Evaluation of Permeability of Superpave Mixes in Maine

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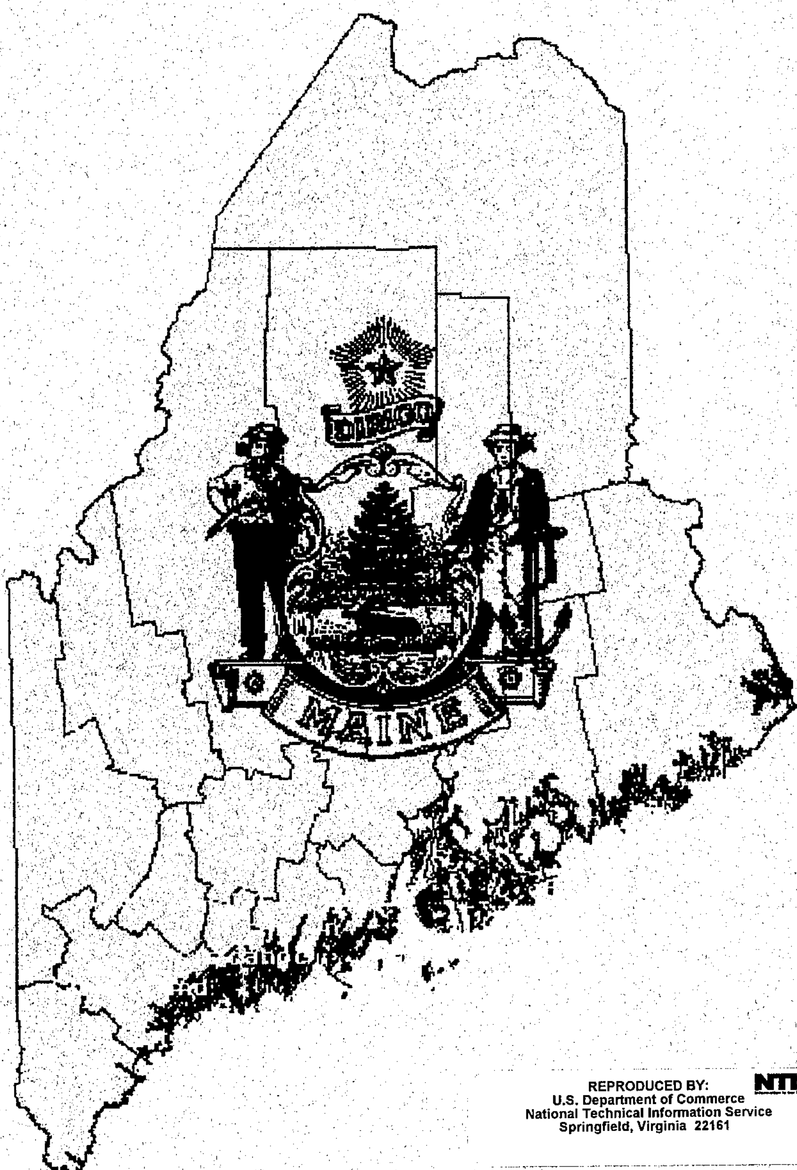

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16. Abstract (limit 200 words)

