VERMONT AGENCY OF TRANSPORTATION

Contract #STP-SPR-PL-1 (32 & 33)
EA #0001032 & 1033, Sub Job #915

PERMEABILITY OF HIGHWAY BASE AND SUB-BASE MATERIAL

Prepared by:

Heindel and Noyes

Prepared for:

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VERMONT AGENCY OF TRANSPORTATION
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Heindel and Noyes
P.O. Box 64709 Burlington, Vermont 05406-4709
• Consulting Hydrogeologists
• Engineers
• Environmental Scientists
802-658-0820
Fax 802-860-1014

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PERMEABILITY OF HIGHWAY BASE AND SUB-BASE MATERIALS

1.0 INTRODUCTION

The Agency of Transportation (AOT) contracted with Heindel and Noyes to carry out a research project directed towards determining the "whole soil" permeability[1] value of a variety of earth media routinely used by the Agency of Transportation as base and sub-base materials. Coupled with developing an experimental technique to acquire the whole soil permeability value, we also performed a variety of other tests common to geotechnical evaluations. These included sample density calculations, moisture content calculations, porosity, grain size distribution analysis, and small-scale permeability tests using a variety of peer reviewed procedures. The methods, techniques, and formulas used to perform these calculations are explained in detail in the Attachment.

The study was divided into three phases. Phase I and Phase II are coincident with the original RFP except that there are several additional materials in the Phase I portion of the research contract which were tested. The additional materials include dense graded crushed stone in a wooden lysimeter (Appendix 1), fine graded crushed stone (Appendix 3), dense graded crushed stone retest (Appendix 10), a second sand borrow in place of a granular borrow (Appendix 9), and an additional reclaimed base without stabilization instead of one with stabilization (Appendix 12). The other materials identified in Phase I are as specified in the original contract.

Under Phase II, three experimental base, sub-base, and drainage materials were evaluated. These included shredded rubber chunks, cement-treated permeable base course and asphalt-treated permeable base course. We also evaluated two other

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[1] Permeability and hydraulic conductivity are used as interchangeable terms in this report.

variations of the Agency's dense graded crushed stone sub-base. These data are tabulated in Appendix 13 through Appendix 17.

The Phase III activities involved field work. During this phase, our original scope called for working with AOT field engineers to develop a small-scale in-situ permeability test which could be used to estimate the whole soil permeability of base and sub-base materials. At a December 19, 1995 meeting with AOT personnel, we reorganized the scope to reflect certain Agency preferences. The new emphasis involved the construction of a large-scale field test to evaluate permeability of a section of roadway which had been constructed in accordance with modern day practices. The redirection in the research contract was designed to resolve conflicts between the Phase I findings and common observations of field personnel working on job sites.

Whereas the Phase I research had shown that the dense graded crushed stone had a permeability which met or exceeded VAOT 704.06A specifications, field personnel had noted that rainwater tended to pond on the same material, implying inferior drainage characteristics. The Phase III work was designed to resolve differences between AOT observations in the field and the Phase I research work.

Organizationally, the first section of the report reviews the methodology used in the preparation and testing of a sub-base type. This includes a step-by-step evaluation of how the soil samples were prepared and placed. Following the "generic" description, test results are discussed. The methods and techniques used to acquire test data are included in the Attachment and are not repeated with the same level of detail in the report narrative.

2.0 TEST TECHNIQUES

A complete outline of test procedures and calculation methods is provided in the Attachment. Instrument schematics and test results may also be found below and in the Attachment. Detailed test procedures are explained below.

2.1 Sample Preparation

This section of the document provides an explanation of sample acquisition and placement of sub-base materials. Test samples were acquired from the Frank W. Whitcomb Construction Corporation and the Hinesburg Sand & Gravel Co., Inc. pit in Hinesburg (owned by Paul Casey). Specialty samples, including rubber chunks, were acquired from Palmer Shredding, Inc. in North Ferrisburgh, Vermont. The Agency of Transportation provided reclaimed base material from road construction projects on Route 140 in Mt. Holly, Vermont and Route 15 in Johnson, Vermont. A sand borrow sample was also supplied by the AOT from the Bob Hill Farm, Bristol, Vermont. Heindel and Noyes prepared the concrete base material by hand-mixing cement with the appropriate sized aggregate. Pike Industries, Inc. provided the asphalt-treated permeable base course, by applying asphalt to the granular material. Aggregate specifications for all materials were supplied by Christopher Benda, P.E., Soils and Foundations Engineer with the AOT's Materials and Research Section.

For the Phase I samples, materials were placed in three 150 mm (6") lifts in both the horizontal and vertical lysimeter. Moisture contents were adjusted by wetting the samples just prior to placement. Moisture contents were typically 3% to 8% by dry weight.

Horizontal permeability testing apparatus

Phase I materials were placed in 150 mm (6") lifts and compacted vigorously with a 200 mm x 200 mm tamping tool. At the completion of compaction, a trowel was used to extract approximately 2-4 kg (5-8 lbs) of aggregate from each of the 150 mm (6") lifts. This material was set aside for grain size analysis and moisture content testing.

Once the aggregate had been collected, a saran-wrapped membrane was carefully molded into the small excavation. Water from a graduated cylinder was then added to the hole to establish the exact volume of material that was extracted. The volume of the hole and the weight of the material removed allowed an exact calculation of the density in each lift.

Once the third lift was completed, the vertical or horizontal permeability lysimeter was prepared for permeability testing.

For Phase II experimental materials, similar placement techniques were used. However, the rubber chunks were not compacted using the standard method. To compact this material, the test cell was covered with a metal plate. Carpenter clamps were ratcheted against the metal plate to consolidate the material to the desired density.

2.2 Lysimeter Testing Techniques

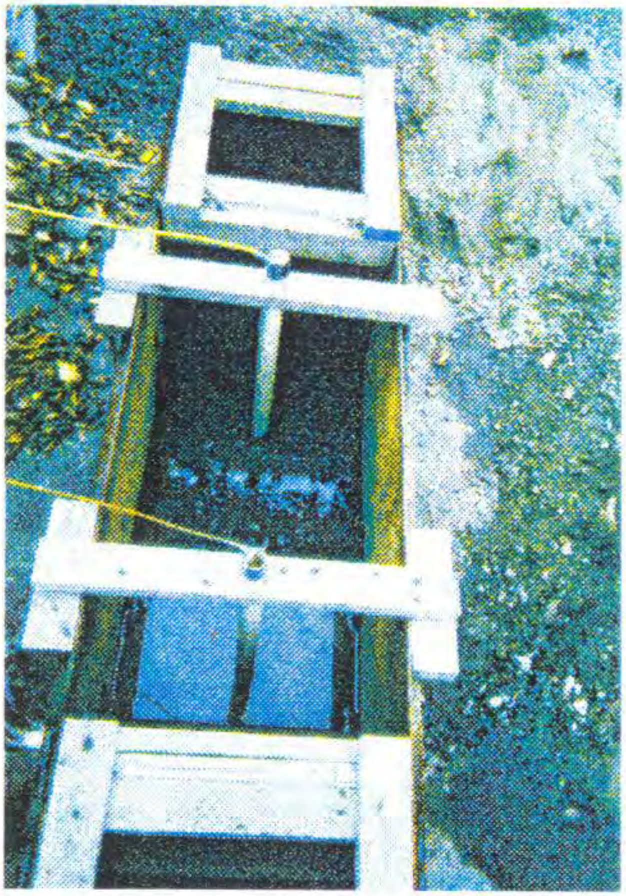
2.2.1 Horizontal Lysimeter Testing

When the sub-base lysimeter was ready for testing, approximately 1,000-1,500 kg of aggregate was added to the test apparatus. To begin the permeability test, approximately 400 liters (100 gallons) of water were added to the void space at both ends of the test device. The rising water surface extruded air from the soil pore spaces, minimizing the volume of trapped air. Bottom-up flushing has been shown in laboratory practice to be the most effective way to saturate a soil element and minimize air blockage problems.

Once the aggregate element had been saturated, a 5-ton hydraulic jack on the "upslope" end of the lysimeter was hand-activated. This allowed the slope of the lysimeter to be adjusted to a predetermined inclination. Typically, three runs were made for each test. Lysimeter base slopes were adjusted to 1%, 2%, and 3%.

Once the upslope end of the lysimeter was elevated, water began moving from the upper void through the aggregate element to the lower void under the influence of gravity. At this point, a pump in the lower cell was activated to cycle water back to the upper cell. Depending upon the permeability of the material in the cell, pump-back rates ranged from milliliters per minute to several liters per minute.

The water was cycled from the lower reservoir to the upper reservoir for the period of time necessary to establish "steady-state" flow-through conditions. Steady-state conditions were determined by measuring water level changes in the upper and lower reservoirs. Measurements on the reservoir were acquired with a Stevens recorder capable of measuring water surface level changes to the nearest 1.5 mm (0.005 feet). Observations of the stabilization in the reservoirs were made for 30 to 60 minutes. When the Stevens recorder showed that at least 30 minutes of equilibrium conditions had been established (no reservoir level change), measurements of the water surface slope in the test aggregate were made.



Top view, horizontal permeability testing apparatus

Horizontal permeability testing apparatus showing
reservoir controls and flow metering device

When the test cell reached equilibrium, the whole soil permeability was calculated using Darcy's Law. Darcy's Law is expressed as:

$$Q = KiA \quad \text{(Equation 1)}$$

where:

Q = equilibrium flow through the lysimeter ($\text{Length}^3/\text{Time}$)
i = hydraulic gradient measured in the monitoring wells (Length/ Length)
A = cross-sectional area of flow (Length^2)
K = hydraulic conductivity (Length/ Time)

Being able to measure flow (Q), the water table slope (i), and the saturated cross-sectional area (A), the hydraulic conductivity (K; permeability) was then calculated from Equation 1. (See Figure 1 on the following page.)

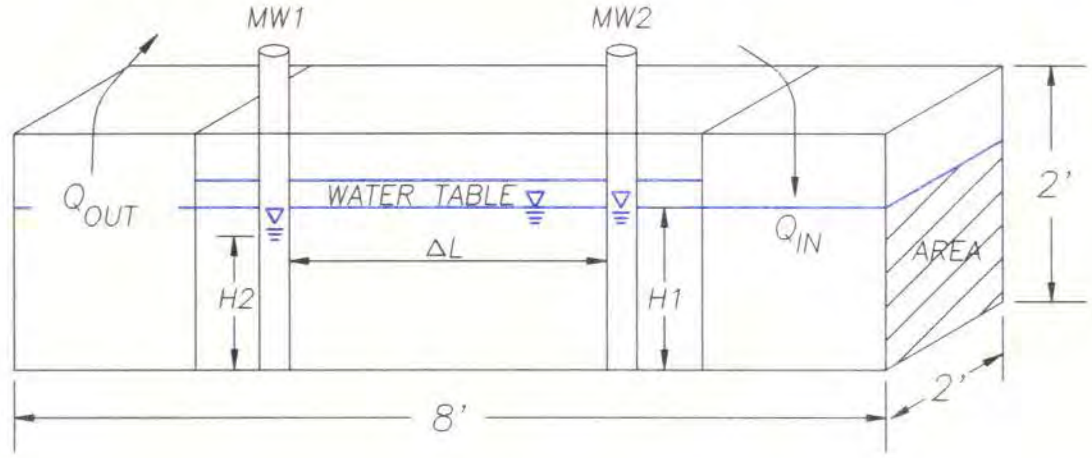
2.2.2 Vertical Lysimeter Testing

The testing protocol for the vertical lysimeter was modified to take into account the orientation of the flow system. In this test device, water was passed vertically down through the compacted cell, normal to the fabric of the compacted material. The compacted aggregate element was placed on an "infinitely" permeable crushed stone layer 50 to 75 mm thick to allow for unrestricted drainage. A reinforcing wire mesh and a layer of filter fabric were installed between the drainage material and the test material to keep the materials from mixing. The estimated permeability of the material was approximately 15,000 m/day (50,000 ft/day). Tests on the filter fabric showed that it would not restrict water flow. A valve installed in the bottom of the lysimeter allowed for free drainage of percolating water from the test cell.

