grains.

Beskow (2) used the following empirical formula to determine the height of capillary rise as a function of particle size:

$$h_c = c_k\left(\frac{1}{d}\right) \tag{1}$$

in meters, where c_k is a constant (0.060 when compaction is high and the temperature is about 20 C), and d is the average particle diameter in millimeters. For natural soils the value of c_k varies, depending on the gradation and degree of compaction of the soil. Beskow found the value to range from 0.060 to 0.085.

The actual capillary saturation developed in a soil is dependent on the method by which the water is added. If the soil has been previously saturated or water is able to percolate down through the soil, a high degree of capillary saturation can be obtained, since most large voids will become filled with water. Water rising in a dry soil due to capillary pressure entraps air in the large voids, resulting in less complete saturation. Material types and states of compaction, and position of water table relative to the pavement may therefore have an important influence on the degree of detrimental frost action by their effects both on the amount of water that can be supplied to the freezing zone, and the rate that water is supplied.

Gradation and Density

Gradation influences permeability and capillarity of soils because it affects the size and distribution of soil voids, or pores. Small voids, resulting from small grains and a distribution of sizes, produce low permeability but high capillarity. Large voids, exhibited by uniform soils or by large grains with no fines present, tend to produce high permeability but low capillarity. The rate at which water will flow through a soil under capillary potential therefore involves some function of gradation.

As the dry density of the soil is increased, the pores become smaller and capillarity increases while permeability is reduced. According to Beskow (2), Winn and Rutledge (16), and Haley (5), increasing the capillarity causes an increase in frost-heave potential of the soil until a critical density is reached. Beyond this point, an increase in density continues to cause an increase in capillarity; however, the steady decrease in permeability becomes the major factor, and the rate of upward flow of water is decreased. It has been suggested (5, 16) that since materials used in the construction of roads are usually compacted beyond the critical density, an increase in compactive effort will cause a slight decrease in frost-heave potential.

The dry density of the soil will depend on the gradation, the size and shape of the particles, the type and magnitude of compactive effort, and molding moisture content. A soil of uniform gradation would be highly porous. A graded soil containing particles of varying sizes so that smaller grains are available to fill the pore spaces among the larger grains results in higher density and smaller pore spaces than that of a uniform soil. Therefore, a soil of uniform gradation is able to tolerate a comparatively higher percentage of fines without detrimental frost action than is a nonuniform soil, because it has more void space. For this reason, the effect of gradation cannot be reduced to a criterion based on a single particle size.

Surcharge

Surcharge in connection with frost action is the load that must be lifted by freezing ice lenses. An increase in the surcharge decreases the rate of heave. Haley (5) and Linell and Kaplar (10) report that the rate of heave for a soil with a 6-psi surcharge is only 10 percent of the rate of heave for the same soil with a 0.5-psi surcharge.

Frost Penetration

The rate and depth of frost penetration in a soil are governed by a wide variety of soil and environmental parameters. Intrinsic soil factors include properties such as specific heat, thermal conductivity, water content, density and concentration of salts. Environmental factors, such as type and thickness of ground cover, air temperature, relative humidity, incident solar radiation, wind, barometric pressure, and precipitation, also play a part (7).

A number of schemes have been proposed for estimating the depth of frost penetration under pavements. One of the most widely used is the modified Berggren equation proposed by Aldrich (1):

$$Z = \lambda\sqrt{\frac{48kF}{L}}$$

in which Z is the depth of penetration of the 32 F isotherm, k is the average thermal conductivity of the soil, L is the latent heat of the soil moisture, and F is the air freezing index. The coefficient λ is a correction factor dependent on the mean annual air temperature, the volumetric heat capacity of the soil, and the average deviation of air temperature from 32 F for the duration of freezing.

Functions of this type have proved useful in many situations but they have a common weakness in that many of the influencing factors mentioned are ignored, and properties such as the thermal conductivity of a composite pavement structure are difficult to measure. They cannot, therefore, be relied upon beyond the limits of prior experience with materials, structural configuration, and environment. Furthermore, the depth of freezing predicted by such factors considers air temperature only in terms of the total freezing index and duration of freeze. Yet the rate of penetration of freezing, as influenced by distribution and magnitude of air temperatures, can have a significant effect on both the depth of penetration of freezing and on the detrimental effects of freezing.

The rate of heave has been found by Beskow (2), Jackson and Chalmers (6), and Haley and Kaplar (4) to be independent of the rate of frost penetration over a fairly wide range. If the rate of frost penetration is slow, thick lenses form, since water has time to move to each lens. If the rate of penetration is increased, there is less time for water to move to a lens and thinner lenses are formed. However, the flow of water, and thus the rate of heave, still remains fairly constant. On the other hand, if the rate of frost penetration is too rapid, the soil is frozen before water has time to move and form lenses, and the soil freezes homogeneously with reduced heave.

If the rate at which the heat is being removed from the sample is not sufficient to maintain frost penetration, then the rate of heave is dependent on the rate of heat extraction. In other words, the rate of heat extraction may be sufficient to continue the growth of ice lenses, but not sufficient to cause movement of the ice front through the soil pores. Therefore, it can be seen that if the rate of frost penetration down to a given depth is fast, the total amount of heave will be less than that produced by a slow rate of frost penetration to the same depth. Otis (12) has observed that some cold winters in New Hampshire have caused less heaving than mild winters. This could be due not only to less freezing and thawing taking place, but also to the faster rate of frost penetration.

