PB2003-100527

Evaluation of Permeability of Superpave Mixes

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Prepared for
The New England Transportation Consortium

July 3, 2002

NETCR 34 Project No. NETC 00-2

Technical Report Documentation Page

1. Report No. NETCR 34	2. Government Accession No. N/A	3. Recepient's Catalog No. N/A
4. Title and Subtitle Evaluation of Permeability of Superpave Mixes		5. Report Date July 3, 2002 6. Performing Organization Code N/A
7. Author(s) Walaa S. Mogawer, Rajib B. Mallick, Matthew R. Teto and William C. Crockford		8. Performing Organization Report No. NETCR 34
9. Performing Organization Name and Address Department of Civil and Environmental Engineering University of Massachusetts, Dartmouth 285 Old Westport Road North Dartmouth, MA 02747		10 Work Unit No. (TRAIS) N/A 11. Contract or Grant No. N/A
12. Sponsoring Agency Name and Address New England Transportation Consortium 179 Middle Turnpike University of Connecticut, U-202 Storrs, CT 06269-5202		13. Type of Report and Period Covered Final 14. Sponsoring Agency Code NETC00-2 A study conducted in cooperation with the U.S. DOT
15 Supplementary Notes N/A		

16. Abstract

The objectives of this study were to evaluate permeability of Superpave mixes and develop procedure for permeability testing. The scope included testing of mixes in the laboratory and in the field, determination of relationships between mix properties and permeability, and development and recommendation of new mix design and in-place testing methods. Results from this study indicate that air voids, gradation and nominal maximum aggregate size have significant effects on permeability of HMA mixes. Amounts of interconnected air voids were found to be significantly higher for coarse graded mixes. A critical permeability of 10^{-3} cm/s is suggested for designing HMA mixes. Porosity test by the vacuum sealing method was found to be a good indicator of mix permeability. Porosity was found to be significantly affected by mix gradation, specifically the percent passing the 2.36 mm sieve. Charts were developed to help mix designers avoid mixes with excessive permeability, by selecting appropriate gradation and in-place air voids. Results of field tests indicated that in-place permeability is significantly affected by air voids and aggregate gradation and nominal maximum aggregate size. Permeabilities of coarse graded mixes with larger nominal maximum aggregate size are more sensitive to change in air voids than relatively fine mixes with smaller nominal maximum aggregate size. A laboratory-field permeameter was developed for testing "true" in-place permeability and also for use as a field quality control tool.

17. Key Words Permeability, porosity, gradation, HMA, nominal maximum aggregate size, air voids	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	21. Price N/A

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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SUMMARY

Hot Mix Asphalt (HMA) is used to provide smooth, stable and durable pavements. Since excessive infiltration of water into the pavements can deteriorate properties of both surface and subsurface layers, water-tightness or permeability of HMA is an important factor in design and construction of HMA pavements. Since the introduction of coarse graded Superpave mixes, there has been some concern regarding excessive permeability of HMA. This concern has primarily been due to the presence of relatively higher amounts of interconnected air voids in coarse graded Superpave mixes. There is a need to determine the effect of critical mix design and construction properties on permeability and develop a permeability testing procedure, such that mixes with excessive permeability can be avoided.

Under NETC 00-2 "NETC 00-2 -Evaluation of Permeability of Superpave Mixes", University of Massachusetts at Dartmouth and Worcester Polytechnic Institute (WPI) were assigned to evaluate permeability of Superpave mixes and develop procedure for permeability testing. This included conducting literature review, survey of state departments of transportation (DOTs), conducting tests, and developing recommendations.

The research team conducted an extensive review of relevant literature on permeability of HMA pavements and a survey of state DOTs. On the basis of these results and Expert Task Group (ETG) meeting, the research team developed a work plan for evaluating the permeability of HMA mixes and developing procedures for permeability testing.

The scope of laboratory testing included compaction of mixes with different gradations and nominal maximum aggregate size to specific air voids, testing the samples for different properties, including permeability and analysis of results. The scope of field testing included testing of field projects, analysis of data and development of a new lab-field permeameter.

Results from this study indicate that air voids, gradation and nominal maximum aggregate size have significant effects on permeability of HMA mixes. Amounts of interconnected air voids were found to be significantly higher for coarse graded mixes. A critical permeability of 10^{-3} cm/s is suggested for designing HMA mixes. Porosity test by the vacuum sealing method was found to be a good indicator of mix permeability. Porosity was found to be significantly affected by mix gradation, specifically the percent passing the 2.36 mm sieve. Charts were developed to help mix designers avoid mixes with excessive permeability, by selecting appropriate gradation and in-place air voids.

Results of field tests indicated that in-place permeability is significantly affected by air voids, aggregate gradation and nominal maximum aggregate size. Permeabilities of coarse graded mixes with larger nominal maximum aggregate size are more sensitive to change in air voids than relatively fine mixes with smaller nominal maximum aggregate size. A laboratory-field permeameter was developed for testing "true" in-place permeability and also for use as a field quality control tool.

CHAPTER 1. INTRODUCTION

1.1. Problem Statement

Permeability of Hot Mix Asphalt (HMA) pavement surfaces has become an important issue since the introduction of coarse graded Superpave mixes in the United States. This is due to the fact that, a high permeability can results in ingress of excessive amounts of water, which can cause serious distress such as stripping. There is some concern among state department of transportation (DOT) engineers and contractors that Superpave coarse graded mixes can be highly permeable compared to conventional mixes, primarily because of the existence of a large number of interconnected voids in these mixes.

Hence, there is a need to evaluate the permeability of dense graded HMA, specifically to evaluate the factors affecting the permeability of HMA. If the factors were fully understood, then it would become easier for the mix designers to design and construct HMA properly, to avoid excessive permeability. Although laboratory methods have been used extensively for evaluating the permeability of HMA, a simple and effective field test method is needed to understand the flow of water in pavements. Currently, there is no established field test method for determination of permeability of HMA.

1.2. Objectives of Research:

The objectives of this study are to evaluate the permeability of Superpave Hot Mix Asphalt (HMA), and prepare recommendations for design criteria of permeability values, and in-place and laboratory permeability testing.

1.3 Format of Report

This report presents the results of NETC 00-2 "Evaluation of Permeability of Superpave Mixes" study, carried out by University of Massachusetts at Dartmouth and Worcester Polytechnic Institute (WPI). The rest of the report is divided in five chapters.

Chapter 2 provides the results of a literature review conducted prior to the beginning of laboratory and field testing in this study.

Chapter 3 provides a summary of state department of transportation (DOT) survey conducted by the researchers.

Chapter 4 outlines the work plan developed on the basis of literature review, state DOT survey and Expert Task Group (ETG) meetings.

Chapter 5 presents details of test methods and materials used in this study.

Chapter 6 discusses the results and analyses of results of laboratory and field tests.

Chapter 7 provides conclusions and recommendations made on the basis of the literature review, survey of state DOTs and laboratory and field testing.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

There has been a considerable effort in the recent years in determination of permeability of HMA in field as well as in laboratory. In the following paragraphs, a review of currently available literature on measurement of permeability of HMA (both in field and in laboratory) and moisture susceptibility is presented. In the following paragraphs, the terms permeability and the coefficient of permeability have been used interchangeably.

2.2 Review of literature

2.2.1. Title: Water damage to the asphalt overlays: case histories.

Author: P.S. Kandhal, C. W. Lubold and F. L. Roberts.

Publication: Journal of Association of Asphalt Paving Technologists (AAPT), Volume 89, 1989.

Introduction: Three case studies of water damaged HMA overlays (over Portland Cement Concrete (PCC) pavements) in Pennsylvania have been reported in this paper. This problem of water damage was caused by the entrapment of water inside the HMA layer because of impervious nature of PCC pavements.

Objectives: The objective of the study was to evaluate the effect of water damage to the HMA pavements.

Scope: Samples were collected from the pavement layers using a jackhammer to avoid any change in water content of pavement material. The samples were tested for in-place water damage, actual moisture content of each layer, subsurface water and/or water vapor migration to upper surface. Cores from the projects were also analyzed for tensile strength to assess moisture-induced damage.

The median moisture content of pavements, reported in a limited nationwide survey of pavements, was 0.34 percent for surface courses and 0.35 percent for binder courses. The specimens tested in this study had moisture contents higher than those median values, such as 1% to 3 % for wearing course and 0.8 % for binder course materials.

Conclusions: Based on the above study following conclusion were drawn:

1. Stripping occurs because of entrapment of moisture due to inadequate surface drainage condition.

2. Stripping phenomenon is not a general problem but a localized problem in areas of projects, which are over saturated with water and/or water vapor due to inadequate subsurface drainage condition. The use of anti-stripping mechanism in surface course as done in usual cases will not reduce the stripping phenomenon unless the subsurface is designed to have a good drainage condition.

2.2.2. Title: Moisture Susceptibility of HMA Mixes: Identification of Problem And Recommended Solutions.

Author: P. S. Kandhal, Associate director, National Center for Asphalt Technology (NCAT).

Publication: NACT report number 92-1, May 1992.

Introduction: There are many factors, which induce stripping in HMA. In this report, some of these factors were investigated and recommendations to avoid the stripping problem were made.

Objectives and Scope: The objectives of the study were to list and discuss factors, which can induce stripping in HMA, and to recommend a methodology for investigation of stripping problem in a project. Another objective was to present a review of current practices of specifying the anti stripping agents, test methods and acceptance criteria.
Conclusions: The first part of the study included the identification of external factors, which cause stripping. The following factors had been identified:
1. *Inadequate Pavement Drainage*: Inadequate pavement drainage system can cause entrapment of moisture, which causes the stripping.
2. *Inadequate Compaction*: This is the most common construction related factor responsible for stripping. Most HMA mixes are designed for air void content between 3-5 percent. It has been seen that mixes with air void content of 4-5 percent does not have interconnected voids and are therefore considered to be impervious. During compaction, the air void content is kept around 8 percent keeping in mind that it will come down to 3-5 percent after 2-3 years of traffic. However, often the void content of mix during laying of pavement is more than 8 percent, which causes intrusion of water inside the pavement surface resulting in stripping.
3. *Excessive Dust Coating on the Aggregate*: Dust on the surface of the aggregates prevents good bonding of asphalt on aggregate surface and hence makes the mix susceptible to stripping.
4. *Use of Open Graded Friction Course (OGFC) Asphalt*: OGFC mixes retain moisture for longer times and do not dry out after rain as fast as conventional dense graded HMA mixes. Often these OGFC mixes are laid over the underlying HMA layer, which can be subjected to stripping action due to the high water content of overlaying OGFC layer and also sometimes due to the pressing action of OGFC layer to HMA layer by traffic load. It was recommended that the void content of the underlying HMA mix should not exceed 4-5 percent to minimize stripping.
5. *Inadequate Drying of Aggregate*: High residual moisture content in the mineral aggregate prior to mixing with asphalt cement binder increases the potential for stripping.
6. *Weak and Friable Aggregate*: Weak and friable aggregates cause degradation of pavement under roller and traffic. This degradation results in new uncoated aggregate surfaces, which can readily absorb water.
7. *Overlays on Deteriorated Concrete Pavement*: Dense graded sub-base material can hold considerable amount of moisture. Sometimes concrete pavements are overlaid with HMA. Moisture entrapped beneath the subbase of the concrete pavement can come up through the cracks and cause stripping of HMA.
8. *Waterproofing Membranes and Seal Coats*: Moisture is condensed beneath pavement surface during cool nights. When this moisture is vaporized due to heat it results in vapor pressure. Sealing of road surface can be detrimental because it can prevent trapped water from getting out and result in build up of vapor pressure, which can cause stripping.
2.2.3. Title: Stripping of in HMA Mixtures: State of The Art and Critical Review of Test Methods.
Author: B. M. Kiggundu, F. L. Roberts.
Publication: NCAT report number 88-2, September 1998.
Introduction: Stripping in HMA pavements is a major distress phenomena. It affects the performance of pavements and increases the cost of pavement maintenance. The causes of stripping are obscured and predictability of stripping in HMA pavements is an

indeterministic phenomena. Therefore, there is a need to study the stripping mechanism and to develop simple and reliable test methods to determine the stripping.

Objectives: The objectives of the study were to get a proper understanding of the mechanism of stripping, to develop a simple laboratory test procedure, which can measure the stripping potential before it could occur, and to evaluate of the need, function and cost-effectiveness of anti stripping additives.

Scope: The scope of the study included a discussion on definition of stripping and stripping mechanism. In addition, the study included outlining the test method and developing the test criteria such as the indirect tensile strength test, immersion compression test, Marshal immersion test (wet evacuation, dry evacuation), resilient modulus test and double punch method. The study concluded by the discussion on the current studies and future possible studies on the topic. The test results of four test methods such as indirect tensile test (Lottman and Tunnicliff-Root conditioning), immersion compression test, 10-minute boil test and Nevada dynamic strip test, performed on aggregates collected from different states, were compiled and rated as success and failure based on the criteria whether the laboratory test was consistent with the expected field conditions or not.

Conclusions: Based on the critical review of the test methods for stripping potential of HMA and the compilation of results obtained from various tests, current tests were ranked from higher to lower success. The ranking made was: Lottman test, Tunnicliff-root test, 10 minute boil test and Nevada dynamic strip test. No recommendations for improving the existing test method or new test method was proposed in this study.

2.2.4 Title: Investigation of Water Permeability of Course Graded Superpave Pavements.

Author: Bouzid Choubane, Gale C. Page and James A. Musselman.

Publication: Journal of Association of Asphalt Paving Technologists (AAPT), Volume 67, 1998

Introduction: This paper investigates the influence of air voids on permeability of HMA. The study presents the results of an investigation of permeability of coarse graded Superpave mixes. A simple and effective method for determination of permeability in laboratory developed during the course of the project has been presented.

Objectives: The objectives of the study were to (1) develop a procedure to determine the permeability of compacted HMA, (2) to determine the extent and causes of the permeability of Superpave projects and (3) to recommend necessary changes to Florida DOT Superpave specifications to incorporate the issues addressed in this study.

Scope: The scope of the study included the followings:

1. Two types of coarse graded Superpave mixes were used in the project with nominal maximum aggregate size 12.5 mm and 19.0 mm respectively.
2. A large number of cores of diameter 145 mm were obtained from the project site in and between the wheel paths.
3. The cores were cut to separate the layers of Superpave mixes of nominal maximum aggregate sizes 19 mm and 12.5 mm for permeability testing. A water-cooled saw with diamond-tipped blades was used for separating the layers.
4. A falling-head water permeability test developed by FDOT was performed on the samples. For each samples, the coefficient of permeability was determined for three tests and then the average was determined.

5. The stripping potential of the samples were determined by conducting the AASHTO T 283 modified Lottman test procedure. The average tensile strength of the conditioned samples was compared with that of the reference samples to determine the stripping potential.
6. The data collected from permeability and stripping potential test was analyzed.
Conclusions: Based on the above study, the following conclusions and recommendations were outlined:
1. The permeability test apparatus used in the study was proved to be effective and convenient to measure the permeability of HMA.
2. Air void content of less than or equal to 6 % was determined to be necessary for a coarse graded mix to be impervious.
3. An average permeability of 100 x 10^{-05} cm/s was determined to be a low enough to prevent infiltration of water into the pavement.
4. It was found that the present FDOT lift thickness criterion of fine graded Marshal mixes was found to be inadequate.
5. Coarse graded mixes appeared to have a greater amount of interconnected voids than fine graded Marshal mixes.
6. Based on the above conclusions, it was recommended that the density specifications of FDOT should be increased to 94 % of G_{mm} (theoretical maximum density) and the in-place permeability should be determined if this density is not achieved in-place.
7. A tentative permeability of 100 x 10^{-05} cm/s was suggested as a threshold limit for evaluating permeability of Superpave mixes.
2.2.5. Title: AHTD's Experience with Superpave Pavement Permeability.
Author: Jerry. R. Westerman, Arkansas State Highway and Transportation Department.
Publication: Arkansas Superpave Symposium, January 21, 1999.
Introduction: Pavements of 37.5 mm, 25 mm and 12.5 mm nominal maximum aggregate size were constructed in Arkansas through 1997. They all had been designed on the coarser side of the maximum density line of aggregate gradation and below the restricted zone. The mixes performed well as anticipated. However, in a heavy and wetter than normal August the pavements exhibited signs of excessive permeability. In this report, the results of permeability survey of 16 Superpave sites have been reported.
Scope: In this study, permeability measurements of 16 Superpave sites were collected from field survey and the results were analyzed to evaluate the several mix properties. In the first analysis, variation in permeability for variation in percent air voids was evaluated with test data from 47 specimens collected from the 16 sites. The second analysis was performed to evaluate the variation of permeability for variation of lift thickness. Next, the joint variation of permeability over the variation of percent air voids and the lift thickness was evaluated. A multiple regression line was obtained from this joint variation, from which the permeability coefficient was modeled as a function of percent air void and lift thickness.
Conclusions and recommendations: Based on the investigation, the following conclusions and recommendations were provided:
1. Three ranges of permeability have been proposed, namely, high, low and impervious with their respective range of permeability values - $k = 10^{-04}$ cm/s was selected as the break point between high and low permeability.

2. Seventy percent of Superpave mixes tested had permeability values was greater than the above value of 10^{-04} cm/s.
3. Pavements having air voids in excess of 6.5 percent were found to have permeability of more than 10^{-04} cm/s.
4. For 12.5 mm NMAS mixes, a lift thickness of 50 mm had been proposed for constructing pavements with permeability less than 10^{-04} cm/s. Hence, a lift thickness and to maximum nominal aggregate size ratio of 4 (four) has been recommended.

2.2.6 Title: Automatic Field Permeameter for Drainage Properties of Porous Asphalt.
Author: T. F. Fwa, S. A. Tan, C. T. Chuai, Center for Transportation Research, Department of Civil Engineering, National University of Singapore, 10 Kent Ridge Crescent, Singapore.
Publication: Journal of Testing and Evaluation, American Society of Testing and Materials, 1999.
Introduction: It is important to measure the permeability coefficient of pavement materials in order to determine the drainage capacity of pavements. Currently used methods of the permeability measurement are not efficient in measuring the true drainage capacity of the pavements. The present study describes the development of a permeameter, which can be used for expedient measurement of permeability of pavement materials.
Objectives: There were three objectives of this study. The first objective was to develop field equipment for nondestructive testing of the in-place permeability of pavement material. The second one was to develop the basic theoretical background of the measurement procedure. The third objective was to investigate the reproducibility of results of single equipment and the reproducibility of the results from two similar equipment.
Scope: It was assumed that the flow of water through the pores of pavement is nonlinear in nature. Therefore, generalized Darcy's equation $v = k_1 i^n$ was used to model the flow through pores of the pavement material, where v, k_1, i, n were velocity, permeability coefficient, hydraulic gradient and a constant, respectively. The variation of head over time, h(t), was assumed to be of the form $h = h(t) = a_0+a_1t+a_2t^2+a_3t^3$. The coefficients were calculated based on the regression analysis of measured data. The value of gradient, i, was calculated as $i = i(t) = (h(t)+d))/d$, where, d was the thickness of surface course. The value of velocity, v, was calculated as $v = v(t) = dh(t)/dt$. The variation of v over the variation of i was plotted as log(v) vs log(i). The slope of the line was the value of n. The permeability coefficients k_1 was calculated as $k_1 = v$ for $n = 1$.

The value of k_1 was considered to be the pseudo three-dimensional permeability of the pavement material. A three dimensional axi-symmetric isotropic finite element model of the pavement material was created. Analysis was performed on the finite element model for a range of permeability values and surface course thickness. This led to the establishment of a relationship database.

The pseudo three-dimensional permeability developed earlier was then converted to the isotropic permeability k. A laboratory verification program was then performed using seven sets of porous samples to validate the conversion relationship, which was developed earlier to convert the pseudo three dimensional permeability values to isotropic permeability values.

The anisotropy of the permeability values were also determined in the following manner. The rate of discharge at the field was measured. The samples from the field were tested in the laboratory for vertical permeability values k_z. Using that value of vertical permeability of the sample, the finite element analysis was performed to determine the horizontal permeability k_x by trial and error, which gave the same discharge measured at the field. The anisotropy ratio was measured as the ratio k_x/k_z..

A 14 km long road area was selected and 42 sites were selected to measure for the test equipment. For each site, three tests were done and the average was calculated. The reproducibility of the single equipment was measured by testing the same place three times. The repeatability of the equipment was tested by doing the same experiment by two different groups (with their own equipment); one group was the contractor's group and the other one was the project teams own group.

Conclusions: Based on the above study the following conclusions were drawn:

1. The developed permeameter was a good device to determine the in-place permeability of the pavement in 2-4 minutes.
2. A good agreement between the results of single equipment and the results between different equipment was observed.
3. The anisotropy ratio between horizontal and vertical permeability was measured to be between 1.3 and 7.0 with an average of 2.68.

2.2.7. Title: Permeability of Superpave Mixtures: Evaluation of Field Permeameter.

Author: L. A. Cooley.

Publication: NCAT report number 99-1, February 1999.

Introduction: Superpave mixtures are generally coarser than the other HMA mixtures. The air voids in Superpave mixtures are larger than the other conventional dense graded mixtures. Since the voids are larger, the chances of interconnected voids increase. That means, Superpave mixtures are expected to be more permeable than other conventional pavement mixtures at similar air voids. This necessitates the development of a permeability measurement procedure, which can provide accurate and repeatable results.

