SPECIAL REPORT 96-20

CRREL

Testing of Materials from the Minnesota Cold Regions Pavement Research Test Facility

Susan R. Bigl and Richard L. Berg

September 1996

Abstract: The U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) conducted various laboratory tests on pavement materials from the Mn/ROAD facility. The tests helped to characterize the behavior of materials under season frost conditions, and to provide input necessary for modeling the materials with the Mechanistic Pavement Design and Evaluation Procedure under development at CRREL. This report describes test results that define the physical characteristics, such as grain size, specific gravity, Atterberg limits, organic content, and compaction, as well as hydraulic properties, such as moisture retention and hydraulic conductivity, frost susceptibility, and unfrozen moisture content of two subgrade samples and two base materials from Mn/ROAD.

How to get copies of CRREL technical publications:

Department of Defense personnel and contractors may order reports through the Defense Technical Information Center:

DTIC-BR SUITE 0944
8725 JOHN J KINGMAN RD
FT BELVOIR VA 22060-6218
Telephone 1 800 225 3842
E-mail help@dtic.mil
msorders@dtic.mil
WWW http://www.dtic.dla.mil/

All others may order reports through the National Technical Information Service:

NTIS
5285 PORT ROYAL RD
SPRINGFIELD VA 22161
Telephone 1 703 487 4650
1 703 487 4639 (TDD for the hearing-impaired)
E-mail orders@ntis.fedworld.gov
WWW http://www.fedworld.gov/ntis/ntishome.html

A complete list of all CRREL technical publications is available from:

USACRREL (CECRL-TL)
72 LYME RD
HANOVER NH 03755-1290
Telephone 1 603 646 4338
E-mail techpubs@crrel.usace.army.mil

For information on all aspects of the Cold Regions Research and Engineering Laboratory, visit our World Wide Web site:
http://www.crrel.usace.army.mil

Special Report 96-20

US Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

Testing of Materials from the Minnesota Cold Regions Pavement Research Test Facility

Susan R. Bigl and Richard L. Berg

September 1996

Prepared for
MINNESOTA DEPARTMENT OF TRANSPORTATION

PREFACE

This report was prepared by Susan R. Bigl, Research Physical Scientist, Civil and Geotechnical Research Division, Research and Engineering Directorate, U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), Hanover, New Hampshire, and by Dr. Richard L. Berg, formerly a Research Civil Engineer at CRREL.

This work was funded through Agreement 64632, Task Order 1 with the Minnesota Department of Transportation (Mn/DOT) and a Construction Productivity Advancement Research (CPAR) project, *Construction of Roads in Seasonal Frost Areas*, between Mn/DOT and CRREL.

The authors thank George Cochran of the Minnesota Road Research Project and Dr. Vincent Janoo of CRREL for technically reviewing the manuscript of this report.

Soils testing is a time-consuming and labor-intensive activity and the information reported here is the result of work done by a team of personnel who work in the soils laboratory at CRREL. Their efforts are greatly appreciated. Jeffrey Stark, soils laboratory manager, coordinated and initiated the work, and designed some new devices to aid molding and processing frozen samples. Rosanne Stoops conducted the grain-size analysis, Atterberg limits, specific gravity, and organic content tests. Richard Roberts conducted the frost susceptibility tests and some of the compaction tests. Charles Smith determined the remaining compaction curves. Jon Ingersoll conducted the hydraulic property tests—moisture retention and hydraulic conductivity. And finally, Dr. Patrick Black determined the unfrozen moisture content characteristics.

CONTENTS

ILLUSTRATIONS

Figure

TABLES

EXECUTIVE SUMMARY

Laboratory tests were conducted on pavement materials from the Minnesota Road Research Project (Mn/ROAD) to characterize their behavior under seasonal frost conditions, and to provide input necessary for modeling the materials with the Mechanistic Pavement Design and Evaluation Procedure under development at CRREL. Test results described in this report include those to generally characterize physical properties: grain-size distribution, specific gravity, Atterberg limits, organic content, hydraulic properties (moisture retention and hydraulic conductivity), and compaction. Also included are tests more specifically related to freeze/thaw processes: frost susceptibility and unfrozen moisture content at subfreezing temperatures. Results of resilient modulus tests determined in both the frozen and thawed (or unfrozen) condition are reported separately (Berg et al. 1996).

The materials reported on here include four samples of the clay subgrade from beneath the Mn/ROAD site and the two bases with the least (class 6 special) and greatest (class 3 special) amounts of the fine fraction. When this testing was performed, the two bases with intermediate amounts of fines (class 4 special and class 5 special) were unavailable. However, to conduct subsequent modeling with the Mechanistic Design Procedure (Bigl and Berg 1996), it was necessary to approximate their behavior using properties of similar materials. Therefore, this report includes characterization test results conducted previously on materials most closely matching the specified size gradations of the class 4 and 5 subbases. A subbase from taxiway A at the Albany, New York, airport (Cole et al. 1987) substituted for the class 4 special subbase. Dense-graded stone, from a Winchendon, Massachusetts, test site (Cole et al. 1986) substituted for the class 5 special. These materials are referred to here, respectively, as TAS (taxiway A subbase) and DGS (dense-graded stone).

Three of the four subgrade samples have grain size distributions that classify them as sandy lean clays, while the fourth is classified as a clayey sand. Both the class 3 special, a well-graded sand, and the class 6 special, a well-graded gravel with sand, met the Mn/DOT specifications. The TAS material is finer at the no. 40 and no. 200 sieve sizes than the specifications for the class 4 special, so that its predicted behavior may not be exactly the same as the actual material. Dense-graded stone meets the specifications for class 5 special except for slightly exceeding the amount of fines at the no. 200 sieve.

Frost-susceptibility test results indicate that two of the subgrade samples rank as being highly frost susceptible; the other two subgrade samples rank medium in frost susceptibility. Of the base materials, data on the class 3 and substitute class 4 materials are unavailable; the DGS material (class 5 substitute) ranked medium and the class 6 special material ranked as having negligible frost susceptibility.

Moisture retention and unstaturated hydraulic conductivity tests were conducted in a pressure cell permeameter at tensions ranging from 0 to 700 cm of water (0 to 10 lb/in.^{2}). Water contents by weight percent had the following ranges: subgrades 14–22%, class 3 special 5–12%, TAS 5–9%, DGS 3–17%, and class 6 special 1–18%. Hydraulic conductivities in cm/hr ranged as follows: subgrades 10^{-2} to 10^{-5}

cm/hr (3×10^{-8} to 3×10^{-11} m/s), class 3 special 4.5 to 10^{-4} cm/hr (10^{-5} to 3×10^{-10} m/s), TAS 2.7 to 10^{-4} cm/hr (8×10^{-6} to 3×10^{-10} m/s), DGS 5.5 to 10^{-5} cm/hr (10^{-5} to 3×10^{-11} m/s), and class 6 special 4.7 to 10^{-5} cm/hr (10^{-5} to 3×10^{-11} m/s).

The variation of unfrozen moisture content with temperature was determined using pulsed nuclear magnetic resonance. Subgrade samples contained about 5% unfrozen moisture at temperatures below –2°C; class 3 special and class 6 special materials contained less than 1% unfrozen moisture at these temperatures. Unfrozen moisture content data are not available for the substitute materials.

Testing of Materials from the Minnesota Cold Regions Pavement Research Test Facility

SUSAN R. BIGL AND RICHARD L. BERG

INTRODUCTION

This is one of four reports that describe work conducted by the U.S. Army Cold Regions Research and Engineering Laboratory related to the Minnesota Road Research Project (Mn/ROAD) constructed by the Minnesota Department of Transportation (Mn/DOT). The emphasis of this report is to summarize information resulting from various laboratory tests conducted to characterize materials from Mn/ROAD. Another report discusses the results of resilient modulus testing of the Mn/ROAD materials (Berg et al. 1996). A third report describes computer modeling that applies the mechanistic design procedure under development at CRREL to some of the Mn/ROAD test sections (Bigl and Berg 1996a), and the final report summarizes information in the first three reports (Bigl and Berg 1996b).

The laboratory tests discussed here include frost susceptibility (along with the physical properties: grain-size distribution, specific gravity, optimum density and moisture content at specified compactive efforts, Atterberg limits, and organic content), hydraulic properties, and unfrozen moisture content.

Materials received

Laboratory testing was performed on samples of the clay subgrade from beneath the Mn/ROAD site and on two of the materials that were used as base and subbase in the pavement sections at Mn/ROAD. During the testing, a double nomenclature was developed for the subgrade samples. Mn/DOT refers to the samples as no. 563, 564, 565, and 566. We alternatively refer to these same respective materials as samples 1171, 1193, 1206, and 1232.

The base and subbase materials tested included the class 3 special subbase, a material with a high percentage of fines, and the class 6 special base, which has a relatively small amount of fines. The "special" specifications for the base and subbase materials were established specifically for Mn/ROAD, and are different from Mn/DOT's normal base/subbase specifications. Class 3 special and class 6 special materials were initially transmitted to us as separate size fractions. We created some samples by mixing these fractions to achieve gradations near the center of the limits specified by Mn/DOT; these samples are referred to as "blended" materials. Subsequently, we received samples of these materials drawn from stockpiles created for Mn/ROAD. We refer to these as "stockpile" samples.

Mn/DOT also used two other subbase materials at the Mn/ROAD facility, termed class 4 special and class 5 special, which have percentages of fines that lie intermediate between class 3 special and class 6 special. Testing of these materials was accomplished under a later contract. However, in order to model the predicted damage of test sections that include class 4 special and class 5 special materials, their behavior was approximated using data from materials tested during prior studies that most closely matched their specified size gradations. A "dense-graded stone," that had been tested during a cooperative study in Winchendon, Massachusetts, was the material in our database that most closely matched the size gradation specifications of the class 5 special subbase. A subbase from taxiway A at the Albany, New York, airport most closely matched the gradation of the class 4 special subbase specifications. We report here, where available, the comparable data for these substitute materials. A full report of their original testing can be found in Cole et al. (1987) for the Albany taxiway A subbase and in Cole et al. (1986) for the dense-graded stone.

Matrix of laboratory testing

Table 1 summarizes the matrix of laboratory tests conducted on the Mn/DOT materials and includes recommended future work. The table includes the tests that had been conducted on the class 3 special and class 6 special "blended" samples prior to receiving the "stockpile" materials. Further testing of the blended samples was stopped when the stockpile materials were received.

TEST RESULTS

Physical properties

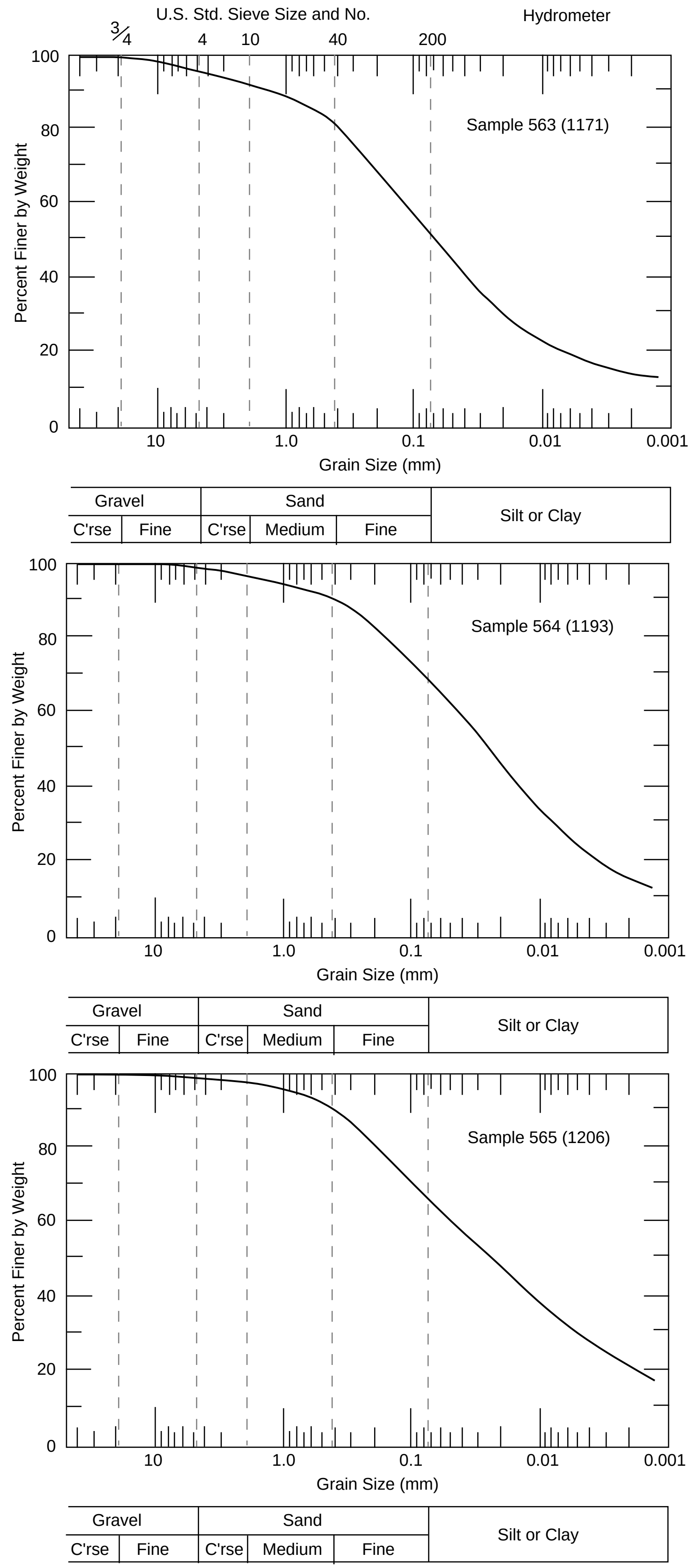
Grain size distribution

We analyzed the particle size of the materials according to ASTM standard D422-63 and classified them according to ASTM D2487-83 as shown in Table 2. Table 2 also lists the equivalent classification according to AASHTO (1990). The resulting grain-size distribution curves are shown in Figure 1; final data from the analyses are in Appendix A. Figure 1 includes the revised specification limits for the class 3 special and class 6 special materials. The blended class 3 special material is slightly finer at sieves no. 10 and no. 40 than required by the specifications; the class 3 special stockpile meets the specification limits. Grain size distribution data are unavailable for the

Table 1. Laboratory tests performed on Mn/ROAD materials.