Vertical permeability testing apparatus

FIGURE 1

AOT HIGHWAY PERMEABILITY DARCY TEST APPARATUS



$$K = \frac{Q}{i A} \qquad \text{WHERE } i = \frac{\Delta H}{\Delta L}$$

Q = FLOW RATE THROUGH THE LYSIMETER

K = THE HYDRAULIC CONDUCTIVITY COEFFICIENT

A = CROSS SECTIONAL AREA OF THE MEDIA

$\frac{H2 - H1}{\Delta L}$ = DIFFERENCE IN HEAD BETWEEN TWO MONITORING WELLS DIVIDED BY THE DISTANCE BETWEEN THE WELL POINTS.

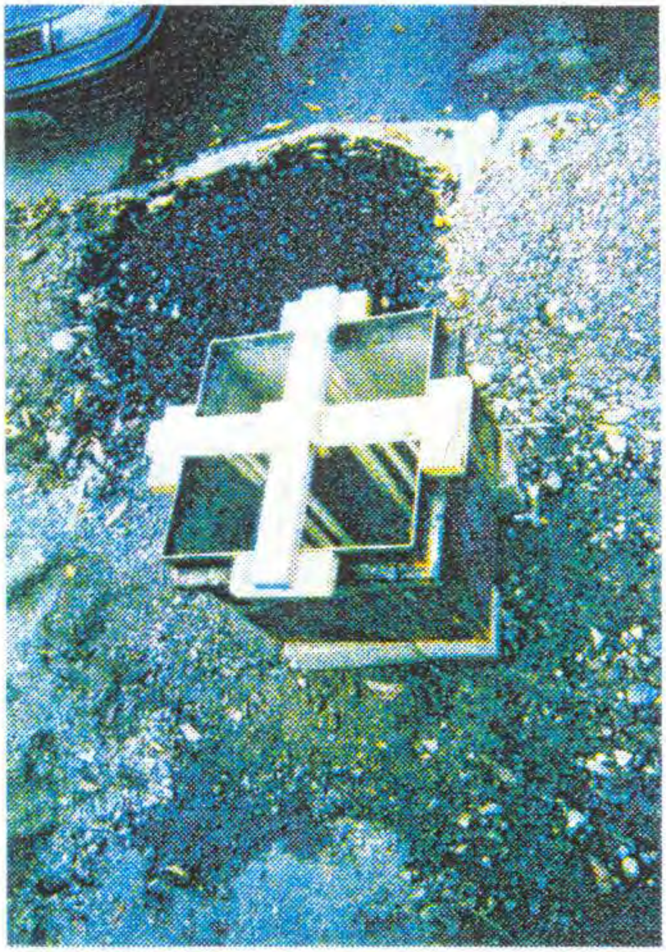
At the start of the test, water was added to the bottom of the lysimeter and allowed to rise slowly through the test cell, forcing out as much air from the pore space as possible. When the water reached the surface of the compacted material, flow through the test cell was adjusted to maintain a veneer of water at the soil/ atmosphere interface. At this point, flow was reversed; water was allowed to move from the top of the lysimeter to the bottom. The flow out of the bottom of the lysimeter was measured in volumetric containers or by a water meter. The flow rate was adjusted so that the water surface elevation was kept just at the air/soil interface. After no change in flow rate or water level occurred for 30 to 60 minutes, the test device was considered to be in equilibrium.

The hydraulic gradient in the lysimeter was measured in four banks (suites) of three piezometric devices which were designed to measure the head in the soil element at depths of approximately 15, 25, and 35 cm below the soil surface. The hydraulic gradient was measured when flow into the lysimeter equaled flow out of the lysimeter and the water surface elevation at the soil/atmosphere interface was stable.

Knowing the hydraulic gradient, cross-sectional area, and flow through the system, the vertical permeability was determined using the Darcy equation. (See Figure 2 on the following page.)

2.3 Small-Scale Test Procedures

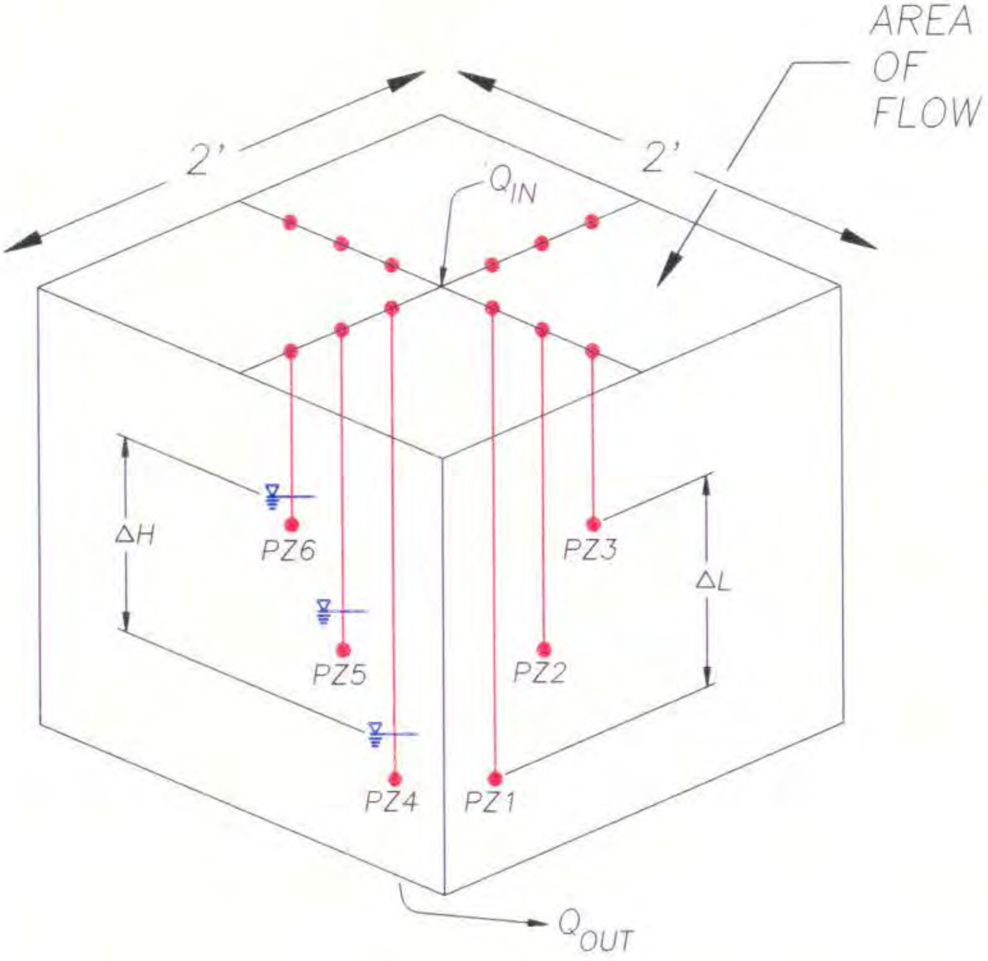
At the completion of the large-scale tests, a number of small-scale permeability (hydraulic conductivity) tests were also conducted in the sub-base materials. The small-scale tests were carried out to develop a correlation between the small-scale test and the whole soil permeability. The objective of this portion of the research was to develop a "correction factor" which could be applied, material by material, to a small-scale in-field test. This correction factor would allow field engineers to obtain an accurate assessment of what the actual permeability of the road subgrade would be without the logistics problems associated with large-scale tests.



Vertical Permeability Testing Apparatus - Top View of Instrument Array

FIGURE 2

AOT HIGHWAY PERMEABILITY
VERTICAL PERMEABILITY APPARATUS



$$K = \frac{Q}{iA} \qquad \text{WHERE } i = \frac{\Delta H}{\Delta L}$$

Q = FLOW RATE THROUGH THE LYSIMETER

K = THE HYDRAULIC CONDUCTIVITY COEFFICIENT

A = PLAN VIEW AREA OF THE LYSIMETER

$\frac{\Delta H}{\Delta L}$ = DIFFERENCE IN HEAD BETWEEN PIEZOMETER INTAKE PORTS DIVIDED BY THE DISTANCE BETWEEN THE ENDS OF THE PIEZOMETER PORTS.

Several types of small-scale tests were undertaken. These included "slug tests" in the monitoring wells contained in the horizontal lysimeter, resaturation type tests (Bouwer method) in the vertical lysimeter, and "K_M" type tests in the vertical permeameter. Each of these is discussed below.

2.3.1 Slug Tests

After the lysimeter testing was completed, the lysimeter box was lowered to zero percent slope and the water levels within the lysimeter allowed to equilibrate. When water levels in the soil were horizontal, a solid cylindrical object (slug) of known volume was inserted into one of the monitoring wells to displace the water contained in the well. Initially, the water level in the well rose as the slug was inserted. Once the displaced water had returned to equilibrium, the slug was quickly removed. This created an "instantaneous drawdown" in the monitoring well.

At the same time the solid cylinder was removed, a data logger/pressure transducer assembly was activated. The data logger recorded water level recovery in the monitoring well. These data were used in the slug test formula (see Attachment, page 3, for a typical calculation) and the permeability was computed. Slug tests in each test cell permitted a direct comparison of saturated permeability values from small-scale and lysimeter tests. (See Figure 3 on page 11.)

2.3.2 Resaturation Tests

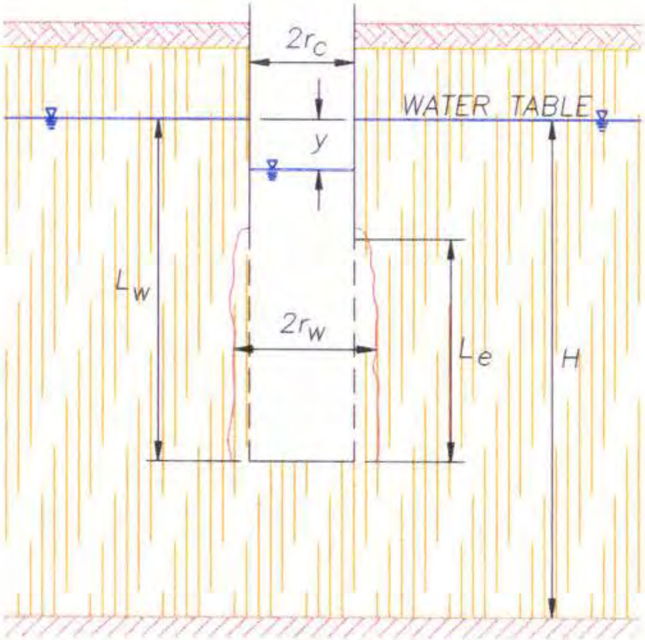
After the lysimeter drained to field capacity, a 4" monitoring well was installed in the vertical lysimeter to effect resaturation-type tests. Field capacity of the material was achieved after the aggregate element had fully drained from gravity effects and only residual water content remained. In the resaturation test, water was added to the permeameter until an equilibrium or steady-state rate was achieved. Knowing the steady-state inflow rate and the boundary conditions around the permeameter, the resaturated permeability was calculated. Samples of this calculation are shown in the Attachment (page 5). (See Figure 4 on page 12.)

2.3.3 Small-Scale Vertical Permeability Tests

Estimates of vertical permeability were calculated from the results of "K_M"-type tests, using the equation $K_V = K_M^2 / K_N$. The K_M test procedure calls for the installation of a plastic permeameter flush with the base of the aggregate test surface. The soil outside of the permeameter is then backfilled and compacted to prevent leakage around the base of the test device. When the test is ready, a series of uniform falling head cycles are recorded. These results are analyzed to produce the K_M test data. (See Figure 5 on page 13.)