Objectives: The objectives of the study were to evaluate four field permeameters and select the best one on the basis of correlation with the laboratory permeability test results, repeatability and ease of use. The other objective was to develop the standard test procedure associated with the selected permeameter.

Scope: To achieve the above objectives, three project sites were visited. On each site, field permeability was tested using the four field permeameters and cores collected from the sites were tested in laboratory for permeability, using Florida DOT method. Among the four field permeameters, referred as FP1, FP2, FP3, and FP4 in the report, FP1 and FP3 were developed by NCAT and FP2 and FP4 were provided by commercial suppliers. The data from each project was analyzed to determine results from which permeameter correlated best with the results from the accepted laboratory permeameter, and repeatability and ease of use. In this study, the field and laboratory permeameters were both typical falling head type permeameters.

Conclusions: Based on the above study, it was found that two of the four permeameters namely, FP3 and FP4 showed good correlation with the laboratory permeameter in terms of results and repeatability. Between these two permeameters, the one, namely FP3, which had the best ease of use, was selected as the best field permeameter for testing of permeability in field. This permeameter developed by NCAT was unique from the other three permeameters because it used the three tier standpipe - each tier consist of standpipe of a particular diameter starting from the top with lowest diameter to the bottom of highest diameter. A flexible rubber base was used for sealing the base.

2.2.8 Title: Asphalt Permeability Testing: Specimen Preparation and Testing Variability.

Author: G.W. Maupin, Virginia Transportation Research Council, 530 Edgemont Road.

Publication: Transportation Research Record No. 1723, 2000.

Introduction: Wet sawing is a process that is used to isolate the HMA surface layer from the other layers of the field cores. But wet sawing results in sealing of the flow paths and thereby a reduction in permeability. Also, the permeability results from cores taken from the same project can have wide variation. In this study, these two issues have been investigated.

Objectives: The objectives of the study were to determine the effect of sawing on the permeability results of laboratory specimens and to study the variability of permeability measurements from laboratory and field specimens.

Scope: Sawing was done on laboratory specimens to find out its effect on permeability. Two mix sampled from construction site were taken. For each mix, two sets of specimen were tested, one in room temperature and the other in cooled ice bath (to prevent the asphalt from smearing and restricting the flow path). Each type of samples was tested for permeability before and after the sawing of the sample. A falling head test method was used to determine the permeability of each sample.

Variation of permeability measurements was investigated in field as well as in laboratory. In field, 13 projects with good quality control practice were selected. The quality control of the projects was based upon the specified standard deviations of Void in Total Mix (VTM) of less than 1.3 percent. From these data, coefficient of variation (COV) for each project site was calculated. Then considering two allowable average permeability values, the number of samples required to maintain the particular confidence interval based on sample variance and target values was calculated. In this calculation, the t distribution of the sample population was assumed.

Laboratory specimens were also tested to find out the variability in permeability measurements. Three different mixes were tested. For each mix, samples with five VTM were tested and for each VTM, three to five specimens were tested. The variability of permeability results due to the use of various operators in the field was also investigated.

Conclusions: Based on the above study the following conclusions were drawn :

1. Sawing process decreases permeability of HMA specimens by 30 to 45 % for no ice bath conditioning and by 53 % with ice bath conditioning.
2. The value of covariance as a measure of variability of permeability values had a range of large variation from 0 % to as high as 133 %.
3. Effect of different operators performing permeability tests was significant. The difference was in the slope of the regression line drawn to correlate the permeability and VTM results.

2.2.9. Title: Influence of Shape of Aggregates on the Performance of Permeable Asphalt Mixture.

Author: J. Zhang, T. Fujiwara, I. Ozaku, M. Nakamura, Iwate University, Government of Prefecture of Fukushima, Metropolitan Expressway Public Corporation.

Publication: Paper presented at the 80th Annual Meeting of the Transportation Research Board, Washington D.C, 2001
Introduction: It has been a usual practice to use permeable pavement surfaces in some parts of the world, especially in Japan. But with the repeated use of this type of roads (commonly known as the Open Graded Friction Courses in the USA), the performance of the pavement surface deteriorates as a result of reduction of permeability of the pavement. The authors hypothesized that since the void structure of the pavement material depends on the aggregate size and shape, the shape of aggregates can have an influence on the permeability of the pavement. This paper examined the effect of shape of aggregates on the permeability of the pavements.
Objectives: The objectives of the study were to determine the effect of shape of the aggregates on the permeability of Permeable Asphalt Mixtures (PAM).
Scope: Aggregates shapes were represented in this study by the volume of the solids of the mix. Mixes with four kinds of aggregates, with different percentage of the solid volume were tested. The same total void content was maintained throughout the test. The investigation was performed for two cases, each of which decreases permeability of PAM, namely, the intrusion of dust inside the pavement pores and the change of density due to compaction of pavement material at the construction site.
Conclusions: Based on the above study the following conclusions were drawn:
1. Shape of the aggregate or the percentage of solid volume to the total volume of the mix has no influence on the void content of the mix.
2. The continuous round voids changes to rounder voids as a result of increase in the percentage of solid volume to total volume. The rounder the voids are, the more permeable is the pavement. Therefore, the increase in the percentage of volume of solid over the total volume of the mix is beneficial for PAM.
3. Increase in percentage of volume of solids to the total volume of the mix results in an increase in wear resistance and dynamic stability of the pavement.
2.2.9 Title: Development of A Simple Test for Evaluation of In-Place Permeability of Asphalt Mixes.
Author: Rajib Mallick, L. A. Cooley, M. Teto and R. Bradbury.
Publication: International Journal of Pavement Engineering, 2001, Vol. 2(2), pp 67-83.
Introduction: Superpave mixes (coarse mixes) have been found to be more permeable than other mixes at the same air void level. There is a lack of a simple equipment, which can be used for efficient measurement of in-place permeability. This study discusses the development of a new permeameter, and presents the results of a study conducted with the new permeameter.
Objective: The objectives of this study were to develop and evaluate a simple in-place permeability test for dense graded HMA and to determine the effect of gradation and in-place density on permeability of these mixes.
Scope: The scope of the study included the following:
1. A new in-place permeameter was developed.
2. Conventional fine and coarse graded Superpave sections were identified, and permeability testing was done at the field using the new equipment. Cores were obtained from these sections.
2. In laboratory, the cores were tested for permeability and density. The necessary data used for this purpose was obtained from project information.

3. The data obtained from field and laboratory determination of permeability was analyzed to determine the effect of different mix design and construction factors on permeability.

Conclusions: Based on the above study, the following conclusions were drawn:

1. The developed in-place permeameter can be used to obtain the reasonable indication of in-place permeability of HMA mixes and results obtained are consistent with the expected results of mixes with different air voids and gradation.
2. The permeability of HMA mixes increases significantly above a critical VTM, which is depended on the type of mix.
3. Gradation of HMA mix has a significant influence on its permeability. Coarse graded mixes can show significant permeability for a lower air void content than fine graded mix with the same nominal maximum aggregate size.

2.3. Summary

A review of available literature on permeability of HMA indicates that the findings can be broadly classified into three categories - studies regarding the development of an appropriate permeability measurement procedure for field as well as for laboratory samples; studies on the effects of different material properties on permeability of the pavement materials and finally, studies on moisture damage of HMA pavement. Each of the above cases is discussed briefly in the following paragraphs.

2.3.1 Studies on development of appropriate permeability measurement

Cooley [2.2.7] discussed the evaluation of four field permeameters and the selection of the best one, which gave correlation with the laboratory results. Choubane et. al. [2.2.4] discussed procedures of measurements of permeability. Mallick et. al. [2.2.10] also discussed development of a new permeameter, which can be used to measure in-field permeability of HMA with ease and efficiency. All of the field permeameters and the laboratory permeameter were of falling head type, which involved measurement of only the vertical permeability. Studies by Maupin [2.2.8], Westerman [2.2.5], Zhang et al [2.2.9], have also reported measurement of the vertical permeability of the pavement material only. Fwa et al. [2.2.6] developed a falling head type of field permeameter, which was used for expedient measurement of field permeability. In his study, the measured pseudo three-dimensional permeability of the pavement material had been converted to the constant permeability in all direction by performing a finite element analysis of the pavement section. It has been shown that there could be considerable anisotropic behavior of permeability of the pavement material. In their study, the change of head over time had been assumed to be of a cubic polynomial nature. It is expected that due to the complicated voids structure of the pavement material, the actual variation of head over time is a complex phenomena rather a simple cubic polynomial variation and needed to be verified through a detailed analysis of the flow mechanics. In addition, the paper is not clear about the conversion mechanism, which was adopted for converting the pseudo three-dimensional permeability of the field to isotropic permeability.

2.3.2 Studies on the effects of material and sample properties on permeability

Several authors had examined causes that affect the permeability values of HMA pavement materials. Maupin [2.2.8] examined the effect of sawing on laboratory permeability. It was shown that the sawing process actually reduces permeability by causing smearing of asphalt and sealing off voids. Westerman [2.2.5] examined the effect of voids and lift thickness on permeability values. He concluded that a lift thickness to maximum nominal aggregate size ratio of 4 (four) has to be provided to reduce the permeability. Zhang et al [2.2.4] examined the effect of aggregate size on permeability and recommended a higher value of solid volume percentage, for an increased wear resistance and dynamic stability of the pavement surface.

2.3.3 Studies on moisture damage on pavement

Authors of every report on moisture damage of HMA pavements have pointed out stripping as the most significant manifestation of moisture damage. They have also mentioned that the stripping is a complex process and some of them have tried to give a definition and mechanism of stripping of HMA pavements. Among various factors contributing to stripping in asphalt pavement surfaces, the most common one has been identified as inadequate surface drainage capacity of the pavement (Kandhal [2.2.1], Kandhal [2.2.2], Kiggundu [2.2.3]). Other factors include inadequate compaction of HMA, excessive dust coating on aggregate, inadequate drying of aggregate and entrapment of subbase water in overlays of concrete pavements. Also Kandhal et. al. [2.2.1] pointed out that the conventional pavement materials have moisture content between 0.34 % to 0.35 % and that pavements with moisture content greater than these values can exhibit stripping problem.

2.4 Conclusions from literature review

In relation to the current New England Transportation Consortium (NETC) study on evaluation of permeability of Superpave mixes, the following conclusions can be made from the literature review:

1. Air voids and mix gradations are the most significant factors affecting permeability of HMA mixes.
2. There is a need to identify a suitable laboratory method for identification of excessive permeability potential of mixes. Results from such a test method should be sensitive to those mix properties which have significant effect on mix permeability.
3. Development of a proper field permeability device is needed. This tool is needed for both quality control of construction and for measurement of actual permeability of in-place mixes. This tool should be capable of evaluating the composite permeability (both vertical and horizontal) of pavements.
4. For the purpose of implementing good practices for design and construction of HMA mixes with respect to permeability, there is a need to develop test criteria for approving and accepting mixes.

2.5 References

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[2.2.2] Prithvi S. Kandhal. Moisture Susceptibility of HMA Mixes: Identification of Problem and Recommended Solutions. NCAT Report Number 92-1, May 1992.

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[2.2.5] Jerry. R. Westerman. AHTD's Experience with Superpave Pavement Permeability. Arkansas Superpave Symposium, January 21, 1999.

[2.2.6] T. F. Fwa, S. A. Tan, C. T. Chuai, Automatic Field Permeameter for Drainage Properties of Porous Asphalt. Journal of Testing and Evaluation, ASTM, Issue 1, 1999.

[2.2.7] Larry Allen Cooley, Jr. Permeability of Superpave Mixtures: Evaluation of Field Permeameter. NCAT Report Number 99-1, February 1999.

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[2.2.9] Jinxi Zhang, Tadashi Fujiwara, Izuru Ozaki and Mitsuru Nakamura. Influence of Shape of Aggregates on Performance of Asphalt Mixtures. Paper Presented at the 80th Annual Meeting of the Transportation Research Board, Washington D.C, 2001.

[2.2.10] Rajib Mallick, Larry Allen Cooley, Mathew Teto and Richard Bradbury. Development of a Simple Test for Evaluation of In-Place Permeability of Asphalt Mixes. International Journal of Pavement Engineering, 2001, Vol. 2(2).

CHAPTER 3: SURVEY OF STATE DEPARTMENTS OF TRANSPORTATION (DOTS)

3.1 Introduction

A survey of state DOTs across the United States was conducted in order to obtain answers to several important questions related to permeability of Hot Mix Asphalt (HMA) pavements. The survey questions were mailed to the materials engineer in the respective state DOTs and the answers were compiled. The answers to the different questions are presented in the following paragraphs.

3.2 Results of Survey

3.2.1 Question 1: Do you have any specifications related to permeability of surface and binder HMA courses?

State	Yes	No	Comment
GA		1	
AL		1	
NC		1	Do not currently have a permeability specification
ME		1	
KS		1	
AZ		1	
IL		1	
UT		1	
TX		1	
FL	1		Specification based on research report. Basis documented in AAPT report "Investigation of Water Permeability of Coarse Graded Superpave Mixes" Journal Association of Asphalt Paving Technologists Volume 67 1998
LA		1	Not Yet.
CT		1	
MI		1	
IN		1	Not directly. Density controls are based on a %Gmm criteria with penalties applied for exceeding established limits. Rarely are high void mixtures removed and replaced.
CO		1	
SC		1	South Carolina tries to control permeability with specifications on design air voids and in-place density related to rice max. density.
OH		1	
IA		1	
MN		1	
NH		1	

3.2.1 Question 1: Do you have any specifications related to permeability of surface and binder HMA courses? (continued)

State	Yes	No	Comment
RI		1	
MS		1	
VT		1	
MT		1	
WI		1	No permeability specifications at this time.
ND		1	
PA		1	
Total	1	26	

3.2.2 Question 2: Do you conduct permeability test on Superpave mixes in the lab?

State	Yes	No	Comment
GA		1	
AL		1	We have experimented with various permeability tests in the laboratory but have found them all unsatisfactory for two reasons: First, laboratory permeability tests are difficult to perform, time consuming, and the repeatability of the results is not very good. Second, we feel that the field permeability (as constructed) is far more important than laboratory permeability.
NC	1		Not routinely
ME		1	Tests have been conducted for an experimental project for Worcester Polytechnic Institute.
KS	1		Occasionally. Air Permeability, Similar to ASTM D3637
AZ		1	
IL		1	Not at this time. However, we did purchase a lab permeameter in June of 1999. It was purchased from A&S Distributors located in Odessa Florida. (Since receiving the permeameter we performed a repeatability study.
UT		1	
TX		1	

3.22 Question 2: Do you conduct permeability test on Superpave mixes in the lab? (continued)

State	Yes	No	Comment
FL	1		We use flexible membrane device manufactured by Karol Warner Soil Test Inc. See the attached Florida Test method. Test Method is conducted on field cores, but tested in laboratory. Field Cores only and only on coarse graded mixes. Note ASTM developing test method for permeability of asphalt mix. If used I recommend trimming off top/bottom if gyratory pucks used. Cores better.
LA	1		Modified Lab Permeability test. 6" metal with air sealing flex membrane inside metal mold. Constant head discharge. Falling head inlet.
CT		1	
MI		1	Not yet. Plan to.
IN		1	
CO		1	
SC		1	
OH	1		Florida DOT Apparatus
IA	1		We do not routinely measure lab permeability. We do some research on HMA permeability using a basic "falling-head" permeameter.
MN		1	
NH		1	
RI		1	
MS		1	Not on a routine basis. Have conducted some laboratory work using constant head permeameter. After making changes to our Superpave specifications, this has been done in two years.
VT		1	We do have a Florida permeability apparatus that we have done some testing with.
MT		1	
WI		1	No permeability tests being conducted, at this time, in the lab.
ND		1	
PZ		1	
Total	6	21	

3.2.3 Question 3: Do you conduct permeability test on Superpave mixes in the field?

State	Yes	No	Comment
GA		1	
AL		1	
NC		1	
ME		1	Again. MDOT did collect data for WPI.
KS		1	
AZ		1	
IL		1	Not at this time. However, we had a field permeameter made that is similar to the NCAT field permeameter. The permeameter was completed at the beginning of June 2001. The intent is to become familiar with the apparatus in the field and to use it in a joint tape evaluation targeted later in the 2001 construction season.
UT		1	
TX		1	
FL	1		Karrol Warner commercial version of FL developed device (Laboratory test conducted on field core)
LA		1	Not yet
CT		1	
MI		1	
IN		1	
CO		1	
SC		1	
OH		1	
IA		1	We do not routinely measure field permeability. To our knowledge, there are no devices that can actually measure permeability in the field. We do some research on the field HMA permeability with the NCAT device.
MN		1	We did some test with the NCAT device. We are currently purchasing one and will set up an evaluation procedure.
NH		1	
RI		1	
MS		1	Not as a requirement. We are conducting permeability test using the NCAT Field Permeability device as part of research on this issue.
VT		1	
MT		1	

3.2.3 Question 3: Do you conduct permeability test on Superpave mixes in the field? (continued)

State	Yes	No	Comment
WI		1	No permeability tests being conducted in the field, as a requirement, but we are looking at it in a research type mode. We are using the NCAT model equipment (3 tier standpipe).
ND		1	
PA		1	
Total	1	26	

3.2.4 Question 4: What is the in-place moisture content, on average, of your well performing and poor performing pavements (surface and binder)?

State	Not measured	N/A	Comment	Measured
GA	1		Not measured.	
AL	1		We do not measure the in-place moisture contents of out HMA.	
NC			When? At time of placement <1.0%	1
ME	1			
KS		1		
AZ			Moisture content in Arizona is normally very low, less than 0.25%.	1
IL	1		We do not typically test for or track data on in-place moisture content. Projects performing density nuclear gauge to core correlations do obtain data showing percent absorption by volume for several cores of varying density. This data is just additional since it has not been reported or analyzed. When low density is obtained, the % absorption has typically been in the range of 3% to 8%.	
UT	1		No record.	
TX		1	N/A	
FL	1		Not measured. No data Available. Not measured. Stripping/Moisture damage not a significant problem in FL. This is verified by coring of all our pavement rehab projects.	
LA			Generally >8% voids = poor	1
CT	1		We don't monitor "in-place" moisture. Samples taken at the HMA plant typically run 0.1 - 0.2%	

3.2.4 Question 4: What is the in-place moisture content, on average, of your well performing and poor performing pavements (surface and binder)? (continued)

State	Not measured	N/A	Comment	Measured
MI		1	Unknown	
IN	1		Difficult to measure. A few pavement sections have been probed with moisture sensors. Moisture contents in Non-surface mixtures are strongly influenced by efficiency of drainage layers and underdrain systems.	
CO		1	(Not Answered)	
SC		1	Information is not available.	
OH		1	??????	
IA		1	Do not know	
MN			0.3% is specification level. Seldom is problem.	1
NH	1		I am not sure. In-place moisture content is not measured in NH.	
RI		1	Not available.	
MS		1	Is this on plant produced mix or mix that has been on roadway some length of time? If on mix being in-place for a number of years, then this information is not available	
VT		1		
WI			On Average, Probably less than 0.70%	1
MT	1			
ND			Best Performers have moisture contents as close to zero percent as possible.	1
PA	1		Have not collected data.	
Total	11	10		6

3.2.5 Question 5: Do you have any problems with stripping in your pavements? If yes, please list the probable causes.

State	YES	NO	Comments
GA	1		Old underlying mixes prior to use of hydrated lime.
AL	1		We have had some stripping problems in our pavements. We feel this was caused by contractor not completely drying the (stripping prone) aggregates before coating the aggregates with asphalt. Our specifications no longer allow the use of aggregates that tend to strip. With all our other aggregates, most contractors use liquids ant-strips. These liquid anti-strips perform well.
NC	1		1. Lack of anti-strip additive when needed 2. Dust coated aggregate 3. High VTM and/or high in-place voids (low densities) 4. Excessive coarse textured mixtures
ME		1	
KS	1		Occasionally. Mix gradation to even on the coarse bound mixes.
AZ		1	No significant problems when appropriate mineral and mixture used. Stripping problems rare since either lime or commonly used in virtually all mixes.
IL	1		Probable causes: 1. Aggregate resources (several known strippers) 2. Low in-place density 3. Poor drainage
UT		1	We require lime in all our mix from 1% to 1.5% of mix. The lime is added in a slurry form at hot mix plant. Since then we have not noticed moisture damage yet.
TX	1		In some areas they use river gravel.
FL		1	Have not had stripping problems on first Superpave project that contained granite aggregate and had high in-place air voids (>10%) Not a problem.
LA		1	Generally not on new pavements. When pavements drain, stripping does not occur. In presence of moisture and load stripping occurs.
CT	1		We have only experienced sporadic stripping problems. No definitive causes determined.
MI		1	
IN		1	
CO	1		Sporadically. Probable causes: Aggregate Quality, Segregation, Lack of Treatment (lime), Low density.