Kaplar (9) suggests that because the heave for any given depth of penetration of freezing is dependent upon rate of frost penetration, the total amount of frost heave of a laboratory test specimen is not a good measure of frost susceptibility of a soil. The rate of heave, however, because it is uniform over a fairly wide range of penetration rates, is well suited to this purpose. It is for this reason that the classification shown in Table 1 has been adopted by CRREL, based on an average rate of frost heave in mm/day for a penetration rate of $\frac{1}{4}$ to $\frac{3}{4}$ in. per day in a standard laboratory test.

FREEZING TESTS

In the summer of 1965 initial freezing tests on this study were run in CRREL cabinets developed by Kaplar. Samples were obtained of four materials from different

TABLE 2

RESULTS OF STANDARD ENGINEERING TESTS

Material	Specific Gravity	Optimum Moisture Content[a]	Optimum Dry Density[a] (pcf)	Liquid Limit (%)	Plastic Limit (%)	Unified System Classification
B0	2.69	5.6	135.3	18.4	NP	SP-SM
C0	2.72	5.1	142.6	17.2	NP	GP-GM
R0	2.70	6.8	136.2	18.6	NP	SW-SM
D0	2.72	6.5	141.0	20.9	NP	GP
G0	2.74	12.5	112.4	23.9	NP	SM
G2	2.74	15.0	108.6	23.6	NP	SM
L0	2.76	6.75	142.7	17.8	NP	SP
L1	2.76	—	—	17.8	NP	SP-SM
L2	2.76	—	—	17.8	NP	SP
L3	2.76	—	—	17.8	NP	SP
W0	2.75	6.70	139.9	15.8	NP	SM
W1	2.75	—	—	15.8	NP	GW-GM
W2	2.75	—	—	15.8	NP	GW-GM
W3	2.75	—	—	15.8	NP	SM
P0	2.72	9.10	131.8	18.0	NP	SW-SM
P1	2.72	—	—	18.0	NP	SW-SM
F0	2.64	6.00	130.7	16.6	NP	SM
F1	2.64	—	—	16.6	NP	SM

[a] ASTM D 1557-64T, Method C.

regions of New Hampshire. Classification data for the materials, identified as B0, C0, R0, and D0, are summarized in Table 2. Typical results of cabinet freezing tests on these materials are shown in Figure 1. The equipment and methods followed are those documented in the literature by Kaplar (8, 9, 10). Freezing penetration rates were approximately ½ to 1 in. per day.

Figure 1 shows that the rate of heaving diminished as the depth of penetration increased. This was attributed to the surcharge effect of wall friction due to lateral expansion of the specimen against the mold, adhesion, or other boundary effect. This made the interpretation of heave rate difficult and somewhat ambiguous in some cases.

Frost susceptibility of the specimens tested varied from medium to very low (Table 1). Modification of grain-size distributions by addition of course material (larger than No. 10 sieve) and by removal of particles finer than a No. 200 sieve produced slight changes in heave rate but did not consistently affect the frost susceptibility classification. No precise relationship existed between the rate of heave and percent finer than 0.02 mm, although in general the heave rate increased with fines (Fig. 2). The association of classification symbols with specimens in Figure 2 also indicates that for a given percent finer than 0.02 mm, lower heave rates occur with poorly graded materials and higher rates with well-graded materials.

In order to quantify gradation beyond the percent finer than 0.02-mm size, the fineness modulus was introduced. A plot of heave rate vs the ratio of fineness modulus to percent finer than 0.02 mm is shown in Figure 3. The evident trend suggested further study of gradation influences on the rate of heave, but further testing, including a much wider variation in material sizes, is necessary.

To continue freeze testing during the academic year, it was necessary to develop equipment and techniques that could be applied in a limited space in a conventional soils laboratory.

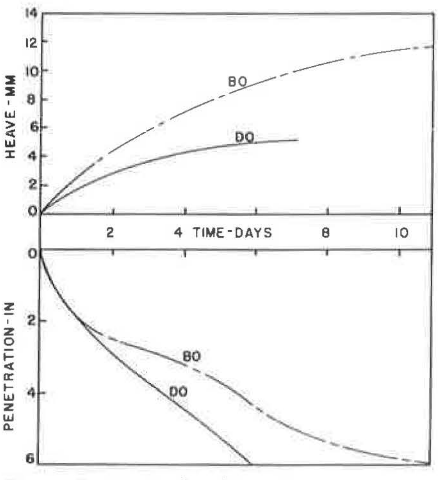

Figure 1. Typical cabinet freezing test results.