	Physical properties							
Material	*Grain size*	*Specific gravity*	*Atterberg limits*	*Organic content*	*Compact test*	*Frost suscept.*	*Hydraul. prop.*	*Unfrozen moisture*
Subgrade								
1171 (563)	o	o	o	o	o	o	o	o
1193 (564)	o	o	o	o	o	o	–	o
1206 (565)	o	o	o	o	o	o	o	o
1232 (566)	o	o	o	o	o	o	o	o
Class 3 sp								
Blended	o	o	–	–	o	–	o	–
Stockpile	o	o	o	–	o	F	o	o
Class 4 sp								
Taxiway A subbase	•	•	–	–	–	–	•	–
Class 5 sp								
Dense–graded stone	•	•	•	–	–	•	•	–
Class 6 sp								
Blended	–	o	–	–	o	o	o	–
Stockpile	o	o	–	–	o	F	–	o

Notes:
o work completed in this study
• data estimated from previous studies
F recommended future work
– no plan to complete this cell in test matrix
"Blended" materials were created from two components supplied by Mn/DOT
"Stockpile" materials were furnished from stockpiles created for the Mn/ROAD project

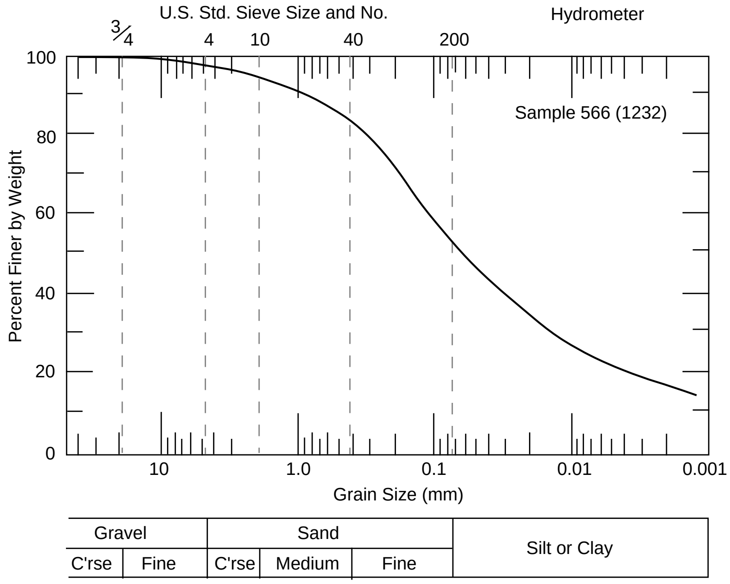


a. Subgrade sample 1171 (563).

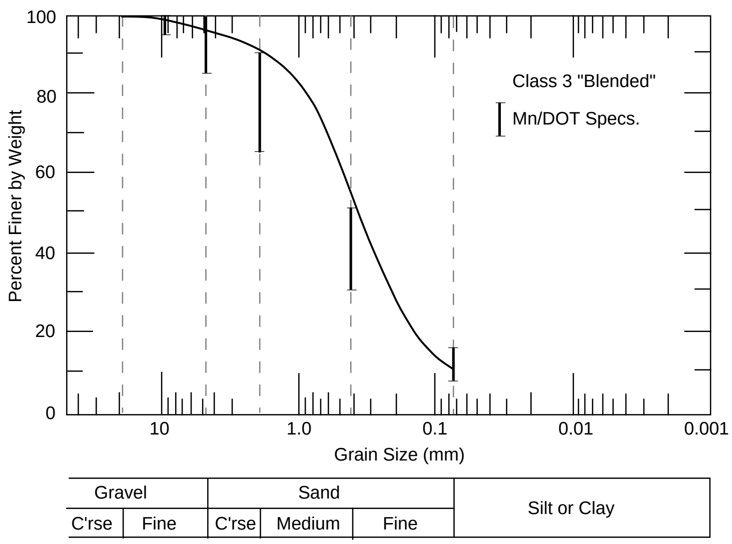
b. Subgrade sample 1193 (564).

c. Subgrade sample 1206 (565).

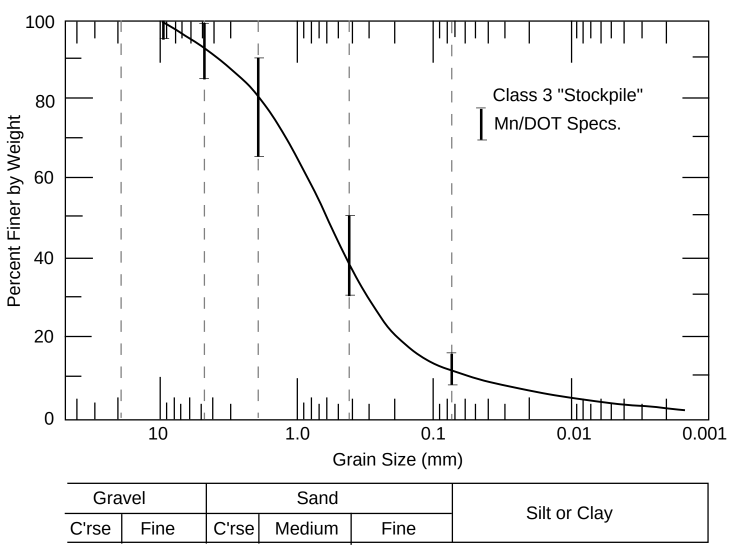
Figure 1. Grain size distribution of Mn/ROAD materials. Figures 1e to 1g that show the subbase and base materials include the range of Mn/DOT specifications.



d. Subgrade sample 1232 (566).

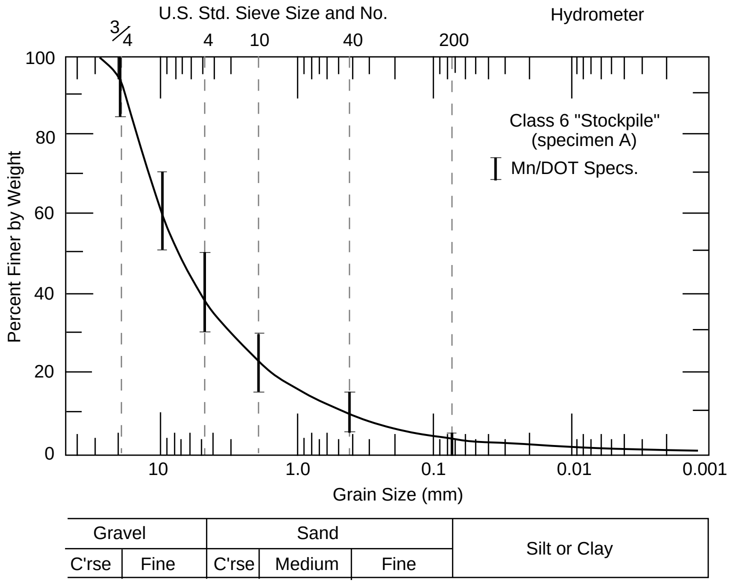


e.Class 3 special blended.



f. Class 3 special stockpile.

Figure 1 (cont'd). Grain size distribution of Mn/ROAD materials. Figures 1e to 1g that show the subbase and base materials include the range of Mn/DOT specifications.



g. Class 6 special stockpile, specimen A.

Figure 1 (cont'd).

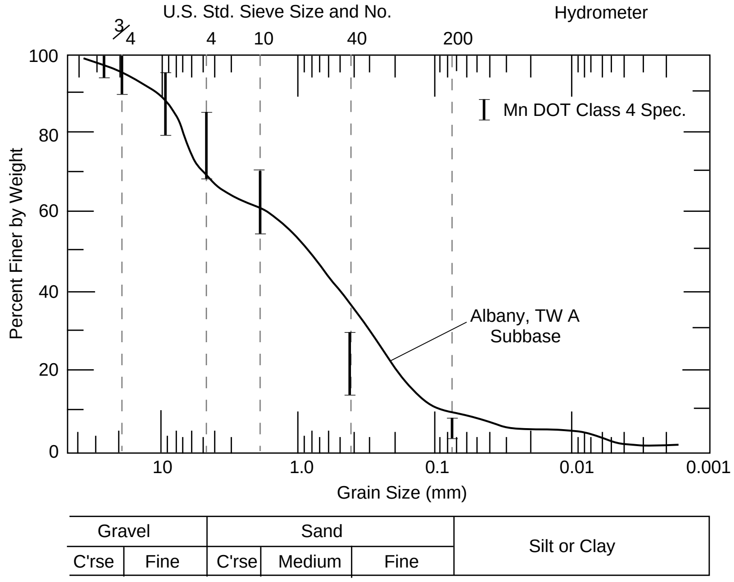
Table 2. Physical properties of Mn/ROAD materials.

Material	*Classification*		*Specific*	*Atterberg limits*		*Organic content*
	ASTM	*AASHTO*	*gravity*	*LL*	*PI*	*(%)*
Subgrade						
1171 (563)	SC, Clayey sand	A-6	2.70	30.6	10.6	1.1
1193 (564)	CL, Sandy lean clay	A-6	2.70	31.2	14.3	1.4
1206 (565)	CL, Sandy lean clay	A-6	2.70	37.0	18.5	1.5
1232 (566)	CL, Sandy lean clay	A-6	2.71	26.4	10.9	0.7
Class 3						
Blended	SW, Well-graded sand	—	—	—	—	—
Stockpile	SW, Well-graded sand	A-1-b	2.69	17.0*	1.2*	—
Class 4						
Albany taxiway A subbase†	SM, Silty sand	A-1-b	2.73	—	—	—
Class 5:						
Dense-graded stone†	GW, Well-graded gravel	A-1-a with sand	2.81	23*	3*	—
Class 6:						
Blended	GW, Well-graded gravel	A-1-a	2.79	—	—	—
Stockpile		with sand		2.74	—	—

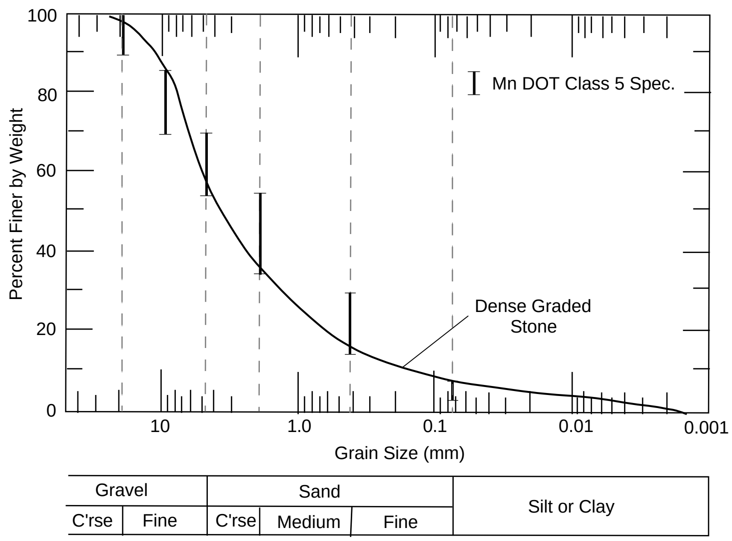
* minus no. 40 sieve fraction.
† from Cole et al. (1986, 1987)

class 6 special blended material; however, the gradation of the class 6 special stockpile meets specifications.

Grain size distribution of the materials substituted for class 4 special and class 5 special are shown in Figure 2, along with the Mn/DOT specifications. The taxiway A subbase substituted for the class 4 special is finer than the specifications at the no. 40 and no. 200 sieve sizes, so that its predicted behavior may not be exactly the same as the actual material. Dense-graded stone, the substitute for class 5 special



a. Albany taxiway A subbase/class 4 special base.



b. Dense-graded stone, Winchendon/ class 5 special base.

Figure 2. Grain size distribution of substitute materials and specifications for equivalent Mn/ROAD bases.

subbase, meets the specifications except for slightly exceeding the amount of fines at the no. 200 sieve.

Atterberg limits

Atterberg limits were performed on all the subgrade materials and on the fraction of the class 3 special stockpile material that passed the no. 40 sieve (ASTM D4318-84; Table 2). Limits of the minus no. 40 sieve fraction of the dense-graded stone are also noted in Table 2. Cole et al. (1987) did not conduct Atterberg limit tests on the Albany taxiway A subbase.

Specific gravity

Table 2 includes the results of the specific gravity tests conducted on the Mn/DOT materials according to ASTM D854-83. Also listed are the results for the substitute materials from Cole et al. (1986, 1987).

Organic content

Organic contents were conducted only on the subgrade materials, using ASTM D2974-87, Method C with a maximum furnace temperature of 500°C. Results are given in Table 2. No organic content data are available for the substitute materials.

Table 3. Compaction test results—Mn/ROAD materials.

Material	*Maximum dry density lb/ft 3 (Mg/m3)*	*Optimum water content (wt %)*	*Method employed*
Subgrade			
1171 (563)	120.1 (1.92)	13.8	CE-55
1193 (564)	120.6 (1.93)	13.2	CE-55
1206 (565)	117.8 (1.89)	15.5	CE-55
1206 (565)	105.5 (1.69)	18.0	CE-12
1206 (565)	102.1 (1.64)	20.4	5 K
1232 (566)	124.4 (1.99)	11.9	CE-55
Class 3			
Blended	117.0 (1.87)	11.0	CE-12
Stockpile	131.8 (2.11)	7.6	CE-55
Stockpile	123.7 (1.99)	11.0	CE-12
Class 6			
Blended	132.3 (2.12)	4.1	CE-55
Stockpile	130.4 (2.09)	2.1	CE-55
Stockpile	120.8 (1.93)	4.0	CE-12

Notes:
CE-55 is similar to AASHTO T-180
CE-12 is similar to AASHTO T-99
5 K has a compactive effort of 5,000 ft-lb/ft^3 (239 kJ/m^3)

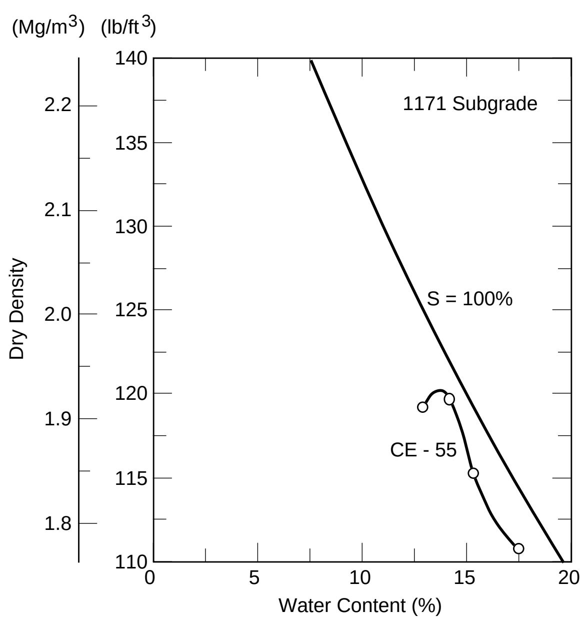
Compaction

Results of the compaction tests are shown in Figure 3 and summarized in Table 3, along with the method used. Appendix B contains raw data from the tests. We used three compactive procedures in the tests conducted: 1) Army method CE-55 (MIL-STD-621A, method 100), which is similar to the modified AASHTO compaction test (AASHTO T-180-74) and involves a compactive effort of 55,000 ft-lb/ ft^3 (2,630 kJ/m^3); 2) method CE-12 (MIL-STD-621A; equivalent to AASHTO T-99-81), which provides 12,000 ft-lb/ft^3(575 kJ/ m^3) of compactive effort; and 3) a procedure providing 5,000 ft-lb/ft^3 (239 kJ/m^3) of compactive effort using the same equipment used for the CE-55 and CE-12 methods. In all cases, a mechanical compactor with a "sector foot" was used to compact the samples.