3.2.5 Question 5: Do you have any problems with stripping in your pavements? If yes, please list the probable causes (continued)

State	YES	NO	Comments
SC		1	South Carolina did have a stripping problem in the late 1970's. We started using hydrated lime in our mixes in 1982 and that seemed to have solved our stripping problem.
OH	1		Low-moderate in some but not most mixes. Causes: 1. Aggregate Geology 2. Low binder content 3. Permeability and freeze thaw
IA		1	Iowa DOT currently uses a conservative specification that requires the use of lime when significant quantities of suspect aggregates are in the JMF. We have not had stripping problems on these pavements.
MN	1		Yes, High in-place voids, certain aggregates that are more susceptible. Our current specifications now require moisture sensitivity tests and tighter void control. They appear to be performing better.
NH		1	We have not identified stripping problems in NH. Cores for preliminary engineering purposes would indicate it and while I have seen some stripping of cold mixes, I have not seen it on hot mix.
RI		1	Not observed in our dense mixes.
MS	1		Chert gravel aggregate. All stripping is caused by water being moved through the pavement by high stresses from trucks.
VT	1		There is no formal support for this information but we have experienced stripping in the lower layers of our pavements (binders and base) and we believe that the intrusion of moisture was the cause of the stripping.
MT	1		Related to the moisture. 1.5% hydrated lime is added to minimize these problems.
WI		1	Wisconsin doesn't really have a stripping problem regarding performance, but they may be due to the specification governing use of antistrip additives, which we've had in place since 1992.
ND	1		Minor stripping problems, typically at cracks causing depressions at the cracks. Really shows up on older pavements with emulsion bases.

3.2.5 Question 5: Do you have any problems with stripping in your pavements? If yes, please list the probable causes. (continued)

State	YES	NO	Comments
PA	1		Typically low density and poor drainage conditions are present.
Total	15	12	

3.6 Summary

In the survey five questions were asked to obtain information about permeability specification, laboratory and field permeability test methods, moisture content of good and poor performing pavements and causes of moisture related damage in HMA pavements. The answers from the state DOTs indicate that at this time there is no general consensus on the applicability of any particular laboratory or field permeability measuring device/method, nor is there any good or reliable information on moisture content of good and poor performing HMA pavements. However, many states seem to be concerned about permeability problem and some of them have conducted/are conducting studies to determine suitable methods of measuring permeability, and to determine acceptance/approval criteria.

Most of the states indicated experience with stripping and a majority of these states had identified specific aggregate types and/or inadequate drainage as the cause of stripping. Summaries of responses for each question are provided in the following paragraphs.

3.6.1 Specification related to permeability

Only one (Florida) out of twenty seven states (that responded) had indicated the use of specification directly related to permeability. Florida DOT's specification is based on the results of their investigation of permeability of coarse graded Superpave mixes. Two states, Indiana and South Carolina, had indirectly tried to control permeability of HMA pavements by through their design density/air voids and in-place air voids specification.

3.6.2 Permeability test on Superpave mixes in the laboratory

Six of the twenty seven states that responded to this question indicated the use of permeability test on Superpave mixes in the laboratory. However, one of the three states, Florida, indicated the use of field cores and not laboratory compacted specimens for laboratory testing. Two other states, Ohio and Vermont use the Florida DOT permeability testing method, along with the Karol-Warner permeameter. Louisiana DOT uses a modified laboratory permeability test with constant head discharge. Arguments against the use of any specific laboratory permeability test (as indicated by Alabama DOT) seems to be difficulty, considerable amount of time and poor repeatability involved in most laboratory permeability tests. Also, permeability of "as-constructed" mix is indicated to be more important than "laboratory" permeability.

3.6.3 Permeability test on Superpave mixes in the field

Only one (Florida) of the twenty seven states that responded indicate the use of field permeability test. It must be noted though that Florida uses field cores but tests them in the laboratory. Five of the remaining states are either planning to use or to evaluate the

National Center for Asphalt technology (NCAT) permeability device. One state commented that there is no device that can actually measure permeability in the field.

3.6.4 Moisture content of good and poor performing pavements

Almost all of the states were unclear about the moisture content of in-place mixes – twenty one out of twenty seven states responded as "not measured" or "not available". While six states indicated the practice of measuring the moisture content of pavements, four gave actual maximum allowable or noted moisture contents – North Carolina (< 1%), Minnesota (< 0.3 %), Wisconsin (< 0.7 %) and Arizona (< 0.25%).

3.6.5 Problem of stripping and probable causes

Almost half of the states surveyed indicated stripping problem, associated with either specific types of aggregates or pavement drainage problems. Common causes of stripping, as identified by the different states are : 1. Insufficient drying of aggregates prior to mixing in the plant, 2. Use of stripper aggregates, 3. Dust coating on aggregates, 3. High in-place air voids, 4. Excessive coarse textured mixes, 4. Poor drainage, 5. Mix segregation, and 6. Permeability and freeze and thaw.

The most significant problem, related to pavement surface layer, seems to be associated with either specific types of aggregate or lack of adequate drainage. Lack of drainage is not a mix design problem but rather a roadway design problem. Regarding stripper aggregates, many states with stripping experience have either specified the use of anti-strip agent or specified against the use of stripper aggregates.

In relation to the current NETC study, two other important causes have been identified – one related to high air voids (or low in-place densities), and the other is related to high permeability of surface courses. In both cases stripping of either surface and/or binder and base layers have been observed. Stripping in surface, binder and base layers seem to be aggravated in the presence of moisture and load, and can occur under freeze-thaw conditions as well. Therefore, in general, the conclusion is that, as far as mix design and construction is concerned, the most significant cause of stripping is the ingress of large amounts of water into the pavement.

3.7 Conclusions from survey of state DOTs

The following conclusions can be made on the basis of the survey of state DOTs. These conclusions are made in reference to the current NETC project on permeability of HMA mixes.

1. A considerable number of states have/had experience with stripping problems.
2. The most significant mix design and construction related cause of stripping has been identified as high permeability – either due to the nature of the mix or due to high in-place air voids.
3. In order to avoid mixes with high permeability, a few states are considering the use of laboratory permeameter for testing of samples in the laboratory. However, there is no general consensus on the use of a specific type of permeameter or the type of sample to be used for testing – laboratory specimen or in-place cores.
4. Some states are evaluating and considering the use of a field permeameter, such as the NCAT permeability measuring device, for testing in-place mixes. However, at present there is no general guideline or criteria for accepting/rejecting mixes on the basis of permeability testing.

5. There is no reliable information about the moisture content of good or poor performing pavement (specifically surface layers), although many of the states have indicated that it is the movement of water or freeze-thaw condition that causes stripping in surface, binder and base layers. Obviously, in many cases, water getting inside the surface layer finds its way to binder and base layers and affects the performance of all three layers. If excessive amounts of water do get inside the surface layer and freeze, then stripping damage can be expected in surface layers. However, information regarding critical amount of moisture or the moisture content that can cause such a damage is not available.

CHAPTER 4: PROPOSED PLAN OF STUDY

On the basis of the literature review, the survey of state DOTs and meetings with the members of the Expert Task Group (ETG) for this project the following plan of study was developed. Each step in the plan is presented with its justification, tasks and method of approach.

1. Task 1: Evaluation of effect of factors on mix permeability

There are two steps, which need to be taken during the design and construction of a HMA pavement, which can eliminate the chance of getting pavements with excessive permeability. First, the mix should be designed in such a way that it is not excessively permeable even at normally expected in-place voids. Second, the mix should be compacted in the field to a density that is needed for avoiding excessive permeability. It is quite possible that mixes with certain gradations would require higher than commonly used in-place densities. However, this density should still be one that is practically achievable with existing/commonly used construction equipment.

The first step in determining a way of designing a mix and determining the required in-place density is to determine the various mix design factors that can have significant effect on mix permeability. On the basis of the literature review, air voids and mix gradations seem to be the primary candidates for evaluation of effects on permeability.

One key question that is raised at this point is that which method of permeability, since there is no universally accepted method, should be used for this task? The best possible approach is to conduct that permeability test which allows close control of test conditions, and which allows evaluation of various factors in the most practical and time-efficient way. Considering these factors, the laboratory permeability test, using the Karol-Warner device and the Florida DOT method, was selected for this task.

2. Task 2: Determine a suitable permeability test procedure

Once the effect of gradation and air voids is understood, it is still required to evaluate the currently used laboratory permeability method in order to recommend a method for regular used. If this method is found to be inadequate, it is necessary to suggest an alternative – a better method.

3. Task 3: Determination of critical permeability

Once a suitable method for determination of permeability or permeability potential has been identified, the question is how to use them in a way such that mixes with excessive permeability can be avoided? Obviously the answer to this question lies in the determination of a critical permeability. The critical permeability is one, above which, the pavement lets in excessive amount of water. Again, the question is, how much water is too much water? In an approach that was initially considered by the research team and the Expert Task Group (ETG) for this project, the critical permeability was defined as one which lets in adequate amount of water to partially (upto a certain degree) saturate a pavement layer and increase its moisture content above a certain level. However, the key step in defining the "certain" moisture content was dependent on information regarding moisture content of good and poor performing pavements.

As noted in Section 2, a clear answer regarding moisture content of good and poor performing pavements was not available from the literature or the survey of state DOTs.

Hence, it was necessary to consider a different approach. This approach has been explained in Chapter 5: Results and Analysis.

4. Task 4: Determine a method for determination of field permeability

One argument against conducting laboratory permeability has been the inadequacy of this method to predict the actual field permeability. State DOTs have indicated that field permeability is more important than laboratory permeability, and also that no existing method can actually measure field permeability. Obviously, three big questions are raised from these survey results – 1. What is the purpose of conducting field permeability? 2. How does field permeability related to laboratory permeability? and 3. What is the best use of measuring field permeability?

In order to answer these questions it is necessary consider available information from field permeability tests. This is because since there is no established method of field permeability testing, it is not possible to develop any correlation between laboratory and field permeability from this project. However, there is scope of development of a new field permeameter that can be used in the best possible way. Figure 4.1 shows the overall approach and the different tasks.

It is noted that one of the objectives was to evaluate the effect of thickness of HMA layers on conductivity of water. This work required testing of HMA layers of same mix but different thickness. Projects with such a range of layers were not made available in the testing phase. Hence, the objective of evaluating the effect of lift thickness could not be accomplished. However, results of a project conducted by WPI researches for Maine Department of Transportation would provide some guidance regarding the selection of appropriate lift thickness for avoiding excessive permeability. These results and recommendations are provided in Maine DOT Technical Report ME 00-1, November 1999.

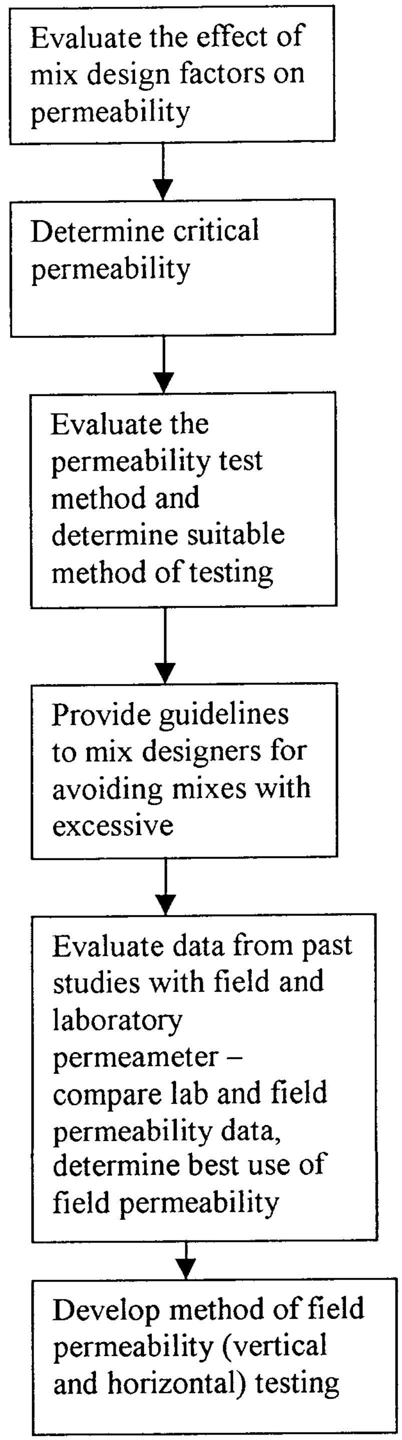


FIGURE 4.1 Plan of study

CHAPTER 5. TEST AND MATERIALS INFORMATION

5.1 Testing

The scope of this project involved two types of tests – one associated with compaction and production of samples of Hot Mix Asphalt (HMA) in the laboratory and the other related to permeability testing.

150 mm diameter (six inch) samples were compacted to different air voids out of loose mix, with a Pine Superpave gyratory compactor (Model AFG1) (AASHTO TP4). The mixes were heated to compaction temperature (supplied by the respective state DOTs) prior to compaction. After compaction the samples were cooled down to room temperature, and tested for bulk specific gravity. Bulk specific gravity was determined by two methods – the saturated surface dry method (SSD) (AASHTO T166) and also by using a vacuum sealing method (ASTM D130-01) (equipment shown in Figure 5.1.1, method presented in Appendix A). The vacuum sealing method basically consists of the use of a vacuum sealed sample (inside a bag) for determination of volume of the sample (as opposed to filling in the voids with water in the SSD method). The theoretical maximum density (TMD or G_{mm}) values were obtained from mix information sheets provided by the state DOTs. In some cases the TMD values were determined in the laboratory (AASHTO T209). Air voids of samples were determined from bulk specific gravity and TMD values.

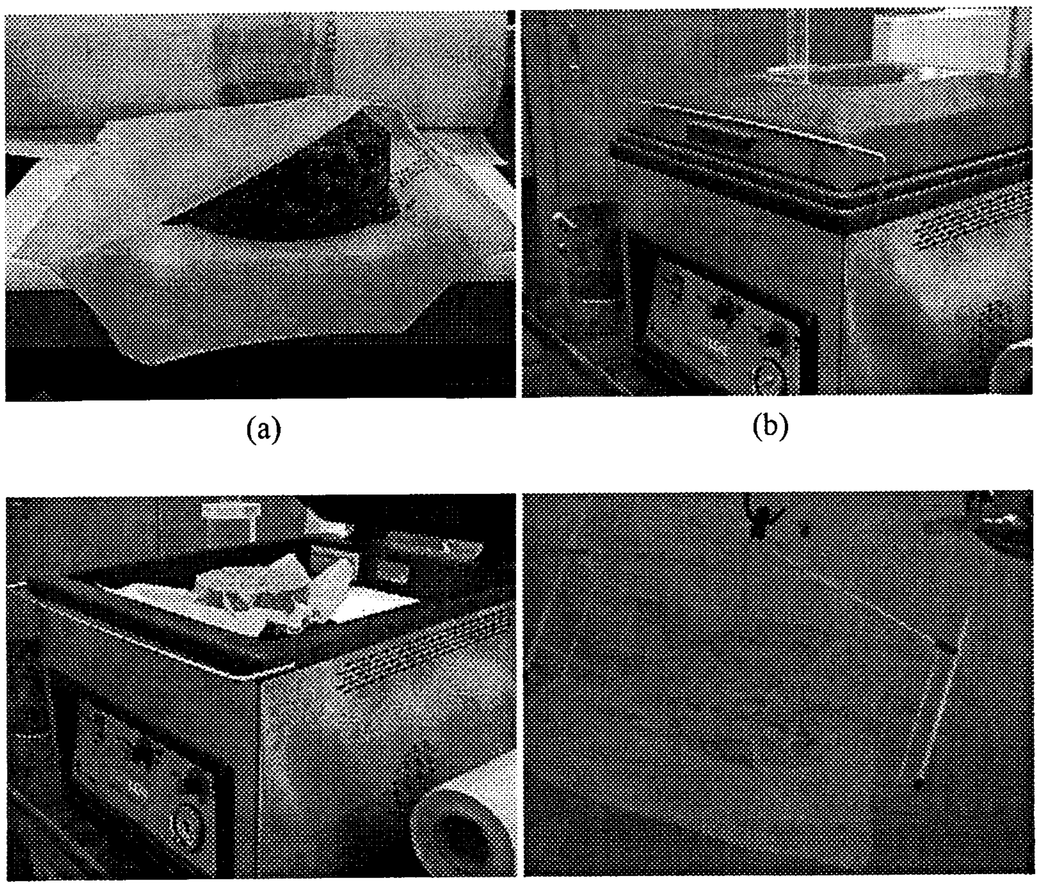
Permeability testing of HMA samples were conducted with a Karol Warner falling head permeability device (Figure 5.1.2), using the Florida DOT (FM 5-565) method (provided in Appendix B). In this method, basically, a stand pipe over a HMA sample is filled with water and the rate of vertical flow of water through the HMA sample is determined by noting the drop of water in the stand pipe in a specific time. The HMA sample is saturated prior to testing.

For all the HMA samples, porosity was also determined, with the vacuum sealing method. Porosity is defined as the percentage air void in the compacted sample that is accessible to water. In this method a sample is vacuum sealed inside a bag and a density, ρ_1 is calculated by using the method outlined in ASTM D130-01. The same sample while under water is opened and a second density, ρ_2 is determined. Since the sample is under complete vacuum prior to opening the bag, ρ_2 will yield an apparent or maximum density of the compacted sample. The density ρ_2 includes the volume due to inaccessible air voids.

$$\%\ \text{Porosity} = \%P = \left(\frac{\rho 2 - \rho 1}{\rho 2}\right) X100$$

where:
ρ_1= the vacuum sealed density of compacted sample
ρ_2= density of the vacuum sealed sample after opening under water

Two field permeability tests were conducted (one in Maine and another in Vermont), using the WPI permeameter, developed in a study for Maine DOT in 1999. The method consists of using a falling head device to determine the rate of flow through



(a) (b) (c) (d)

FIGURE 5.1.1 Use of CoreLok™ (a) sample in bag, (b) CoreLok™ device, (c) sample in sealed bag, (d) sample in water inside the sealed bag

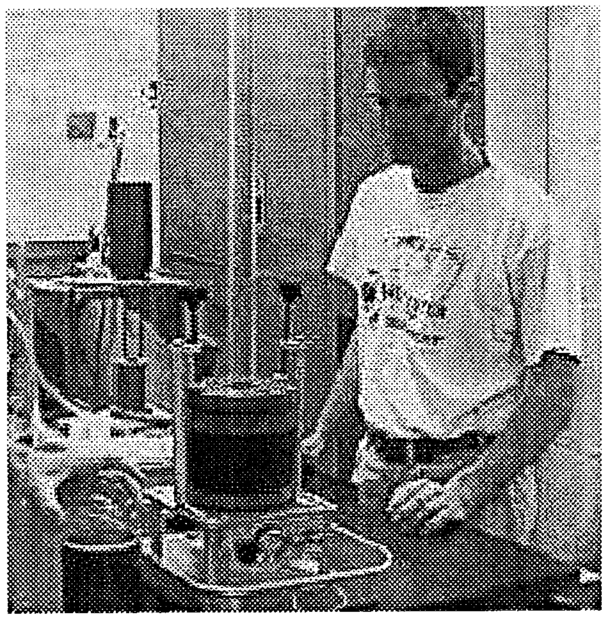
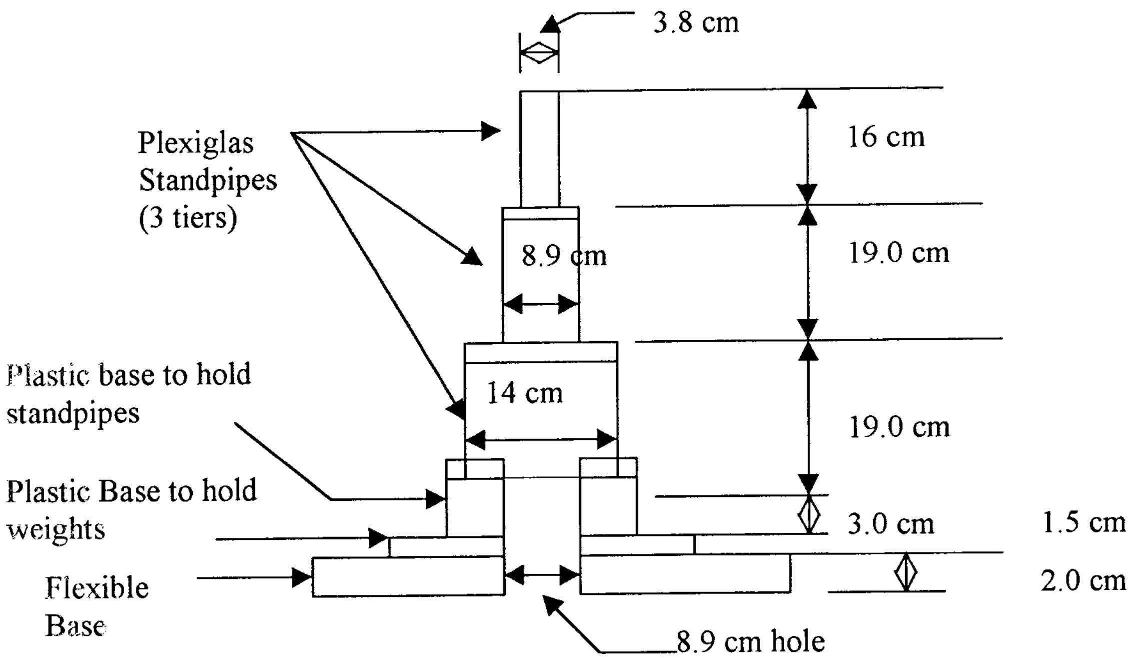


FIGURE 5.1.2 Permeability device

the pavement surface. Surface flow through the sides is restricted by providing a sealing system (equipment is shown in Figure 5.1.3, method is presented in Appendix C).