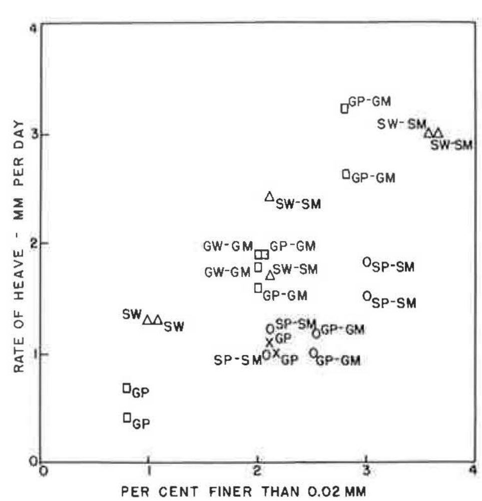

Figure 2. Rate of heave vs percent finer than 0.02 mm.

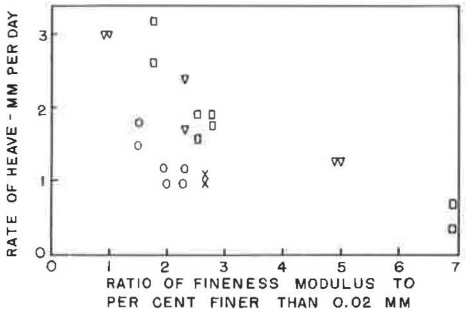

Figure 3. Rate of heave vs ratio of fineness modulus to percent finer than 0.02 mm.

It was not feasible to duplicate the freezing cabinets and cold-room facilities available at CRREL that are suited to extensive research programs. It was also desired to reduce the length of time per test if possible, and to eliminate or minimize the decay of heave rate during the test shown in Figure 1. The first of these criteria was met by using Peltier thermoelectric batteries as freezing units. Testing time was shortened by increasing the rate of penetration of the 32 F isotherm somewhat and by freezing only about 3 in. of specimen instead of 6. Introduction of a new specimen mold composed of Lucite rings resulted in stable heave rates for the duration of the test.

Apparatus

Two Peltier thermoelectric batteries were obtained with characteristics specified for the present application. Each battery has a maximum heat pumping capacity of 300 Btu/hr operating at 4.5 amps and 12 volts dc. Operating characteristics, indicating that actual capacity is a function of ambient temperature as well as input current, are shown in Figure 4. At 0 C (32 F) cold plate and 25 C (77 F) ambient temperature, the maximum capacity is 68 Btu/hr.

The cold plate is a $5\frac{3}{8}$-in. diameter circular disc, which fits a cylindrical soil specimen molded in Lucite rings. A 2-in. separation between hot and cold junctions is enclosed with rigid foam insulation to minimize heat flow to the specimen during freezing.

Specimens are molded in a cylinder consisting of seven Lucite rings with an internal diameter of 5.46 in. and a wall thickness of 0.25 in. Five of the rings are 1.00 in. high and the remaining two are 0.50 in. high. The seven rings are stacked with one of the $\frac{1}{2}$-in. rings at the top and the other at the bottom and inserted in a steel cylinder for stability. The soil is then compacted in layers so as to achieve uniform density throughout the specimen. The specimen and mold are then removed from the steel cylinder and thermocouples are inserted at 1-in. intervals from the top of the sample to a depth of 3 in. The specimen is then ready to be placed in the freezing apparatus.

The freezing container is a 12 by 12 by 14-in. block built from 1-in. sheets of rigid foam plastic insulation. A $6\frac{1}{4}$-in. diameter hole is cut in the center of the block to a depth of $7\frac{1}{2}$ in. and lined with a waxed cardboard mold $7\frac{1}{2}$ in. high. A constant head water supply is attached to the bottom of the cylinder. A $5\frac{1}{2}$-in. diameter, $\frac{1}{2}$-in. thick

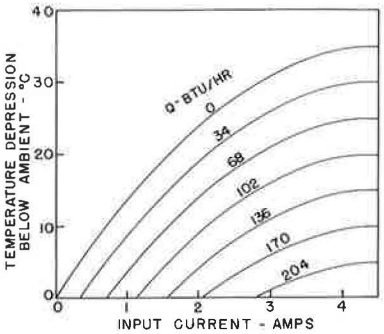

Figure 4. Peltier battery operating characteristics.

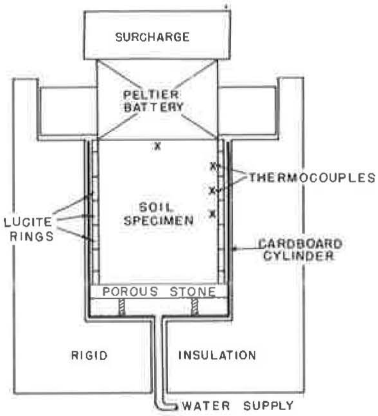

Figure 5. Cross section of freezing apparatus.

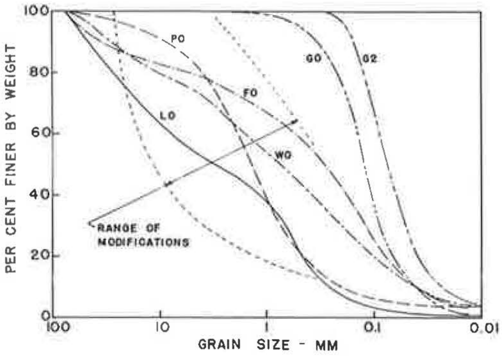

Figure 6. Grain-size distributions of samples.

porous stone is supported 1 in. from the bottom of the cylinder. The specimen, with ring mold intact, is inserted in the inner cylinder and the Peltier battery placed on top of the specimen. A surcharge may be mounted on the battery if desired. A dial gage mounted on the battery permits observation of change of sample height or heave at any time during the test. A schematic cross section of the apparatus is shown in Figure 5.