AOT HIGHWAY PERMEABILITY
SLUG TEST ANALYSIS

FIGURE 3



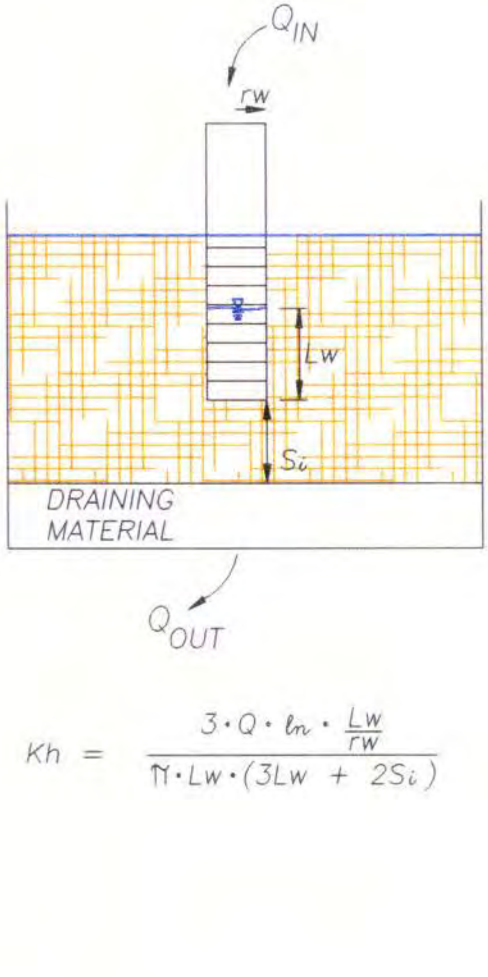
WHERE:

$$K = \frac{\dfrac{r_c^2 \cdot \ln \dfrac{Re}{rw}}{2 \cdot Le}}{T_1 \cdot \ln \dfrac{Y_0}{Y_1}}$$

$$\ln \frac{Re}{rw} = \frac{1}{\dfrac{1 \cdot 1}{\ln \dfrac{Lw}{rw}} + \dfrac{C}{\dfrac{Le}{rw}}}$$

AOT HIGHWAY PERMEABILITY
Kh PERMEABILITY TEST

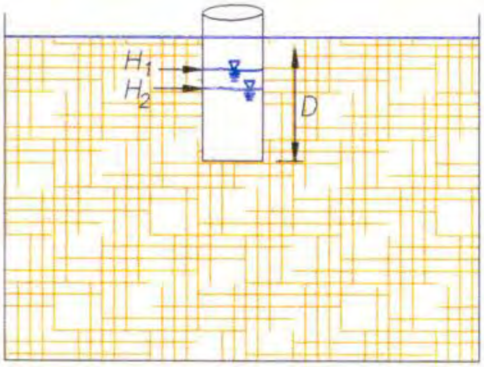
FIGURE 4



$$Kh = \frac{3 \cdot Q \cdot \ln \cdot \frac{Lw}{rw}}{\pi \cdot Lw \cdot (3Lw + 2Si)}$$

AOT HIGHWAY PERMEABILITY
K_m PERMEABILITY TEST

FIGURE 5



$$K_m = \frac{411 \cdot D}{\Delta T} * \ln\left(\frac{H_1}{H_2}\right)$$

While the K_M test offered some installation advantages, the number of steps in the calculations and assumptions which needed to be made about boundary conditions and aggregate types made some of the test results questionable. There were also substantial problems with side wall leakage around the test device. Therefore, a low level of reliability is placed on this particular method. A description of the calculation technique is provided in the Attachment (pages 5-6).

2.3.4 Other Tests

A number of other tests in the horizontal lysimeter were also run. The additional testing served as a QA/QC check on experimental procedures and lent confidence to calculated permeabilities. These used a variety of equations which are published in the literature.[2] The main value of these tests were to provide independent methods from which to calculate hydraulic conductivity. These are reported as "Flat Box Theim" and "Flat Box Darcy" (Attachment, page 4). After reviewing these test data, we believe the Darcy analysis provides the best estimate of hydraulic conductivity because it involved the fewest assumptions of test conditions we could not measure.

At the request of AOT staff, we also ran a number of salt tracer tests (Attachment, page 2). For this test, a saline solution was added to the entry void and electrical conductivity values were recorded at the monitoring wells as the brine infiltrated the aggregate element. These tests were designed to determine if "short circuiting" of water in the lysimeter was leading to test results which <u>overestimate</u> permeability values. The test data (Appendix 2, pages 15-16) showed breakthrough curves consistent with slug flow. We concluded that short circuiting of water along preferential pathways was not a problem in the test device.

3.0 DATA QUALITY/DATA CONTROL

Throughout the study, we used a series of checks and balances in the data acquisition and analysis. In each of the Appendices, all the test information has been independently checked by a separate investigator. Extra analyses of the horizontal permeability were also made to ensure that the permeability values being reported were representative of the materials tested. Examples of the quality assurance/quality control procedures are discussed below.

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[2] Darcy, H., 1856. Les Fontaines Publiques De La Ville De Dijon. V. Dalmont, Paris, 647 p.
Thiem, G., 1906 Hydrologische Methoden. Leipzig, 56 p.

As discussed, all the soil elements were laid in three separate lifts. Each one of the lifts underwent testing for grain size distribution, density, porosity, and initial moisture content. Since the investigator was aware of the compactive effort, this provided a good internal control for evaluating sample similarity and variability. On page 5 of each Appendix, the density, porosity, and permeability values for each of the compacted lifts and tested slopes are presented. The "average" value from the three individual trials is presented in the summary section at the beginning of each appendix.

For the actual horizontal permeability measurements (the core of the study), hydraulic conductivity for each material type was computed for three sample runs. Individual steady-state calculations were provided for a 1% slope, 2% slope, and 3% slope. Because permeability is a constant of the medium, comparisons of the variation in calculated value give an indication of the precision of measurements achieved with the large-scale lysimeter. Generally speaking, results were within 10% to 25% of each of the tested slopes for a particular material; individual test runs are discussed in the following section of the report.

Grain size distribution testing by our laboratory provided values which were similar to the Agency of Transportation laboratory values. Comparisons of our grain size distribution tests with those from the AOT lab are provided in the Attachment on pages 7-8. Since the AOT used a wet sieve technique (we used a dry sieve technique), the AOT lab tended to produce a grain size distribution curve with a larger measure of fines. This is because some of the silt and clay fraction particles contained in very small aggregates are not recognized by dry sieving. The minor difference in the sieve testing results has not changed the results of the study.

All calculations and plots contained in the Attachment and Appendices were independently checked by H&N staff. The protocol called for the originator of the calculations to submit them to an independent reviewer with the education and experience necessary to check both the calculation and theory for each test. This was accomplished throughout the study.

4.0 STUDY RESULTS

4.1 Phase I Results

The Phase I results are summarized in the Attachment (page 7) and Table 1 in the text below. The summary table in the Attachment provides a concise view of the most important information collected during the study. All of the test details are contained in the Appendix referenced at the top of the summary table. Test results are summarized in the first few pages of each Appendix, followed by specific measurements and calculations.

The summary table in the Attachment presents the following:

- test dates over which individual materials were evaluated;
- the average porosity for the materials tested (the value reported is the average of three tests, one in each of the three lifts);
- a summary of the large-scale vertical, horizontal, and small-scale tests for each of the materials;
- the anisotropy for each material (K_H/K_V; horizontal permeability/vertical permeability), as determined from the large-scale tests. No value is reported for the small-scale tests as the data are not reliable;
- results of the grain size evaluation compared to AOT specifications where appropriate; and
- the dry density of the material tested and its moisture content.

Table 1 below provides testing results for porosity, dry density, moisture content, and vertical and horizontal hydraulic conductivity by Darcy Analysis.

TABLE 1 **PHASE I RESULTS**	ACTIVITY				
	Average Porosity	Lysimeter Test by Darcy Calculation		Dry Density	Moisture Content
		Horizontal Hydraulic Conductivity	Vertical Hydraulic Conductivity		
Dense Graded Crushed Stone, Wood Lysimeter (A-1)	22.5%	12,121.92 ft/day	Not available	117.59 lbs/ft^3	8.71%
Dense Graded Crushed Stone, Metal Lysimeter (A-2)	13.3%	14,831.94 ft/day	Not available	133.1 lbs/ft^3	7.49%
Fine Graded Crushed Stone (A-3)	6.57%	538.06 ft/day	Not available	147.11 lbs/ft^3	4.79%
Coarse Graded Crushed Gravel (A-4)	14.77%	812.0 ft/day	92.88 ft/day	135.45 lbs/ft^3	3.8%
Fine Crushed Gravel (A-5)	15.09%	100.49 ft/day	22.71 ft/day	136.03 lbs/ft^3	2.99%
Sand Borrow (A-6)	14.08%	34.43 ft/day	11.42 ft/day	137.7 lbs/ft^3	2.96%
Sub-base of Gravel (A-7)	8.58%	630.90 ft/day	183.78 ft/day	131.64 lbs/ft^3	2.04%
Reclaimed Base w/o Stabilization (A-8)	14.23%	231.32 ft/day	4.03 ft/day	138.8 lbs/ft^3	1.95%
Sand Borrow 2 (A-9)	16.75%	23.92 ft/day	4.40 ft/day	128.5 lbs/ft^3	6.89%
Dense Graded Crushed Stone (A-10)	13.33%	5251.12 ft/day	2376.0 ft/day	133.1 lbs/ft^3	7.49%
Bituminous Concrete Base (A-11)	10.57%	641.10 ft/day	1.40 ft/day	145.31 lbs/ft^3	1.40%
Reclaimed Base w/o Stabilization (A-12)	12.44%	392.91 ft/day	37.21 ft/day	140.73 lbs/ft^3	2.64%

4.1.1 Dense Graded Crushed Stone

Horizontal Permeability

There were three separate lysimeter tests of the dense graded crushed stone: wooden lysimeter (Appendix 1), metal lysimeter (Appendix 2), and metal lysimeter re-test (Appendix 10). Appendix 1 contains the results of the first and only test run in the wooden lysimeter. The wooden lysimeter served as a prototype instrument to test aggregate loading and testing protocol. The trial produced a horizontal permeability in excess of 3,700 m/day (12,000 ft/day). As shown by the average porosity of approximately 22.5% and the unit mass of only 1,883.79 kg/m^3 (117.59 lbs/ft^3), the desired compactive effort had not been achieved because the wood frame structure absorbed the energy applied to the soil element. The "lighter" compactive effort (dry density 1,883.79 kg/m^3 , porosity 22.5%) indicated that permeabilities greater than 3,048 m/day (10,000 ft/day) can be achieved by this material if it is not compacted to sub-base specifications.

Following pilot testing with the wooden lysimeter test, a 6.4 mm thick steel lysimeter was constructed. The dense graded crushed stone was run again (Appendix 2) and yielded a permeability of about 4,500 m/day (14,800 ft/day). In this instance, however, the average porosity had been substantially reduced and the dry density raised to 2,130.66 kg/m^3 (133 lbs/ft^3).

Dense graded crushed stone provided by Whitcomb Construction Co., Winooski, VT

After reviewing the test data with AOT staff, we offered to retest the same dense graded crushed stone from wooden lysimeters using a revised compaction and placement protocol in the metal lysimeter. Appendix 10 summarizes the results of those studies and shows that, on the second compactive effort on the same material, the permeability was substantially reduced to a value of 1,600 m/day (5,251 ft/day).[3] The results of the testing show that the dense graded crushed stone easily exceeds the 305 m/day (1,000 ft/day) permeability recommendation set in the USDOT Federal Highway Administration Publication #FHWA-SA 92-008 §11.5.

Small-Scale Test Results

Small-scale slug tests from this material (Appendix 2 and Appendix 10) underestimated the whole soil value by a factor of 100 (±) compared to the three large-scale lysimeter tests. It is believed that the fine grained fraction of the soil matrix was smeared along the walls of the test cylinder and impeded flow of water out of the test device. This resulted in a lower than expected value.

4.1.2 Fine Graded Crushed Stone

Horizontal Permeability

The results of testing on fine graded crushed stone are contained in Appendix 3. While this material does not have a formal "designation" in the VAOT specification, it was tested because it is a commercially available material which could conceivably be used in either base or sub-base applications. This material yielded a permeability of 164 m/day (538 ft/day), with an average porosity of 6.57% and a density of 2,356.7 kg/m^3 (147.11 lbs/ft^3). This material achieved the highest density of any of the Phase I or Phase II materials.

Small-Scale Tests

The slug tests for this material yielded a permeability value of 0.631 m/day (2.07 ft/day). The ratio of the lysimeter to the small-scale permeameter test was 260:1.