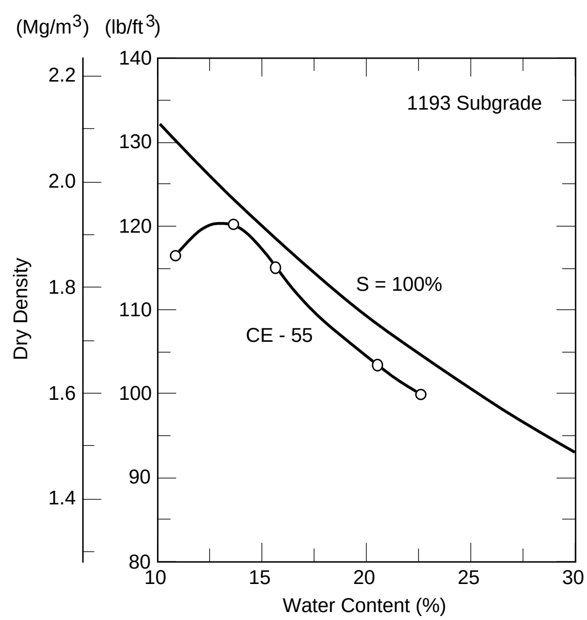
Cole et al. (1987) did not provide compaction data for the class 4 special and class 5 special subbase substitute materials.

Frost susceptibility

Frost susceptibility tests were conducted using the procedures described in Chamberlain (1987). Frost susceptibility was determined by subjecting

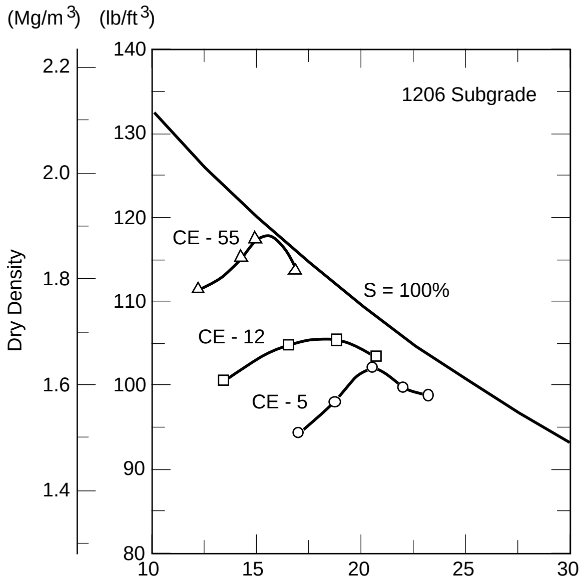


a. Subgrade sample 1171 (563).

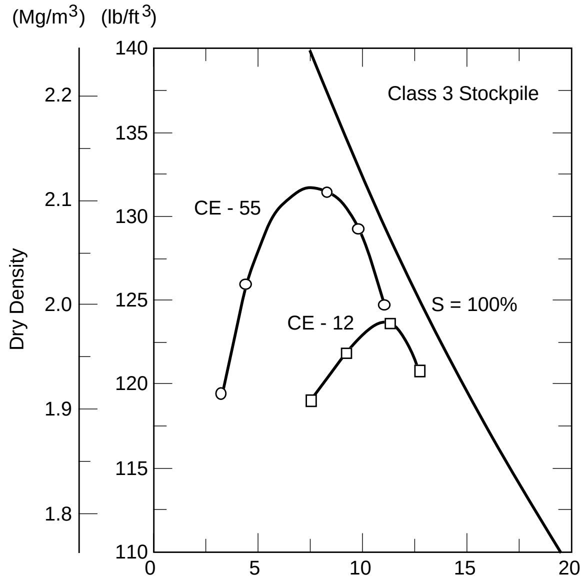


b. Subgrade sample 1193 (564).

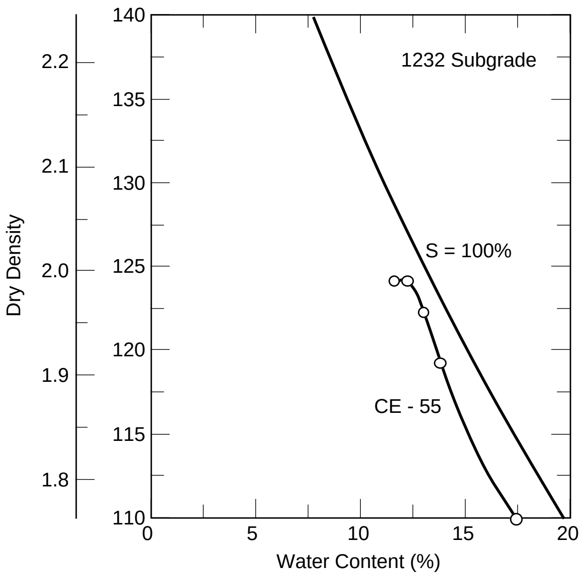
Figure 3. Compaction test results.



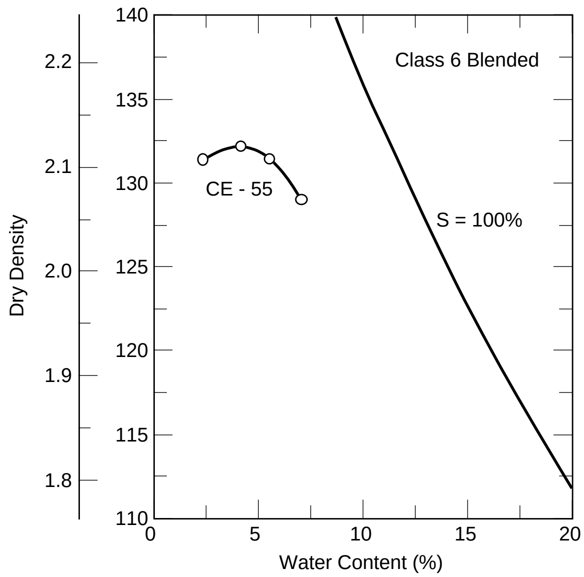
c. Subgrade sample 1206 (565).



e. Class 3 special blended.



d. Subgrade sample 1232 (566).



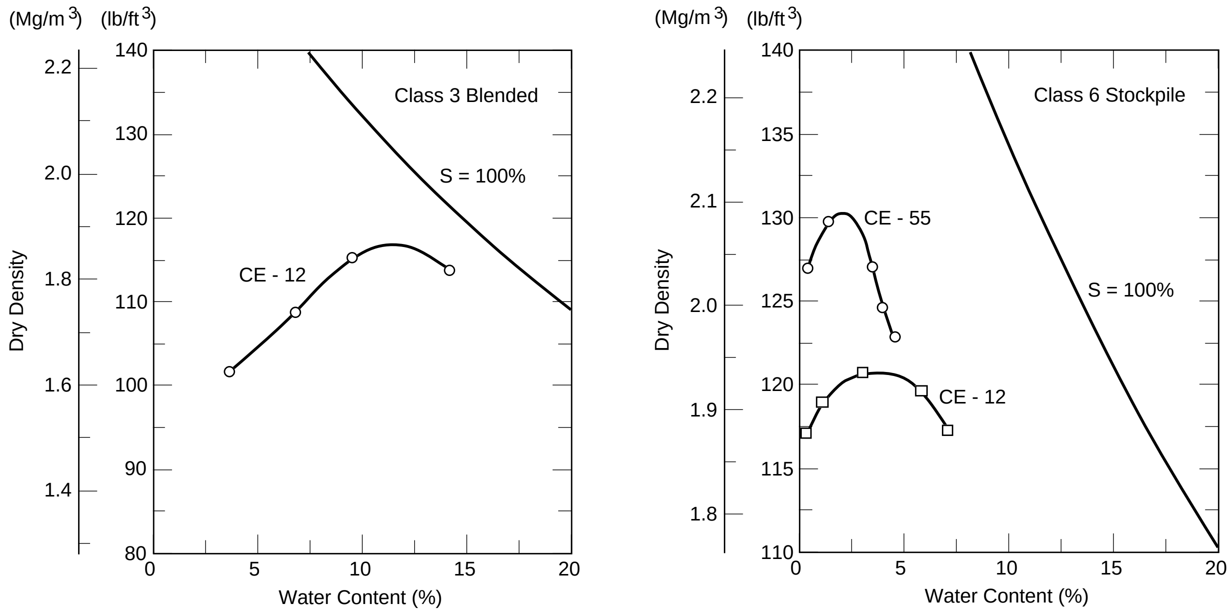
f. Class 3 special stockpile.

Figure 3 (cont'd). Compaction test results.

a soil sample to two freezing cycles and determining the heave rate during the first 8 hours of each cycle. The 8-hr heave rate was then converted to an equivalent heave rate in mm/day. The heave rate from the two cycles can vary significantly, especially if the soil contains large amounts of clay. To determine the thaw weakening of the soil at the completion of the test, a CBR (California Bearing Ratio) test is run on the thawed sample after allowing drainage for 24 hours. The sample's frost susceptibility classification is then determined

Table 4. Tentative frost susceptibility criteria (from Chamberlain 1987).

Frost susceptibility classification	*8-hr heave rate (mm/day)*	*Thaw CBR (%)*
Negligible	< 1	> 20
Very low	1–2	20–15
Low	2–4	15–10
Medium	4–8	10–5
High	8–16	5–2
Very high	>16	< 2



g. Class 6 special blended. *h. Class 6 special stockpile.*

Figure 3 (cont'd).

using the criteria shown in Table 4. Results from these tests are used as a relative index rather than a quantitative predictor of behavior.

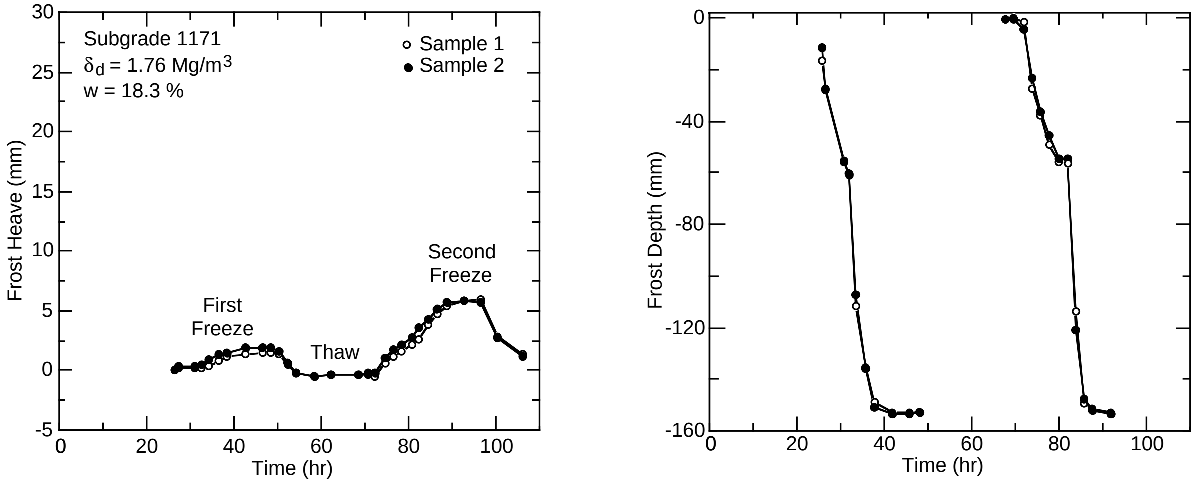
A partial frost susceptibility test was conducted on the class 3 special stockpile material, but equipment problems were discovered while running the test, and the results are not presented.

Table 5 summarizes the frost susceptibility test results for the subgrade samples and the class 6 special blended material. Figure 4 plots time variation of the frost heave and frost depth data recorded during the tests, which are also reported in Appendix C. It should be noted that when samples of subgrade 1206 and 1232 were frozen a third time to prepare them for the frozen resilient modulus testing, both soils heaved at a rate that would have been considered highly frost susceptible. The data suggest that the frost susceptibility of the subgrade may increase with increasing freeze-thaw cycles.

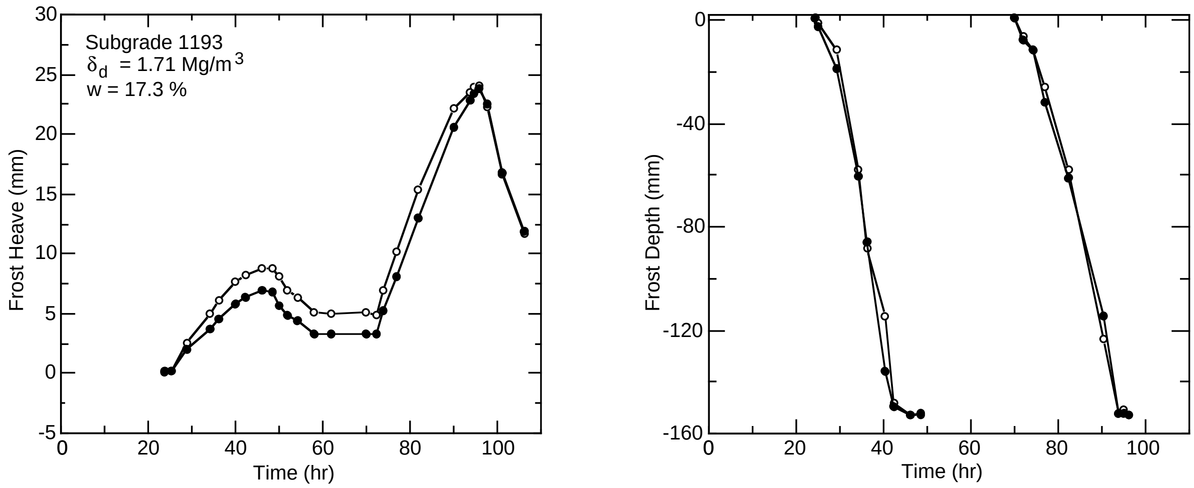
Table 5. Frost susceptibility test results.

	1st freeze cycle		*2nd freeze cycle*		*CBR test*		
Material	*Hv rate (mm/day)*	*Rating**	*Hv rate (mm/day)*	*Rating**	*CBR (%)*	*Rating**	*Overall rating*
Subgrade							
1171 (563)	1	V. low	7.5	Medium	2	High	Medium
1193 (564)	9.3	High	22.5	V. high	<1	V. high	V. high
1206 (565)	9.3	High	16	High	<1	V. high	V. high
1232 (566)	1	V. low	7.5	Medium	2	High	Medium
Class 5 (dense stone)							
Sample 1	3.0	Low	3.0	Low	7	Medium	Low
Sample 2	NF	—	4.3	Medium	11	Low	Medium
Sample 3	5.5	Medium	5.4	Medium	11	Low	Medium
Sample 4	5.3	Medium	5.3	Medium	12	Low	Medium
Class 6							
blended	<1	Negl.	<1	Negl.	29	Negl.	Negl.