Freezing Procedure

After a specimen is prepared and placed in the freezing apparatus, it is saturated from the bottom by raising the water table about 1 in. per hour until the top of the sample has been reached and the water table then held constant for 16 hours. During this interval current is applied to the Peltier battery to cool the specimen. In order to allow cooling of the specimen without freezing, the input current is adjusted according to Figure 4 so that Q will be zero when ΔT equals the difference between the ambient temperature and the freezing temperature of water.

At the end of the 16-hour cooling period, the water table is lowered to ½ in. above the bottom of the specimen, and the input current to the battery is increased to begin freezing the specimen. Again, the necessary input current is dependent upon the room temperature and is determined from Figure 4. A heat pumping capacity of 65 Btu per hour was found to produce freezing rates generally between 3 and 7 in. per day for the materials tested. The input current is adjusted as necessary during the test to offset significant changes in the ambient temperature, which otherwise would change the rate of heat pumping.

Heave (change in height) and thermocouple readings are made until the penetration of the 32 F isotherm has reached a depth of 3 in.

Materials Tested

Six samples were taken from potential base sources and in-service bases. Two samples were sand; the remaining four were all natural gravelly sands. Each material was subjected to standard tests for specific gravity (ASTM D 854-58), moisture-density relations (ASTM D 1557-64 T, Method C), and Atterberg limits (ASTM D 423-61 T and D 424-59). The results of the tests and the classification in the unified system are given in Table 2. A complete grain-size analysis including sieve and hydrometer analyses (ASTM D 422-63) was made on each material; the distribution curves are shown in Figure 6.

In order to facilitate the molding of specimens, all stones larger than 1 in. were removed and replaced with a representative sample of material between ¼ in. and 1 in. in accordance with ASTM D 1557-64 T.

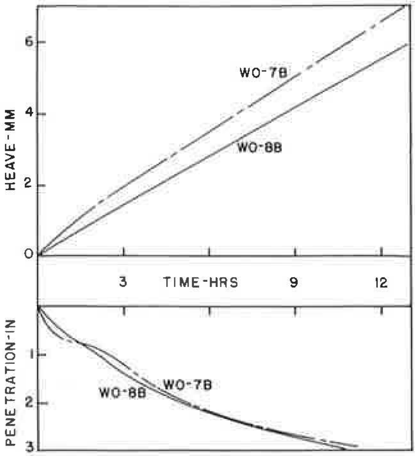

Figure 7. Typical Peltier battery freezing test results.

RESULTS

Plots were made of heave vs time and penetration of the 32 F isotherm vs time for each specimen frozen. Figure 7 shows two typical examples of the plots. The top ½ in. of the specimens tends to heave faster than the rest of the specimen (Fig. 7). This high initial rate of heave was attributed to supercooling and the resulting quick-freeze immediately following nucleation, and to irregularities at the surface of the specimen. Thermal changes in the battery and nonuniform freezing of the top of the specimen may also be contributing factors. After approximately ½ in. of penetration, the heave was substantially linear and independent of minor variations in rate of penetration of the 32 F isotherm (Fig. 7).

Time rates of penetration and heave were taken from the plots as the slopes of the linear portions of the curves and summarized in Tables 3 and 4. Table 3 includes specimens frozen in the CRREL cabinets. The results of two series of Peltier battery tests are given in Table 4. Series I tests, summarized in Table 4, were conducted with no adjustment of battery input current to compensate for the effects of ambient temperature fluctuations. Table 4 also includes the Series II tests, in which battery input current was adjusted periodically to keep the rate of heat pumped constant for the duration of the test. Initial void ratios of all specimens are also given in Tables 3 and 4.

DISCUSSION OF RESULTS

Of primary importance in development of the laboratory freezing test was to keep the duration of test to a minimum. Early experience with the ring-type mold and freezing rates of a few inches per day consistently indicated heave patterns similar to those in Figure 7. Once initial freezing occurred, heave rates remained essentially constant for all subsequent freezing of the specimen. No additional information about heave rate was obtained by freezing beyond the first few inches. Duration of test for any rate of penetration of the 32 F isotherm could thus be cut in half by freezing only the upper half

TABLE 3

SUMMARY OF CABINET FREEZING TESTS

(a) Tapered Cylinders Mold

Specimen	Void Ratio (e)	Heave Ratio (mm/day)	Penetration Rate (in./day)
L0-1	0.261	0.57	0.57
L0-2	0.246	0.43	0.44
G0-1	0.626	0.1	0.7
G0-2	0.601	0.1	0.4
G2-1	0.645	0.1	0.3
G2-2	0.648	0.2	0.3
F0-1	0.315	2.1	0.8
F0-2	0.311	2.1	0.8
P0-1	0.353	6.0	0.4
P0-2	0.357	5.5	0.4
W0-1	0.262	3.01	0.58
W0-2	0.258	3.34	0.59