4.1.3 Coarse Graded Crushed Gravel

Horizontal Permeability

Appendix 4 provides the detailed calculations associated with the coarse graded crushed gravel material. The horizontal permeability from the Darcy analysis was 247 m/day (812 ft/day), slightly less than the 1,000 ft/day threshold contained in the USDOT Publication. The porosity was 14.77% at a density of 2,242.8 kg/m^3 (135.45 lbs/ft^3) and 3.8% moisture content.

Vertical Permeability

After testing the first two materials, it was determined that the horizontal permeability testing lysimeter was not adaptable for vertical permeability testing. Therefore, Appendix 4 provides the first test information on vertical permeability measurements conducted in a second metal lysimeter we had constructed of the same 6.4 mm steel. The vertical hydraulic conductivity was measured as 28.31 m/day (92.88 ft/day) at 3.8% moisture content and a dry mass of 2,242.8 kg/m^3 (140 lbs/ft^3). The anisotropy[4] ratio was 8.74:1. Based upon a visual inspection of the flattened horizontal fabric created by the compactive effort, decreased vertical permeability was the predicted result. The hydrogeology literature indicates that natural formations with no apparent textural variations often have horizontal to vertical permeability ratios of 10:1 or more.

Coarse crushed gravel purchased from Hinesburg Sand & Gravel, Hinesburg, VT

---

[4] Ratio of horizontal to vertical permeability

Small-Scale Test

The slug test for the coarse graded crushed gravel yielded a horizontal permeability of 5.02 m/day (16.48 ft/day). This is about 1/50 of the whole soil permeability determined by the lysimeter test (247 m/day, or 812 ft/day). These data suggest that, if the field engineer were testing the subgrade by small-scale methods, he or she would multiply the in-situ result by 50 in order to determine the actual permeability value of the sub-base.

It is important to note that before a correction factor is applied to small-scale test results, a statistically significant number of tests need to be performed. Small-scale permeability tests need a statistically significant sample before the geometric "mean" can be applied to the calculated whole soil permeability value. Soils with a permeability value of >30 m/day (100 ft/day) would typically require 5 to 10 tests every 1 to 3 acres, assuming the subgrade was relatively homogeneous in its composition.

4.1.4 Fine Crushed Gravel

Horizontal Permeability

Detailed calculations for the fine crushed gravel properties are contained in Appendix 5. The horizontal permeability from the lysimeter analysis was calculated to be 30.63 m/day (100.49 ft/day). This value is substantially below the recommended permeability of 1,000 ft/day for drainage base and sub-base materials. The porosity was measured at 15.09% at a density of 2,179.2 kg/m^3 (136.03 lbs/ft^3) and an initial moisture content of 2.99%.

Fine crushed gravel purchased from Hinesburg Sand & Gravel, Hinesburg, VT

Vertical Permeability

The vertical permeability was calculated to be 6.92 m/day (22.71 ft/day). The same mass and moisture contents reported for the horizontal test are assumed to be representative of this material as it came from the same material base and underwent the same compactive effort.

Comparing the vertical permeability to the horizontal permeability results in an anisotropy factor of 4.42:1 (100.49 ft/day ÷ 22.71 ft/day). A general observation made of the test data is that "native" materials tend to have smaller anisotropy factors than manufactured materials. This may be the result of inherent grain size distribution characteristics of the sandy/gravelly materials tested. In essence, higher permeability contrast from manufactured materials may be the result of compaction of the fines within the interstices of the soil body.

Small-Scale Test

Slug Test: The slug test resulted in a value of 2.87 m/day (9.43 ft/day). Comparing the whole soil permeability test to the small-scale permeability test resulted in a ratio of 10.65:1. The same comments relating to a statistically valid sample set apply.

4.1.5 Sand Borrow

Horizontal Permeability

Detailed calculations for the sand borrow are contained in Appendix 6 (sand borrow 1) and Appendix 9 (sand borrow 2). The whole soil permeability test for these materials resulted in horizontal permeability values of 10.49 m/day (34.43 ft/day) and 7.29 m/day (23.92 ft/ day), respectively. These values were well below the sub-base recommendation of 1,000 ft/day and, in fact, suggests that the sand borrow (either gradation) should not be used for standard drainage applications because this value was considerably below what would be considered the minimum suitable drainage specification (100-500 ft/day)[5].

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[5] Note the minimum suitable permeability value can be calculated using Darcy's Law for a specific set of site conditions.

Sand borrow 2 provided by VAOT from the Bob Hill Farm, Bristol, VT

Sand borrow purchased from Hinesburg Sand & Gravel, Hinesburg, VT

Vertical Permeability

The vertical hydraulic conductivity of this material was measured at 3.48 m/day (11.42 ft/day) and 1.35 m/day (4.42 ft/day). The porosity of the two sample sets was 4.08% and 16.75%. The density for sand borrow 1 and sand borrow 2, respectively, was 2,205.95 kg/m^3 (137.7 lb/ft^3) and 2,058.57 kg/m^3 (128.5 lbs/ft^3), and a moisture content of 2.96% and 6.89%.

Comparing the horizontal to vertical hydraulic conductivity results in anisotropy ratios of 3.01:1 (Appendix 6) and 5.43:1 (Appendix 10).

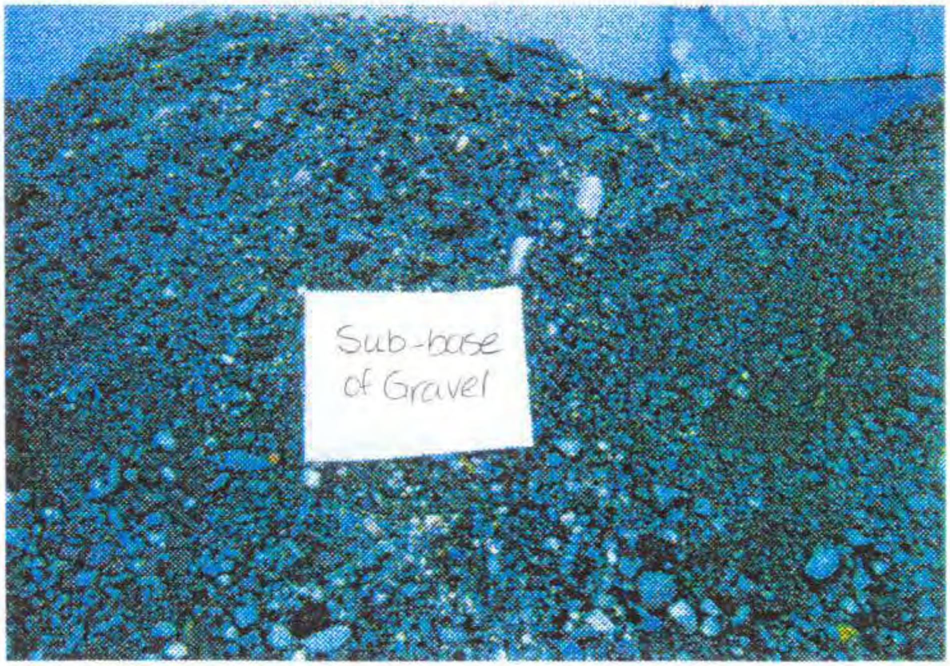
Small-Scale Test

The small-scale slug tests carried out in these materials resulted in values of 0.27 m/day (0.87 ft/day) and 0.68 m/day (2.22 ft/day). As discussed above, these low values are likely related to the influence of fines at the interface between the test device and the soil matrix. The ratios of the large-scale to small-scale horizontal tests were 39.57:1 and 10.73:1. The range of the permeability values for the whole soil test and the ratios reported in this section of the report are consistent with values expected for these materials.[6]

4.1.6 Sub-base of Gravel

Horizontal Permeability

Detailed calculations for the sub-base of gravel are contained in Appendix 7. The whole soil permeability test yielded a value of 192.30 m/day (630.90 ft/day). The porosity was calculated to be 8.58% at a weight of 2,108.87 kg/m^3 (131.64 lb/ft^3) and moisture content of 2.04%.



Sub-base of gravel purchased from Hinesburg Sand & Gravel, Hinesburg, VT

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[6] Freeze, Allen R., and Cherry, John A., Groundwater, Prentice Hall Inc., 1979.

Vertical Permeability

Vertical permeability was determined to be 56.02 m/day (183.78 ft/day). The anisotropy ratio K_H/K_V was calculated to be 3.43:1. This value is consistent with isotropic materials.

Small-Scale Tests

Slug tests conducted in this material resulted in a value of 18.6 m/day (61.81 ft/day). The ratio of the large-scale horizontal test to the small-scale test was 10.21:1. This is consistent with ratios found in the other materials.

Reclaimed base 2 provided by VAOT from Route 15, Johnson, VT

4.1.7 Reclaimed Base Without Stabilization

Horizontal Permeability

Two test runs were made for reclaimed base without stabilization. These are included in Appendix 8 (reclaimed base) and Appendix 12 (reclaimed base 2). Horizontal permeability for these materials were measured as 70.51 m/day (231.32 ft/day) (Appendix 8) and 119.76 m/day (392.91 ft/day) (Appendix 12). This range is not surprising, given the fact that the reclaimed base involves the admixture of the bituminous concrete surface with whatever subsoils were contained in the section of roadway from which it was removed.

Reclaimed base provided by VAOT from Route 140, Mount Holly, VT

Vertical Permeability

Vertical permeability in the two materials tested ranged from 1.23 m/day (4.03 ft/day) to 11.34 m/day (37.21 ft/day) for a density varying from 2,223.57 kg/m^3 (138.80 lbs/ft^3) to 2,225.5 kg/m^3 (140.73 lbs/ ft^3) and moisture contents from 1.95% to 2.64%. Porosities for the two samples were similar, with 14.23% for reclaimed base 1 (Appendix 8) and 12.44% for reclaimed base 2 (Appendix 12). The horizontal to vertical permeability ratios were 57.32:1 and 10.53:1, respectively. This significant variation and the high $K_H : K_V$ ratio are most likely the result of large pieces of pavement in the vertical lysimeter, reducing the effective cross-sectional area.

Knowing that the coefficient of permeability has a natural variation of nearly 20 orders of magnitude for earthen materials, the difference between these values falls within the range of expected natural variation.

Small-Scale Tests

Small-scale permeability tests for the two materials ranged in values from 2.55 m/day (8.38 ft/day) to 3.03 m/day (9.95 ft/day). The ratio of small-scale tests to large-scale tests varied from 27.6:1 to 39.48:1. Considering the origin of these materials from a "man-made" source, we would consider the range of variability to be within expected limits.

4.1.8 Bituminous Base

Detailed calculations for the bituminous base are contained in Appendix 11. The whole soil tests indicated this material has a permeability of 195.41 m/day (641.10 ft/day). Test data indicate that this was very close to the sub-base of gravel which indicated a permeability of 192.29 m/day (630.90 ft/day). Testing of the bituminous base was performed in the wooden lysimeter.

Type 1 bituminous concrete base provided by
Whitcomb Construction Co., Winooski, VT

Vertical Hydraulic Conductivity

Additional test runs were not possible due to the limited volume of material available and the cohesive nature of the asphalt in the lysimeter. At the risk of destroying the metal lysimeter, vertical permeability testing was not conducted.

4.1.9 Grain Size Distribution

Table 2 (following page) summarizes grain size distribution for Phase I materials tested performed by VAOT. Individual grain size analysis for each material can be found in its appropriate Appendix. Figure 6 illustrates the grain size distribution of Phase I materials (see also Table 2 on page 27).