5.2 Mixture information

At the beginning of the study a number of mixes were obtained from various state DOTs in New England. Although the plan was to obtain different types of mixes from all six New England states, mixes were actually obtained from three states – Massachusetts, New Hampshire and Connecticut DOTs. However, these mixes represented a wide variety in gradation. Table 5.2.1 shows the mix gradations. The ETG recommended that these mixes be compacted to three different air void (voids in total mix, VTM) levels – 5, 7 and 10 percent for testing the effect of air voids on permeability. For each air void content, three replicates were decided to be used. Hence the matrix of samples used for laboratory permeability testing consisted of 90 samples, in total, as shown in Table 5.2.2. The actual number of samples compacted were greater than 90, since some trial and error was needed to achieve the specific air voids in compacted samples.



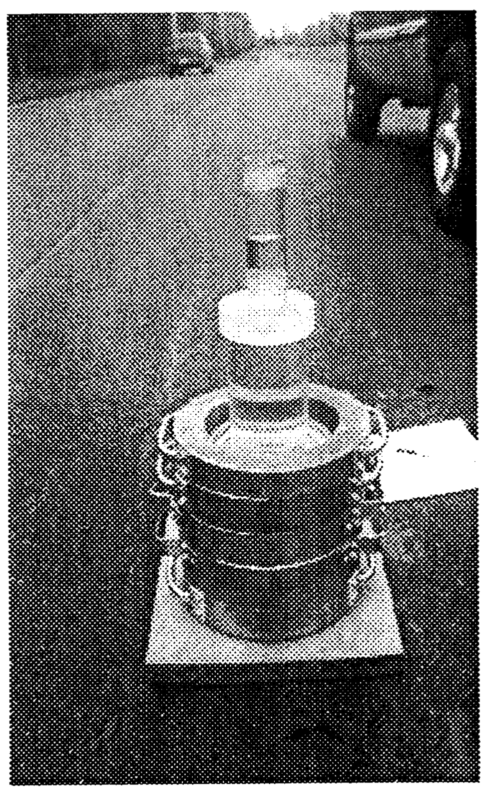


FIGURE 5.1.3 Sketch and photo of permeameter.

TABLE 5.2.1 Mix information

State	Mix	Sieve Size, mm	Percentage Passing	Asphalt Content, %
CT	TD 12.5	19	100	4.6
		12.5	93	
		9.5	74	
		4.75	43	
		2.36	30	
		1.18	22	
		0.6	15	
		0.3	9	
		0.15	6	
		0.075	3.6	
	TP 12.5	19	100	5.1
		12.5	96	
		9.5	83	
		4.75	48	
		2.36	33	
		1.18	23	
		0.6	18	
		0.3	12	
		0.15	7	
		0.075	3.7	
	TW 9.5	19		6.0
		12.5	100	
		9.5	99	
		4.75	71	
		2.36	46	
		1.18	33	
		0.6	24	
		0.3	15	
		0.15	8	
		0.075	4.5	
	LW 9.5	19		5.7
		12.5	100	
		9.5	99	
		4.75	62	
		2.36	44	
		1.18	30	
		0.6	20	
		0.3	13	
		0.15	8	
		0.075	4.3	

TABLE 5.2.1 Mix information (continued)

State	Mix	Sieve Size, mm	Percentage Passing	Asphalt Content, %
CT	LW 12.5	19	100	5.1
		12.5	97	
		9.5	75	
		4.75	43	
		2.36	31	
		1.18	21	
		0.6	14	
		0.3	9	
		0.15	6	
		0.075	3.9	
MA	MA 19.0	25	100	4.2
		19	95	
		12.5	70	
		9.5	56	
		4.75	39	
		2.36	29	
		1.18	21	
		0.6	16	
		0.3	10	
		0.15	7	
		0.075	4.3	
NH	CPI 1 19.0	25	100	4.8
		19	99	
		12.5	80	
		9.5	63	
		4.75	42	
		2.36	25	
		1.18	17	
		0.6	10	
		0.3	7	
		0.15	5	
		0.075	3.5	
	CPI 2 12.5	19	100	6.4
		12.5	99	
		9.5	90	
		4.75	62	
		2.36	46	
		1.18	34	
		0.6	23	
		0.3	13	
		0.15	6	
		0.075	3.5	

TABLE 5.2.1 Mix information (continued)

State	Mix	Sieve Size, mm	Percentage Passing	Asphalt Content, %
ME	ME 214	19	100	6.0
		12.5	100	
		9.5	96	
		4.75	60	
		2.36	41	
		1.18	27	
		0.6	17	
		0.3	10	
		0.15	7	
		0.075	5	
VT	RT 4	19	100	4.8
		12.5	99	
		9.5	82	
		4.75	57	
		2.36	37	
		1.18	24	
		0.6	16	
		0.3	10	
		0.15	6	
		0.075	3.5	

TABLE 5.2.2 Matrix of samples (laboratory compacted)

Mix	VTM, %		
	5	7	10
TD12.5	XXX	XXX	XXX
TP12.5	XXX	XXX	XXX
TW9.5	XXX	XXX	XXX
LW9.5	XXX	XXX	XXX
LW12.5	XXX	XXX	XXX
MA19	XXX	XXX	XXX
CPI19	XXX	XXX	XXX
CPII12.5	XXX	XXX	XXX
ME214	XXX	XXX	XXX
VT Rt4	XXX	XXX	XXX

Note: X – denotes one sample, total number of test samples: 90

CHAPTER 6: RESULTS AND ANALYSIS

6.1 Evaluation of factors affecting permeability of HMA

Mixes with different nominal maximum aggregate size (NMAS), gradation and air void content (VTM) were tested in the laboratory for permeability. The results are shown in Table 6.1.1. Note that the term "permeability" has been used in place of coefficient of permeability. In order to understand the effect of different factors, the permeability values were plotted against air voids (determined by the SSD method) for each NMAS. The plots, shown in Figure 6.1.1, indicate an increase in permeability with an increase in air voids. Regression curves, along with equations and coefficient of determination (R^2) are also shown. In the plots, there is a difference in the degree of the effect of air voids on permeability between mixes with different NMAS – it seems that 19 mm NMAS mixes are the most sensitive to change in air voids, and that 12.5 mm NMAS mixes are more sensitive to air voids than 9.5 mm NMAS mixes, that is, higher the nominal maximum aggregate size, greater is the increase in permeability for an unit increase in the air voids.

One important thing that can be noted is that the regression between air voids and permeability becomes weaker with an increase in NMAS. Since permeability is dependent on air voids and the size of air void pores or inter-connectivity of air voids, there is no obvious explanation for this. Most probably what is happening is, because of the presence of a significant amount of interconnected air voids in mixes with higher NMAS, the air voids determined for 12.5 and 19.0 mm NMAS mixes at high air voids (above 5 percent) are not accurate. This has resulted in poor and fair regression between air voids and permeability for the 19.0 mm and the12.5 mm NMAS mixes, respectively, as compared to an excellent regression for 9.5 mm NMAS mixes. Because of the fact that the air voids data for the 19 mm NMAS mixes, particularly those at high air voids (for some of them it was not possible to conduct the SSD bulk specific gravity test) are suspect, and the fact that most of the surface courses are made up of 9.5 mm and 12.5 mm NMAS mixes, a decision was taken by the researchers to consider only the 9.5 mm and 12.5 mm NMAS mixes from this point in the study. With respect to the effect of gradation and nominal maximum aggregate size on permeability, a better explanation can be obtained from a comparison of test results from SSD bulk specific gravity testing and the vacuum sealing method. In general, the SSD bulk specific gravity of the coarse graded mixes were difficult to obtain since the water drained out too fast from the samples before any meaningful data can be obtained. In the case of the 19 mm coarse graded mix from NH, it was not possible to obtain any bulk specific gravity data using the SSD method at 10 % VTM. Note that AASHTO T-275 (Bulk Specific Gravity of Compacted Bituminous Mixtures Using Paraffin-Coated Specimens) was not used in this study.

A comparison of VTM obtained from SSD and vacuum seal methods (Table 6.1.1) reveals that in most cases the SSD voids are lower than the vacuum seal method voids. An explanation of this observation is that since some water always runs out of the sample during the SSD test prior to obtaining the SSD mass, the volume of the sample is underestimated, resulting in overestimation of density and hence underestimation of air voids. This error becomes more significant at higher air voids, since the potential of the water to run out should increase with an increase in air voids. This is shown in Figure 6.1.2, which shows that for each mix the difference between the SSD and the vacuum

TABLE 6.1.1 Voids and permeability (laboratory testing) of mixes

State	Mix	Target VTM, %	Sample #	VTM, SSD %	VTM, vacuum seal %	Porosity %	Permeability cm/s
CT	TD 12.5	5%	1	4.47	4.74	7.33	0.00183
			2	5.48	6.26	8.89	0.00205
			3	4.56	5.42	8.14	0.00260
		7%	3	6.85	8.10	10.72	0.00665
			12	6.79	8.28	10.73	0.00685
			13	6.53	8.37	10.95	0.00747
		10%	1	11.95	11.99	14.01	0.0261
			2	9.06	11.33	14.04	0.0254
			3	8.89	10.98	13.53	0.0220
	TW 9.5	5%	1	4.48	4.68	3.48	0.000105
			2	5.30	5.76	3.97	0.000173
			3	4.60	5.05	3.06	0.000128
		7%	2	6.66	7.10	5.18	0.000304
			6	6.63	7.05	5.09	0.000371
			9	6.97	8.94	7.52	0.000438
		10%	2	9.75	10.30	9.26	0.00181
			5	9.93	10.51	8.94	0.00202
			6	9.86	10.44	9.89	0.00227
	LW 12.5	5%	1	4.74	6.26	5.30	0.000399
			2	4.65	5.60	3.45	0.000643
			3	4.83	5.63	4.36	0.000632
		7%	1	7.16	8.11	8.33	0.00204
			5	7.39	8.73	8.87	0.00410
			6	7.46	8.29	8.40	0.00184
		10%	4	9.71	12.18	12.70	0.0130
			6	10.39	13.17	14.01	0.0250
			7	9.78	11.24	11.91	0.0129
	TP12.5	5%	2	4.98	5.26	3.88	0.000295
			3	4.95	5.12	3.17	0.000308
			4	4.99	5.45	4.77	0.000505
		7%	1	7.53	7.79	6.66	0.00118
			2	7.54	8.12	6.42	0.000870
			7	6.95	7.27	5.93	0.000908
		10%	1	9.92	9.86	8.38	0.00318
			2	9.72	10.86	8.03	0.00183
			3	10.17	10.88	10.52	0.00156

Note:
VTM – voids in total mix, SSD – saturated surface dry method, Permeability – Coefficient of permeability

TABLE 6.1.1 Voids and permeability (laboratory testing) of mixes (continued)

State	Mix	Target VTM, %	Sample #	VTM, SSD %	VTM, vacuum seal %	Porosity %	Permeability cm/s
CT	LW9.5	5%	1	5.40	5.76	4.08	0.000366
			3	4.79	5.28	4.26	0.000476
			4	4.60	5.00	3.74	0.000369
		7%	1	7.05	7.61	6.42	0.000904
			2	7.15	7.70	6.90	0.000748
			3	6.88	7.46	6.40	0.000617
		10%	7	10.39	11.53	11.95	0.00477
			8	10.76	11.53	12.09	0.00676
			9	10.46	11.51	11.85	0.00683
MA	MA 19.0	5%	2	4.97	5.78	4.87	0.000318
			3	5.35	5.95	5.39	0.00252
			4	5.43	5.99	4.71	0.0005
		7%	2	7.27	8.19	8.38	0.000819
			3	7.16	8.22	8.70	0.00165
			4	7.29	8.41	5.93	0.00199
		10%	2	10.17	11.31	9.87	0.00438
			3	10.19	11.21	12.14	0.00601
			4	9.98	10.88	11.84	0.00668
NH	CPI 19.0	5%	1	5.28	6.56	7.26	0.00243
			3	5.37	6.68	7.64	0.00296
			5	5.25	6.63	7.89	0.00526
		7%	1	7.14	9.60	10.88	0.0203
			2	6.84	9.20	10.80	0.00947
			10%_01	7.19	11.44	11.46	0.0243
		10%	6	Not available	12.18	Not available	0.0315
			8	Not available	12.11	12.26	0.0225
			9	Not available	12.40	12.01	0.0251
	CPI 12.5	5%	1	5.13	5.14	5.23	0.0000365
			3	5.12	5.00	5.16	0.0000741
			4	5.01	4.61	4.97	0.0000741
		7%	1	7.25	7.18	7.28	0.000289
			5	7.17	6.94	6.90	0.000312
			6	7.33	8.45	8.49	0.000379
		10%	2	9.91	10.22	10.67	0.00382
			3	9.90	10.66	11.51	0.0045
			5	10.15	10.44	10.54	0.00399

Note: VTM – voids in total mix, SSD – saturated surface dry method, Permeability – Coefficient of permeability

TABLE 6.1.1 Voids and permeability (laboratory testing) of mixes (continued)

State	Mix	Target VTM, %	Sample #	VTM, SSD %	VTM, vacuum seal %	Porosity %	Permeability cm/s
ME	ME 214	5%	1	5.32	Not available	Not available	0.000278
			2	4.94	7.64	5.071	0.000227
			3	5.06	5.75	4.005	0.0001371
		7%	1	6.58	6.78	5.127	0.0006786
			2	7.25	8.00	Not available	0.0007281
			3	6.65	7.46	6.658	0.0008513
		10%	6	10.31	Not available	Not available	0.004273
			8	9.63	10.56	10.326	0.004185
			9	9.95	12.16	11.781	0.003997
VT	Rt 4	5%	1	4.63	5.66	5.299	0.0006057
			3	5.23	5.05	4.716	0.0004067
			5	5.03	6.03	4.227	0.000577
		7%	1	6.99	7.99	7.570	0.001489
			2	7.06	7.90	7.504	0.001153
			3	7.17	8.26	7.386	0.001912
		10%	6	9.79	11.63	11.411	0.007034
			8	9.64	11.22	11.005	0.006210
			9	9.09	11.22	11.208	0.006960

Note: VTM – voids in total mix, SSD – saturated surface dry method, Permeability – Coefficient of permeability

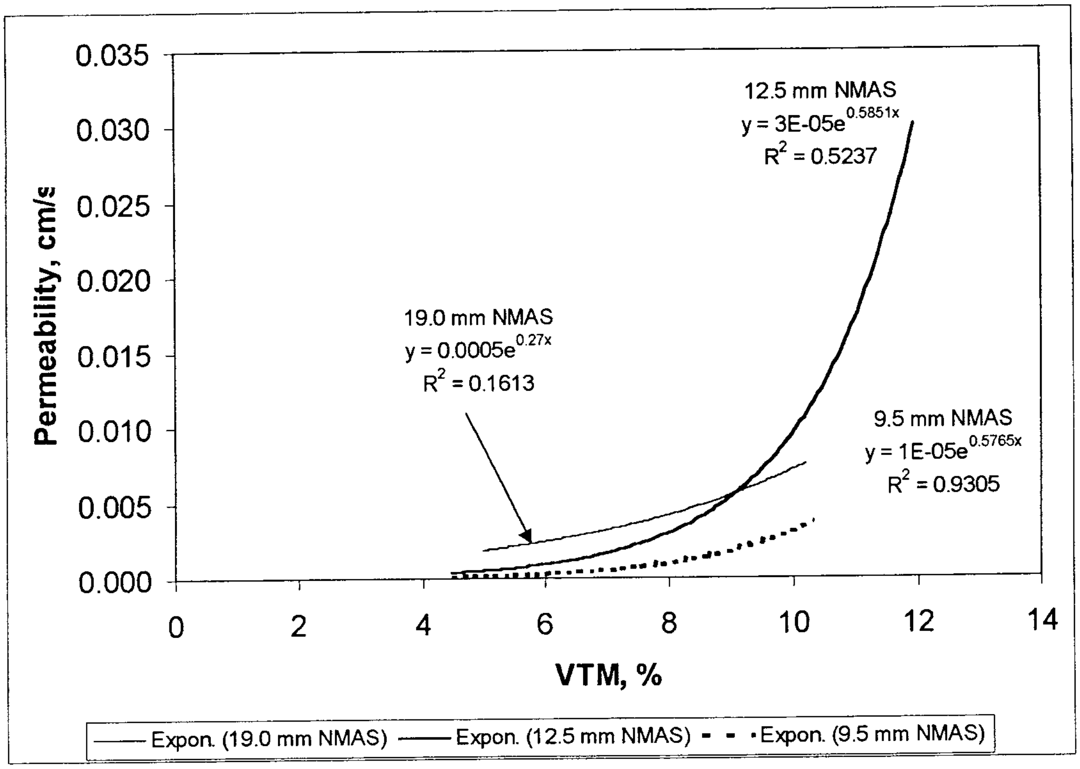


FIGURE 6.1.1 Plot of permeability versus air voids (laboratory compacted samples)

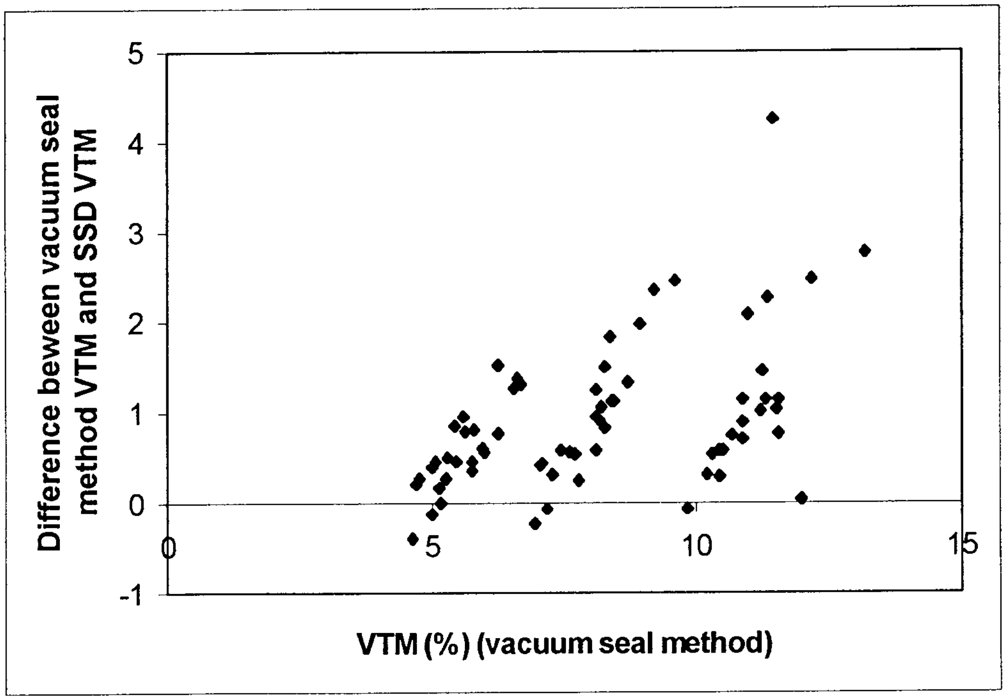


FIGURE 6.1.2 Plot of air voids versus difference of vacuum seal method air voids and SSD air voids

seal method air voids increases with an increase in air voids (as obtained from vacuum seal method).

Determination of a suitable permeability test procedure

Water flows through accessible voids or pore spaces in a pavement. Hence, the rate of flow must be related to the amount of water accessible voids, or porosity, in some way. Therefore, the permeability or coefficient of permeability must be a function of porosity. Table 6.1.1 shows the porosity versus permeability data, as obtained from laboratory testing. The best model for defining the relationship between porosity and permeability seems to be one of exponential in nature, as shown in Figure 6.1.3 (considering data from 9.5mm and 12.5mm NMAS mixes only). This model ($R^2 = 0.80$) is better than the one with air voids and permeability ($R^2 = 0.55$). If one considers this model, then the critical porosity corresponding to a critical permeability can be determined.

Determination of critical permeability

Since, in general, permeability data for HMA is highly variable, and the nature of the permeability-porosity plot is exponential, it is logical to consider the value of permeability in terms of 10^X, rather than in terms of exact value. As recommended by Florida Department of Transportation (DOT) researchers (7), considering a critical permeability of 10^{-3} cm/second (0.001 cm/s), a critical porosity of 7 percent is determined. Therefore, mix design samples can be checked for permeability potential by conducting porosity tests on samples compacted to construction voids (as determined by SSD method), and a maximum porosity value of 7 percent can be recommended. One important question is, how can one estimate the porosity from knowledge of mix gradation and air voids? To answer this question multiple regression analysis was conducted with porosity and aggregate gradation data. The aggregate gradation was characterized with the help of several parameters, such as percent passing the 2.36 mm sieve (PP2.36), fineness modulus and coefficient of curvature. The results of multiple regression analysis, presented in Table 6.1.2, show that an excellent model can be defined for relating porosity to air voids and percent passing the 2.36 mm sieve (PP2.36).

Next, considering the defined model relating percent air voids, percent passing the 2.36 mm sieve and porosity, a set of curves were plotted for different PP2.36 and different air voids, as shown in Figure 6.1.4. Considering a critical porosity of 7 percent (as determined earlier, corresponding to a critical permeability of 10^{-3} cm/second), critical air voids (as determined by SSD bulk specific gravity and theoretical maximum density) can be determined. A list of critical air voids, for mixes with different percent passing the 2.36 mm sieve, is shown in Table 6.1.3. The critical air voids range from 5 to 7.5 corresponding to PP2.36 of 25 to 45. One can use this table to specify maximum construction air voids for a specific mix.