(b) Ring Mold

Specimen	Void Ratio (e)	Heave Ratio (mm/day)	Penetration Rate (in./day)
L0-1A	0.237	1.17	1.17
L0-2A	0.256	0.88	0.34
G0-1A	0.610	0.2	0.8
G0-2A	0.600	1.5	0.3
G0-3A	0.600	0.3	0.3
G0-4A	0.597	0.9	0.3
G2-1A	0.616	4.0	0.2
G2-2A	0.603	4.4	0.2
F0-1A	0.311	6.9	0.5
F0-2A	0.307	6.5	0.5
P0-1A	0.350	7.8	0.3
P0-2A	0.366	8.6	0.4
W0-1A	0.262	4.58	0.45
W0-2A	0.253	5.22	0.33

TABLE 4

SUMMARY OF PELTIER BATTERY FREEZING TESTS

(a) Peltier Battery; Ring Mold; Series I

Specimen	Void Ratio (e)	Heave Rate (mm/day)	Penetration Rate (in./day)
L0-6B	0.260	1.11	0.94
L0-7B	0.253	1.66	1.14
L0-8B	0.251	1.50	1.38
L0-9B	0.255	1.23	1.06
L1-1B	0.434	3.32	4.31
L1-2B	0.452	2.82	3.31
L2-1B	0.339	1.92	4.56
L2-2B	0.335	2.09	2.69
W0-1B	0.264	8.96	2.24
W0-2B	0.256	7.02	3.41
W0-3B	0.274	7.33	1.89
W0-4B	0.266	7.48	1.17
W1-1B	0.180	8.78	3.97
W1-2B	0.188	8.33	3.43
W1-3B	0.197	9.70	6.74
W1-4B	0.192	8.42	6.05
W2-1B	0.170	5.15	3.25
W2-2B	0.168	4.79	2.74
W2-3B	0.180	4.29	5.08
W2-4B	0.173	5.70	5.69
W3-1B	0.362	17.80	5.00
W3-2B	0.342	18.76	5.82
W3-3B	0.344	14.74	*
W3-4B	0.344	13.73	*
F0-2B	0.313	11.85	2.49
F1-1B	0.387	12.76	2.31
F1-2B	0.380	14.39	1.96
F1-3B	0.404	11.85	1.50
F1-4B	0.392	11.27	2.46
P1-1B	0.397	17.86	1.76
P1-2B	0.397	22.57	2.28

(b) Peltier Battery; Ring Mold; Series II

Specimen	Void Ratio (e)	Heave Rate (mm/day)	Penetration Rate (in./day)
L3-1B	0.274	1.66	4.18
L3-2B	0.255	2.02	5.31
L3-3B	0.243	2.42	6.11
L3-4B	0.251	2.02	6.43
L3-5B	0.249	2.27	4.38
L3-6B	0.249	2.17	3.99
L3-7B	0.256	2.35	5.78
L3-8B	0.255	1.94	6.24
L3-9B	0.256	2.46	6.88
L3-10B	0.262	2.09	7.03
W0-5B	0.243	12.40	5.78
W0-6B	0.243	11.90	6.62
W0-7B	0.251	12.50	6.06
W0-8B	0.251	10.76	5.57
W0-9B	0.262	12.65	6.08
W0-10B	0.264	10.41	5.82
W0-11B	0.251	10.79	4.58
W0-12B	0.256	10.46	4.73
W0-13B	0.255	11.60	5.46
W0-14B	0.255	10.69	5.29
F0-3B	0.318	11.44	3.49
F0-4B	0.311	12.66	3.99
F0-5B	0.318	12.37	3.44
F0-6B	0.311	9.58	4.50
P1-3B	0.416	16.74	2.54
P1-4B	0.436	18.05	2.80
G2-1B	0.600	7.02	3.26
G2-2B	0.597	6.26	3.71
W3-5B	0.355	15.00	3.88
W3-6B	0.339	13.44	4.15

*Thermocouple failure.

of the specimens. In further testing, therefore, temperature recordings were obtained only to a depth of 3 in. Heave rates were computed disregarding the initial 2 hours of freezing.

It is significant that the shape of the heave vs time curves appears to be a function of the mold used to contain the specimen. As was noted previously and shown by Figure 1, the rate of heave decreased as freezing progressed in cabinet tests using a "tapered cylinder" mold. If this phenomenon was truly a result of bonding or friction of the specimen against the mold wall as was previously suggested, the effect should be reduced or eliminated by slicing the mold into rings and omitting the tie-down bolts. Thus, each ring would be free to rise with the specimen independent of lower sections of the mold or mechanical ties.

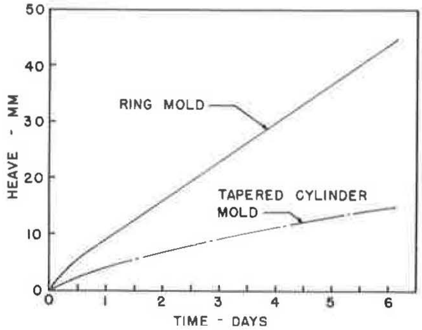

Figure 8. Effect of mold type on heave of a typical gravelly sand.