TABLE 2
AOT Highway Permeability
VAOT Grain Size Distribution Plots (Percent Passing)
Phase I Materials

Sieve Size (mm)	Reclaimed Base (1)	Reclaimed Base (2)	Sand Borrow (2)	Sub-base of Crushed Gravel (Coarse)	Sub-base of Crushed Gravel Fine	Sub-base of Gravel	Sand Borrow (1)	Dense Graded Crushed Stone (1)	Dense Graded Crushed Stone (2)	Bituminous Crushed Base
75	100									
50		100				100		100		
37.5	98.6	95		100		98		97	100	100
25		90		94	100	92		82		95
19	90.9	87		82	98	87	100	76	88.8	80
12.5		78		65	79	79		66	77	68
9.5	79.1	69	100	55	68	74	89.2	58		
6.3									55.1	
4.75	67.8	48	99.1	36	47	60	72.4	43	46.5	48
2.36		30		24	31	36		32		33
2	49.8		92.2				46.8		30	
1.18		18		17	22	16		25		
1									22.7	
0.85	30		75.7				26.7		21.2	
0.6		11		13	16	7		20		17
0.425	17.1		47.4				17.3		12.7	
0.3		6		10	12	4		15		
0.25	12.1		25.5				12.7		7.4	
0.15	9.53	4	13.5	7	9	3	9.68	11		
0.125									4.1	
0.075	6.75	2.5	6.68	5.4	5.9	2.2	6.65	7.3	2.2	4
See App. #	8	12	9	4	5	7	6	1 & 2	10	11

PARTICLE SIZE DISTRIBUTION - PERMEABILITY STUDY - PHASE I

VAOT GRAIN SIZE TESTING

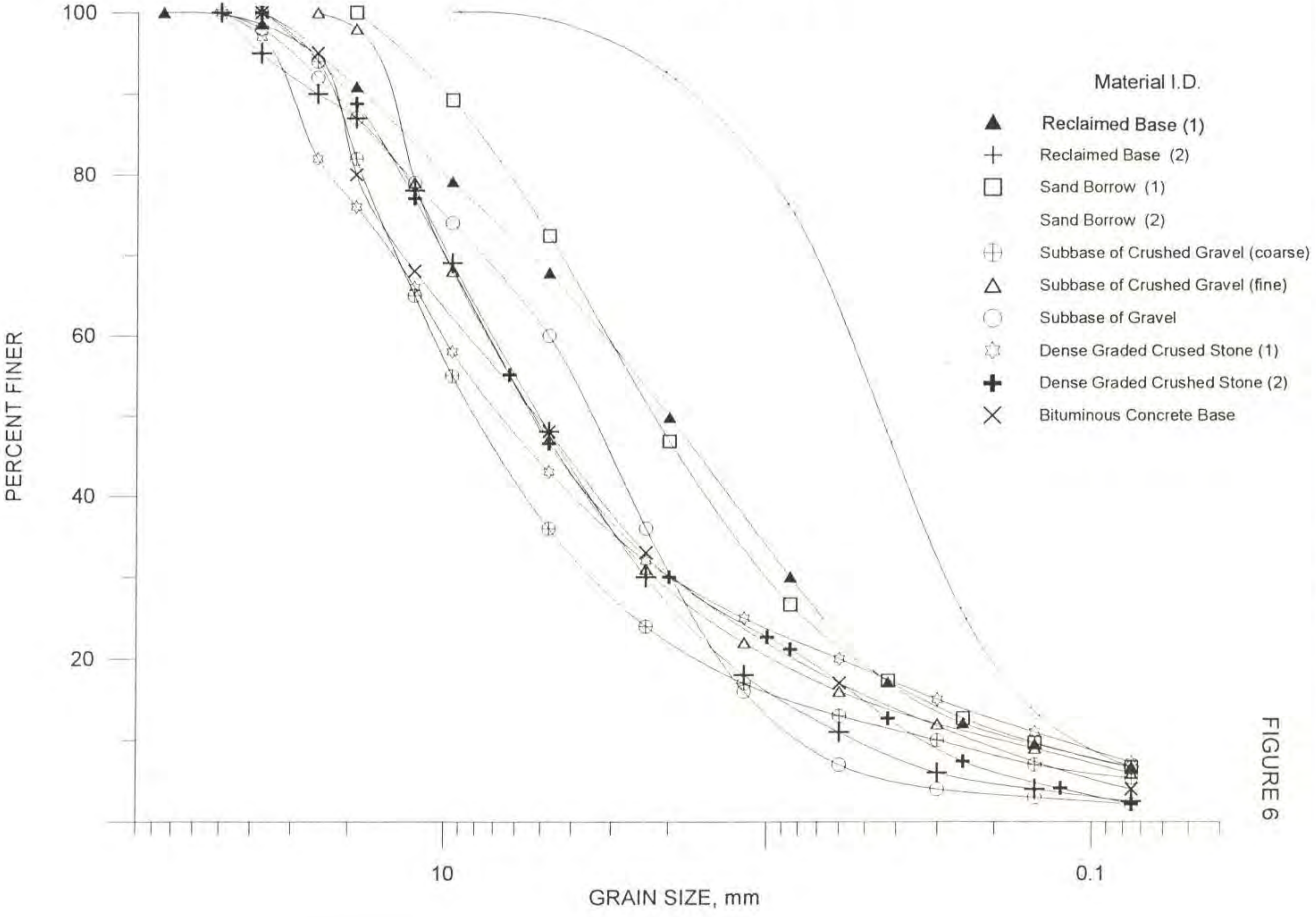


FIGURE 6

4.2 Phase II Results

4.2.1 Introduction

At the completion of the Phase I testing (conventional materials), we began testing the experimental Phase II materials. The materials investigated included 76 mm (3") rubber chunks, cement-treated base course, and an asphalt-treated permeable base course. In addition to these experimental materials, we also evaluated two other grain size distributions of the dense graded crushed stone. These were intended to investigate the effect of fine grained materials on the performance of the sub-base. The Phase II results are summarized in Attachment (page 7) and Table 3 (below). Additionally, Phase II test results are summarized in each of the appropriate Appendicies. Table 3 provides testing results for porosity, dry density, moisture content, and vertical and horizontal hydraulic conductivity by Darcy Analysis.

TABLE 3 **PHASE II RESULTS**	ACTIVITY				
	Average Porosity	Lysimeter Test by Darcy Calculation		Dry Density	Moisture Content*
		Horizontal Hydraulic Conductivity	Vertical Hydraulic Conductivity		
Rubber Chunk (Appendix 13)	45.4%	28512 ft/day	4585.68 ft/day	46.15 lbs/ft^3	0.56%
Cement-Treated Base Course (Appendix 14)	14.38%	9849.6 ft/day	7051.73 ft/day	138.39 lbs/ft^3	240 lb/yd^3 * (cement content)
Asphalt-Treated Permeable Base Course (Appendix 15)	46.58%	34560 ft/day	8822.68 ft/day	85.75 lbs/ft^3	2.7% * (asphalt content)
Coarse Dense Graded Crushed Stone (Appendix 16)	20.42%	5184 ft/day	1810 ft/day	129.36 lbs/ft^3	1.50%
Fine Dense Graded Crushed Stone (Appendix 17)	14.62%	1296 ft/day	481.04 ft/day	137.65 lbs/ft^3	2.35%

* Admixture content reported for Cement-Treated Base Course and Asphalt-Treated Permeable Base Course

4.2.2 Rubber Chunks

Technical data and calculations for the rubber chunks sub-base are contained in Appendix 13. Due to the fact that the rubber chunks could not be compacted using the strike plate, we manufactured a 6.4 mm steel plate that fit just inside the lysimeter. Using large woodworking clamps, we then forced the rubber chunks downward to the desired compactive density. Test data are summarized in Appendix 13.

Shredded rubber chunk provided by Palmer Automotive, North Ferrisburg, VT

Horizontal Permeability

The horizontal permeability of the rubber chunks was calculated to be 8,690 m/day (28,512 ft/day). For this test run, the rubber chunks had an average porosity of 45.4%, a density of 739.32 kg/m^3 (46.15 lbs/ft^3), and a moisture content of 0.56%. The permeability value compares favorably with some clean stone commonly used in drainage applications.

Vertical Permeability

To establish vertical permeability, the rubber chunks were compacted with a similar type metal plate inside of the vertical lysimeter. This time, however, holes were drilled in the surface of the metal plate to allow for the free movement of water down into the test cell. The vertical permeability was calculated to be 1,397 m/day (4,585 ft/day). Dividing the horizontal permeability by vertical permeability resulted in an anisotropy ratio of 6.22:1.

Small-Scale Tests

Small-scale testing via the slug test resulted in a value of 12.17 m/day (39.93 ft/ day). This value was substantially smaller than the vertical or horizontal lysimeter tests. The ratio of the lysimeter to small-scale test was 714:1. We expect that this smaller value is related to the anomalous medium characteristics that the rubber chunks present to the small-scale permeameter. The compactive nature of the rubber chunk simulated an imbricated media, reducing vertical permeability.

4.2.3 Cement-Treated Base Course

Field and laboratory calculations for the cement-treated base course are contained in Appendix 14. For this material, we mixed 142 kg/m^3 (240 lbs/yd^3) of Type I Portland cement in with a 19 mm (¾-inch) washed stone base course material at our laboratory. We then compacted and allowed the material to harden in place. After the base course material cured for 24 hours, we then performed the additional testing.

Cement-treated base course mixed at Heindel and Noyes' North St. facility, using washed stone aggregate purchased from Hinesburg Sand & Gravel, Hinesburg, VT

The horizontal permeability for this material was calculated to be 3,002 m/day (9,849 ft/day). Physical inspection of the sample indicated that there were large continuous open pores within the matrix (see photograph). The binder material cemented individual stone particles together, creating a stable, open network of flow channels.

Vertical Hydraulic Conductivity

The same material was placed in the vertical test apparatus. In this instance, it yielded a value of 2,148 m/day (7,051 ft/day). The horizontal to vertical permeability ratio was 1.39:1, the lowest value obtained for any of the materials we investigated. The more isotropic nature of this material is likely to be the result of the man-made mixing and placement of the sub-base.

For this test, the cement-treated sub-base had a density of 2,210.76 kg/m^3 (138 lbs/ft^3), a porosity of 14.38%, and a cement content of 240 lbs/yd^3.

Small-Scale Test

A small-scale slug test in this material (well was set in place at the time of material placement) revealed a value of 35.28 m/day (115.74 ft/day). The ratio of the large-scale to small-scale tests was 85:1. We expect that flow to the permeameter was diminished by the movement of cement against the exterior of the monitor well.

4.2.4 Asphalt-Treated Permeable Base Course

The asphalt-treated permeable base course was mixed at the Pike Industries plant in South Burlington, Vermont. The aggregate contained 2.7% AC-20 asphalt mixture by mass. Our office transported the hot asphaltic material from the batch plant to the laboratory where it was placed in the lysimeter test device. The material was placed and compacted at approximately 250° to 270° Fahrenheit, making it relatively pliable at the time of placement. The asphaltic material was set in three lifts and compacted in the same manner as the other materials.

Horizontal Permeability

The horizontal permeability for the asphalt-treated permeable base course was 10,534 m/day (34,560 ft/day). This value was the highest of any recorded during the study and is consistent with the high porosity value of 46.58%. The dry density of this material was 1,373.72 kg/m^3 (85.75 lb/ft^3) with a 2.7% asphalt content at the time of sample removal.

Asphalt-treated permeable base course provided by Pike Industries, Williston, VT

Vertical Permeability

Testing of this material in the vertical lysimeter produced a vertical permeability of 2,689 m/day (8,822 ft/day). The horizontal to vertical permeability ratio was 3.92:1, which was similar to the dense graded crushed stone (2.21:1) (see Appendix 10); testing of its coarse variant (Appendix 16) yielded a horizontal to vertical ratio of 2.86:1, and the fine variant (Appendix 17) yielded a ratio of 2.69:1.

Small-Scale Test

The small-scale permeability for this material was 26.82 m/day (88 ft/day). The ratio of the lysimeter test to the small-scale test was 392:1. This anomalously high ratio was likely related to the compaction of the open pore space around the monitoring well used in the small-scale test, and the alteration of the slotted sections in the pipe due to the elevated temperature and the smearing of asphalt on the well screen filter material.

4.2.5 Coarse Dense Graded Crushed Stone

Horizontal Permeability

Test results for the coarse variant of the dense graded crushed stone are contained in Appendix 16. This material was designed to test the effect of removing the percentage of fine material (passing the 200 sieve) from ~6% to 0%. The results of the lysimeter test indicated a permeability of 1,580 m/day (5,184 ft/day), which was similar to that of the standard dense graded crushed stone material (Appendix 10).

Coarse dense graded crushed stone provided by
Whitcomb Construction Co., Winooski, VT

Vertical Permeability

The vertical hydraulic conductivity of this material was measured at 551.69 m/day (1,810 ft/day). This resulted in an anisotropy ratio of 2.86:1. In comparing this to the Appendix 10 material, the testing results were very similar (2.21:1). For the test material, we achieved an average porosity of 20.42%, which was significantly above the Appendix 10 material (13.33%). The density was 2,072.35 kg/m^3 (129.36 lb/ft^3) at a moisture content of 1.5%.