From Figure 6.1.4 it can be noted that for a mix with approximately 45 percent passing the 2.36 mm sieve, a porosity of 7 per percent corresponds to VTM of 7 percent. Most of experiences from the past (in the pre-Superpave era) has been with mixes with 40-45 percent passing the 2.36 mm sieve, and a VTM of 7 percent has often been recommended and used, without any significant permeability or durability (related to excessive aging) problem. Therefore, the selection of 7 percent porosity as a critical porosity seems to be well justified.

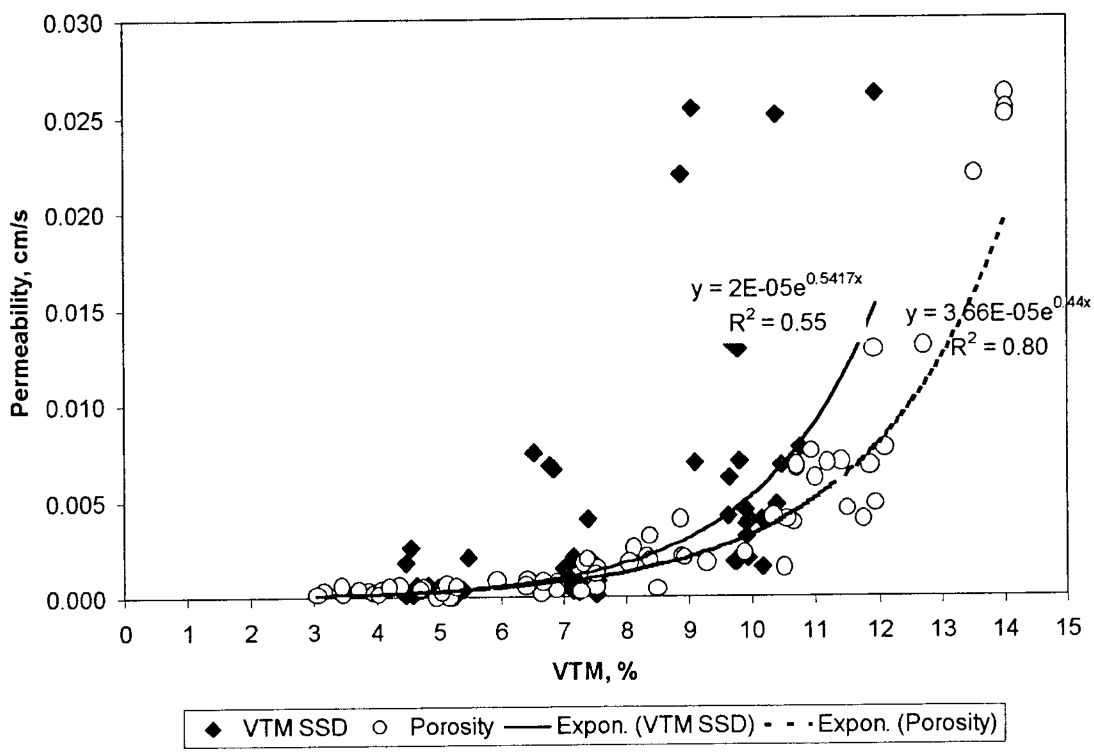


FIGURE 6.1.3 Plot of permeability versus porosity and permeability versus air voids, considering 9.5 mm and 12.5 mm mixes only

TABLE 6.1.2 Results of multiple regression analysis with mix gradation, air voids and porosity

Regression Summary
Porosity vs. 2 Independents
Row exclusion: perm #1_12.5_9.5.svd

Count	68
Num. Missing	3
|R|	.897
R Squared	.804
Adjusted R Squared	.798
RMS Residual	1.406

ANOVA Table
Porosity vs. 2 Independents
Row exclusion: perm #1_12.5_9.5.svd

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	2	526.694	263.347	133.281	<.0001
Residual	65	128.432	1.976		
Total	67	655.126			

Regression Coefficients
Porosity vs. 2 Independents
Row exclusion: perm #1_12.5_9.5.svd

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
Intercept	3.472	1.225	3.472	2.834	.0061
Air Voids, SSD	1.260	.080	.861	15.686	<.0001
PP2.36	-.127	.028	-.251	-4.575	<.0001

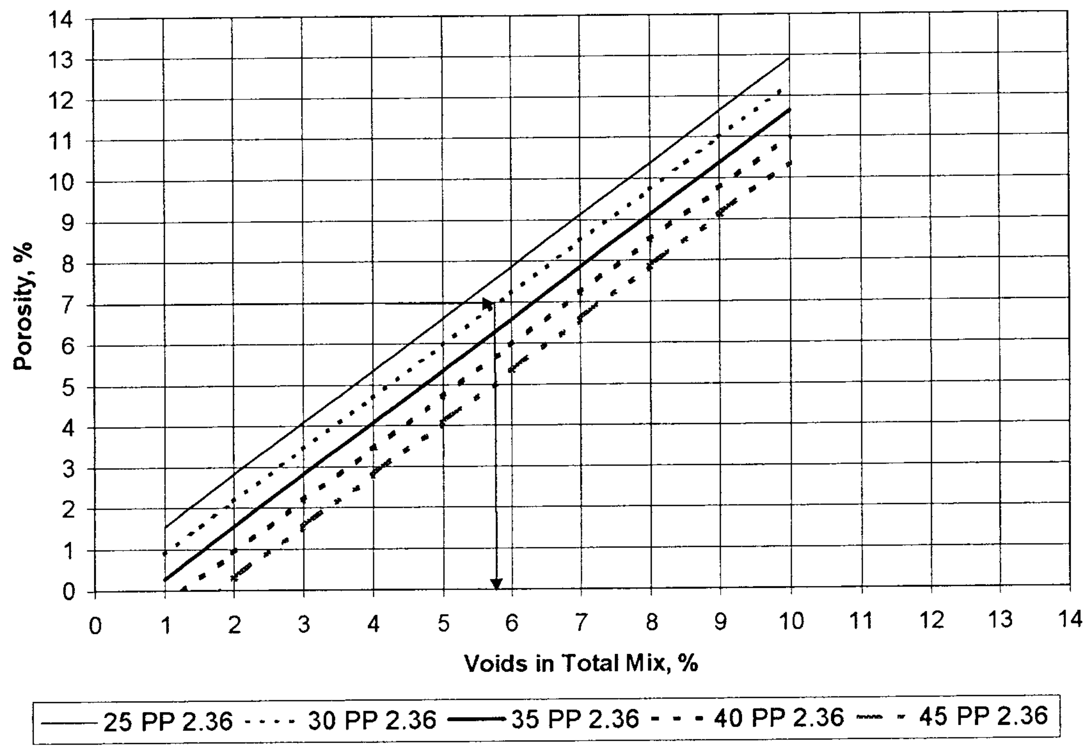


FIGURE 6.1.4 Plots of air voids versus porosity for mixes with different percentage passing the 2.36 mm sieve

TABLE 6.1.3 Critical air voids for mixes with different gradations

Percent passing the 2.36 mm sieve	Critical Air Voids, %
25	5
30	6
35	6.5
40	7
45	7.5

From Figure 6.1.5 one can determine the critical PP2.36 value for any specific air voids. Table 6.1.4 shows a list of critical PP2.36 for a range of air voids. One can use the values from this table to select suitable gradation(s) during mix design for a specific construction air voids. For example, if it is known that realistically an air voids below 6 percent cannot be achieved, and then one can select a specific PP2.36 (greater than 31 percent) such that the porosity of the resulting mix is below 7 percent air voids.

A question that arises from the analysis of the data is that which parameter should be used during mix design to prevent mixes from being excessively permeable – is it laboratory permeability test or is it porosity test? Obviously measuring permeability is a more direct approach. However, since porosity shows a very good relationship with permeability, perhaps porosity is a good mix design parameter candidate also. This argument becomes stronger when one considers the coefficient of variation of the permeability and the porosity tests. Table 6.1.5 shows the coefficient of variation (CV) for each set of samples as well as average CV for porosity and permeability data. The average CV for permeability testing is about three times the average CV of porosity. Hence, as a regular test procedure, because of better repeatability, porosity seems to be more appropriate than permeability. Also, determination of porosity is simple and rapid as compared to laboratory permeability test. Since asphalt laboratories can use the vacuum sealing device to determine the bulk specific gravity of compacted HMA, the determination of porosity will be just an additional step when testing for bulk specific gravity.

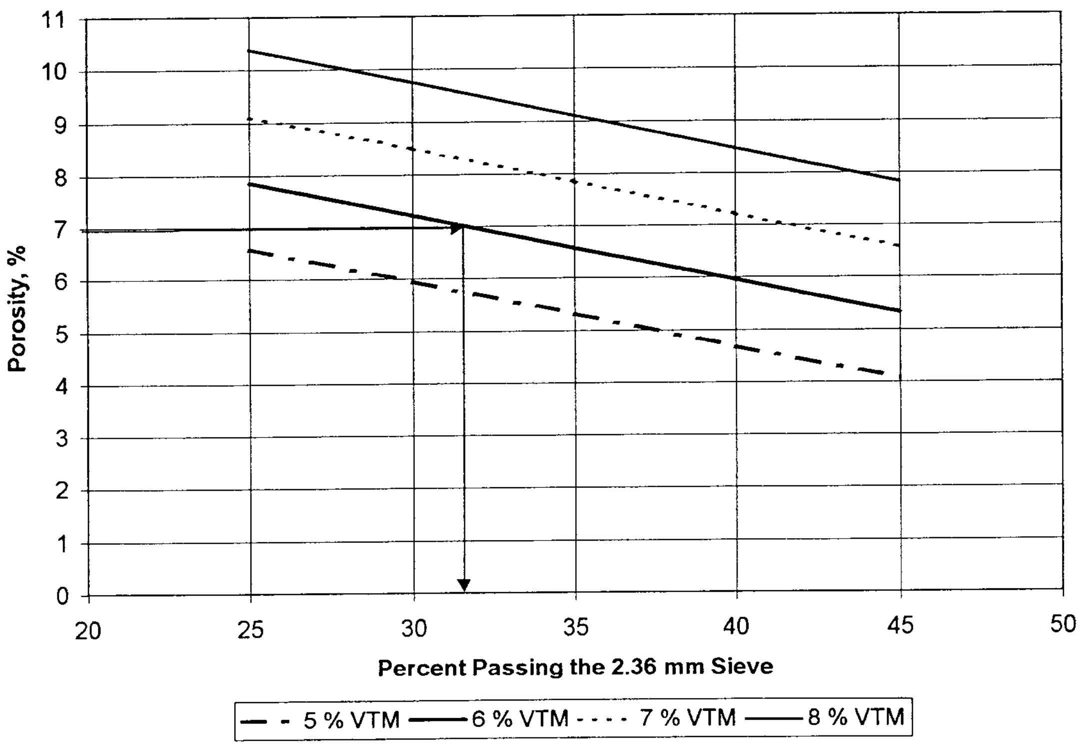


FIGURE 6.1.5 Plot of percent passing the 2.36 mm sieve versus porosity for different air voids

TABLE 6.1.4 List of critical percent passing the 2.36 mm sieve for specific air voids

Air Voids	Allowable percent passing the 2.36 mm sieve
5	> 25
6	> 31
7	> 41
8	> 45

TABLE 6.1.5 Coefficient of variation of porosity and permeability testing

Target VTM	Porosity, %	Coefficient of variation, Porosity, %	Coefficient of Permeability, cm/s	Coefficient of variation, coefficient of permeability, %
5%	7.3	9.59	0.001826	18.52
	8.8		0.002047	
	8.13		0.002602	
7%	10.7	1.21	0.006647	6.14
	10.7		0.006849	
	10.9		0.007471	
10%	14.0	2.09	0.026135	9.05
	14.0		0.025357	
	13.5		0.021963	
5%	3.8	20.38	0.000294	31.96
	3.1		0.000307	
	4.7		0.000505	
7%	6.6	5.89	0.000118	70.49
	6.4		0.00087	
	5.9		0.000908	
10%	8.3	15.02	0.00318	39.63
	8.0		0.00183	
	10.5		0.00156	
5%	3.4	12.97	0.000104	25.61
	3.9		0.000172	
	3.0		0.000128	
7%	5.1	23.20	0.000304	18.02
	5.0		0.000371	
	7.5		0.000438	
10%	9.2	5.13	0.001808	11.43
	8.9		0.002024	
	9.8		0.002273	
5%	4.0	6.60	0.000366	15.46
	4.2		0.000475	
	3.7		0.000368	
7%	6.4	4.29	0.000904	18.99
	6.8		0.000748	
	6.4		0.000617	
10%	11.9	1.03	0.00477	23.71
	12.0		0.00776	
	11.8		0.00683	

TABLE 6.1.5 Coefficient of variation of porosity and permeability testing (continued)

Target VTM	Porosity, %	Coefficient of variation, Porosity, %	Coefficient of Permeability, cm/s	Coefficient of variation, coefficient of permeability, %
5%	5.3	21.15	0.000399	24.70
	3.4		0.000643	
	4.3		0.000632	
7%	8.3	3.46	0.002037	46.95
	8.8		0.004096	
	8.3		0.001842	
10%	12.7	8.26	0.013027	41.15
	14.0		0.025045	
	11.90		0.012860	
5%	5.23	2.63	3.65E-05	35.25
	5.16		7.41E-05	
	4.97		7.41E-05	
7%	7.28	10.98	2.89E-04	14.31
	6.90		3.12E-04	
	8.49		3.79E-04	
10%	10.67	4.83	3.82E-03	8.62
	11.51		4.50E-03	
	10.54		3.99E-03	
5%	Not available	---	2.784E-04	33.45
	5.071		2.227E-04	
	4.005		1.371E-04	
7%	5.127	---	6.786E-04	11.81
	Not available		7.281E-04	
	6.658		8.513E-04	
10%	Not available	---	4.273E-03	3.39
	10.326		4.185E-03	
	11.781		3.997E-03	
5%	5.299	11.30	6.057E-04	20.30
	4.716		4.067E-04	
	4.227		5.770E-04	
7%	7.570	1.24	1.489E-03	25.05
	7.504		1.153E-03	
	7.386		1.912E-03	
10%	11.411	1.81	7.034E-03	6.76
	11.005		6.210E-03	
	11.208		6.960E-03	
Average		8.24		23.36

6.2 Determine a method for determination of field permeability

While laboratory permeability test is important for mix design, field permeability is considered by many as more important than laboratory permeability. This is because, field permeability test can determine the permeability characteristics of the actual pavement mix as opposed the laboratory mix. One of the states surveyed also indicated that to their knowledge there is no available permeameter that can actually determine (the true) permeability in the field.

A review of the typical field permeameters used in the US shows that the allegation is at least partially true. This is because, in all existing field permeability testing methods (such as the NCAT and the WPI permeameter) basically a composite permeability is measured on the surface, without any specific determination of vertical and horizontal permeability components. In fact, the determination of permeability in these cases is at best an approximation and a stretching of the basic premises on which Darcy's law is based. One option is to obtain cores from the field and test them in the laboratory. Data from a Maine DOT study show (Reference 1.2.10) that there is considerable difference between lab and field permeability of field cores. This is because in the lab testing only vertical permeability is measured, while in the field testing, the flow of water is restricted to vertical direction only on the surface, but not beneath the surface, where the water flows in both vertical and horizontal direction. Hence it is impractical to conduct testing of cores in the laboratory and consider it to be the same as in-place permeability testing. If one needs to find the true in-place permeability then the method should be conducted in-place and at the time of construction.

There can be two uses for the field permeameter. One use is in the determination of the true field permeability. To accomplish this one needs to find out true vertical or true horizontal permeability. While this goal is more oriented towards academic and research purpose, the other more practical and probable use is in control of quality of construction. Results obtained from testing with both NCAT and WPI permeameters indicate that the results are sensitive to air voids and hence the test procedure can in fact be used for quality control purposes. Figure 6.2.1 shows results of data collected from a Maine DOT study conducted by WPI in 1999. As was expected, the data show that as the in-place air voids increase, so does permeability. However, the relationship does not appear strong ($R^2 = 0.39$). Collectively, the data does suggest that the permeability of the pavements studied increased significantly at an in-place air void content of about 7 percent.

To provide a clearer picture of the permeability characteristics for the projects studied, plots of in-place air voids versus field permeability were prepared for each NMAS (Figures 6.2.2 through 6.2.6). Figure 6.2.2 shows the relationship for the fine graded 9.5 mm NMAS project. As can be seen, the correlation between density and permeability is strong for this project ($R^2 = 0.86$). This figure illustrates that as density decreases (or air voids increase) the permeability increases. This figure also shows that this particular mix appears to become excessively permeable at approximately 8.5 percent air voids. At air void contents above 8.5 percent, the permeability increases significantly and becomes very sensitive to a change in air void content. At 8.5 percent voids, the field permeability was approximately 70×10^{-5} cm/sec.

Figure 6.2.3 presents the relationship between in-place air voids and permeability for the coarse graded 9.5 mm NMAS pavement. Increases in in-place air voids resulted in

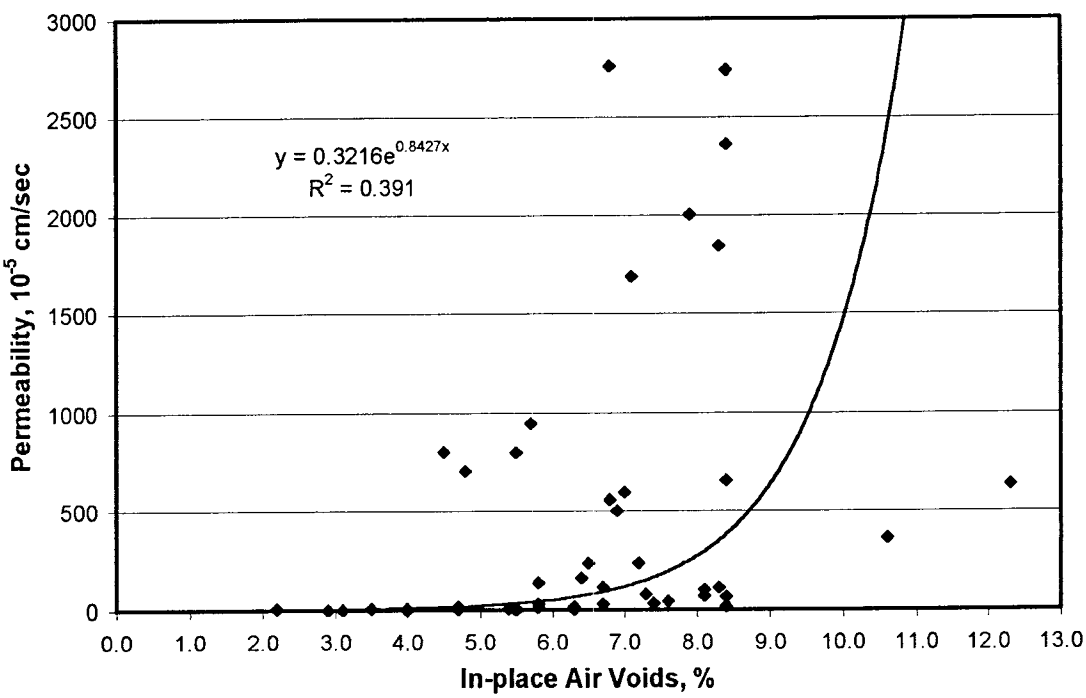


FIGURE 6.2.1 Plot of in-place air voids versus permeability for all data.