The effect of the mold is shown in Figure 8, which gives heave vs time curves for two specimens of a typical gravelly sand frozen simultaneously in a CRREL cabinet. The upper curve in Figure 8 is for a specimen molded and frozen in a Lucite ring mold. The lower curve is for a specimen of the same material in the "tapered cylinder" mold. Similar response was obtained in a number of tests using a variety of gravelly sands. It should be noted that the apparent restricting effect of the "tapered cylinder" is not as great in high-heaving materials as in low, and in fact is not noticeable at all in numerous tests on fine-grained soils reported in the literature. Also, use of the ring mold does have a minor disadvantage in that it precludes accurate determination of degree of saturation of the specimen prior to testing. It would appear, however, for a test designed for evaluation of granular base course materials that are typically low heaving, that adoption of the ring mold has substantial merit.

A review of Table 4 indicates some variation of heave rates for each material. There is also some variation in rates of freezing, but there is no consistent relationship between heave rate and freezing rate. While previous work had indicated that heave rate was independent of rate of penetration of the 32 F isotherm in the range of $\frac{1}{4}$ to $\frac{3}{4}$ in. per day, the effect of higher rates of penetration was uncertain. As pointed out earlier, however, there is considerable evidence that rate of heat extraction is more significant than rate of penetration of freezing temperatures in influencing heave rate. In addition, it is expected that minor variation in specimen void ratios and gradations would contribute to variation of heave rates among specimens of the same material.

In the development of procedures, considerable attention was given to techniques involving a minimum of operator attention and manipulation during testing. To this end, initial attempts were made to run the actual freezing period without adjustment of battery current. In the absence of a controlled environment, however, variation in ambient temperature was so great as to require occasional adjustments. The possibility of using a liquid-cooled Peltier battery is now being investigated. This would provide a more constant temperature at the hot plate and therefore more precise control of the rate of heat extraction from the soil specimen being frozen. Alternatively, it would be possible with some modification to provide for automatic control of input current to provide a constant rate of heat extraction over reasonable ambient fluctuations.

In order to provide a quantitative evaluation of the reliability of the test, a number of replicate specimens of each material was tested. The results, which appear in Table 4, show that on the basis of heave rate, the test clearly distinguishes among materials of similar type. A one-way analysis of variance is given in Table 5, which compares the variation of heave rate among materials to variation within materials. The ratio of mean squares in this analysis is 70. The probability that this ratio would occur by chance is substantially less than 0.05 percent.

It should be noted that these data are from all Peltier battery tests in the two series of tests. The first series, given in Table 4, was run with no control of heat extraction rate during freezing. This resulted in a greater variation of heave rates within materials that occurred in the second series in which rate of heat extraction was controlled. It is evident from Table 4 that such control resulted in a much smaller variance of heave rate for specimens of a given material.

Further examination of results of the second series (Table 4b) indicated a trend of heave rates associated with freezing units. Two Peltier batteries and associated insulated containers were used in the tests. Results from one tended to be slightly higher than results from the other, the difference being statistically significant at the 95 percent level. This could be due to differences in calibration of the batteries and/or to insulating qualities of the containers. Additional investigation of this effect is necessary.

Tests on 10 replicate specimens of a low-heaving material (L3) and 10 of a high-heaving material (W0) were run. The data from these tests were analyzed to determine the number of replicates needed to be confident that the average measured heave rate is

TABLE 5

ANALYSIS OF VARIANCE

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio
Mean	4558.1195	1	—	—
Among materials	1693.5167	11	153.956	70.01
Within materials	107.7742	49	2.199	
Total	6359.4104	61	—	—

$P(F \leq 3.90) = 0.9995$

TABLE 6

NUMBER OF SPECIMENS REQUIRED TO ESTIMATE THE ACTUAL HEAVE RATE OF A MATERIAL

Permissible Error (mm/day)	Material			
	High Heaving (W0)		Low Heaving (L3)	
	Probability Level 90%	Probability Level 95%	Probability Level 90%	Probability Level 95%
±0.50	12	15	3	4
±0.75	6	8	3	3
±1.00	5	6	3	3
±1.25	4	5	2	2
±1.50	3	4	2	2

within a specified range of the true heave rate for that material. The results of this analysis are given in Table 6. On the basis of these two materials, it appears that three tests of a low-heaving material (on the order of 2 mm/day) are sufficient to give an average measured heave rate within 0.5 mm/day of the true heave rate at the 90 percent confidence level. Three specimens of a higher heaving material (on the order of 12 mm/day) would predict the true heave rate to within 1.50 mm/day at the 90 percent confidence level.

The implications of these analyses are especially important with respect to test apparatus, for if the reliability of the heave rate obtained from constant heat extraction tests, regardless of rate of penetration of the 32 F isotherm, is confirmed, the necessity for temperature measurements is eliminated. Hence, thermocouples and associated equipment would not be necessary for a standard laboratory classification test, and the equipment and procedure would be simpler and less costly. Further investigation of this question is currently under way.

At the present stage of development, the freezing test requires a total run time of about 2 days. A specimen can be molded and saturated in one day, cooled overnight, and frozen during the following 16- to 24-hour period.