Small-Scale Test

A slug test in this material resulted in a permeability value of 10.45 m/day (34.29 ft/day). When compared to the lysimeter test, this gave a large-scale to small-scale test ratio of 151:1. The slug test value for this particular run is approximately one-third of the Appendix 10 material (81.31 ft/day). The test results simply reflect the variability inherent in the small-scale test and emphasize the need to conduct a statistically significant number of tests before the "mean" is identified.

4.2.6 Fine Dense Graded Crushed Stone

Horizontal Permeability

The last of the Phase II materials was a fine dense graded crushed stone. All calculations are contained in Appendix 17. This material represented the addition of fines to the sub-base mixture. The percent passing the 4 sieve was increased from the typical material specification of ~40% to 53%. As a consequence of this, the horizontal and vertical permeability of the material was substantially reduced. The value reported for the horizontal permeability is 395.02 m/day (1,296 ft/day). This is nearly one-fourth that of the comparable "spec" sub-base material. It is, however, greater than 1,000 ft/day, the threshold recommended in the USDOT Publication #FHWA-3A 92-008 and demonstrates that this material does meet that specification.

Fine dense graded crushed stone provided by
Whitcomb Construction Co., Winooski, VT

Vertical Permeability

The vertical permeability of this material was calculated to be 146.61 m/day (481 ft/day). The dry mass of the material was 2205.15 kg/m^3 (137.65 lbs/ft^3), with an average porosity of 14.62% and a moisture content of 2.35%. The anisotropy ratio for this material is 2.69:1. This is very similar to the ratios for other materials. However, the effects of the fines are easily observed on the permeability value.

Small-Scale Test

A small-scale test in this material revealed a value of 7.83 m/day (25.7 ft/day). The ratio of the large-scale to small-scale tests was 50.4:1. We expect that flow to the permeameter was diminished by the movement of fine sands and silts against the exterior of the monitoring well.

4.2.7 Grain Size Distribution

Table 4 (below) summarizes grain size distribution for Phase II materials based on tests performed by VAOT. Individual grain size analysis for each material can be found in the appropriate Appendix. Table 5 (page 37) and Figure 10 on page 38 summarize grain size testing for the variations of dense crushed stone. Figure 7 (page 39) illustrates grain size distribution for Phase II materials.

TABLE 4 - AOT HIGHWAY PERMEABILITY
VAOT Grain Size Distribution Plots (Percent Passing)
Phase II Materials

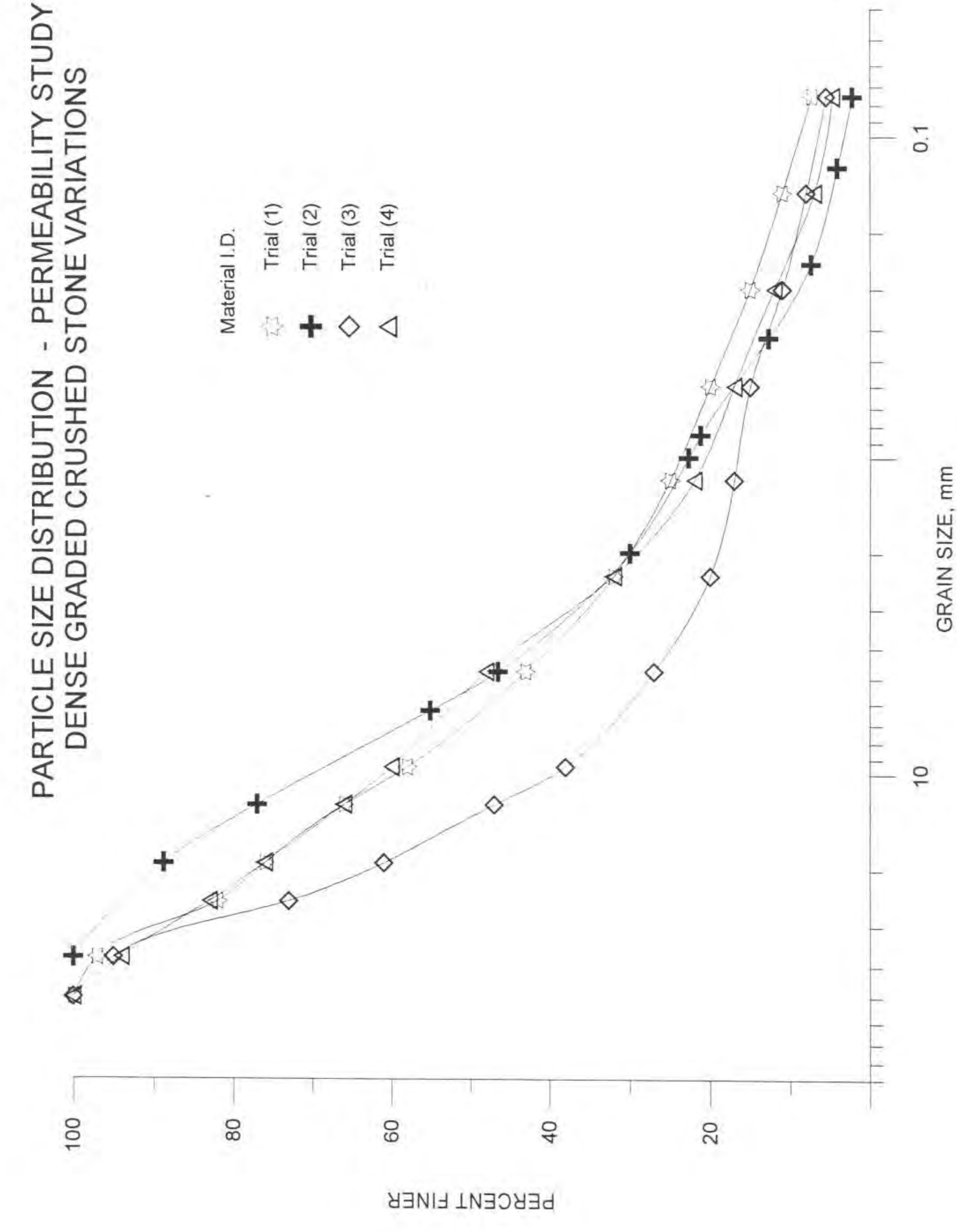
Sieve Size (mm)	Cement-Treated Permeable Base	Shredded Rubber Chunks	Dense Graded Crushed Stone (3)	Dense Graded Crushed Stone (4)	Asphalt-Treated Permeable Base
75		100			
50			100	100	
37.5			95	94	
25	100		73	83	100
19	99	1.7	71	76	72.1
12.5	58		47	66	49.5
9.5	21		38	60	
6.3					
4.75	3		27	48	12.1
2.36	2		20	32	
2					
1.18	2		17	22	
1					
0.85					
0.6	2		15	17	
0.425					
0.3	2		11	12	2.4
0.25					
0.15	1		8	7	
0.125					
0.075	0.9		5.5	4.7	1.4
See Appendix	14	13	16	17	15

TABLE 5

AOT Highway Permeability
VAOT Grain Size Distribution Plots (Percent Passing)
Dense Graded Crushed Stone

Sieve Size (mm)	Dense Graded Crushed Stone (1)	Dense Graded Crushed Stone (2)	Dense Graded Crushed Stone (3)	Dcense Graded Crushed Stone (4)	Phase III Test Pit (1)	Phase III Test Pit (2)
75						
50	100		100	100	100	100
37.5	97	100	95	94	97	91
25	82		73	83	78	75
19	76	88.8	61	76	66	67
112.5	66	77	47	66	56	56
9.5	58		38	60	50	50
6.3		55.1				
4.75	43	46.5	27	48	41	41
2.36	32		20	32	34	34
2		30				
1.18	25		17	22	29	29
1		22.7				
0.85		21.2				
0.6	20		15	17	24	25
0.425		12.7				
0.3	15		11	12	17	18
0.25		7.4				
0.15	11		8	7	10	10
0.125		4.1				
0.075	7.3	2.2	5.5	4.7	5.7	5.6
See Appendix	1 & 2	10	16	17	18	18

FIGURE 10



PARTICLE SIZE DISTRIBUTION - PERMEABILITY STUDY
DENSE GRADED CRUSHED STONE VARIATIONS

PARTICLE SIZE DISTRIBUTION - PERMEABILITY STUDY - PHASE II

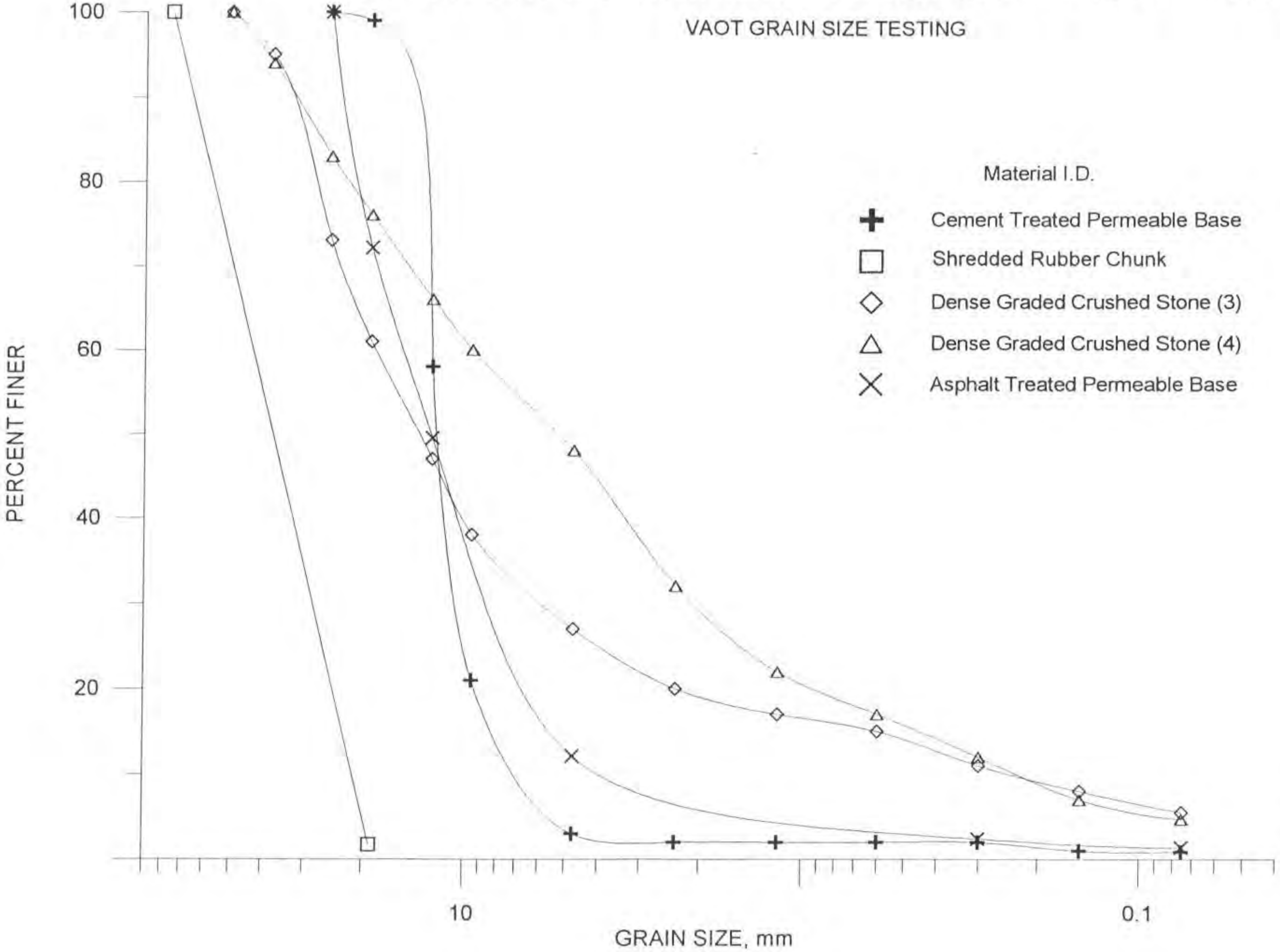
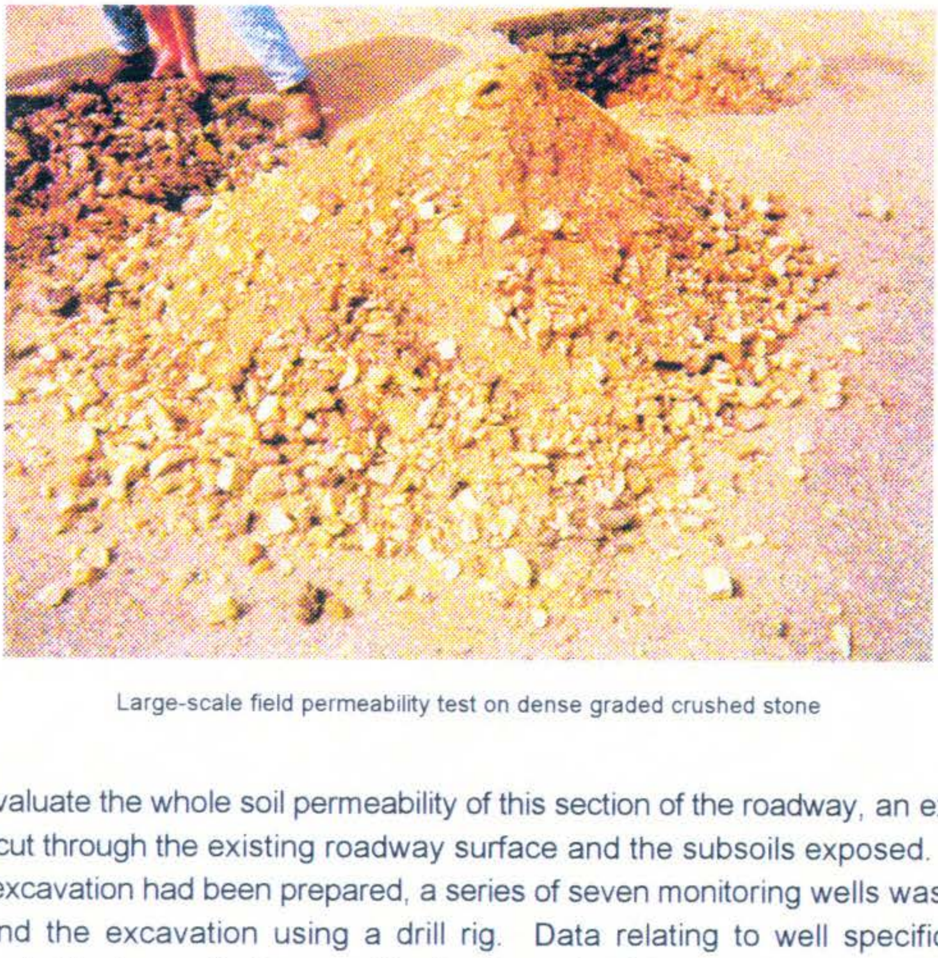