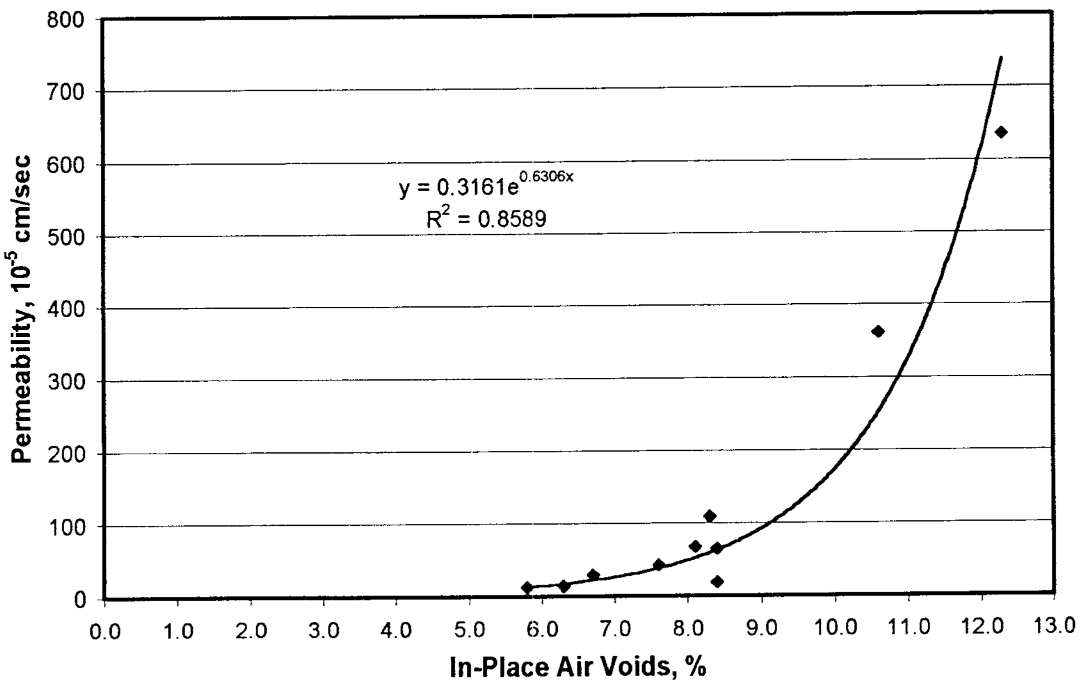


FIGURE 6.2.2 Plot of in-place air voids versus permeability for 9.5 mm fine mix

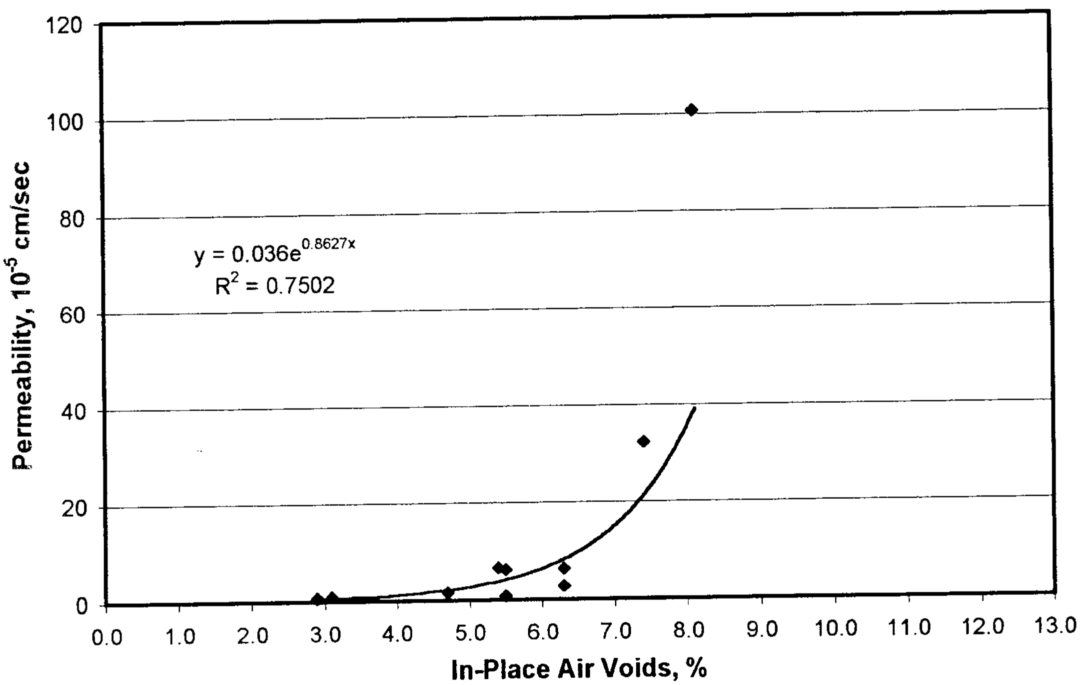


FIGURE 6.2.3 Plot of in-place air voids versus permeability for 9.5 mm coarse mix

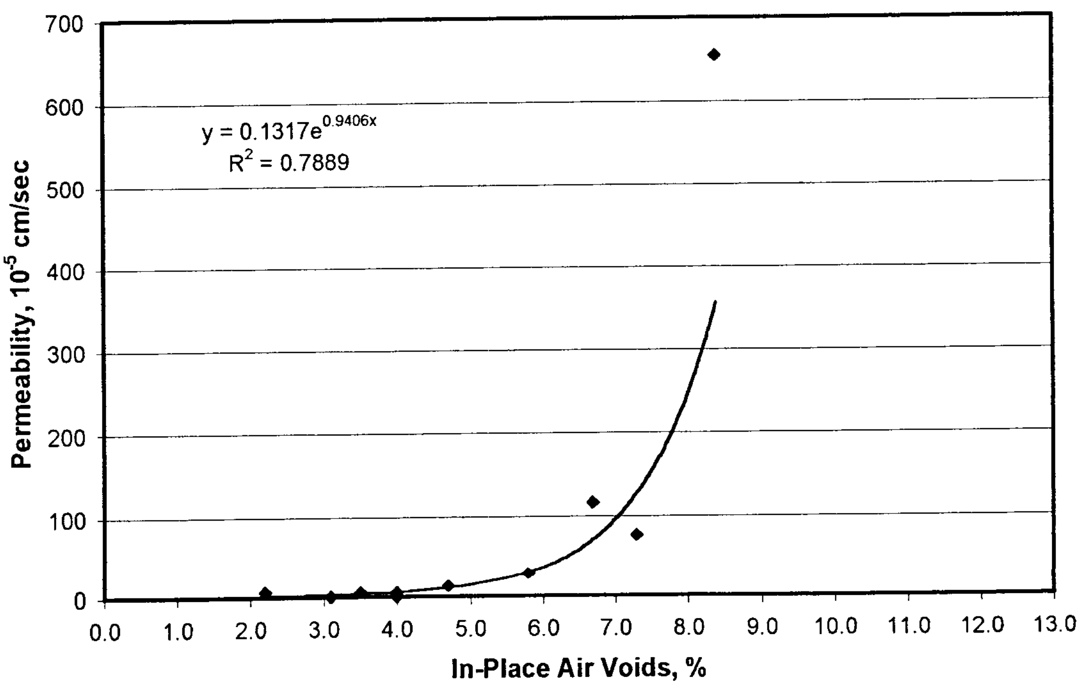


FIGURE 6.2.4 Plot of in-place air voids versus permeability for 12.5 mm coarse mix

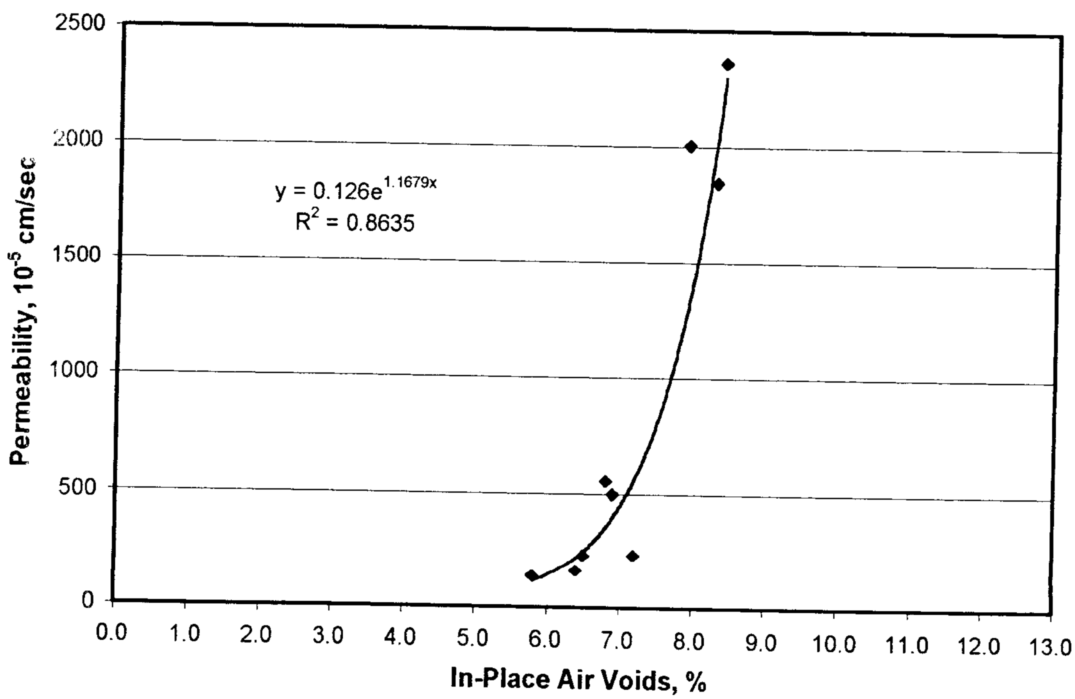


FIGURE 6.2.5 Plot of in-place air voids versus permeability for 19 mm coarse mix

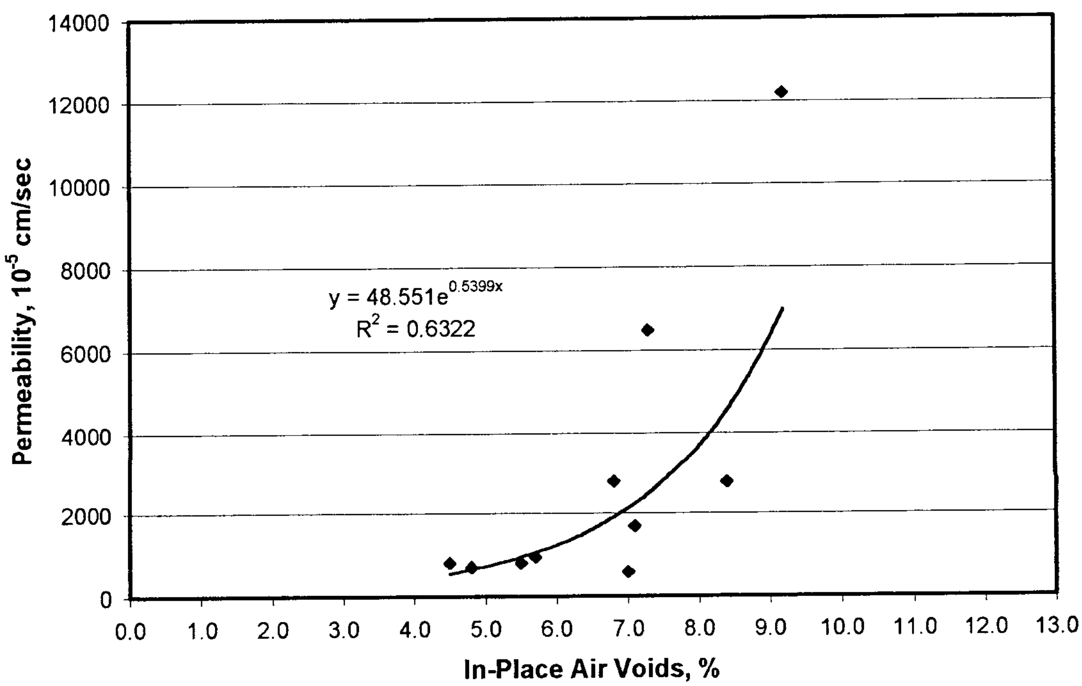


FIGURE 6.2.6 Plot of in-place air voids versus permeability for 25 mm coarse mix

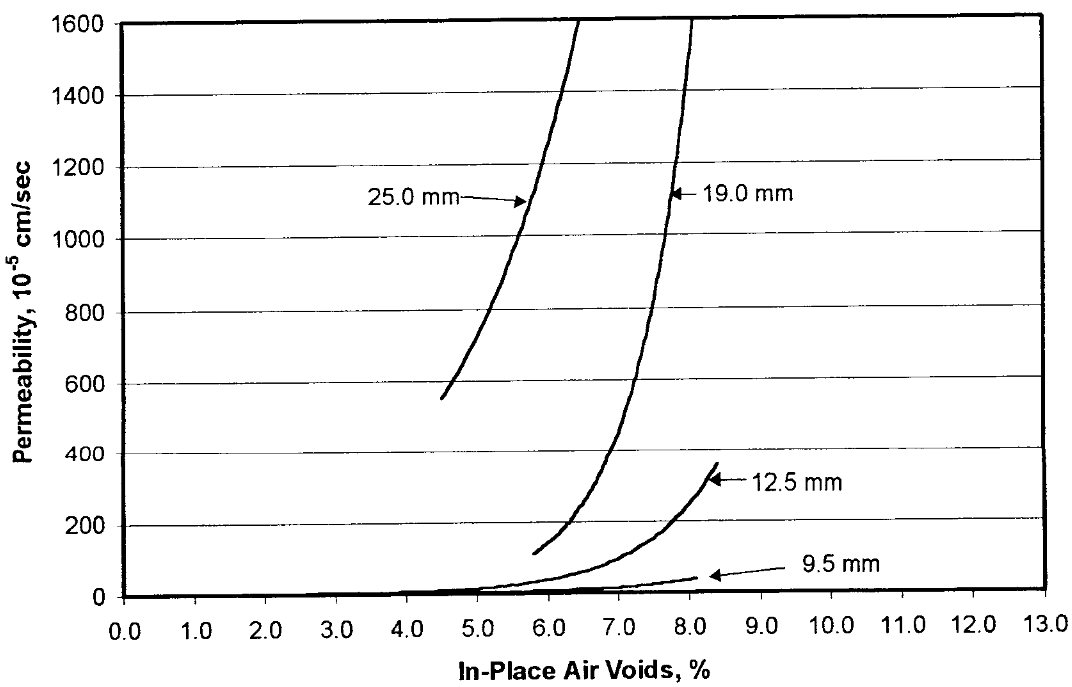


FIGURE 6.2.7 Best fit curves for in-place air voids versus permeability for different NMAS

increased permeability. Figure 6.2.3 also showed a good correlation ($R^2 = 0.75$). At first glance, it appears that this coarse graded 9.5 mm NMAS becomes permeable at around 6 percent air voids. However, the y-axis scale should be looked at closely. For Figure 6.2.3, the maximum y-axis value is only 120 x 10^{-5} cm/sec. By comparison, Figure 6.2.2 had a maximum y-axis value of 800 x 10^{-5} cm/sec. Also of interest on Figure 6.2.3 were the actual in-place air voids. Only two of the testing locations had in-place air voids in excess of 7 percent while Figure 6.2.2 showed that seven of the ten testing locations had in-place air voids in excess of 7 percent. Therefore, the magnitude of permeability values shown in Figure 6.2.3 does not appear to be excessive. However, based on the regression line it appears that the permeability of pavement depicted in Figure 6.2.3 would become very sensitive to a change in air voids at air void contents in excess of 8 percent.

The third project, shown in Figure 6.2.4, was a coarse graded 12.5 mm NMAS mix. This figure also shows a strong correlation between in-place density and permeability ($R^2 = 0.79$). For this mix, it appears that the permeability of the pavement increases very rapidly at in-place air void contents above 7 percent. This void level resulted in a permeability value of approximately 100 x 10^{-5} cm/sec.

Figure 6.2.5 presents the density and permeability data for the 19.0 mm NMAS coarse graded mix. Again, a very strong correlation was noted for the data ($R^2 = 0.86$). In-place air void contents on this project varied from approximately 6 percent to 8.5 percent. Figure 6.2.5 shows that within this range permeability varied greatly. Based on the figure, the permeability of the mix becomes very sensitive to air voids at in-place air void contents greater than approximately 6.5 percent. This void level corresponds to a permeability of about 250 x 10^{-5} cm/sec. Note that in general the air voids were above 6 percent in this case.

The final project evaluated was a 25.0 mm NMAS coarse graded mix (Figure 6.2.6). The range of permeability values shown in Figure 6.2.6 is much higher than those shown in Figures 6.2.2 through 6.2.5. In-place air void contents ranged from approximately 4.5 to 10 percent. Similar to the other projects, decreases in density lead to increased permeability. The correlation shown in Figure 6.2.6 is not as strong as previous correlations, but is still good ($R^2 = 0.63$). It appears that this pavement became excessively permeable (permeability > 10^{-3} cm/s) below 6 percent air voids.

Figure 6.2.7 illustrates the effect of NMAS on the permeability characteristics of pavements. Of the two 9.5 mm NMAS mixes evaluated, only the coarse graded is shown in Figure 6.2.7 as the other mixes shown are also coarse-graded. This figure clearly shows the effect of NMAS. As the NMAS increases, the permeability also increases at a given void level. For instance, at an in-place air void content of 6 percent the following permeabilities were observed for each NMAS:

9.5 mm NMAS ≈ 6 x 10^{-5} cm/sec
12.5 mm NMAS ≈ 40 x 10^{-5} cm/sec
19.0 mm NMAS ≈ 140 x 10^{-5} cm/sec
25.0 mm NMAS ≈ 1200 x 10^{-5} cm/sec

For the mixes evaluated, the permeability increased by an order of magnitude for each NMAS. This data clearly shows that larger NMAS mixes have more potential to be permeable.

Results from two of the three mixes tested in the field are reported. One of the mixes tested was an HMA overlay on Route 6 in the Lincoln area (in Maine). The test section was on a downhill section of roadway. It was not possible to set up another test section within the testing day, since production and laydown were stopped for a considerable amount of time because of inconsistencies between plant and specified asphalt contents. Although the permeameter worked well, the resulting data, because of the roadway slope, are suspect. Hence it was decided not to use this data in the analysis.

The results for the two other mixes are shown in Table 6.2.1. The ME 214 was a 30 mm thick 9.5 mm NMAS slightly coarse (PP2.36 = 41) mix, whereas the VT Rt4 was a 45 mm thick 12.5 mm NMAS coarse graded (PP2.36 = 37) mix. For the ME 214 mix, a pneumatic tired roller was used as finish roller, whereas for the Rt4 mix, a pneumatic tired roller was used an intermediate roller and a steel wheel roller was used a finish roller.

Figure 6.2.8 shows plots of in-place permeability versus air voids for these two mixes. The permeability values of the ME 214 mix (at similar air voids) are significantly lower than the permeability values of the Rt 4 mix. Of the two mixes, the Rt 4 results show good correlation between permeability and air voids ($R^2 = 0.88$). Since the increase in permeability with an increase in air voids is due to the increase in interconnected air voids, it is obvious that there are less interconnected air voids in the ME 214 mix than in the Rt 4 mix. Hence the two plots confirm the effect of aggregate size and gradation on in-place permeability. That is, in-place permeability is sensitive to air voids and aggregate size and gradation – three very important quality control parameters that are monitored (directly or indirectly) during HMA pavement construction.

Hence, it seems that field permeability can be utilized as a quality control tool during construction. To achieve this goal, one needs an automated field permeameter that can be used reliably and quickly in a construction site. More specifically, while in the laboratory, the porosity test can be used to evaluate *mixes*, the field permeameter can be used effectively for evaluating *construction*.

TABLE 6.2.1 Voids and permeability (field testing) of mixes

State	Mix	Core Number	Voids in Total Mix, %			Permeability, cm/s
			Intact core	Top Lift	Bottom Lift (s)	
ME	Rt 214	2	9.9			5.19E-06
		3		9.5	8.2	3.98E-03
		4		8.5	17.1	5.19E-06
		5	7.8			5.19E-06
		6		6.7	8.9	1.16E-04
		7	8.9			1.74E-04
		8		8.6	18.9	6.84E-04
		9		8.8	9.9	1.31E-03
VT	Rt 4	1		7.5	8.3	3.99E-03
		2		8.5	9.8	5.49E-03
		3		7.2	9.5	3.55E-03
		4	7.6			4.19E-03
		6		6.4	12.6, 12.1	2.43E-03
		7		10.2	7.2	7.73E-03
		8		6.4	10.3	3.59E-03
		9		6.8	10.6	2.73E-03

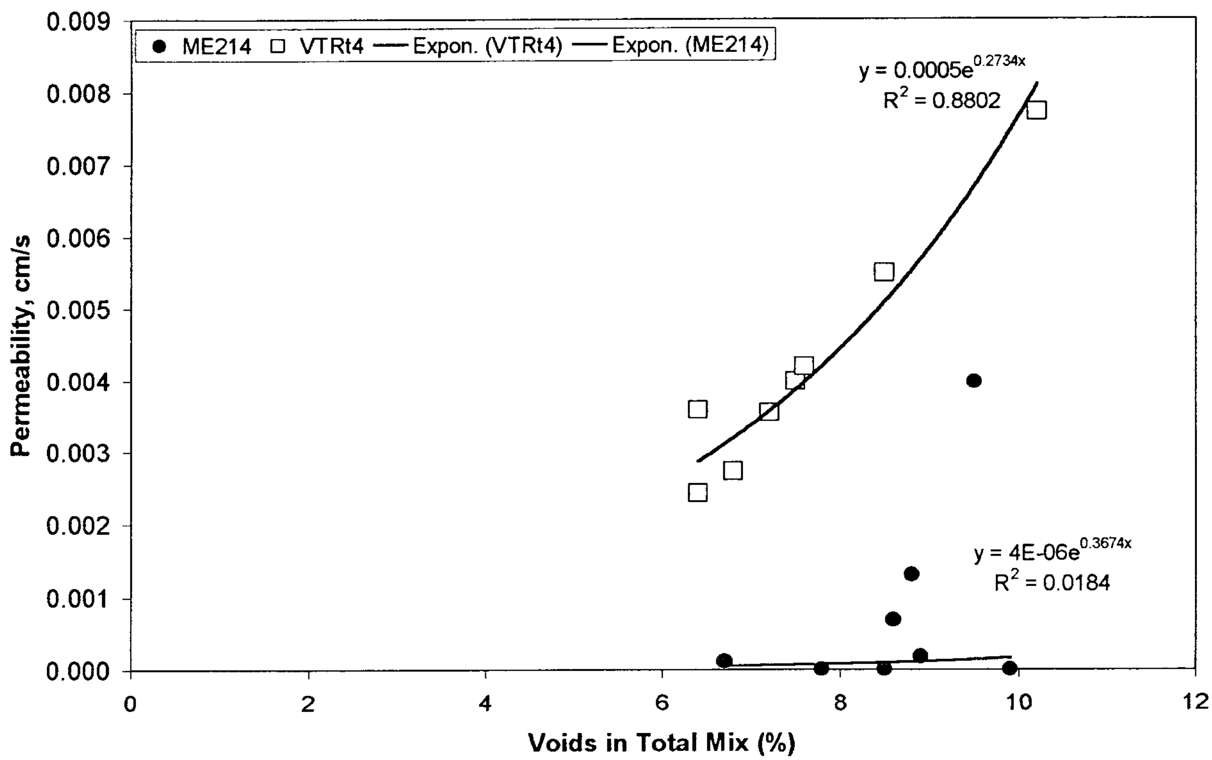


FIGURE 6.2.8 Plot of permeability versus air voids for ME and VT projects

6.3. Development of a Laboratory-Field Permeameter

Keeping the two requirements – measurement of true permeability and quality control- in the mind, this research team developed a new permeameter as part of this NETC study. Dr. William Crockford was the primary consultant in the design and fabrication this equipment. The equipment was manufactured by Shedworks, Inc., of **Welborn Texas** Basically, this equipment can be used for conducting both laboratory and in-place testing, by using two separate permeability cells. In fact, the "laboratory" testing cell can also be used in the field, for testing field cores, if so desired. The unique feature of this equipment is that it allows coring in through the pavement (and conducting permeability without removing the core) and determination of "true" horizontal permeability. Since it also allows determination of composite permeability (at the surface), the vertical permeability can be estimated by factoring out the measured horizontal permeability. A schematic of the equipment and its operation is shown in Figure 6.3.1. A detailed description of the equipment is provided in the following paragraphs.