CONCLUSIONS

A single grain-size characteristic, such as percent finer than 0.02 mm, is not sufficient to predict the response of natural granular materials to freezing. Further, in order to obtain useful information about probable performance in service, frost susceptibility of granular materials or pavement base courses must be measured in terms that can be related to the detrimental aspects of frost action on pavements. It appears that the rate of heaving of a saturated specimen during freezing from the surface with a continuous supply of free water at the bottom, is a simple and useful indicator of severity of frost susceptibility.

A Peltier thermoelectric battery was used effectively as a heat sink to freeze cylindrical specimens $5\frac{1}{2}$ in. in diameter and 6 in. high. Rigid foamed plastic provided adequate insulation to permit freezing at normal room temperature. The time rate of heaving of the specimen during freezing at a constant rate of heat extraction reliably distinguished between gravels varying only moderately in gradation and insignificantly in mineral type, plasticity, and specific gravity. The materials tested were types commonly used for base courses and typically considered low-heaving materials.

The heave rate of the gravels was generally dependent on the degree of restraint provided by the mold. Specimens frozen in cylindrical molds clamped to a base plate heaved rapidly at first; however, heave rate tapered off to a very low rate after a few hours of freezing. When using a mold consisting of several rings unclamped and free to move vertically, the heave varied linearly with time, after an initial rapid rise, until the specimen was completely frozen. Under these conditions it was feasible to obtain heave rates from freezing periods of from 16 to 24 hours.

Statistical analysis shows that the test has the ability to distinguish between materials on the basis of heave rate at an extremely high probability level. If heave rate can be well correlated with actual field performance, the freezing test proposed could be an efficient and effective method for quickly determining acceptance or rejection of proposed base and subbase materials.

ACKNOWLEDGMENTS

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Discussion

I. V. KALCHEFF, Research and Testing Engineer, National Crushed Stone Association, Washington—The authors should be complimented for a fine paper dealing with a problem of major importance to highway engineering. The laboratory evaluation of this complex phenomenon of frost heaving in granular bases and subbases appears to have been simplified and the time of testing shortened. The empirical method as proposed by the authors, however, should be carefully correlated with field performance prior to using it as a basis for acceptance or rejection. Factors such as the overburden load, moisture availability, uniformity of density and gradation, etc., may have a great influence on the frost heave susceptibility of a material in the field. Also, the limited capacity of the Peltier battery should be considered, together with the physical properties of the material under investigation. The rapid freezing should be followed by a rapid thawing for evaluation of excess water dissipation and load supporting capacity. In addition, each material should be tested for the range in gradation that normally occurs in production of materials and construction practices.

For example, in the AASHO Road Test (18) the "Crushed Stone Base Course, Special," after construction was reported to have a mean of 11.5 percent passing the No. 200 sieve with a standard deviation of 0.86. The crushed stone base course, Type A, used for the shoulder construction, had a mean of 12 percent passing the No. 200 sieve and 90 percent of the tests were in the range of 9.5 to 14.5 percent.

Normal variability, like those in the two stone bases used for the AASHO Road Test, should be considered. Rather than testing the mean gradation for rate of frost heave, it would be more realistic to test those gradations that may be at the limits of the gradation tolerance. If both of these are evaluated in terms of rate of frost heave, the differential heaving would be more applicable for consideration.

The National Crushed Stone Association (NCSA) has conducted numerous laboratory researches concerned with frost heaving in bases and subbases and the prevention of spring weakening. As an example of such studies, I would like to present an evaluation of the effect of material variability on the compaction characteristics of a stone base, the triaxial strength (after capillary saturation), drainability, and the rate of frost heave.

Specimen Preparation

The materials were weighed cumulatively in amounts sufficient for molding specimens of 6 in. in diameter and 8 in. in height. After thorough mixing with the molding moisture content, the material was placed in split steel molds in 2-in. lifts and each layer compacted by 50 blows of a mechanical drop hammer weighing 10 lb and having an 18-in. drop. After placement and compaction of the final layer, each specimen was vibrated for 15 sec under a surcharge weight of 85 lb (19).

Strength Tests

The strength properties of the various mixtures were determined by the triaxial method of test used by the Texas Highway Department (20).

Water Permeability

The drainability test for the mixtures was performed on 6-in. diameter, 8-in. high specimens by determining the amount of water percolating through the test sample in a given time. The water was supplied from a starting height of 30 in. above the top of the specimen.

Frost Heave

For frost heave evaluation testing, each specimen, after capillary saturation, was wrapped in thin polyethylene film and individually insulated with granulated cork. Specimens seated on porous stones were than placed in a freezing cabinet (21). A source of free water was provided at all times to within ½ in. of the bottom of each