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EVALUATION OF PERMEABILITY OF SUPERPAVE MIXES IN MAINE

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EVALUATION OF PERMEABILITY OF SUPERPAVE MIXES IN MAINE

by

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ABSTRACT

Dense graded hot mix asphalt (HMA) mixtures are designed to have low permeability to resist excessive penetration of water and avoid durability problems. There is a general concern that Superpave coarse graded mixes are more permeable, at similar void levels, compared to fine graded mixes. This study was carried out to evaluate the permeability of Superpave mixes used by Maine department of transportation, and determine the effect of voids, gradation and lift thickness on permeability. A field permeameter was developed on the basis of the National Center for Asphalt Technology field permeameter, and was used for testing projects with 9.5 mm, fine and coarse, 12.5 mm coarse, 19 mm coarse, and 25 mm coarse graded mixes. Testing of cores taken from location of field testing were also conducted in the laboratory according to Florida department of transportation method. Samples of loose mix obtained during construction were also compacted to different thickness in the laboratory, prior to permeability testing. Results from permeability tests indicated that mixes with different gradations and nominal maximum aggregate size have significant increase in permeability at different voids in total mix content. Field testing showed that 25 mm coarse, 19 mm coarse, 12.5 mm coarse and 9.5 mm coarse mixes show significant increase in permeability at 5, 6, 7 and 8 percent voids in total mix respectively, whereas a 9.5 mm fine mix showed a significant increase in permeability beyond eight percent voids in total mix. A high ratio of percent passing 4.75 mm and 0.6 mm sieve can indicate a coarse mixture, and a significant increase in permeability at lower void in total mix, compared to a mix with lower ratio of percent passing 4.75 mm and 0.6 mm sieve. A field permeability of 0.001 cm per second can be considered as a critical permeability separating low and high permeability mixes. Field permeability of 19 mm and 25 mm coarse graded mixes are significantly higher than laboratory permeability, at similar voids in total mix content, most likely due to presence of horizontal flowpaths and high horizontal permeability. It is recommended that in-place construction voids in total mix of coarse graded Superpave 9.5 mm and 12.5 mm mixes be kept below 7 percent, and construction voids in total mix of 19 mm and 25 mm coarse graded mixes be kept below 6 percent. It is also recommended that field permeability tests be conducted for all mixes, especially 19 mm and 25 mm coarse graded mixes in order to get true indication of permeability of these mixes. All of the mixes tested in this project showed permeability below critical permeability at or below 5 percent in-place construction voids. Hence, the average specified 5 percent construction voids in total mix or 95 percent of theoretical maximum density seems to be justified for Superpave coarse graded mixes used by Maine department of transportation.

Key Words: permeability, HMA, field permeameter, gradation, lift thickness, voids

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INTRODUCTION

Effect of Permeability on Properties of Hot Mix Asphalt (HMA)

Permeability is defined as the rate at which pressurized gas or liquid passes through a porous medium, or simply the ability of a medium to permit flow. In the case of hot mix asphalt (HMA) pavements, the pressurized fluid is water (from rain) and the porous medium is HMA material. The invasion of water into a HMA pavement can adversely affect the durability of (HMA) pavements. The most harmful effect takes place through stripping. Stripping is defined as the breaking of the adhesive bond between the aggregate surface and asphalt binder. The result of stripping is pavement distress in the form of cracking or surface raveling. Also, a combination of excessive water due to a high permeability, and air, can result in premature oxidation of the asphalt binder and disintegration of the pavement. Hence a high permeability which results in percolation of a large amount of water into the pavement structure is detrimental for the durability of the pavement (1). It has been reported that in Ontario, HMA mixes are designed with a air voids content of two to three percent to make it almost impervious to water (2).

A recent survey of Superpave pavements in eight states (3) has shown that Superpave mixes tend to be more permeable than conventional mixes. Superpave coarse graded mixes (with gradation passing below the Restricted Zone) contains a higher percentage of coarse aggregate than conventional (fine graded) mixes. 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. However, the National Center for Asphalt Technology (NCAT) has identified several field permeability testing devices for HMA, which have shown good potential for evaluation of permeability of HMA (4). There is a need to use field testing device to evaluate the permeability of different types of HMA such as Superpave coarse and fine graded mixes. The results from such a study would help the state DOT engineers and contractors to identify change in gradation needed (if any), and identify proper density levels and lift thickness for mixes with different nominal maximum size aggregates to avoid permeability problems. This paper reports the results of a study carried out to evaluate the permeability of dense graded HMA used by Maine department of transportation.

Objective

The objectives of this study are to evaluate the permeability of Superpave mixes used by Maine DOT, and determine the effect of gradation, lift-thickness, and in-place density on permeability of these mixes.

Scope

This study was conducted in two parts: field and laboratory. A field permeameter was developed as a part of this study for conducting permeability testing in the field. A commercially available laboratory permeameter was used for testing permeability in the laboratory. The overall scope of the field study consisted of identification of conventional fine and coarse graded Superpave sections, conducting field permeability, coring, and obtaining loose mix from plant. In the laboratory, the cores were tested for density (air voids) and permeability. The loose mix was compacted to different thickness at a particular air voids (voids in total mix, VTM) level, and tested for permeability. The data from field and laboratory testing was analyzed to evaluate the permeability of different types of mixes, and evaluate the effect of different mix design and construction factors on permeability.