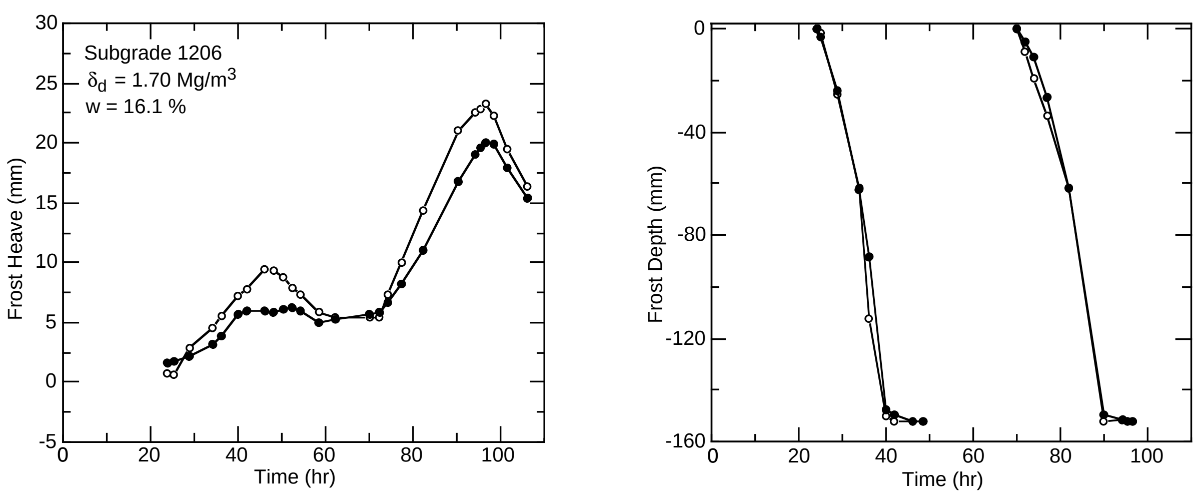
* Frost susceptibility rating



a. Subgrade sample 1171 (563).

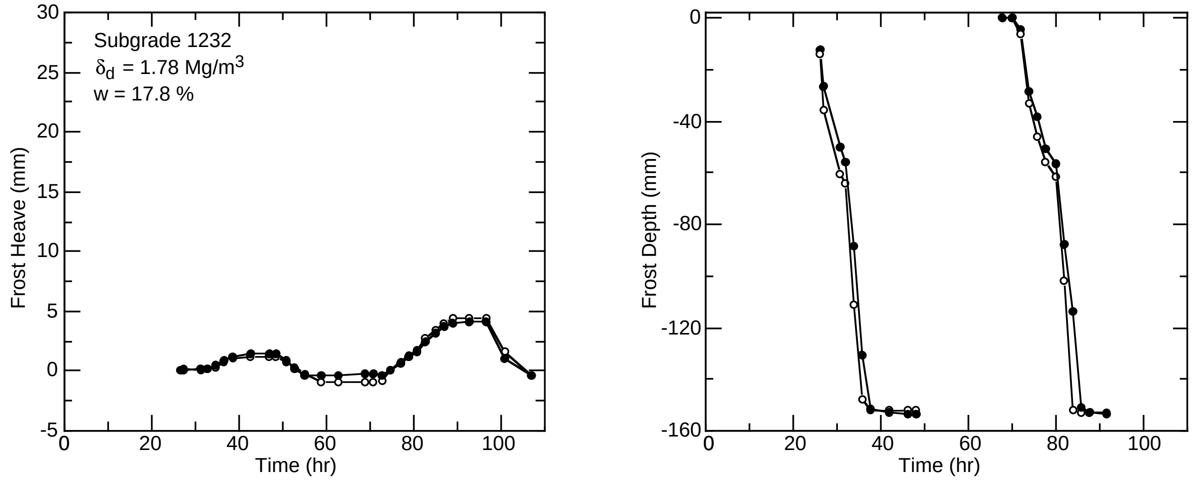


b. Subgrade sample 1193 (564).

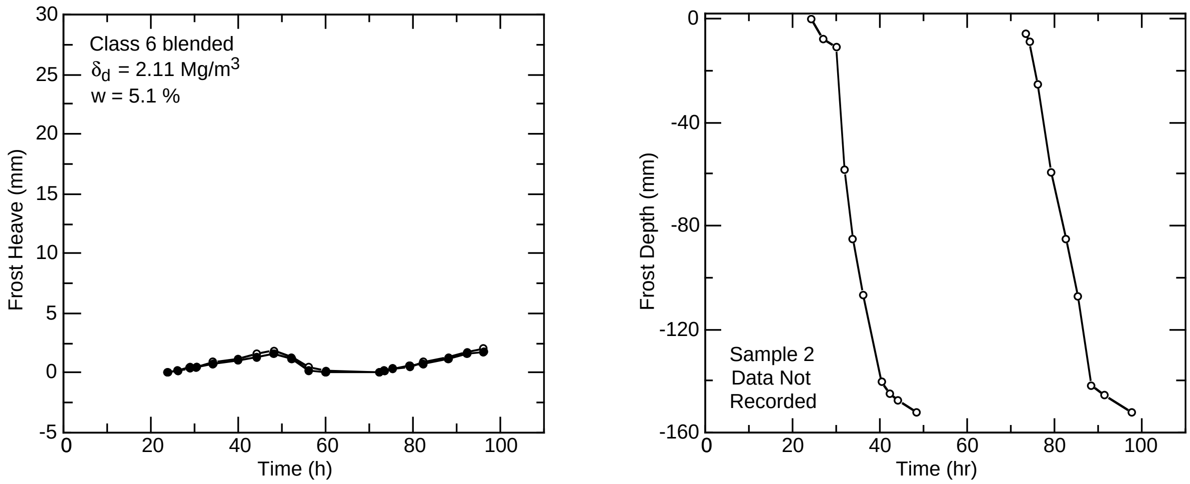


c. Subgrade sample 1206 (565).

Figure 4. Data from frost susceptibility test on Mn/ROAD materials.



d. Subgrade sample 1232 (566).



e. Class 6 special blended.

Figure 4 (cont'd).

Of the two substitute materials, frost susceptibility data are available only for dense-graded stone, as reported by Chamberlain (1986). Figure 5 shows the heave data, which are summarized in Table 5.

The data indicate that the frost susceptibility classifications of the subgrades range from medium to very high. The well-graded class 6 special base has negligible frost susceptibility, and the dense-graded stone (class 5 substitute) ranks as having medium frost susceptibility.

Hydraulic properties

Moisture retention and unstaturated hydraulic conductivity tests were conducted in a pressure cell permeameter using the procedures described in Ingersoll (1981). A typical moisture retention test begins with a saturated sample that is dried incrementally to determine point values of moisture content and pore pressure head, during what is termed the drying or extraction phase of the test. Incremental amounts of moisture are then reintroduced to the sample in the wetting or absorption phase. At each moisture condition, an unstaturated hydraulic conductivity test is also conducted. Materials tested included subgrade samples 1171, 1206, and 1232; class 3 special and class 6 special blended materials; and class 3 special stockpile material. Data are also available for both substitute materials for class 4 special and class 5 special. Appendix D contains data from the moisture retention and unstaturated hydraulic conductivity tests.

The coarse nature of the class 6 material required a modification of the sample preparation procedure described by Ingersoll (1981). An 1/8-in. (3-mm) layer of coarse sand was placed at the contact with both the lower and upper porous plates of the test cell to allow proper capillary action at these interfaces. It is extremely difficult to obtain accurate data at tensions near saturation on the class 6 material because it drains so easily. Be aware, then, that the low tension data points are estimates, while the values at higher tensions are more accurate. To check that the inserted sand layers were not a large influence on the hydraulic test, a conventional saturated permeability test was also run on the class 6 special material. The result was 6.0 cm/hr, which compares favorably with 4.7 cm/hr from the pressure cell permeameter.

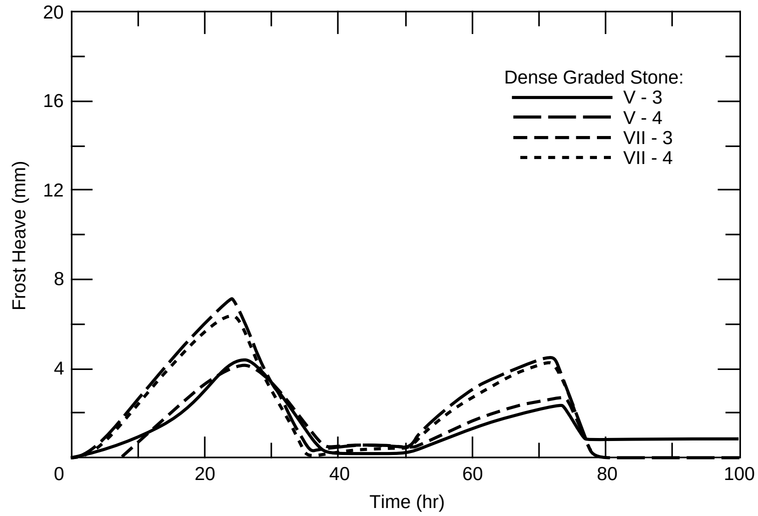


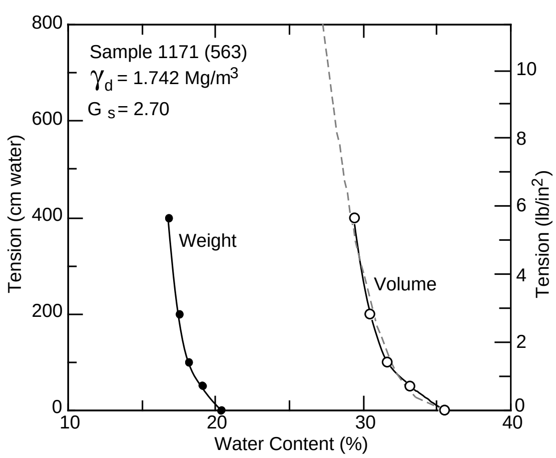
Figure 5. Data from frost susceptibility test on dense-graded stone (from Chamberlain 1986).

A final note is that the test on the subgrade sample 1171 was terminated during the extraction phase because an unknown amount of water was lost. Extraction values are also the only data available for the class 3 special blended subbase, class 6 special blended base, dense-graded stone base, and taxiway A subbase.

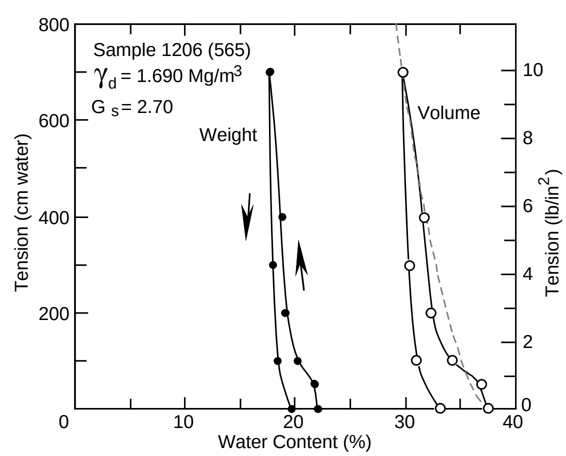
Figure 6 shows results of the moisture retention tests expressed both as weight and volumetric percentages. To view the results in terms of tension in kilopascals, divide the centimeters of water units by a factor of 10. The dashed lines in Figure 6 represent the calculated values used in the mechanistic design procedure to approximate the data using an equation in the form of Gardner's (1958), as follows:

$$\theta_u = \frac{\theta_o}{A_w \left| h_p \right|^{\alpha} + 1} \qquad (1)$$

where θ_u = volumetric unfrozen water content (%)
θ_o = soil porosity (%)
h_p = pore pressure head (cm of water)
A_w = Gardner's multiplier for the moisture characteristics
α = Gardner's exponent for the moisture characteristics.

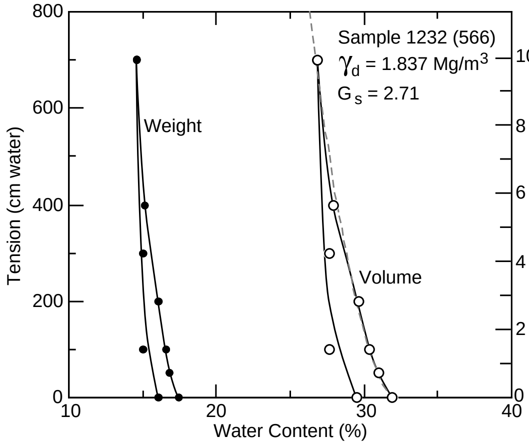


a. Subgrade sample 1171 (563).

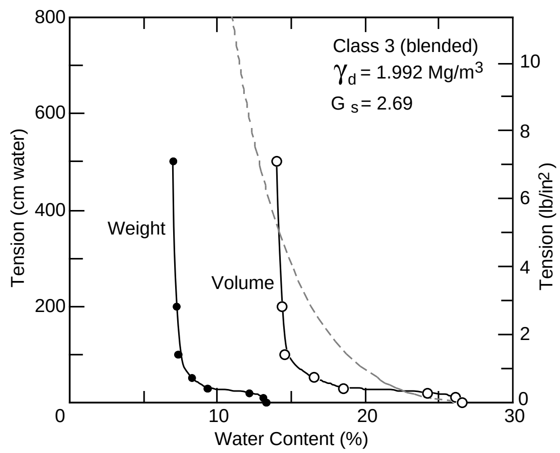


b. Subgrade sample 1206 (565).

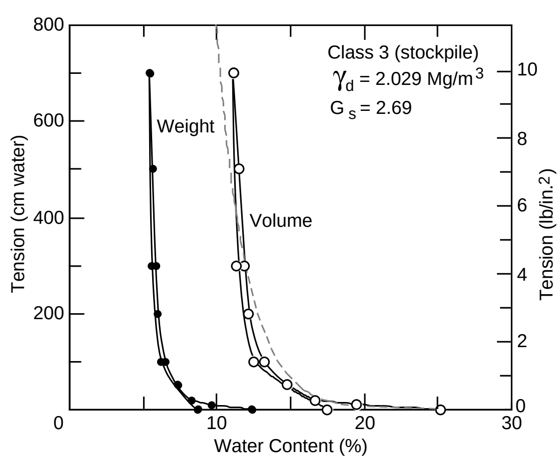
Figure 6. Moisture retention test results. Dashed line represents Gardner's equation approximation of the extraction data.



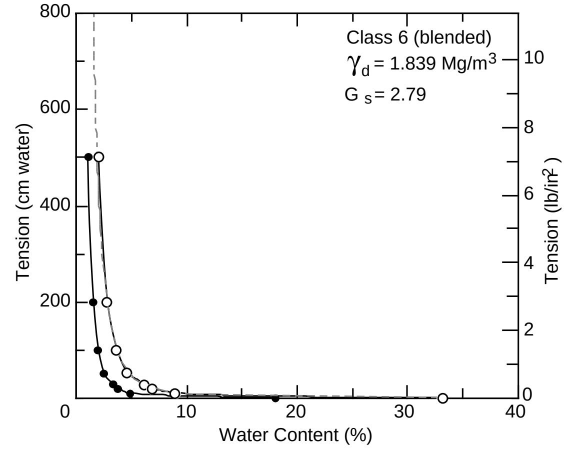
c. Subgrade sample 1232 (566).