TABLE 7

PHYSICAL PROPERTIES OF GRADED CRUSHED LIMESTONE BASES

Specification	Sample				
	A	B	C	D	E
Identification:					
Maximum size of aggregate, in.	1½	1½	1½	1½	1½
Gradation:					
Total percent passing 1½ in.	100	100	100	100	100
¾ in.	67	71	74	78	81
⅜ in.	44	50	56	62	68
No. 4	27	35	42	50	57
No. 16	11	18	24	31	37
No. 50	4	9	15	20	25
No. 200	1	4	8	12	16
Bulk specific gravity, dry	2.71	2.71	2.71	2.71	2.71
Molding moisture, percent	4.2	4.4	4.4	4.7	4.8
Dry density, pcf (compacted)	133.3	143.5	147.7	147.6	146.6
Density, percent solids[a]	78.9	85.0	87.5	87.4	86.8
VMA, percent[b]	21.1	15.0	12.5	12.6	13.2
Drainage factor, ml/hr, avg.[c]	18,000	70	10	6	3
Rate of frost heave, mm/day[d]	0.4	0.9	2.6	3.8	4.6
Triaxial strength, max. load in psi at indicated lateral pressures:					
0	12	59	81	105	104
3	82	140	150	153	143
5	92	147	153	185	163
10	150	228	250	230	240
15	163	252	294	278	252
20	196	268	302	316	309

[a] Computed from the theoretical maximum density using the bulk specific gravity of the aggregate.
[b] Defined as the bulk volume of the compacted mixture minus the volume of the aggregate from its bulk specific gravity.
[c] Amount of water draining through a 6-in. diameter, 8-in. height.
[d] Freezing of specimens from the top down at an average rate of ½ in./day.

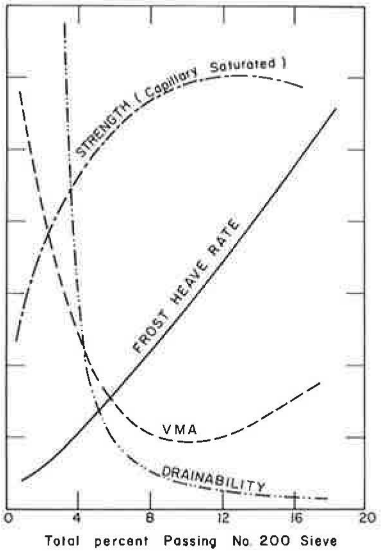

Figure 9. General characteristics of graded crushed stone base as affected by the quantity of material passing No. 200.

specimen and was available to the specimens through capillary action. A surcharge of about ⅓ psi was placed on each specimen and the specimens were frozen from the top down at an average rate, generally, of ½ in. per day. Measurements of temperature and change in height were recorded periodically and the rate of heave established for the given frost rate penetration.

Discussion of Test Results

Results of tests on 1½-in. maximum size aggregate in five different combinations of crushed limestone are given in Table 7 and shown graphically in Figure 9. The amount passing the No. 200 sieve was used as the independent variable, but it represents the given gradation as shown in the table.

While the rate of heave was approximately constant for a given gradation and a given rate of frost penetration under similar conditions of water availability, it was of a different value even for a small variability in the materials. It should be recognized, therefore, that because the base or subbase is not of a constant gradation, differential heaving would occur. Therefore, consideration should be given also to other physical properties of bases, namely, the release of hydrostatic pressure through drainage during the thawing season, some type of test on load-bearing capacity, material compactability, and material uniformity.

Thus, the criterion of frost heave alone cannot be used for acceptance or rejection of proposed materials for bases and subbases in areas subject to seasonal frost, but could be included as a determination of the differential heave that may occur under critical environmental conditions. The materials engineer then will be in a position to do something with the available materials, either reprocess them to eliminate excessive fines or stabilize them in an economical manner to render the fines innocuous to frost action.

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R. M. LEARY, J. L. SANBORN, J. H. ZOLLER, and J. F. BIDDISCOMBE, Closure—The authors thank Kalcheff for his thoughtful consideration of the paper and for drawing attention to a number of significant points with respect to freeze testing of granular materials. His data tend to confirm the indication that rate of heave of specimens, during freezing, does distinguish between similar materials. As indicated in the paper, if this distinction can be significantly related to field performance, the test may be extremely useful in material selection.

It is certainly true that frost susceptibility should not be used as the sole basis for material selection. The authors believe that one criterion of selection should be the response of material to freezing temperatures when these are anticipated in service. This, of course, in no way implies that other criteria, such as strength, durability, toughness, ease of compaction and permeability, should be put aside.

Kalcheff's remarks with respect to material variability are indeed pertinent. While his own tests indicate some correspondence between percent finer than the No. 200 sieve and rate of heave of specimens at constant rate of penetration of 32 F isotherm, it should be recognized that a substantial variation in grain-size distribution is confounded in his tests, and the data presented have considerable scatter. His observation that ". . . the rate of heave . . . was a different value even for a small variability in the materials" is further evidence that such a test is sensitive enough to produce the necessary distinction among materials. In addition, the test described by the authors is readily run under varying conditions to determine effects of factors such as density, gradation, and overburden, thus permitting the designer to account for these factors in selecting materials for use in pavements. The factor of moisture availability should be considered also, as suggested by the discusser, although this relates to factors other than the frost susceptibility of a particular layer of material.

With respect to the capacity of the Peltier battery, it is not believed that this influences the evaluation of materials as long as the heat pumping capacity is adequate for the particular test. In the tests described, the battery was run substantially below capacity in most cases, and at no time did the heat pumping fall below the desired level due to lack of battery capacity. It is possible that for different classes of soils, different rates of heat removal would prove more satisfactory. Further investigation of the optimum rate of heat removal for a wide range of materials is essential.