FIGURE 7

4.3 Phase III - Large-Scale Field Permeability Test

4.3.1 Introduction

In our December 1995 presentation to the Vermont Agency of Transportation, staff engineers were concerned that the coarse graded crushed stone could not have a permeability value as high as that reported from the Phase I study. The basis for staff concerns was founded on a number of field observations. The field staff noted that sub-base materials often had ponded water which did not drain downward into the sub-base profile for extended periods of time. Because of these observations, we revised the project test schedule to evaluate these concerns. The revision to the project scope involved the substitution of a large-scale vertical and horizontal permeability field test instead of the work which was planned for the small-scale test. Field testing was performed on the unused portion of the Southern Connector (I-189) in South Burlington, Vermont, west of Pine Street. The results of the field test are contained in Appendix 18.

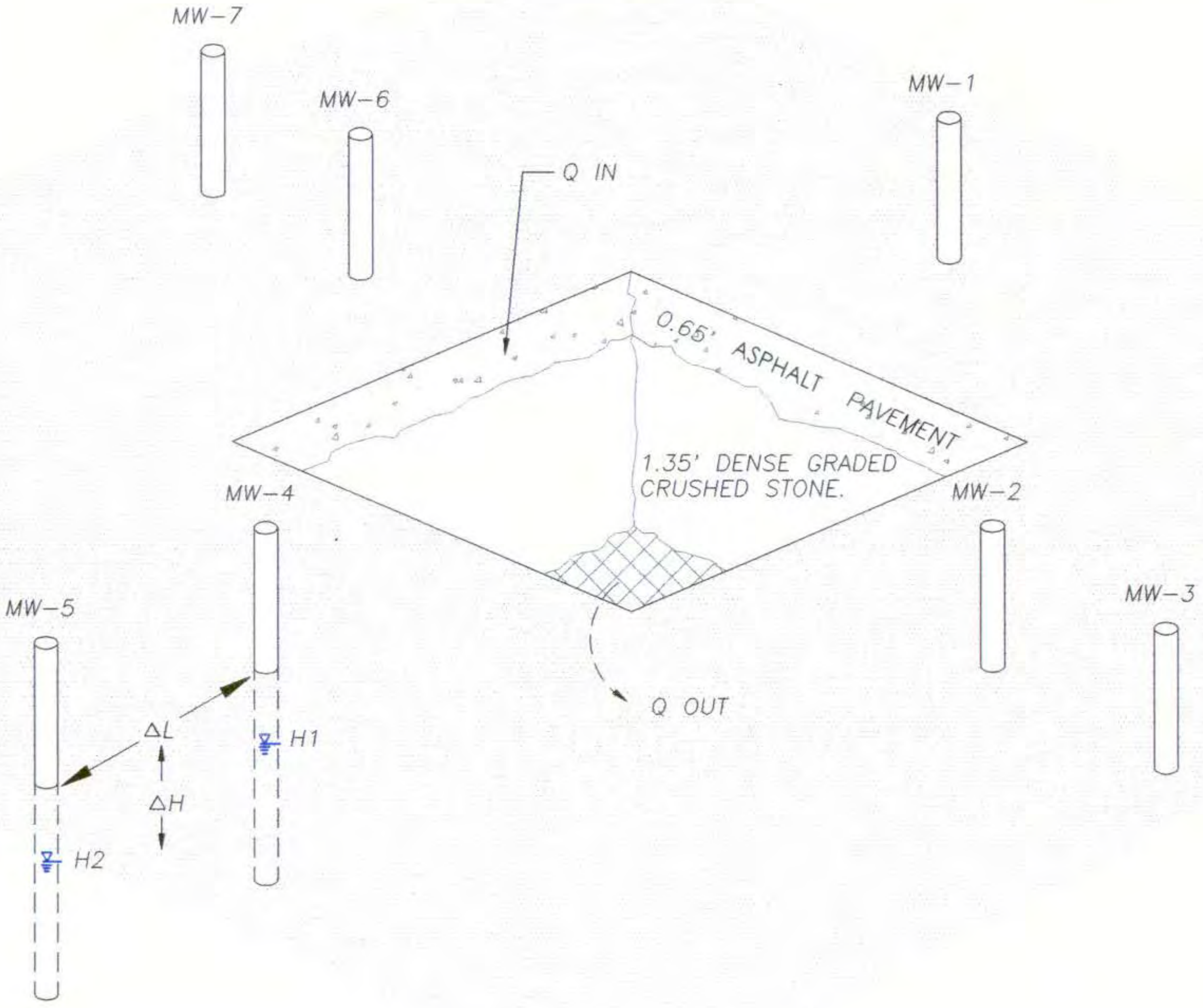


Large-scale field permeability test on dense graded crushed stone

To evaluate the whole soil permeability of this section of the roadway, an excavation was cut through the existing roadway surface and the subsoils exposed. After the test excavation had been prepared, a series of seven monitoring wells was installed around the excavation using a drill rig. Data relating to well specifications is presented in Appendix 18, page 11. A schematic of the completed field test device is shown on the following page and contained in Appendix 18, page 13.

AOT HIGHWAY PERMEABILITY
DARCY FIELD TEST ANALYSIS

FIGURE 8



$$K = \frac{Q}{iA} \qquad \text{WHERE } i = \frac{\Delta H}{\Delta L}$$

Q = EQUILIBRIUM FLOW RATE INTO EXCAVATION

K = THE HYDRAULIC CONDUCTIVITY COEFFICIENT

A = SQUARE AREA OF WETTED SURFACE

$\frac{H1 - H2}{\Delta L}$ = DIFFERENCE IN HEAD BETWEEN MONITORING WELLS DIVIDED BY THE DISTANCE BETWEEN THE WELLS.

Monitoring well installation at field permeability testing

The average density of the material removed from the sub-base, as determined by AOT staff via a nuclear gauge, was 1,954.44 kg/m^3 (122 lbs/ft^3), with an average porosity of 35.19%. The moisture content of the soils under the paved surface was 1.19%. These data indicate that both the porosity and the density of the material were less than the compacted materials used in Phase I lysimeter testing.

Horizontal Permeability

After all the background measurements, test dimensions and specifications had been acquired, the field loading test began. Water was supplied by a stationary 10,000 gallon tanker.

A total of 800 gallons of water were added to the test site over a period of ~120 minutes. At equilibrium, the inflow rate into the excavation was 24.26 l/min (6.41 gal/min). Equilibrium conditions were assessed by noting the loading rate at which the water surface elevation in the excavation and surrounding monitoring wells remained constant.

Once equilibrium conditions were achieved, pumping into the excavation was discontinued and the rate of drainage was monitored. It took approximately 45 minutes for the water surface elevation to drain from the equilibrium level to the bottom of the excavation. At the completion of the drainage cycle, fine material contained in the sub-base had collected in a muddy sump at the base of the excavation. A plot showing the rate of drainage is shown in Appendix 18, page 12.

Monitoring well array and experiment setup for field permeability test

Horizontal Permeability Test

Once equilibrium conditions were achieved, a Darcy calculation was used to calculate permeability. Flow from the test injection point influenced the wells (MW-3, 4, 5, and 6) in front of the excavation.

At equilibrium, the saturated thickness of the sub-base layer was approximately 0.905 meters, over a 2.25-meter-wide wetting front. Substituting these values into Darcy's Law resulted in a permeability value of 1,290 m/day (4,093 ft/day) (Appendix 18, page 5). This value is similar to, but slightly lower than, the dense graded crushed stone we reported from the lysimeter study.

Vertical Permeability Test

No direct analog to the lysimeter test is available on this site. Small-scale vertical permeability test techniques did not produce results which we consider to be reliable comparisons to the lysimeter test.

Small-Scale Tests

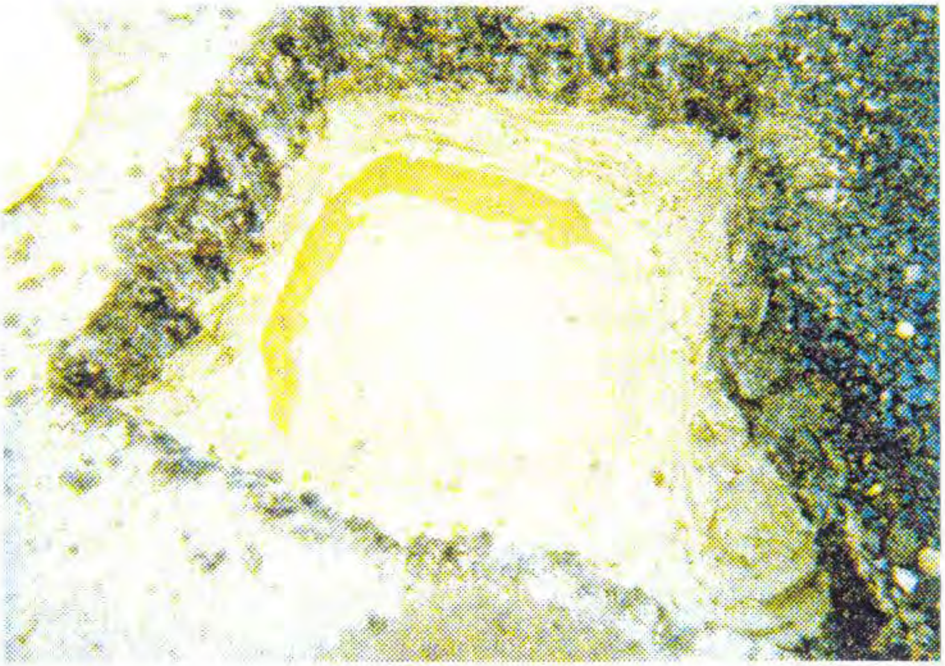
Because the subgrade is in the unsaturated zone, the small-scale test for this site was completed using the resaturation protocol (Bouwer test approach). The horizontal permeability value calculated from the Bouwer type test was 2.22 m/day

(7.28 ft/day) (see Appendix 18, page 1). The same technique used in the lysimeter reported a value of 0.32 m/day (1.06 ft/day) when the horizontal permeability by the lysimter test was 1,600 m/day (5,251 ft/day) (see Appendix 10). Test data show the resaturation test underestimated the actual permeability of the sub-base by a substantial margin.