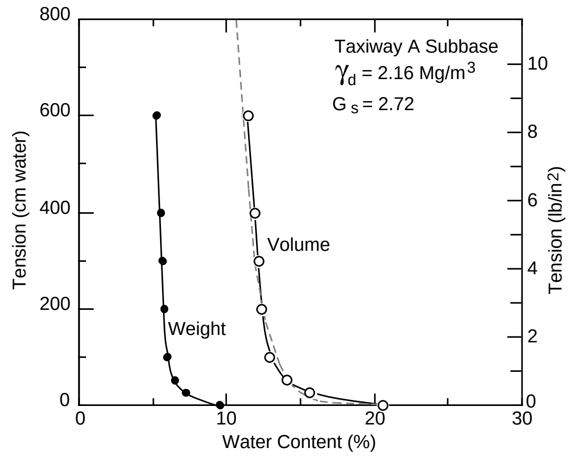
d. Class 3 special blended.



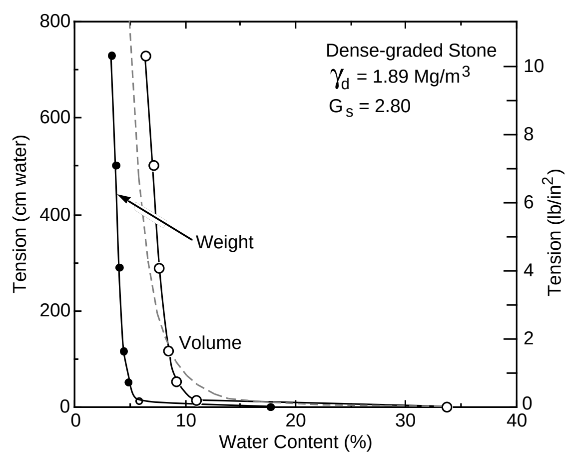
e. Class 3 special stockpile.



f. Class 6 special blended.



g. Taxiway A subbase.



h. Dense-graded stone.

Figure 6 (cont'd). Moisture retention test results. Dashed line represents Gardner's equation approximation of the extraction data.

Table 6. Coefficients for hydraulic properties in the form of Gardner's equations.

Material	*Moisture retention* A_w	α	*Hydraulic conductivity* A_K	β
Subgrade				
1171 (563)	0.01232	0.4760	0.1647	1.5905
1206 (565)	0.002399	0.7134	0.0005713	2.6395
1232 (566)	0.002260	0.6790	0.001885	1.8129
Class 3				
Blended	0.026538	0.5933	0.0010507	3.5199
Stockpile	0.1735	0.3239	1647.1	0.7207
Class 4				
Taxiway A aubbase	0.1520	0.2690	6.59×10^{-5}	2.9620
Class 5				
Dense-graded stone	0.4961	0.3660	3.912	1.3930
Class 6				
Blended	1.0001	0.4444	1.0729×10^{-6}	5.8979

We determined point values of θ_u and h_p in the moisture retention test and fitted eq 1 to the extraction curve using a least squares approach to determine the best fitted parameters A_w and α. Table 6 lists these parameters for the samples tested.

Results of the hydraulic conductivity tests are displayed vs. pore water tension in Figure 7. Again, the dashed line in Figure 7 is the best fit approximation used in the model to represent the unsaturated hydraulic conductivity using the equation:

$$K_H = \frac{k_s}{A_K \left| h_p \right|^{\beta} + 1} \tag{2}$$

where K_H = unsaturated hydraulic conductivity (cm/hr)

k_s = saturated hydraulic conductivity (cm/hr)

h_p = pore pressure head (cm of water)

A_K = Gardner's multiplier for hydraulic conductivity

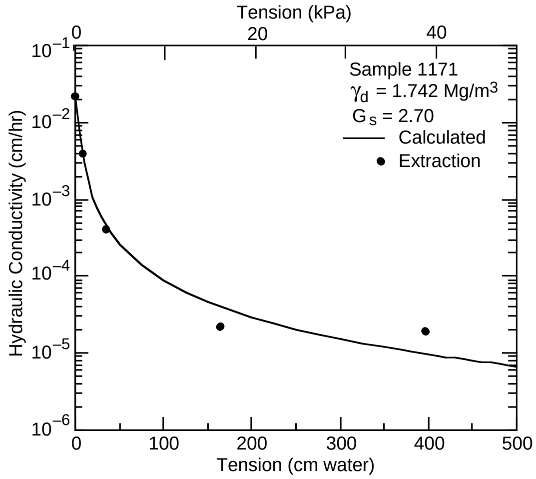
β = Gardner's exponent for hydraulic conductivity.

We determined point values of K_H and h_p for each sample and fitted eq 2 to the extraction data using a least squares approach to determine the best fitted parameters A_K and β (Table 6).

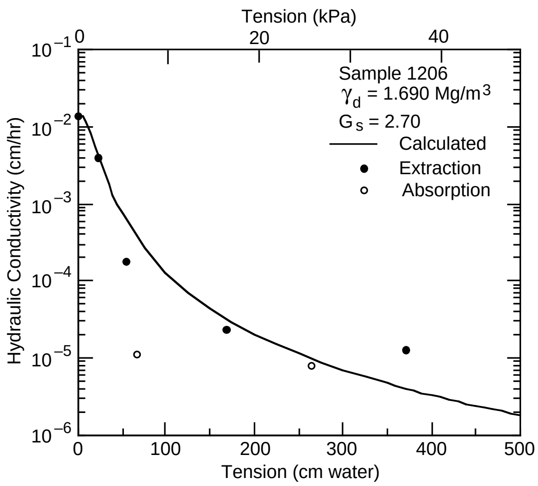
Figure 8 shows the relationship between degree of saturation and hydraulic conductivity for the materials tested and for the substitute materials. Exponential regression curves fit to the data, which include both extraction and absorption values, are shown in Table 7.

Table 7. Coefficients for hydraulic properties relating hydraulic conductivity (k, cm/hr) to degree of saturation (S, %) in the form $k = A \times 10^{B \times S}$.

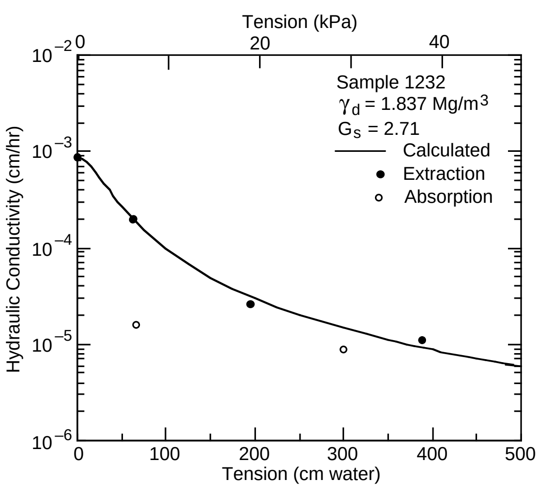
Material	*A*	*B*
Subgrade		
1171 (563)	8.539×10^{-21}	0.184
1206 (565)	9.503×10^{-22}	0.189
1232 (566)	5.880×10^{-20}	0.161
Class 3		
Blended	3.035×10^{-11}	0.114
Stockpile	1.061×10^{-9}	0.100
Class 4		
Taxiway A subbase	1.981×10^{-10}	0.103
Class 5		
Dense-graded stone	8.3491×10^{-5}	0.050
Class 6		
Blended	1.063×10^{-4}	0.056



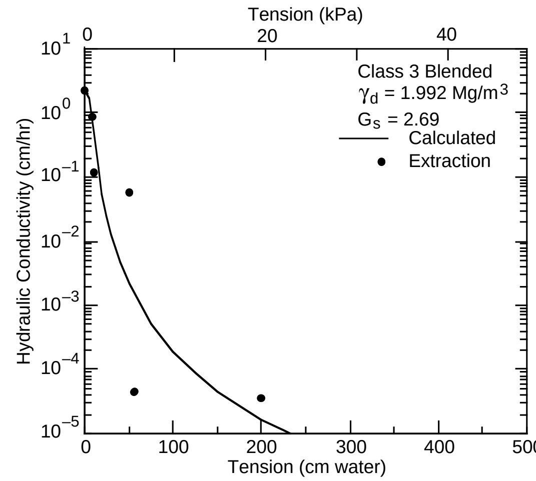
a. Subgrade sample 1171 (563).



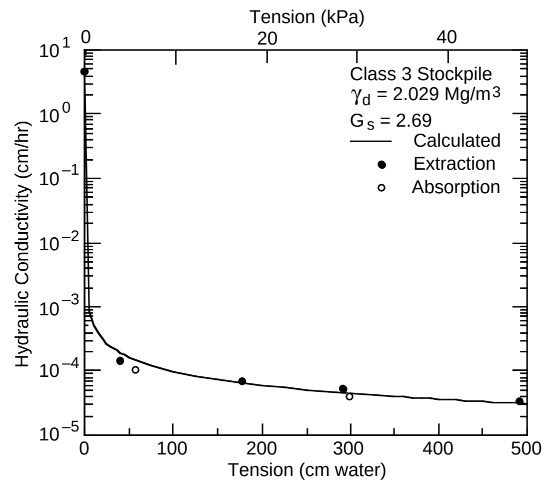
b. Subgrade sample 1206 (565).



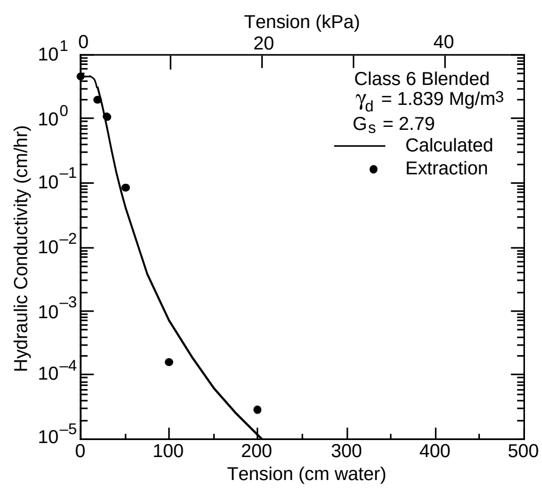
c. Subgrade sample 1232 (566).



d. Class 3 special blended.

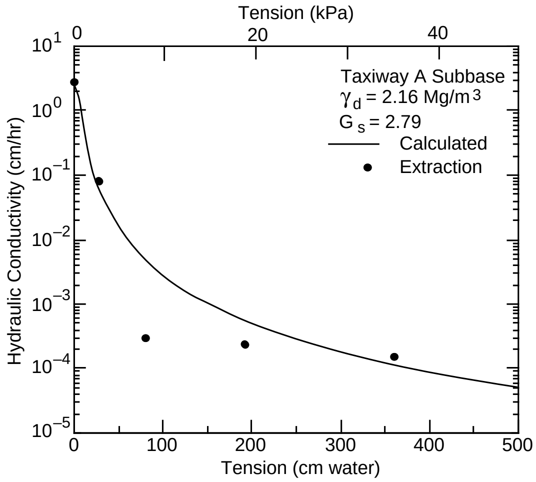


e. Class 3 special stockpile.

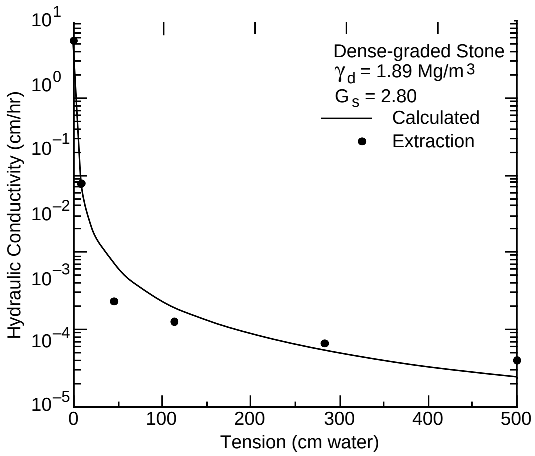


f. Class 6 special blended

Figure 7. Tension vs. hydraulic conductivity curves. Solid line represents Gardner's equation approximation of the extraction data.

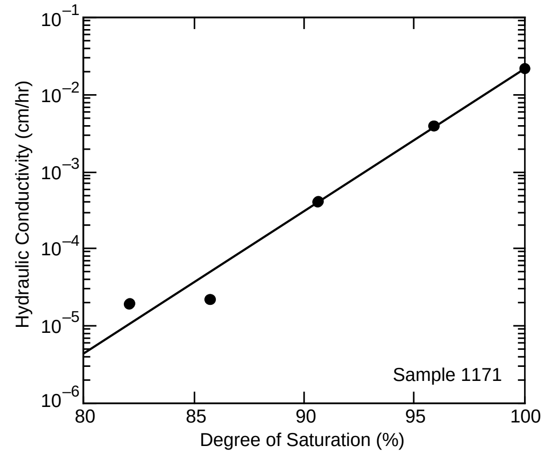


g. Taxiway A subbase.

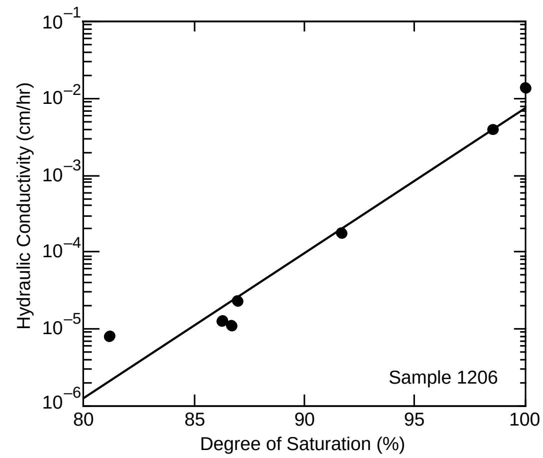


h. Dense-graded stone.

Figure 7 (cont'd). Tension vs. hydraulic conductivity curves. Solid line represents Gardner's equation approximation of the extraction data.



a. Subgrade sample 1171 (563)



b. Subgrade sample 1206 (565).

Figure 8. Degree of saturation vs. hydraulic conductivity curves. Solid line is an exponential regression fitted to both the extraction and absorption data, when available.

The best fit lines shown in Figures 7 and 8 are those that are generated from eq 1 and 2. Other equations may fit data from some samples better, but the Gardner's form equation is that currently employed in the mechanistic design procedure.