General description

The permeameter can be used for lab or field measurement of the water permeability of pavement materials having properties within the range of its flow rate. Basic components of the system are:

Pressurized water source

- Pressure vessel
- Actuator and instrumentation module
- Data acquisition system.

Additional components required for field testing include:

- Electrical power source (e.g. gas powered generator)
- Core rig with concentric core barrel assembly
- Water pressure tank
- Mobile base.

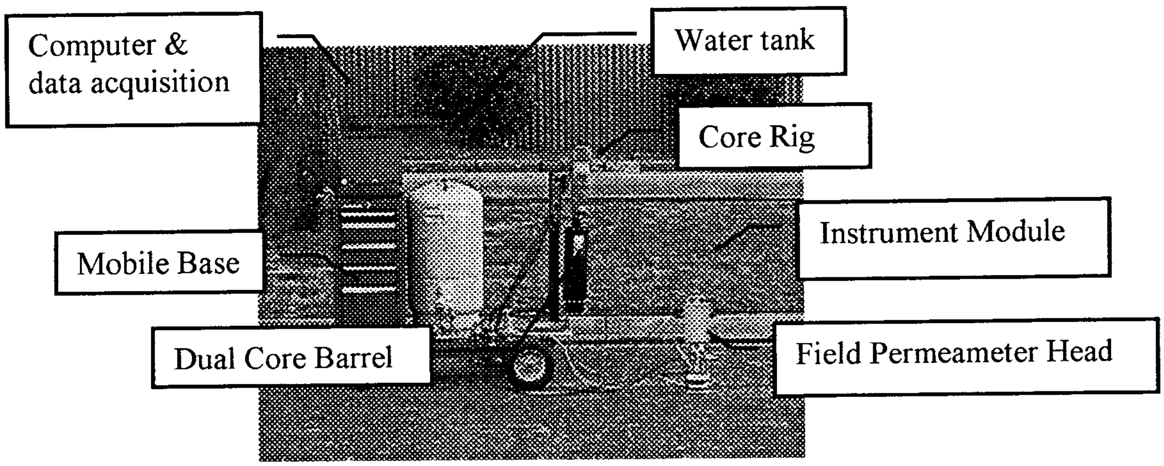


FIGURE 6.3.1 Basic machine.

Permeameter Heads: Three different types of permeameter head are available: (1) a no-core type field head as shown in Figure 6.3.2, (2) a core type field head as shown in Figures 6.3.3 and 6.3.4,and (3) a lab type head. The lab type permeameter head is similar to many lab permeameters that use confining pressure. The field units differ from most other permeameters. A membrane failure in the lab permeameter is simple to repair and the repair technique is obvious when the unit is disassembled. The no-core type permeameter does not have a membrane, but does have a rubber seal at the bottom that may need to be replaced from time to time and its replacement technique is obvious. With the core type permeameter head, it is very important to use extreme care when replacing a failed membrane.

There are three very small pieces of hypodermic needle that penetrate the membrane and conduct fluid or gas from one part of the device to another. Since this device must be placed in a very small space in a ring cut in the pavement, there is no room to put ports on the diameter of the pressure vessel. Therefore, the ports have been drilled vertically through the wall of the pressure vessel. There is one hole drilled completely through the wall from top to bottom. This hole is for the low side pressure transducer connection and there is a small piece of hypodermic needle at each end of this hole. There is another hole drilled into the wall for a shorter depth. This hole is for the confining pressure and there is a small piece of hypodermic needle here too. The hypodermic sections are tapered on one end and are of different lengths. It is best to keep the needles in the same holes when replacing membranes. The membrane can be stretched over the wall and then the sharp end of the needle can be used to punch through the rubber into the hole. This seems to be a more efficient method than putting the needles in the holes and pulling the membrane over them to puncture them. Use caution because the wall thickness of the pressure vessel is relatively thin. Therefore, if you pull on the membrane too much after puncturing it with the needles and before you put the end caps on the permeameter, you will probably stretch it enough to cause a leak around the needle. You are better off to let the area around the needle relax to a "snug, low-stretch" fit than a "tight" fit and just accept a small amount of looseness in the membrane if that is what happens after the end ring and cap have been replaced and tightened with the tie rods.

Core barrels: The double core barrel (Figure 6.3.4) is made from one standard and one modified core barrel. The inner barrel has been machined by setting it up in a lathe with two dial indicators on the barrel to ensure concentricity, then machining off the standard nut extension and facing the back. This leaves a few threads in the back plate of the barrel. This barrel has also been drilled across the diameter approximately 3-4 inches up from the cutting teeth. This hole allows water that flows through the center of the core rig to come out of the center barrel and go into the space between the center barrel and the outer barrel. If the machining operation done on back of the small diameter barrel does not result in a coupled barrel that has relatively small concentricity problems, it will be necessary to face the inside surface of the back on the large diameter barrel. This should only be done by a machinist with relatively large equipment because it will require a very large boring bar to reach into the barrel without dismantling the barrel and rewelding it.

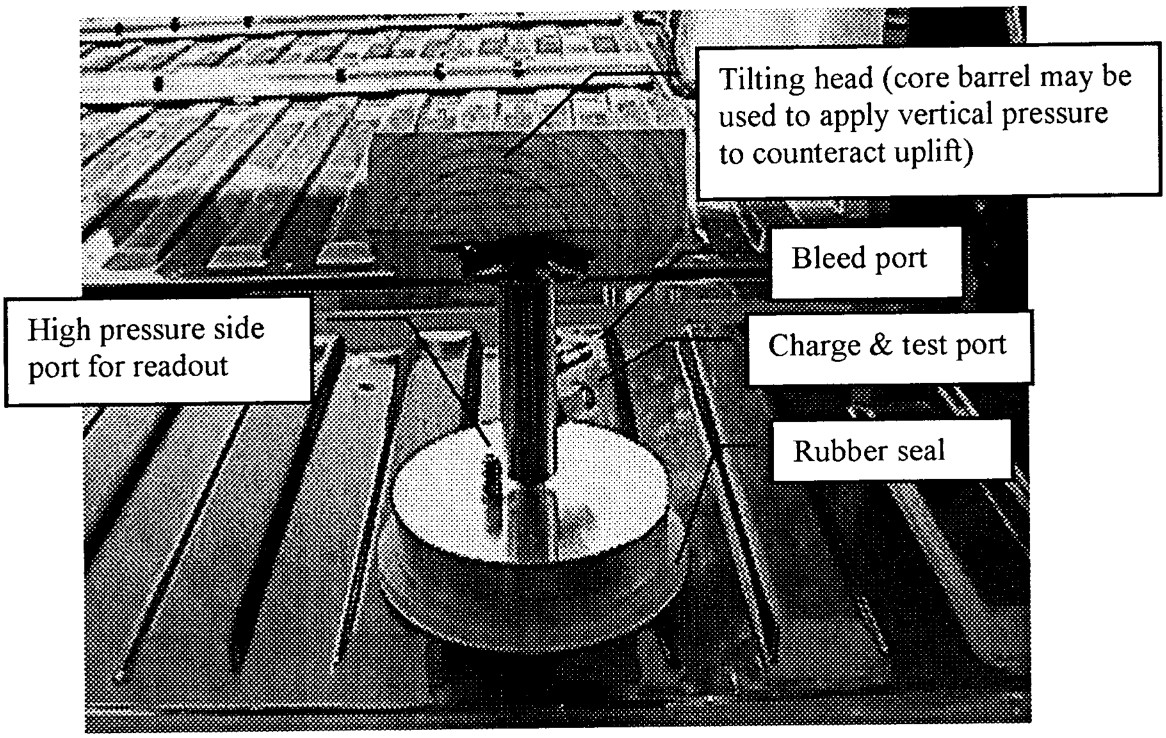


FIGURE 6.3.2 No-core, tilting head permeameter head

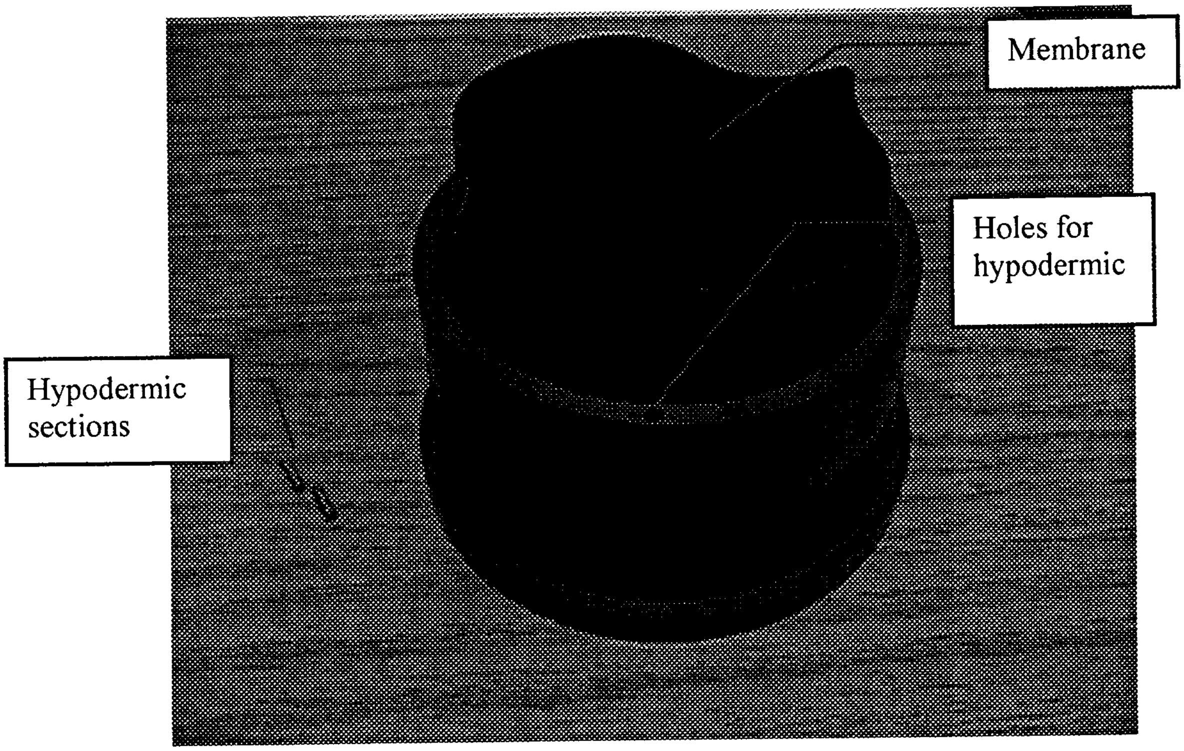


FIGURE 6.3.3 Core type permeameter head being repaired.

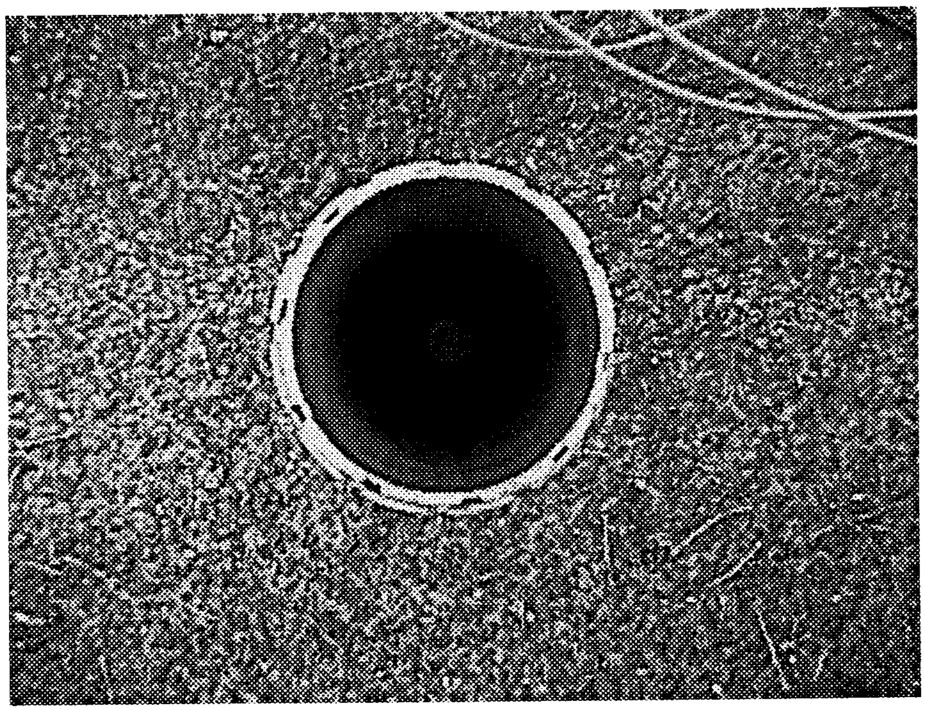


FIGURE 6.3.4 View of double core barrel from cutting teeth end

A 2 inch diameter boring bar was used in a large lathe to face the inside of the prototype. You will be unable to economically get perfect concentricity with standard production core barrels. They are not manufactured specifically for double ring coring, so you must be willing to live with a bit of wobble with this system. With the coupling method used in this system, the inner barrel leads the outer one and has the advantage that it helps to reduce the tendency to wobble any more than the inner barrel causes by itself. This approach has the disadvantage that it may penetrate into the base on a thin pavement before it is deep enough to handle the core type permeameter head. When using the core type permeameter head, avoid breaking through to the base layer below the tack coat. If you break through, the center core of the surface layer may break loose when you bring the core rig back up and this defeats the purpose of using the core type permeameter head. Removal of the inner core barrel is by hand or by use of a "strap wrench" around the protruding end of the barrel. It is preferred that you do not use a large "monkey wrench" or similar type wrench for this unless the barrel is used up and will be replaced. Both barrels and the coupling rod are right hand threads.

After using the core rig, it is recommended that you oil the places where the threads are in the core barrels as best you can so that they do not become rusted in place. Oiling where the nut part of the large barrel so that it soaks down into the coupler and the inner barrel threads will probably be sufficient. If rust becomes a problem and you are having difficulty getting the barrels off the rig, try penetrating oil like "Mouse Milk".

Water or air confinement

Confining pressure may be applied using air or water. In the field, the use of water from the pressure tank eliminates the need for an air compressor. Energy from any standard building hose faucet is stored in the pressure tank. The tank is a standard well system tank that has an internal air bladder and is available in two sizes that have the same diameter. The pressure in the bladder should be checked periodically with a tire gauge and adjustments made to obtain the desired pressure. Use caution when using a high capacity air source so that the conditions on the placard on the tank are not exceeded. When filling the tank with water, the building water pressure must be greater than the bladder air pressure. In general, building water pressure will exceed both the bladder air pressure and the pressure for which the water relief valve is set. Water will drain from the relief valve outlet once the water pressure in the tank exceeds the relief setting. The valve protects the tank from damage due to overpressure. Do not pressurize the tank above the pressure listed on the tank placard.

Instrumentation description and calibration

Differential pressure is used for field testing, gauge pressure is used in the lab. The two approaches are identical when the low side of the transducer is open to atmospheric pressure. The instrumentation module is shown in Figure 6.3.5.

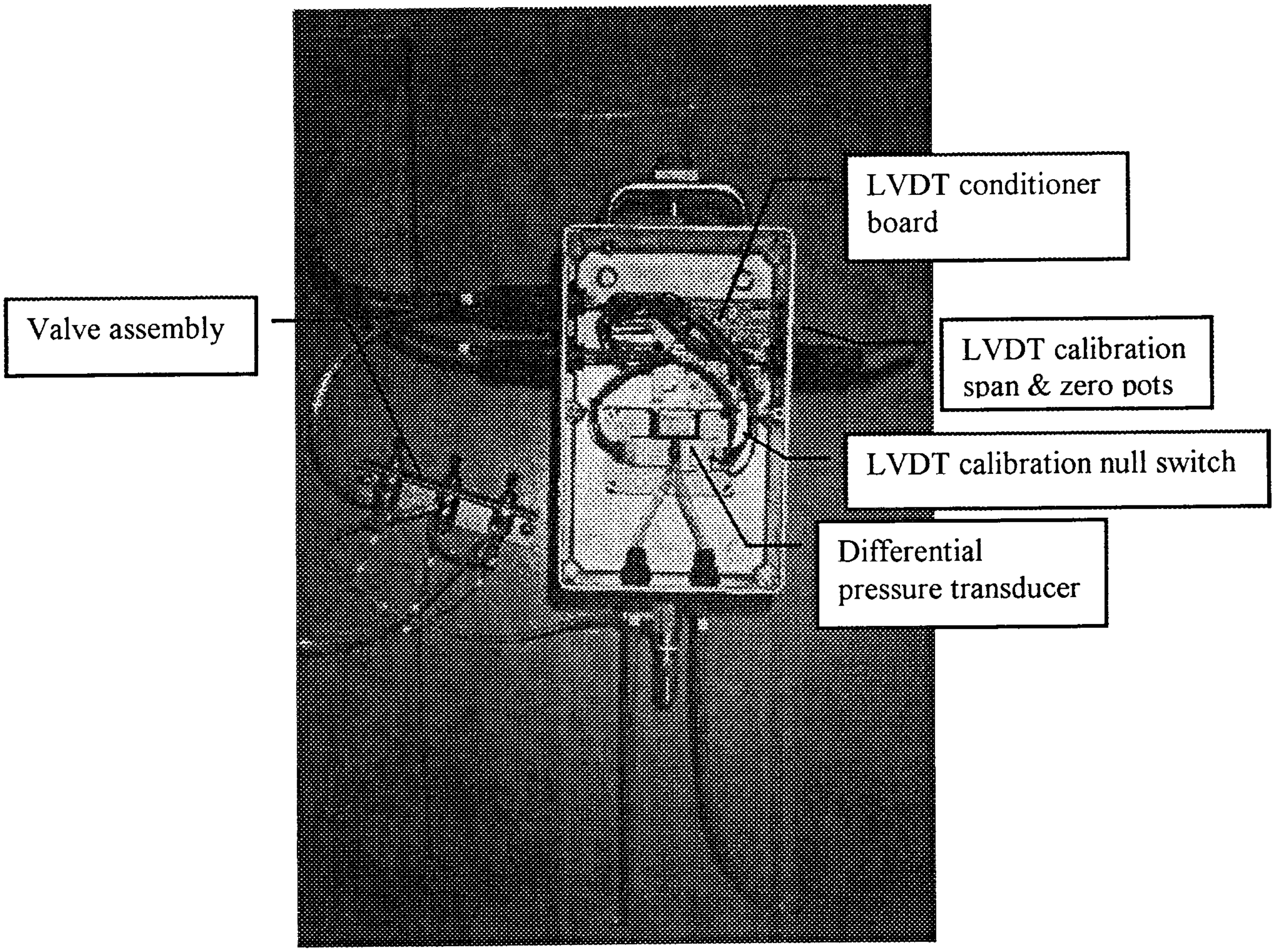


FIGURE 6.3.5 Instrumentation Module

Pressure transducer: The pressure transducer is a silicon sensor with two ports for differential pressure measurement. The high pressure port is the port furthest from the pins. The pin configuration when viewing the sensor looking directly into the ports with the pins facing up is, from left to right:

1. + excitation (7-16VDC)
2. common
3. + signal (VDC)
4. NC

The transducer is calibrated using a pressure source and a sufficiently accurate gauge. A digital pressure gauge is useful for this purpose. Applying pressure to the high pressure port and leaving the other port open to atmosphere turns the transducer into a gauge pressure transducer and the calibration can be checked using a digital gauge in a "T" fitting between the pressure source and the high port. The initial equation describing this relationship is:

$$y = 0.2677x - 1.3906$$

where y is the pressure in psi and x is DC volts.