4.3.2 Vertical Infiltration Evaluation

Following the completion of the field horizontal permeability test, the test site was expanded and prepared for a vertical infiltration test. The objective of this analysis was to determine if the surface of the subgrade was altered to the point where infiltration rates would be impeded. Developing in-situ test data would confirm the observations made by AOT field personnel.

To prepare the test site, the bituminous concrete pavement and sand padding immediately below it were carefully removed in a .45 m x .45 m area. Care was taken not to disturb the sub-base surface so that the condition of the surface prior to application of pavement would be preserved. At the perimeter of the excavation, a thick bentonite paste was carefully applied to the side wall to ensure leakage in the sand cushion would not occur. After the bentonite had been carefully applied and sealed, one inch of water (25.4mm) was carefully added to the surface of the sub-base. At that point, observations of the vertical drainage characteristics of the top course of the sub-base were made.



Vertical infiltration field permeability test on dense graded crushed stone

Field observations showed that it took 45 minutes for the 25.4 mm water depth to penetrate the sub-base, which is equivalent to a percolation rate of 45 mins/in.

Qualitatively comparing the sub-base infiltration rate to the vertical permeability values measured in the lysimeter, test results show that there is a substantial difference between an undisturbed sub-base surface tested in the lysimeter, and a sub-base exposed to machinary and car traffic during road construction.

However, even though the surface course of the sub-base has been altered and made less permeable, the in-situ test data shows that the horizontal permeability of the material is maintained. Observations of the "muddy sump" in the base of the horizontal test device and subsequent observations of the infiltration rate of the traffic-worn surface indicate that there is a "separation" and a fine grained material contained in the sub-base matrix. This separation and concentration of fine grained material may support the AOT staff observation that the granular surfaces subjected to traffic do not drain particularly well.

4.4 Drainage Characteristics of Sediments

Following the completion of all vertical permeability tests in the metal lysimeter, we evaluated the drainage characteristics of the sediments under unsaturated flow conditions. We selected four materials: reclaimed base, bank run gravel ("sub-base of gravel"), sand borrow 2, and fine graded crushed gravel to investigate drainage characteristics.

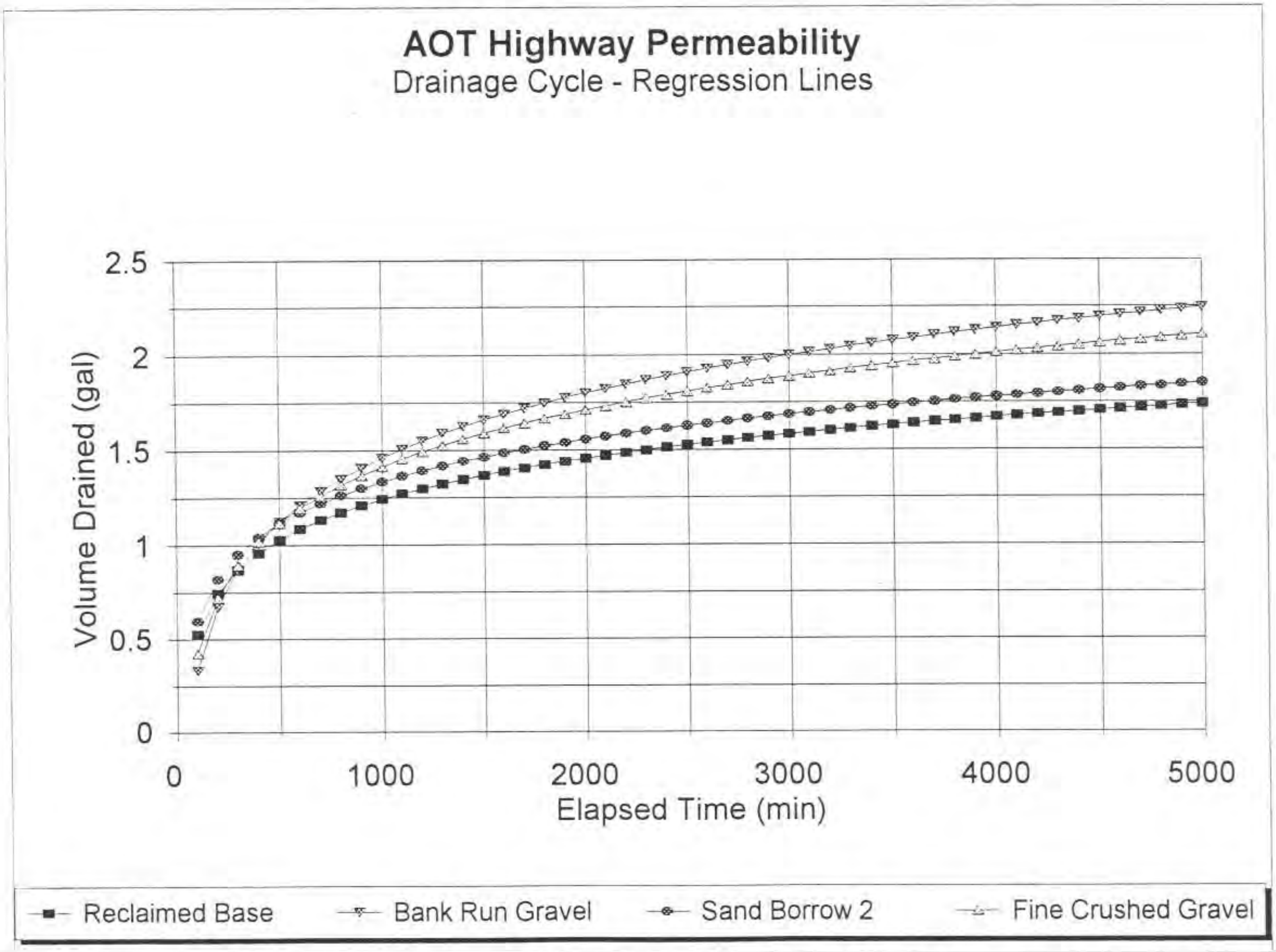
The water content percent was measured at the start of the drainage study. Here, the water content just prior to the inception of drainage varied from about 3.65% (fine crushed gravel) to 6.65% for the reclaimed base.

The drainage cycle in the permeameters was initiated when the piezometric devices indicated that the soil cell was "unsaturated." This could easily be confirmed by determining that the piezometric devices in the cell were dry.

To determine the outflow rate, a calibrated bucket was placed at the outfall valve. A water level recorder was set up on this device to determine the rate of drainage. Generally speaking, all of the soil elements produced approximately 5.7 liters of water over a period of about 1,000 to 1,200 minutes. The sample drainage study on the reclaimed base was extended to approximately 4,050 minutes. This evaluation showed that most of the drainage which occurred was within the first 1,200 to 1,500 minutes.

Looking at the drainage cycle curves, there is a clustering of data around a common drainage curve. Linear regression analyses (Figure 9, below, and Appendix 19, pages 1-4) indicate that a log function is an excellent predictor of the rate of drainage for any of the materials. Correlation coefficients for the data acquired were 0.95 to 0.99. The specific equations relating to the volumetric rate of drainage are shown on page 47.

FIGURE 9



Reclaimed base

$$\Theta = 0.3098 \ln (ET) + ({}^{-}0.8749)$$

Bank run gravel

$$\Theta = 0.4897 \ln (ET) + ({}^{-}1.9205)$$

Sand borrow (2)

$$\Theta = 0.3201 \ln (ET) + ({}^{-}0.8749)$$

Fine Crushed gravel

$$\Theta = 0.4303 \ln (ET) + ({}^{-}1.5565)$$

Where:

Θ = Volume drained (gal)
ln (ET) = Natural log of elapsed time
"0.3098" = x Coefficient
"(-0.8749)" = Constant

The saturated hydraulic conductivity for those same materials ranged from 8.44×10^{-5} m/sec to 2.22×10^{3} m/sec (see table below). The similarity of the curves can be explained by the principles of unsaturated flow in porous media. In the drainage cycle, the largest pores drain first because they have the smallest capillarity effect which can hold water against the force of gravity. Once the large pores drain out, the remaining small pores are the only interstices available to transport water. Therefore, the rate of drainage for these sediments imply that the unsaturated hydraulic conductivity for these compacted materials within the moisture range established by the drainage cycle is similar.

HORIZONTAL HYDRAULIC CONDUCTIVITY (K_H)

Medium	M/S	FT/S	FT/DAY
Reclaimed base (Appendix 12)	1.38×10^{-3}	4.54×10^{-3}	392.1
Bank Run Gravel ("Sub-base of Gravel) (Appendix 7)	2.22×10^{-3}	7.30×10^{-3}	630.9
Sand Borrow #2 (Appendix 9)	8.44×10^{-5}	2.77×10^{-4}	23.92
Fine Crushed Gravel	3.5×10^{-4}	1.16×10^{-3}	100.49

The other key statistic is the amount of time it took before the piezometric devices showed that the soil profile was dry. Here, there was a substantially different result. The finest grained soils maintained the longest time of saturation. The sand borrow generally took three hours before the piezometers indicated the entire soil profile was dry. On the other hand, the gravel material indicated unsaturated conditions were achieved within 30 minutes. The principal advantage of the coarser soils is that they provide for a water-free sub-base in a much shorter period of time.

5.0 STUDY CONCLUSIONS

5.1 General Observations

Heindel and Noyes designed a testing device and testing protocol to establish the whole soil permeability of roadway sub-base materials. The test protocol has proven to be extremely effective in accurately predicting water movement characteristics in a large volume soil sample. The protocol allows the laboratory to determine both the vertical permeability and horizontal permeability of the soils.

In-place densities of aggregate materials which meet Agency specifications can be achieved through hand compaction of the materials. Control of moisture content is somewhat difficult because of the mixing necessary for the one-ton soil samples. Some experimentation with a garden hose and shovel was necessary to bring starting moisture contents generally within the desired 2% to 6% range.

The dense graded crushed stone sub-base specification provides both vertical and horizontal permeability values which meet the USDOT Federal Highway Administration recommendation of 1,000 ft/ day. The minimum permeability value for this material is tested to be 5,000 ft/ day. It is recommended that this sub-base continue to be utilized.

The Phase III testing did confirm observations made by field engineers at Vermont's Agency of Transportation. Field tests have shown that the vertical permeability of the surface of the sub-base of crushed stone can be adversely affected (i.e. reduced) by existing practices. Final grading, which includes the windrowing of material, appears to separate and concentrate the fine grained fractions of the sub-base near the surface course. The vertical permeability of the material is lowered by nearly two orders of magnitude as a consequence of this practice. The VAOT should consider pilot studies to evaluate the elimination of this practice.

Several materials commonly specified for groundwater drainage may not be suitable. Our studies have shown that the two sand borrow specifications provided permeabilities in the range of 6 to 11 m/day (20 to 35 ft/day). In most instances, this material would only be satisfactory for handling very small groundwater discharges. For most applications, a minimum permeability for subdrainage should be several hundred meters per day.

All of the Phase II experimental materials displayed permeability characteristics which would recommend them for sub-base use. Additional experimentation with respect to the mechanical properties of these materials is recommended.

The average of 5 to 10 small-scale tests must be multiplied by a factor of 50 (±) to estimate the whole soil permeability value. Pilot studies of specific materials should be used to establish the correct multiplier.