Unfrozen moisture content

The variation of unfrozen moisture content with temperature was determined by testing each material with a pulsed nuclear magnetic resonance technique (Tice et al. 1982). The cooling curve data are presented in Appendix E and in Figure 9. The figure also includes a curve of calculated values used to represent the data in the mechanistic procedure, produced with an equation in the form:

$$w_u = \alpha \left(\frac{-T}{T_0} \right)^{\beta} \; ; \; T < 0°C \qquad (3)$$

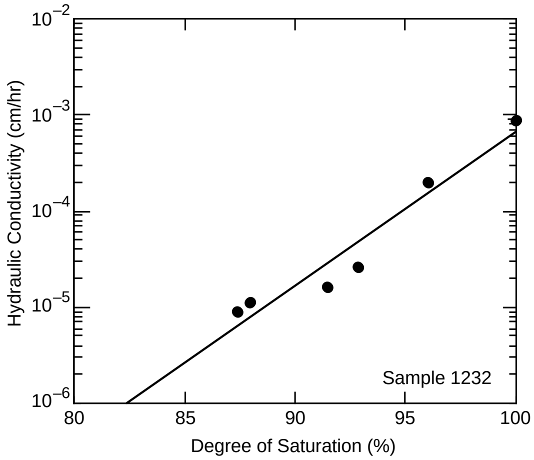
where w_u = gravimetric unfrozen moisture content (%)

T = temperature (°C)

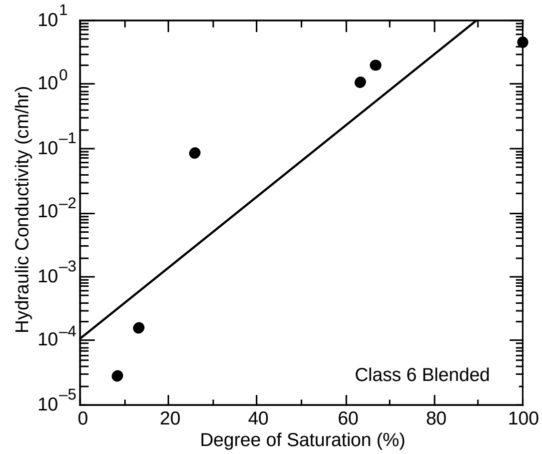
T_0 = 1.0°C

α and β = constants

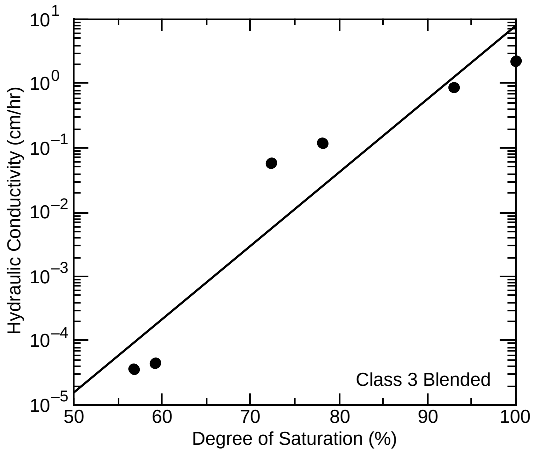
Table 8 presents the constants determined for each sample. The class 6 special stockpile material was split into two fractions above and below the no. 30 sieve. The calculated curve represents the equation developed for the minus no. 30 sieve fraction.



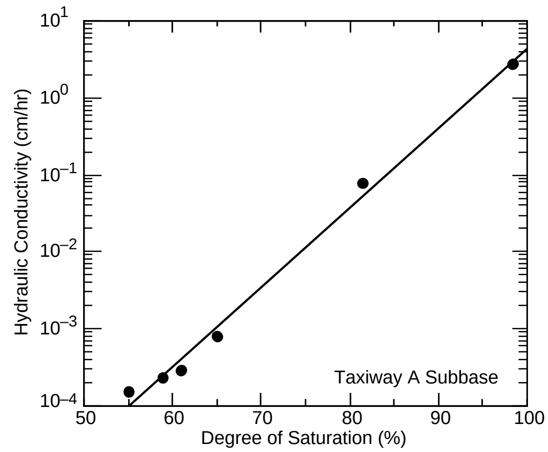
c. Subgrade sample 1232 (566).



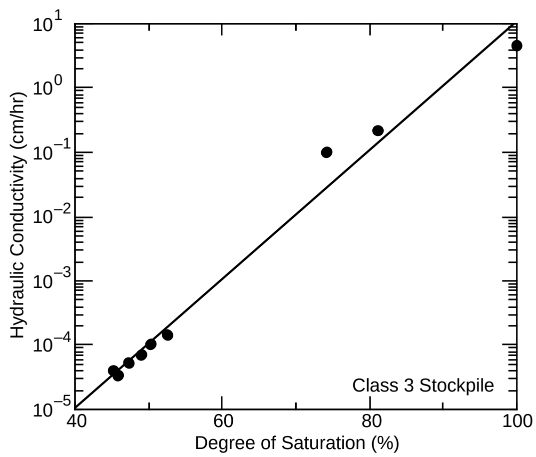
f. Class 6 special blended.



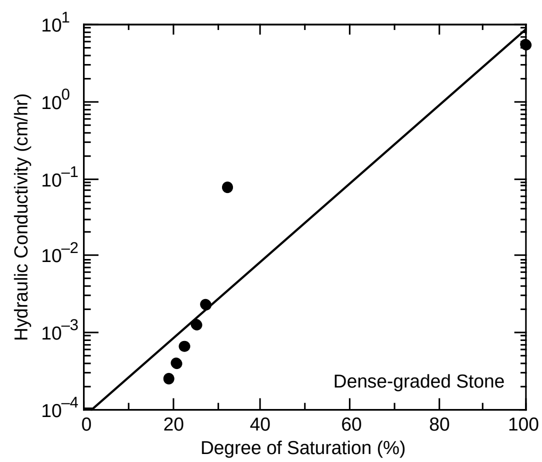
d. Class 3 special blended.



g. Taxiway A subbase.

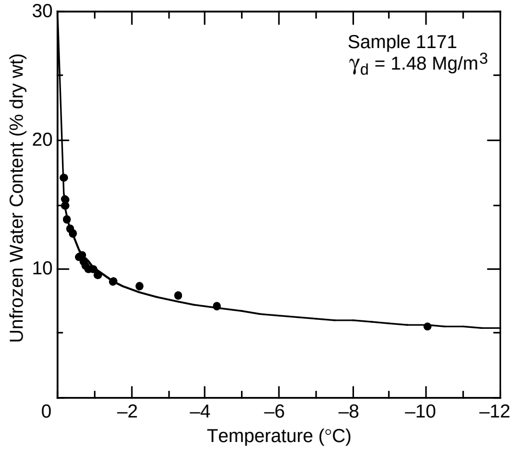


e. Class 3 special stockpile.

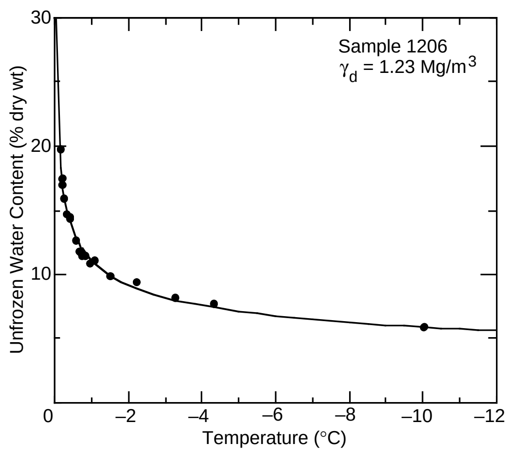


h. Dense-graded stone.

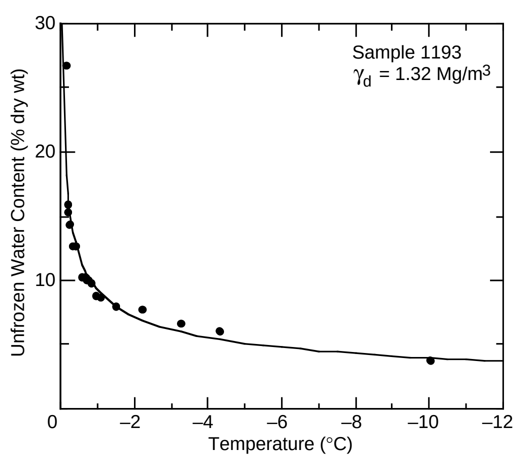
Figure 8 (cont'd). Degree of saturation vs. hydraulic conductivity curves. Solid line is exponential regression fit to both the extraction and absorption data, when available.



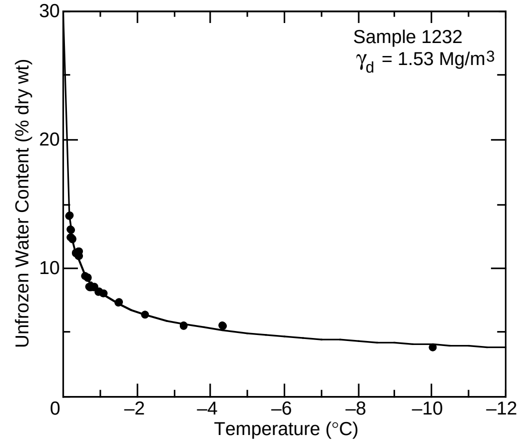
a. Subgrade sample 1171 (563).



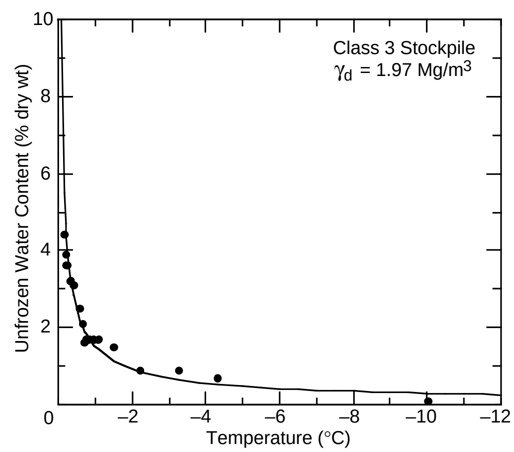
b. Subgrade sample 1193 (564).



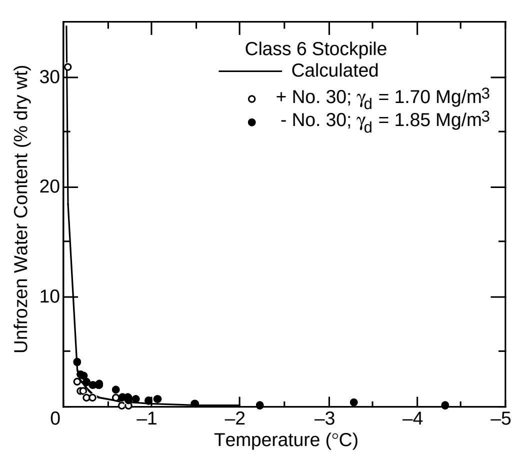
c. Subgrade sample 1206 (565).



d. Subgrade sample 1232 (566).



e. Class 3 special stockpile.



f. Class 6 special stockpile.

Figure 9. Temperature vs. gravimetric unfrozen water content curves. Solid line represents calculated values to approximate the data.

Table 8. Constants for unfrozen moisture content equations (expressed as a percentage).

Material	α	β
Subgrade		
1171 (563)	10.038	–0.250
1193 (564)	9.285	–0.369
1206 (565)	11.085	–0.274
1232 (566)	8.121	–0.303
Class 3		
Stockpile	1.497	–0.709
Class 4		
Taxiway A subbase	3.0*	–0.25*
Class 5		
Dense-graded stone	2.0*	–0.4*
Class 6		
Stockpile		
+ No. 30	0.232	–1.461
– No. 30	0.567	–1.115

*Estimated; no data available

Unfrozen moisture content data are not available for the substitute materials, so constants to approximate their behavior were estimated. Table 8 lists the constants originally estimated for these materials by Cole et al. (1986, 1987); we continue their use.

Note that the subgrade samples contained approximately 5% unfrozen moisture at temperatures below –2°C; the class 3 special and class 6 special materials contained less than 1% unfrozen moisture at these temperatures.

CONCLUSIONS

This report has described the results of laboratory testing conducted to determine the physical and behavioral characteristics of materials believed to represent those that will be incorporated into the Mn/ROAD Research Facility. We can use our full understanding of these characteristics to predict the behavior of these materials with the Mechanistic Pavement Design Procedure under de– velopment at CRREL (Bigl and Berg 1996a). Performance data from Mn/ROAD will allow us to verify/modify the procedure to better predict time to failure of pavement systems.

LITERATURE CITED

American Association of State Highway and Transportation Officials (AASHTO) (1990) Standard specifications for transportation materials and methods of sampling and testing, Part 1. Specifications.

American Society of Testing and Materials (ASTM) (1985) ASTM D 422-63, Standard method for particle-size analysis of soils. 1985 Annual Book of ASTM Standards, Section 4: *Construction*, Vol. 04.08, *Soil and Rock*: *Building Stones.*

American Society of Testing and Materials (ASTM) (1985) ASTM D 854-83, Standard test method for specific gravity of soils. 1985 Annual Book of ASTM Standards, Section 4: *Construction*, Vol. 04.08, *Soil and Rock*: *Building Stones*.

American Society of Testing and Materials (ASTM) (1985) ASTM D 2487-83, Standard method for classification of soils for engineering purposes. 1985 Annual Book of ASTM Standards, Section 4: *Construction*, Vol. 04.08, *Soil and Rock: Building Stones*.

American Society of Testing and Materials (ASTM) (1985) ASTM D 4318-84, Standard test method for liquid limit, plastic limit, and plasticity index of soils. 1985 Annual Book of ASTM Standards, Section 4: *Construction*, Vol. 04.08, *Soil and Rock: Building Stones*.

American Society of Testing and Materials (ASTM) (1987) ASTM D 2974-87 Test method for moisture, ash, and organic matter of peat and other organic soils. 1987 Annual Book of ASTM Standards, Section 4: *Construction*, Vol. 04.08, *Soil and Rock: Building Stones*.

Berg, R.L., S.R. Bigl, J.A. Stark and G.D. Durell (1996) Resilient modulus testing of materials from Mn/ROAD, Phase 1. USA Cold Regions Research and Engineering Laboratory, Special Report 96-19, Mn/DOT Report 96-21.

Bigl, S.R. and R.L. Berg (1996a) Modeling of Mn/ROAD test sections with the CRREL mechanistic pavement design procedure. USA Cold Regions Research and Engineering Laboratory, Special Report 96-21, Mn/DOT Report 96-22.

Bigl, S.R. and R.L. Berg (1996b) Material testing and initial pavement design modeling: Minnesota Road Research Project. USA Cold Regions Research and Engineering Laboratory, CRREL Report 96-14, Mn/DOT Report 96-23.

Chamberlain, E.J. (1986) Evaluation of selected frost susceptibility test methods. USA Cold Regions Research and Engineering Laboratory, CRREL Report 86-14.

Chamberlain, E.J. (1987) A freeze thaw test to determine the frost susceptibility of soils. USA Cold Regions Research and Engineering Laboratory, Special Report 87-1.

Cole, D.M., D. Bentley, G.D. Durell and T. Johnson (1986) Resilient modulus of freeze-thaw affected granular soils for pavement design and evaluation. Part 1. Laboratory tests on soils from Winchendon, Massachusetts, test sections. USA Cold Regions Research and Engineering Laboratory, CRREL Report 86-4.

Cole, D.M., D. Bentley, G.D. Durell and T. Johnson (1987) Resilient modulus of freeze-thaw affected granular soils for pavement design and evaluation. Part 3. Laboratory tests on soils from Albany County Airport. USA Cold Regions Research and Engineering Laboratory, CRREL Report 87-2.

Gardner, W.R. (1958) Some steady-state solutions of the unsaturated flow equation with application to evaporation from a water table. *Soil Science*, **88**: 228–232.

Ingersoll, J. (1981) Method for coincidentally determining soil hydraulic conductivity and moisture retention characteristics. USA Cold Regions Research and Engineering Laboratory, Special Report 81-2.

Tice, A. R., J. L. Oliphant, Y. Nakano and T. F. Jenkins (1982) Relationship between the ice and unfrozen water phases in frozen soil as determined by pulsed nuclear magnetic resonance and physical absorption data. USA Cold Regions Research and Engineering Laboratory, CRREL Report 82-15.