The pressure transducer can be damaged by surging pressure (e.g. "water hammer") and it is not rated for use with water contact. The device has been designed so that the pressure transducer is above the water source so that air becomes trapped in the lines between the transducer and the permeameter. This both protects against water hammer and water contact with the silicon wafer. It is recommended that the lines to the sensor be checked and cleared of any water prior to storage of the instrumentation module. The pressure transducer is positioned in a socket so that it may be easily removed and replaced on the circuit board. The standard pressure transducer is a 1psi range transducer. Larger ranges are available.

LVDT: The volume of water that passes through the specimen is measured by an LVDT mounted to an actuator. Knowing the diameter of the actuator piston allows computation of the volume. The signal conditioning circuitry has a momentary contact switch for setting the zero of the LVDT. The switch must be held down while the zero adjustment pot is turned. The span pot is used to adjust the voltage output to achieve the desired relationship between voltage and displacement. The initial equation describing that relationship is:

$$y = -0.9789x + 9.8015$$

where y is the volume in cubic inches and x is DC volts.

Laptop PCMCIA data acquisition: The computer board used in this apparatus has many features that are not used in this application. For that reason, most of the 37 connections are not used. The 37 pins are assigned as follows (only those in bold are used in this application) (Table 6.3.1).

TABLE 6.3.1 Data acquisition pin connections

1 CTR 1 out	11 DIO 2	**21 CH1 Hi**	31 CH6 Hi
2 CTR 1 gate	12 DIO 3	22 CH2 Lo	32 CH7 Lo
3 CTR 1 CLK	13 LL Gnd	23 CH2 Hi	33 CH7 Hi
4 CTR 3 out	14	24 CH3 Lo	34 NC
5 Ext Trig/Clk	15 LL Gnd	25 CH3 Hi	35 NC
6 CTR 2 gate	16	26 CH4 Lo	36 NC
7 Ext INT	**17 LL Gnd**	27 CH4 Hi	37 NC
8 Dig Gnd	**18 CH0 Lo**	28 CH5 Lo	
9 DIO 0	**19 CH0 Hi**	29 CH5 Hi	
10 DIO 1	**20 CH1 Lo**	30 CH6 Lo	

Software – Beta Version

The initial system required two software components, the acquisition component which is a stand-alone Windows program (Figure 6.3.6) and the analysis component which is an Excel spreadsheet macro (Figure 6.3.7). Production versions of the software will combine the two processes.

The default filenames and the subdirectory for those files is used by name in the Excel macro code. If you change the default filenames and/or the subdirectory in which they are stored, you will get an error in the Excel macro because the code for the macro will not look for other files/subdirectories. If you do not know Visual Basic, the best approach is to run a test leaving the time and data filenames with the default names. Immediately after the test, run the Excel macro and then save the Excel file with a specific name that is meaningful to you. The next time you run a test, the *.dat files will be overwritten, but your stored Excel file will still be available for the first test. The shortcut key for running the Excel macro is ctrl-D.

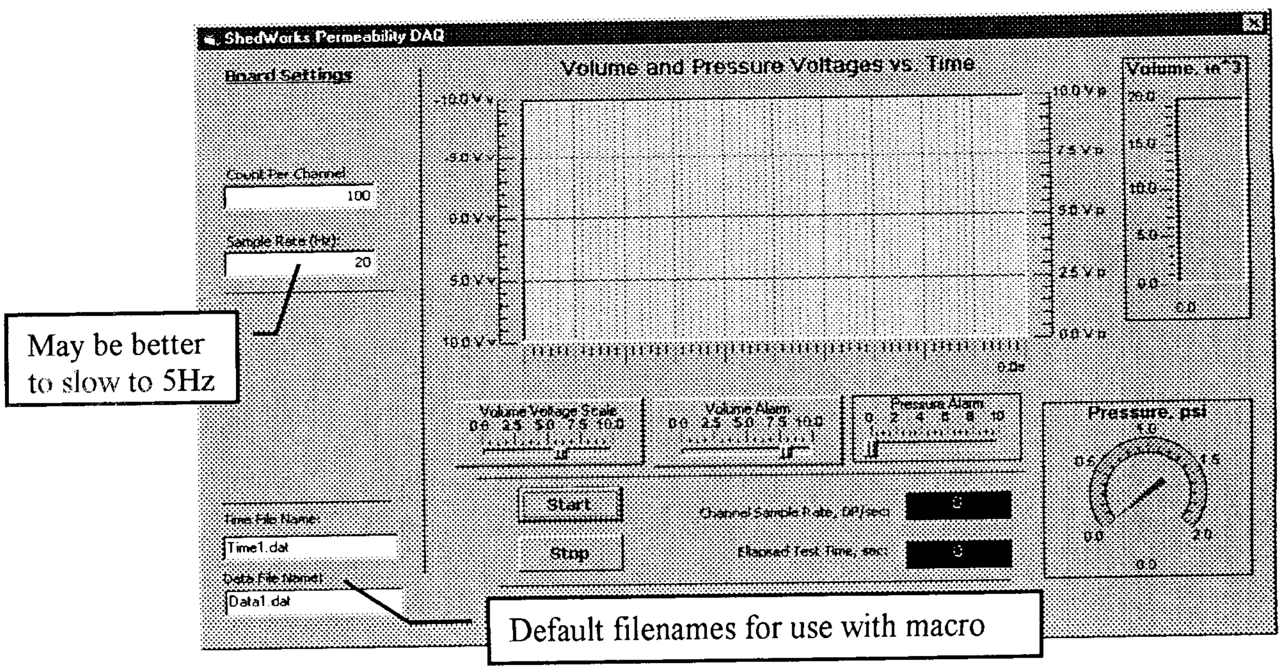
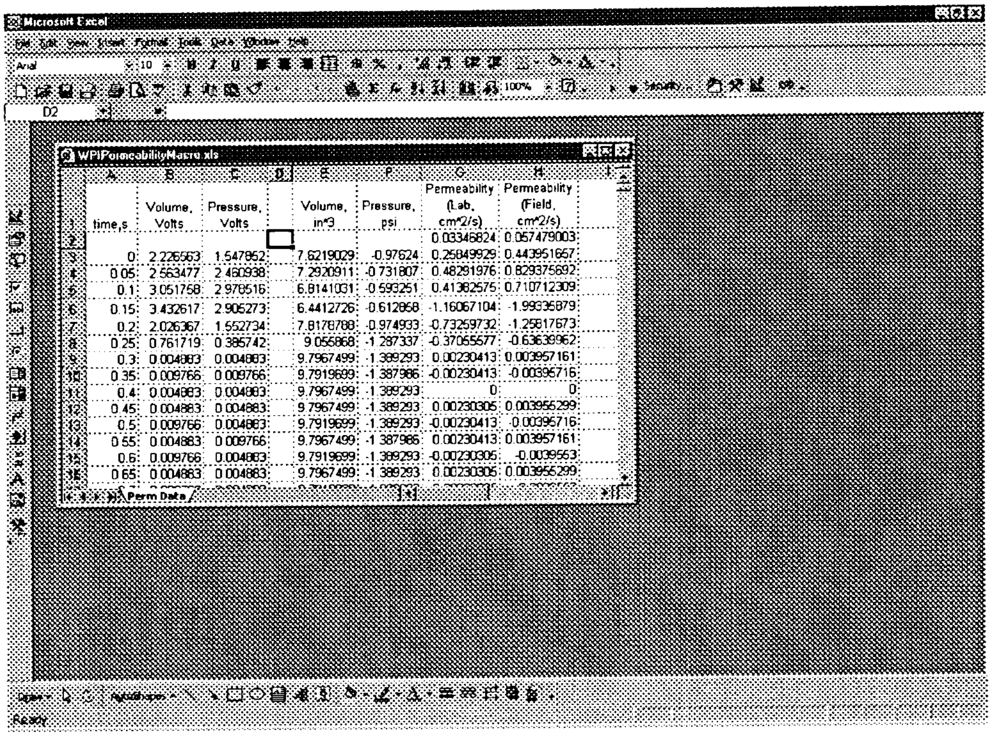


FIGURE 6.3.6 Acquisition Software Screen.



	A	B	C	D	E	F	G	H
1	time,s	Volume, Volts	Pressure, Volts		Volume, in^3	Pressure, psi	Permeability (Lab, cm^2/s)	Permeability (Field, cm^2/s)
2							0.03346824	0.057479003
3	0	2.226563	1.547852		7.6219029	-0.97624	0.25849929	0.443951657
4	0.05	2.563477	2.460938		7.2920911	-0.731807	0.48291976	0.829375692
5	0.1	3.051758	2.978516		6.8141031	-0.593251	0.41382575	0.710712309
6	0.15	3.432617	2.905273		6.4412726	-0.612858	-1.16067104	-1.99335879
7	0.2	2.026367	1.552734		7.8178788	-0.974933	-0.73259732	-1.25817673
8	0.25	0.761719	0.385742		9.055868	-1.287337	-0.37065577	-0.63639962
9	0.3	0.004883	0.004883		9.7967499	-1.389293	0.00230413	0.003957161
10	0.35	0.009766	0.009766		9.7919699	-1.387986	-0.00230413	-0.00395716
11	0.4	0.004883	0.004883		9.7967499	-1.389293	0	0
12	0.45	0.004883	0.004883		9.7967499	-1.389293	0.00230305	0.003955299
13	0.5	0.009766	0.004883		9.7919699	-1.389293	-0.00230413	-0.00395716
14	0.55	0.004883	0.009766		9.7967499	-1.387986	0.00230413	0.003957161
15	0.6	0.009766	0.004883		9.7919699	-1.389293	-0.00230305	-0.0039553
16	0.65	0.004883	0.004883		9.7967499	-1.389293	0.00230305	0.003955299

FIGURE 6.3.7 Excel Macro Analysis Program

Summary procedures

Field (nominal 4" diameter specimen, core type)

Core a 3" deep ring 4" ID X 5" OD

Remove ring from pavement

Apply small vacuum to permeameter with hand pump

Set permeameter in groove

Open valve to permeameter

Apply confinement greater than or equal to the max head to be applied (max head is normally less than 1psi)

Saturate specimen/charge actuator piston

Start data acquisition

Open valve to apply head pressure

Stop acquisition when sufficient data has been obtained or when actuator stops

Close valve to permeameter

Lab (150mm diameter gyratory specimen)

Put permeable spacer on perforated metal platform

Place specimen on top of spacer

Set permeameter over specimen and attach to platform with knobs

Proceed as in field method

Valve operation

There are two main adjustable valves. One valve adjusts the main pressure going to the system and supplies the higher pressure and flows used for coring or for specimen saturation or for specimen confining pressure. The second low pressure adjustable valve adjusts the head pressure in the permeameter.

There are three manual switch valves on the instrumentation module.

1. The left switch routes pressurized water to the upper side of the actuator piston to apply the head pressure. When the switch is positioned toward the box cover plate, head pressure is applied to the specimen at the pressure set by the low pressure adjustable valve. When positioned in the opposite direction, the water on the top of the actuator is allowed to escape through the open outlet on the valve body during repositioning of the actuator to the up position.

2. The center switch routes water to either the bottom side of the actuator piston or to the confining pressure. When this switch is positioned toward the box cover plate, confining pressure is applied to the specimen at the pressure set by the high pressure adjustable valve. When positioned in the opposite direction, pressure is applied to the bottom side of the actuator piston to raise the actuator in preparation for a test.

3. The right hand switch is used in conjunction with the center switch to control confining pressure relief. When this switch is positioned toward the cover plate, and the center switch is in the same direction, the manual pump can be used to apply a vacuum to the pressure vessel so that the vessel can be easily placed over the specimen. When the right hand switch is positioned away from the cover plate, and the center switch is in the same position, pressure is applied to the bottom side of the actuator piston to raise the actuator in preparation for a test.

When the center switch is positioned toward the cover plate, and the right hand switch is positioned in the opposite direction, confining pressure is applied.

The valves are shown in Table 6.3.2 and Figures 6.3.8 and 6.3.9.

TABLE 6.3.2 Switch valves

Function	**Left**	**Center**	**Right**
Vacuum application and placing permeameter over specimen	↓	↑	↑
Charging actuator/saturation prior to test	↓	↓	↓
Running a test with confining pressure	↑	↑	↓
Running a test without confining pressure	↑	↑	Plug source
↑ toward cover plate		↓ away from cover plate	

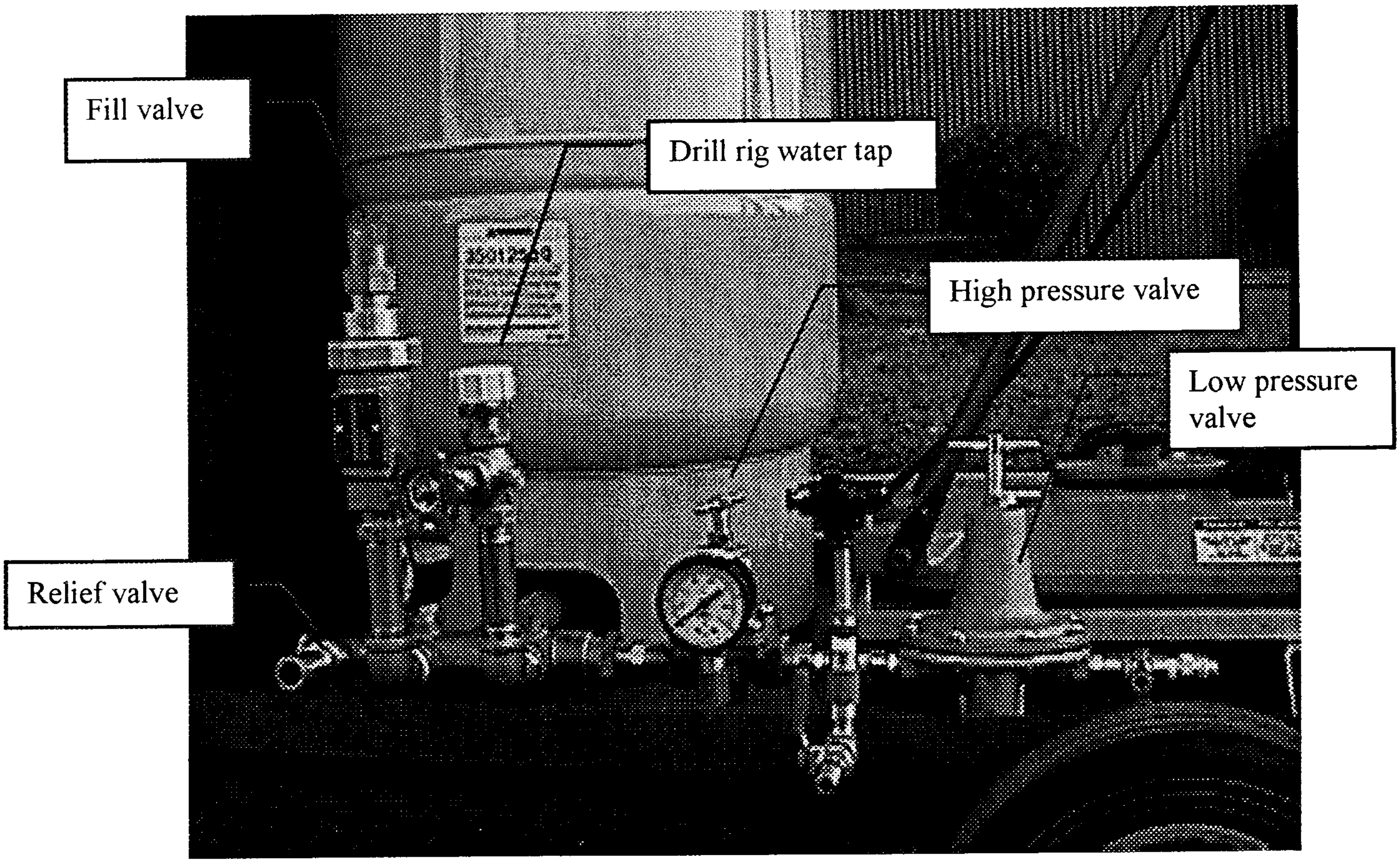


FIGURE 6.3.8 Main valves

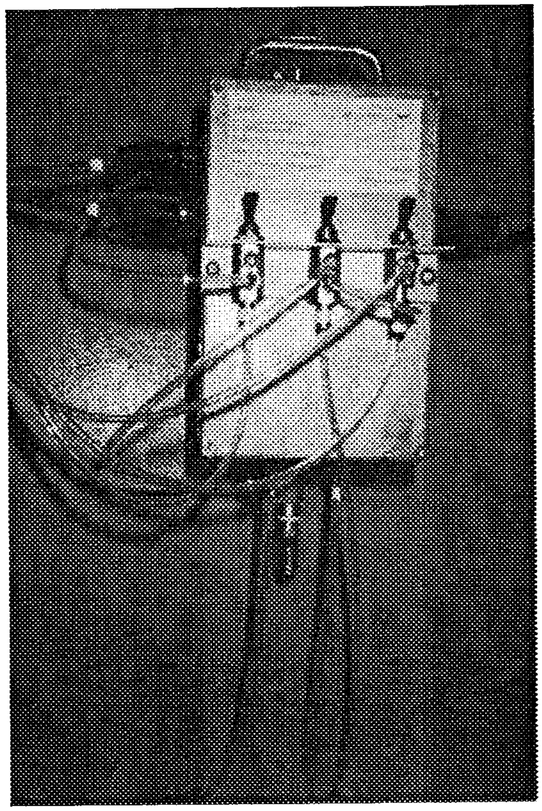


FIGURE 6.3.9 Manual switch valves

The prototype version of the system used a direct connection between the instrumentation module and the permeameter head as in Figure 6.3.1. It was thought that the short connection would reduce volume errors. However, the no-core permeameter shown in Figure 6.3.2 uses a different method. A relatively rigid hose is connected between the module and the permeameter head. This hose must be cleared of air before running the test. For this reason, a bleed port is provided as shown in Figure 6.3.2. When charging the actuator as discussed in Table 6.3.2, you will be providing pressure between the permeameter head and the material on which it is resting. This will trap air between the valve module (Figure 6.3.9) and the permeameter head. The bleed port is used to bleed this air from the system.

It has been found that high pressure charging of the actuator provides significant uplift on the permeameter head which requires offsetting by a vertical force. Since the pavement may not be level, a tilting head mechanism is provided (Figure 6.3.9) to help ensure that the seal will be relatively uniform.

After testing, remove as much water as possible from the actuator to prevent corrosion. For long-term storage, introduce water displacing and/or protective lubricant to the actuator through one of the ports. Make sure any chemicals that go into the actuator do not react with Buna, Teflon, or Viton type seals. If in doubt, do not lubricate.

Water permeability

The permeability is calculated after the test has been completed and the data stored. Microsoft Excel can be used to perform these calculations by invoking the provided Excel macro spreadsheet. This function will be combined with the acquisition program in Version 1.0 of the software.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are provided on the basis of the research conducted in this study, and results of literature review and survey of state departments of transportation.

- The most significant mix design and construction related cause of stripping has been identified as high permeability – either due to the nature of the mix or due to high in-place air voids.
- Air voids and mix gradations are the most significant factors affecting permeability of HMA mixes.
- There is a significant effect of nominal maximum aggregate size (NMAS) on the permeability of coarse graded Superpave designed mixes.
- There is no reliable information about the moisture content of good or poor performing pavement (specifically surface layers), although many of the states have indicated that it is the movement of water or freeze-thaw condition that causes stripping in surface, binder and base layers. Obviously, in many cases, water getting inside the surface layer finds its way to binder and base layers and affects the performance of all three layers. If excessive amounts of water do get inside the surface layer and freeze, then stripping damage can be expected in surface layers. However, information regarding critical amount of moisture or the moisture content that can cause such a damage is not available.
- High permeability of coarse graded mixes is primarily due to the presence of relatively high amounts of interconnected air voids.
- Amount of interconnected voids present in a mix is significantly affected by gradation and nominal maximum aggregate size (NMAS).
- Permeability potential of mixes increase with an increase in air voids, coarseness and nominal maximum aggregate size (NMAS).
- A coefficient of permeability of 10^3 cm/second can be considered to be critical – mixes showing coefficient of permeability above 10^3 cm/second should be characterized as excessively permeable.
- Saturated surface dry (SSD) bulk specific gravity testing method does not produce reliable results for coarse graded mixes, especially at relatively high air voids, such as construction air voids.
- Porosity shows an excellent (and better compared to air voids) correlation with permeability.
- Porosity provides a fast and accurate method of determining permeability of dense graded mixes.
- Porosity of mixes is significantly affected by percent passing the 2.36 mm sieve.
- Porosity test is much more repeatable than the currently used laboratory permeability test.
- Use the chart provided in this report for checking permeability of designed mixes.
- During mix design, estimate porosity of designed mixes and use estimated porosity to select gradation or desirable construction air voids with the help of charts provided in this report.

- In-place permeability is very sensitive to air voids and aggregate gradation and nominal maximum aggregate size (NMAS).
- In-place permeability increases with an increase in air voids, coarseness and nominal maxim aggregate size (NMAS).
- Use the lab-field permeameter developed in this study for quality control of paving projects.
- Use the lab-field permeameter for research in determination of "true" (horizontal and vertical) permeability of in-place mixes. In addition to explanation of effect of various mix design and construction factors on permeability of dense graded mixes, such research will be particularly valuable for improving performance of open graded mixes, such as open graded friction course (OGFC).
- Conduct a workshop for New England state department transportation (DOT) personnel on the use of vacuum seal method for determination of porosity and the use of lab-field permeability equipment.