U. S. Department of Defense (1964) MIL-STD-621A, Test methods for pavement subgrade, subbase, and base-course materials.

APPENDIX A. GRAIN SIZE DISTRIBUTION OF MN/DOT MATERIALS

Sieve Size/No.	Openings (mm)	Percent Passing (by weight) Sample 1171(563)	Sample 1193(564)	Sample 1206(565)	Sample 1232(566)
1.0 (in)	24.50	100.0	100.0	100.0	100.0
3/4 (in)	19.10	99.7	99.9	99.9	99.9
3/8 (in)	9.52	97.6	99.4	99.7	99.1
# 4	4.75	94.7	98.7	99.2	97.8
# 10	2.00	91.3	96.2	98.1	93.9
# 20	0.85	86.7	93.3	95.2	89.0
# 40	0.43	81.2	90.0	90.7	83.2
# 60	0.25	--	--	--	--
# 80	0.18	66.5	80.8	78.4	68.7
#100	0.15	--	--	--	--
#200	0.75	48.2	68.6	64.8	53.1

Hydrometer Results

Diam. (mm)	% Passing Total	Diam. (mm)	% Passing Total	Diam. (mm)	% Passing Total	Diam. (mm)	% Passing Total
0.0423	37.6	0.0367	57.9	0.0380	57.3	0.0413	44.7
0.0304	35.2	0.0270	53.0	0.0279	52.1	0.0302	39.4
0.0199	29.9	0.0182	44.4	0.0183	46.9	0.0197	34.2
0.0143	27.0	0.0134	38.8	0.0134	41.6	0.0141	31.6
0.0115	24.6	0.0112	35.7	0.0105	37.7	0.0117	28.9
0.0085	21.7	0.0081	30.8	0.0080	35.1	0.0084	25.0
0.0061	19.4	0.0057	27.1	0.0058	31.3	0.0060	22.4
0.0030	15.5	0.0030	20.6	0.0029	23.7	0.0029	18.9
0.0013	11.7	0.0013	13.6	0.0013	16.9	0.0013	13.2

Soil Class:	Clayey Sand, SC	Sandy Lean Clay, CL	Sandy Lean Clay, CL	Sandy Lean Clay, CL

APPENDIX A (CONT'D). GRAIN SIZE DISTRIBUTION OF MN/DOT MATERIALS

Sieve Size/No.	Openings (mm)	Percent Passing (by weight) Class 3 Blended	Class 3 Stockpile	Class 6 Stockpile
1.0 (in)	24.50			100.0
3/4 (in)	19.10	100.0		94.1
3/8 (in)	9.52	98.4	100.0	60.3
# 4	4.75	96.0	92.4	38.1
# 10	2.00	91.1	80.0	22.5
# 20	0.85	78.9	61.0	14.5
# 40	0.43	52.6	38.8	10.2
# 60	0.25	33.2	25.1	7.5
# 80	0.18	--	--	--
#100	0.15	18.5	16.6	5.5
#200	0.75	10.7	12.1	3.7

Hydrometer Results

Diam. (mm)	% Passing Total	Diam. (mm)	% Passing Total	Diam. (mm)	% Passing Total
		0.0476	9.6	0.0327	2.4
		0.0341	7.9	0.0210	1.9
		0.0217	7.0	0.0150	1.6
		0.0154	6.1	0.0123	1.4
		0.0126	5.7	0.0087	1.2
		0.0090	4.8	0.0062	1.0
		0.0064	4.4	0.0024	0.6
		0.0045	3.5	0.0013	0.5
		0.0015	1.7		

Soil Class	Class 3 Blended	Class 3 Stockpile	Class 6 Stockpile
	Well-graded Sand, SW	Well-graded Sand, SW	Well-graded Gravel With Sand, GW

APPENDIX B. SUMMARY OF COMPACTION DATA

Sample 1171

Test Method = CE-55 Mold Diam = 6 in; G_s= 2.699

Test Points	1	2	3	4	5
Wet soil + mold (gm)	11233.00	11305.00	11185.00	11086.00	
Mold (gm)	6660.00	6660.00	6660.00	6660.00	
Tare + Wet Soil (gm)	429.57	446.11	403.36	467.23	
Tare + Dry Soil (gm)	382.47	392.84	352.05	400.40	
Tare (gm)	17.28	18.16	17.91	18.21	
Water Content (%)	12.9	14.2	15.4	17.5	
Dry Density (pcf)	119.1	119.5	115.3	110.7	

Optimum Water Content (%) 13.8
Maximum Dry Density (pcf) 120.1

Sample 1193

Test Method = CE-55 Mold Diam = 6 in; G_s= 2.699

Test Points	1	2	3	4	5
Wet soil + mold (gm)	11051.00	11308.00	11190.00	10897.00	10823.00
Mold (gm)	6660.00	6660.00	6660.00	6660.00	6660.00
Tare + Wet Soil (gm)	255.40	185.00	462.30	510.51	502.47
Tare + Dry Soil (gm)	232.11	163.90	402.04	426.72	413.11
Tare (gm)	17.71	9.11	17.90	18.28	18.10
Water Content (%)	10.9	13.6	15.7	20.5	22.6
Dry Density (pcf)	116.4	120.2	115.1	103.3	99.8

Optimum Water Content (%) 13.2
Maximum Dry Density (pcf) 120.6

Sample 1206

Test Method = CE-55 Mold Diam = 6 in; G_s= 2.70

Test Points	1	2	3	4	5
Wet soil + mold (gm)	10909.00	11141.00	11239.00	11182.00	
Mold (gm)	6660.00	6660.00	6660.00	6660.00	
Tare + Wet Soil (gm)	314.43	351.33	404.72	425.04	
Tare + Dry Soil (gm)	282.19	309.74	354.68	366.51	
Tare (gm)	18.03	18.17	17.91	18.28	
Water Content (%)	12.2	14.3	14.9	16.8	
Dry Density (pcf)	111.3	115.3	117.2	113.8	

Optimum Water Content (%) 15.5
Maximum Dry Density (pcf) 117.8

APPENDIX B (CONT'D). SUMMARY OF COMPACTION DATA

Sample 1206 (cont.)

Test Method = CE-12 EQUIV   Mold Diam = 4 in; G_S= 2.70

Test Points	1	2	3	4	5
Wet soil + mold (gm)	6085.00	6206.00	6254.00	6247.00	
Mold (gm)	4364.00	4364.00	4364.00	4364.00	
Tare + Wet Soil (gm)	148.79	183.25	196.34	192.33	
Tare + Dry Soil (gm)	133.46	160.00	168.31	162.57	
Tare (gm)	18.82	18.85	18.87	18.84	
Water Content (%)	13.4	16.5	18.8	20.7	
Dry Density (pcf)	100.5	104.7	105.4	103.3	

Optimum Water Content (%)   18.0
Maximum Dry Density (pcf)   105.5

Test Method = CE-5   Mold Diam = 4 in; G_S= 2.70

Test Points	1	2	3	4	5
Wet soil + mold (gm)	6030.00	6122.00	6221.00	6201.00	6202.00
Mold (gm)	4364.40	4364.40	4364.40	4364.40	4364.40
Tare + Wet Soil (gm)	251.00	256.14	280.36	370.61	296.26
Tare + Dry Soil (gm)	217.35	218.85	235.95	306.07	243.92
Tare (gm)	18.91	18.82	18.71	18.65	18.65
Water Content (%)	17.0	18.6	20.4	22.5	23.2
Dry Density (pcf)	94.3	98.1	102.1	99.5	98.7

Optimum Water Content (%)   20.4
Maximum Dry Density (pcf)   102.1

Sample 1232

Test Method = CE-55   Mold Diam = 6 in; G_S= 2.71

Test Points	1	2	3	4	5
Wet soil + mold (gm)	11374.00	11278.00	11360.00	11403.00	11058.00
Mold (gm)	6660.00	6660.00	6660.00	6660.00	6660.00
Tare + Wet Soil (gm)	208.18	213.41	224.37	215.36	221.50
Tare + Dry Soil (gm)	187.43	188.62	199.60	192.83	190.00
Tare (gm)	8.85	9.09	8.96	9.11	8.80
Water Content (%)	11.6	13.8	13.0	12.3	17.4
Dry Density (pcf)	124.1	119.3	122.3	124.2	110.1

Optimum Water Content (%)   11.9
Maximum Dry Density (pcf)   124.4

APPENDIX B (CONT'D).

Class 3 Blended

Test Method = CE-12 EQUIV   Mold Diam = 6 in; G_S= 2.69

Test Points	1	2	3	4	5
Wet soil + mold (gm)	11672.00	12045.00	12391.00	12520.00	
Mold (gm)	8096.00	8096.00	8096.00	8096.00	
Tare + Wet Soil (gm)	482.49	433.64	523.69	689.72	
Tare + Dry Soil (gm)	466.09	406.83	479.38	605.15	
Tare (gm)	9.28	9.18	8.95	9.18	
Water Content (%)	3.6	6.7	9.4	14.2	
Dry Density (pcf)	101.5	108.7	115.4	113.9	

Optimum Water Content (%)   11.0
Maximum Dry Density (pcf)   117.0

Class 3 Stockpile

Test Method = CE-12 EQUIV   Mold Diam = 6 in; G_S= 2.69

Test Points	1	2	3	4	5
Wet soil + mold (gm)	11013.00	11183.00	11336.00	11286.00	
Mold (gm)	6656.00	6656.00	6656.00	6656.00	
Tare + Wet Soil (gm)	676.20	945.55	996.94	1205.27	
Tare + Dry Soil (gm)	630.03	867.45	897.56	1071.08	
Tare (gm)	18.07	18.11	18.17	18.07	
Water Content (%)	7.6	9.2	11.3	12.8	
Dry Density (pcf)	119.1	121.9	123.6	120.7	

Optimum Water Content (%)   11.0
Maximum Dry Density (pcf)   123.7

Test Method = CE-55   Mold Diam = 6 in; G_S= 2.69

Test Points	1	2	3	4	5
Wet soil + mold (gm)	8344.00	8558.00	9088.00	8914.00	8796.00
Mold (gm)	4152.00	4083.00	4243.00	4083.00	4088.00
Tare + Wet Soil (gm)	727.59	759.11	995.13	922.33	1157.84
Tare + Dry Soil (gm)	705.39	727.62	920.50	841.71	1045.06
Tare (gm)	17.90	17.93	18.03	17.86	17.91
Water Content (%)	3.3	4.4	8.2	9.5	11.0
Dry Density (pcf)	119.3	126.0	131.6	129.7	124.7

Optimum Water Content (%)   7.6
Maximum Dry Density (pcf)   131.8

APPENDIX B (CONT'D). SUMMARY OF COMPACTION DATA

Class 6 Blended

Test Method = CE-55 Mold Diam = 6 in; G_S= 2.79

Test Points	1	2	3	4	5
Wet soil + mold (gm)	11196.00	11301.00	11340.00	11317.00	
Mold (gm)	6618.00	6618.00	6618.00	6618.00	
Tare + Wet Soil (gm)	4728.50	4750.00	5925.00	4966.00	
Tare + Dry Soil (gm)	4634.60	4587.00	5688.80	4663.00	
Tare (gm)	599.00	595.70	1346.00	347.30	
Water Content (%)	2.3	4.1	5.4	7.0	
Dry Density (pcf)	131.5	132.3	131.6	129.1	

Optimum Water Content (%) 4.1
Maximum Dry Density (pcf) 132.3

Class 6 Stockpile

Test Method = CE-12 EQUIV Mold Diam = 6 in; G_S= 2.74

Test Points	1	2	3	4	5
Wet soil + mold (gm)	10654.00	10749.00	10885.00	10961.00	10929.00
Mold (gm)	6655.00	6655.00	6655.00	6655.00	6655.00
Tare + Wet Soil (gm)	878.57	912.69	934.37	1368.90	1254.79
Tare + Dry Soil (gm)	875.15	902.35	907.34	1294.23	1172.49
Tare (gm)	17.90	17.70	18.03	18.08	18.05
Water Content (%)	0.4	1.2	3.0	5.9	7.1
Dry Density (pcf)	117.1	119.0	120.7	119.5	117.3

Optimum Water Content (%) 4.0
Maximum Dry Density (pcf) 120.8

Test Method = CE-55 Mold Diam = 6 in; G_S= 2.74

Test Points	1	2	3	4	5
Wet soil + mold (gm)	8508.00	8562.00	8655.00	8544.00	8729.00
Mold (gm)	4173.00	4087.00	4245.00	4174.00	4252.00
Tare + Wet Soil (gm)	1219.39	1170.10	1226.86	1177.11	1155.65
Tare + Dry Soil (gm)	1214.95	1130.99	1180.24	1126.05	1140.41
Tare (gm)	17.92	18.07	17.95	18.00	18.03
Water Content (%)	0.4	3.6	4.0	4.7	1.4
Dry Density (pcf)	126.9	126.9	124.6	122.7	129.8

Optimum Water Content (%) 2.1
Maximum Dry Density (pcf) 130.4

APPENDIX C. FROST SUSCEPTIBLITY TEST DATA

Subgrade 1171

γ_d = 109.6 pcf; W_{wt}= 18.3 %

Time (hrs)	Heave (mm)		Time (hrs)	Frost Depth (mm)	
	Sample 1	Sample 2		Sample 1	Sample 2
26.5	0.03	0.03	First Freeze		
27.3	0.14	0.39	25.8	-16.89	-11.82
31.0	0.21	0.39	26.7	-27.19	-28.10
32.7	0.15	0.45	30.8	-55.40	-55.64
34.3	0.39	0.93	31.9	-61.38	-60.61
36.5	0.80	1.28	33.6	-111.92	-107.49
38.3	1.15	1.52	35.9	-135.50	-135.72
42.5	1.39	1.88	37.8	-148.78	-150.66
46.6	1.46	1.88	41.9	-152.71	-153.25
48.5	1.52	1.89	45.9	-152.65	-153.18
50.3	1.34	1.54	48.1	-152.62	-153.14
52.2	0.52	0.66	Second Freeze		
54.4	-0.24	-0.21	67.5	-0.29	-0.74
58.3	-0.47	-0.44	69.7	-0.26	-0.71
62.4	-0.41	-0.32	71.7	-2.22	-4.66
68.4	-0.34	-0.31	73.8	-27.14	-23.59
70.6	-0.40	-0.25	75.7	-37.76	-36.20
72.5	-0.45	-0.24	77.8	-49.37	-45.81
74.5	0.60	1.05	80.0	-55.99	-54.75
76.7	1.19	1.70	81.9	-56.30	-54.72
78.6	1.61	2.23	83.8	-113.82	-121.22
80.6	2.14	2.70	85.6	-149.39	-147.46
82.5	2.61	3.58	87.8	-151.69	-152.08
84.5	3.84	4.35	91.9	-152.63	-153.35
86.5	4.67	5.05			
88.8	5.43	5.64			
92.6	5.79	5.77			
96.5	5.91	5.71			
100.4	2.86	2.73			
106.3	1.34	1.22			

[1] The data in this appendix are not original data points. They have been reconstructed by digitizing plots of the original data, which were misplaced.

APPENDIX C (CONT'D). FROST SUSCEPTIBLITY TEST DATA

Subgrade 1193

γ_d = 106.9 pcf; W_{wt} = 17.3 %

Time (hrs)	Heave (mm)		Time (hrs)	Frost Depth (mm)	
	Sample 1	Sample 2		Sample 1	Sample 2
24.0	0.11	0.22	First Freeze		
25.2	0.24	0.17	24.2	0.43	0.43
28.9	2.59	2.05	25.1	-1.46	-2.87
34.2	5.01	3.71	29.3	-11.92	-19.05
36.0	6.13	4.60	34.2	-57.68	-60.58
40.0	7.66	5.84	36.1	-88.59	-85.54
42.2	8.20	6.32	40.2	-114.72	-135.79
46.1	8.80	6.92	42.4	-148.61	-149.39
48.4	8.81	6.87	46.3	-152.76	-152.55
50.1	8.00	5.65	48.4	-152.65	-152.45
51.9	6.90	4.84	Second Freeze		
54.1	6.39	4.38	70.2	0.40	0.51
58.0	5.12	3.29	72.0	-6.51	-7.76
62.1	4.97	3.25	74.2	-11.73	-11.67
70.1	5.06	3.34	77.1	-26.27	-31.91
72.2	4.90	3.29	82.2	-57.68	-61.07
74.0	6.89	5.23	90.2	-123.30	-114.15
76.9	10.12	8.05	93.9	-152.45	-152.39
82.0	15.45	12.98	95.1	-150.72	-152.01
89.9	22.08	20.62	96.2	-152.68	-152.62
93.9	23.56	22.80			
94.8	23.92	23.33			
95.9	24.15	23.80			
97.8	22.24	22.52			
101.2	16.65	16.80			
106.0	11.77	11.85			

APPENDIX C (CONT'D).

Subgrade 1206

γ_d = 106.2 pcf; W_{wt}= 16.1 %

Time (hrs)	Heave (mm)		Time (hrs)	Frost Depth (mm)	
	Sample 1	Sample 2		Sample 1	Sample 2
24.0	0.82	1.67	First Freeze		
25.2	0.65	1.72	24.1	0.34	0.34
29.0	2.85	2.22	25.1	-1.75	-2.94
34.0	4.58	3.19	29.0	-25.52	-23.77
36.1	5.48	3.79	34.0	-61.87	-62.57
40.1	7.27	5.65	36.1	-112.67	-88.14
42.1	7.75	6.01	40.1	-150.40	-147.64
46.2	9.42	6.03	42.0	-151.97	-149.89
48.2	9.37	5.87	46.1	-152.45	-152.04
50.2	8.79	6.06	48.3	-152.00	-152.29
52.2	7.97	6.30	Second Freeze		
54.3	7.33	5.96	70.1	0.09	0.09
58.4	5.88	4.92	72.1	-9.14	-4.94
62.4	5.37	5.24	74.0	-19.70	-11.18
70.1	5.35	5.75	77.1	-33.51	-26.40
72.2	5.42	5.82	82.1	-61.55	-61.85
74.2	7.43	6.66	90.2	-152.31	-149.84
77.3	10.04	8.15	94.1	-151.79	-151.67
82.3	14.37	11.07	95.5	-152.05	-151.95
90.3	21.01	16.84	96.5	-152.33	-151.91
94.4	22.56	18.99			
95.4	22.86	19.64			
96.4	23.22	20.00			
98.3	22.28	19.84			
101.4	19.41	17.91			
106.3	16.31	15.39			

APPENDIX C (CONT'D). FROST SUSCEPTIBLITY TEST DATA

Subgrade 1232

γ_d = 111.2 pcf; W_{wt} = 17.8 %

Time (hrs)	Heave (mm) Sample 1	Heave (mm) Sample 2
26.4	0.08	0.13
27.1	0.14	0.13
31.0	0.10	0.14
32.6	0.16	0.21
34.7	0.40	0.50
36.7	0.70	0.86
38.5	1.00	1.16
42.7	1.13	1.46
46.8	1.15	1.48
48.5	1.15	1.48
50.7	0.75	0.91
52.8	0.29	0.21
54.9	-0.22	-0.37
58.8	-0.91	-0.35
62.8	-0.95	-0.34
68.7	-0.87	-0.21
70.8	-0.86	-0.26
72.9	-0.80	-0.31
74.7	0.08	0.05
76.8	0.73	0.64
78.8	1.32	1.17
80.7	1.80	1.64
82.7	2.68	2.47
84.8	3.38	3.12
86.8	4.03	3.71
88.9	4.45	4.06
92.7	4.40	4.13
96.7	4.42	4.15
100.6	1.58	1.06
106.8	-0.38	-0.32

Time (hrs)	Frost Depth (mm) Sample 1	Frost Depth (mm) Sample 2
First Freeze		
26.0	-14.36	-12.06
27.0	-36.01	-26.75
30.9	-60.63	-49.74
31.8	-64.62	-55.74
33.8	-110.92	-88.12
35.7	-147.57	-130.84
37.8	-152.21	-151.52
41.9	-152.49	-153.14
46.0	-152.44	-153.43
48.0	-152.42	-153.40
Second Freeze		
67.8	0.15	-0.20
69.9	0.18	-0.18
71.8	-6.46	-4.83
73.8	-33.44	-28.52
75.8	-46.42	-38.51
77.8	-56.06	-50.84
79.8	-61.70	-56.83
81.8	-102.34	-87.86
83.7	-152.32	-113.56
85.8	-152.96	-150.94
87.7	-152.93	-152.59
91.6	-152.89	-153.20

APPENDIX C (CONT'D).

Class 6 blended

γ_d = 131.7 pcf; W_{wt} = 5.1 %

Time (hrs)	Heave (mm)		Time (hrs)	Frost Depth (mm)	
	Sample 1	Sample 2		Sample 1	Sample 2
24.0	0.07	0.12	First Freeze		
26.1	0.20	0.18	24.1	0.08	No data
28.9	0.33	0.43	27.1	-7.50	recorded
30.2	0.52	0.50	29.9	-11.24	
34.1	0.95	0.75	32.0	-58.74	
40.1	1.22	1.02	34.0	-84.89	
44.2	1.59	1.40	36.3	-106.84	
48.0	1.85	1.65	40.2	-140.63	
52.1	1.28	1.14	42.2	-145.10	
56.1	0.42	0.21	44.2	-147.82	
60.1	0.14	0.05	48.3	-152.21	
72.2	0.09	0.05	Second Freeze		
73.5	0.22	0.18	73.5	-5.73	
75.3	0.29	0.36	74.2	-8.85	
79.2	0.54	0.56	76.3	-25.21	
82.3	0.85	0.75	79.2	-59.39	
88.2	1.36	1.25	82.6	-85.14	
92.4	1.73	1.57	85.5	-107.42	
96.2	2.05	1.76	88.3	-141.60	
			91.4	-145.67	
			97.6	-152.44	

APPENDIX D. PRESSURE PLATE PERMEAMETER TEST RESULTS

Sample 1171 γ_d = 1.742 Mg/m^3; G_s= 2.70

Moisture Retension		Hydraulic Conductivity	
Extraction		Extraction	
Pressure (cm water)	W (wt) (%)	Pressure (cm water)	k (cm/hr)
0	20.40	0	0.022000
50	19.08	8	0.004000
100	18.15	35	0.000400
200	17.53	164	0.000022
400	16.87	396	0.000019

Sample 1206 γ_d = 1.690 Mg/m^3; G_s= 2.70

Moisture Retension				Hydraulic Conductivity			
Extraction		Absorption		Extraction		Absorption	
Pressure (cm water)	W (wt) (%)	Pressure (cm water)	W (wt) (%)	Pressure (cm water)	k (cm/hr)	Pressure (cm water)	k (cm/hr)
0	22.10	0	19.60	0	0.014000	0	0.000280
50	21.80	100	18.32	25	0.003900	67	0.000011
100	20.23	300	17.91	54	0.000180	264	0.000008
200	19.14			168	0.000023		
400	18.77			370	0.000013		
700	17.66						

Sample 1232 γ_d = 1.837 Mg/m^3; G_s= 2.71

Moisture Retension				Hydraulic Conductivity			
Extraction		Absorption		Extraction		Absorption	
Pressure (cm water)	W (wt) (%)	Pressure (cm water)	W (wt) (%)	Pressure (cm water)	k (cm/hr)	Pressure (cm water)	k (cm/hr)
0	17.40	0	16.08	0	0.000870	0	-
50	16.87	100	15.00	62	0.000200	65	0.000016
100	16.56	300	15.01	194	0.000026	300	0.000009
200	16.10			390	0.000011		
400	15.17						
700	14.63						

APPENDIX D (CONT'D).

Class 3 Blended γ_d = 1.992 Mg/m^3; G_s= 2.69

Moisture Retension		Hydraulic Conductivity	
Extraction		Extraction	
Pressure (cm water)	W (wt) (%)	Pressure (cm water)	k (cm/hr)
0	13.30	0	2.200000
10	13.14	9	0.880000
20	12.20	10	0.120000
30	9.31	56	0.000044
50	8.33	200	0.000036
100	7.33		
200	7.21		
500	7.04		

Class 3 Stockpile γ_d = 2.029 Mg/m^3; G_s= 2.69

Moisture Retension				Hydraulic Conductivity			
Extraction		Absorption		Extraction		Absorption	
Pressure (cm water)	W (wt) (%)	Pressure (cm water)	W (wt) (%)	Pressure (cm water)	k (cm/hr)	Pressure (cm water)	k (cm/hr)
0	12.39	0	8.66	0	4.500000	0	0.250000
10	9.63	100	6.14	40	0.000140	58	0.000100
20	8.24	300	5.60	177	0.000071	300	0.000040
50	7.30			293	0.000052		
100	6.49			490	0.000034		
200	5.99						
300	5.85						
500	5.67						
700	5.46						

Class 6 Blended γ_d = 1.839 Mg/m^3; G_s= 2.79

Moisture Retension		Hydraulic Conductivity	
Extraction		Extraction	
Pressure (cm water)	W (wt) (%)	Pressure (cm water)	k (cm/hr)
0	18.01	0	4.700000
10	4.89	20	2.000000
20	3.74	30	1.100000
30	3.33	50	0.084000
50	2.52	100	0.000160
100	2.01	200	0.000028
200	1.53		
500	1.13		

APPENDIX D (CONT'D). PRESSURE PLATE PERMEAMETER TEST RESULTS

Dense-graded stone γ_d = 1.89 Mg/m^3; G_s= 2.8

Moisture Retension		Hydraulic Conductivity	
Extraction Pressure (cm water)	W (wt) (%)	Extraction Pressure (cm water)	k (cm/hr)
0	17.8	0	5.54000
13	5.82	8	0.07750
51	4.90	46	0.00230
117	4.54	113	0.00130
288	4.05	283	0.00067
500	3.75	500	0.00040
730	3.42	740	0.00025

Taxiway A subbase γ_d = 2.16 Mg/m^3; G_s= 2.72

Moisture Retension		Hydraulic Conductivity	
Extraction Pressure (cm water)	W (wt) (%)	Extraction Pressure (cm water)	k (cm/hr)
0	9.54	0	2.75000
25	7.22	28	0.07900
50	6.53	80	0.00081
100	5.97	192	0.00029
200	5.74	360	0.00023
300	5.65	550	0.00015
400	5.56		
600	5.28		

APPENDIX E. UNFROZEN WATER CONTENT—MN/DOT MATERIALS

Temperature (-°C)	Gravimetric Water Content (%) Sample 1171	Sample 1193	Sample 1206	Sample 1232	Class 3	Class 6 -No. 30	Class 6 +No. 30
0.05							30.9
0.16	17.1	26.7	19.7	14.1	4.4	4.1	2.3
0.20	15.4	15.9	17.5	13.0	3.9	3.0	1.4
0.22	14.9	15.3	17.0	12.4	3.6	2.8	1.4
0.26	13.8	14.3	15.9	12.3	3.6	2.2	0.9
0.34	13.1	12.7	14.7	11.2	3.2	2.0	0.9
0.40	12.8	12.6	14.4	11.0	3.1	2.0	2.1
0.40	12.8	12.6	14.3	11.3	3.1	2.0	2.1
0.59	11.0	10.3	12.6	9.4	2.5	1.5	0.9
0.67	11.1	10.2	11.8	9.3	2.1	0.9	0.2
0.73	10.6	10.0	11.7	8.6	1.6	0.9	0.2
0.74	10.2	10.0	11.5	8.6	1.7	0.7	0.5
0.82	10.0	9.8	11.5	8.5	1.7	0.7	
0.96	10.0	8.8	10.8	8.2	1.7	0.5	
1.07	9.5	8.7	11.1	8.1	1.7	0.7	
1.49	9.0	8.0	9.9	7.3	1.5	0.3	
2.22	8.7	7.7	9.4	6.4	0.9	0.1	
3.28	8.0	6.6	8.2	5.6	0.9	0.4	
4.32	7.1	6.0	7.7	5.5	0.7	0.1	
10.04	5.6	3.7	5.9	3.9	0.1		
Density (Mg/m^3)							
Wet	1.94	1.83	1.75	1.96	2.24	2.30	2.20
Dry	1.48	1.32	1.23	1.53	1.97	1.85	1.70
Water Content (%)							
Gravim.	30.56	38.26	41.89	27.95	13.25	24.16	29.38
Volum.	45.37	50.50	51.62	42.87	26.14	44.70	49.88

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
September 1996

3. REPORT TYPE AND DATES COVERED
Final Report June 1988–December 1990

4. TITLE AND SUBTITLE
Testing of Materials from the Minnesota Cold Regions Pavement Research Test Facility

5. FUNDING NUMBERS
CPAR Project
Agreement No. 64632
Task Order No. 1

6. AUTHORS
Susan R. Bigl and Richard L. Berg

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Cold Regions Research and Engineering Laboratory
72 Lyme Road
Hanover, New Hampshire 03755-1290

8. PERFORMING ORGANIZATION REPORT NUMBER
Special Report 96-20

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Minnesota Department of Transportation
395 John Ireland Boulevard Mail Stop 330
St. Paul, Minnesota 55155

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
MN/RC-96/24

11. SUPPLEMENTARY NOTES
For conversion of SI units to non-SI units of measurement consult ASTM Standard E380-93, *Standard Practice for Use of the International System of Units,* published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

Available from NTIS, Springfield, Virginia 22161

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

The U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) conducted various laboratory tests on pavement materials from the Mn/ROAD facility. The tests helped to characterize the behavior of materials under season frost conditions, and to provide input necessary for modeling the materials with the Mechanistic Pavement Design and Evaluation Procedure under development at CRREL. This report describes test results that define the physical characteristics, such as grain size, specific gravity, Atterberg limits, organic content, and compaction, as well as hydraulic properties, such as moisture retention and hydraulic conductivity, frost susceptibility, and unfrozen moisture content of two subgrade samples and two base materials from Mn/ROAD.

14. SUBJECT TERMS

Dense-graded stone	Material modeling	Mechanistic Pavement Design
Freeze season characteristics	Material performance	and Evaluation Procedure

15. NUMBER OF PAGES
45

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102