Test Plan

Five dense graded Superpave projects were selected for this study. These projects included 9.5 mm, 12.5 mm, 19 mm, and 25 mm nominal maximum aggregate size (NMAS) mixes. Two 9.5 mm mixes were selected – one with a fine gradation, with gradation passing above the maximum density line (and the restricted zone), and one with gradation passing below the maximum density line (and the restricted zone). A field permeameter was developed at the Worcester Polytechnic Institute (WPI) lab. This permeameter was developed on the basis of the NCAT field permeameter (4). This permeameter was used for testing at ten locations per project. One core was obtained at each of these test locations. Testing was done at random locations, immediately behind the finish roller. About 100 kg of loose mixes was also obtained for each of these projects. Mixes were compacted to obtain samples with four different thicknesses, with ratio of thickness to NMAS as 2.5, 3, 3.5, and 4. All of the samples were compacted to 5 percent voids in total mix (VTM), which is the average specified construction VTM for Maine DOT. The cores and the samples were tested for permeability in the laboratory. The data from field testing, and laboratory testing was analyzed to answer the questions regarding effect of different factors on permeability of dense graded HMA. The overall test plan is shown in Figure 1.

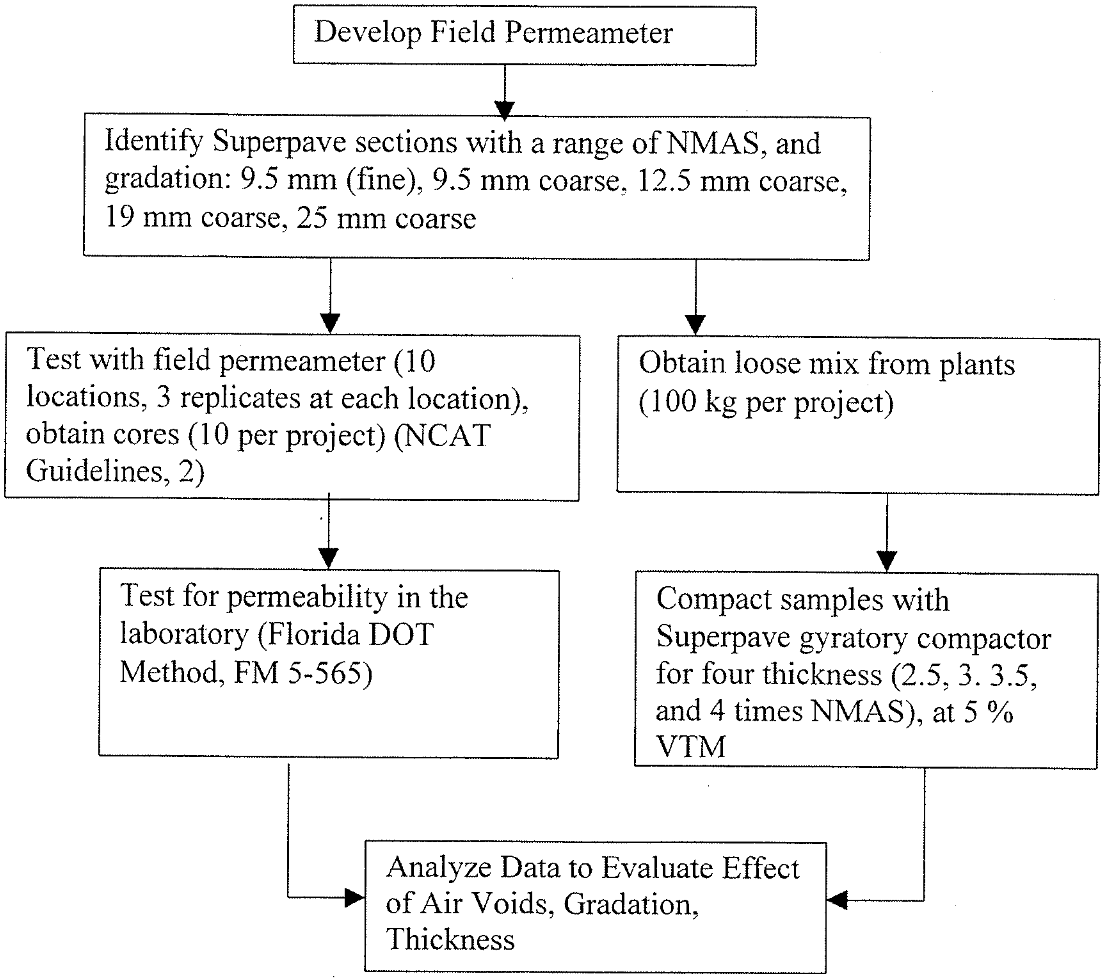


Figure 1. Overall Test Plan

Development of Field Permeameter

A falling head permeameter was planned for use. Basically, a way of letting water flow through a pavement section, without having water flowing through the sides was sought. The NCAT field permeameter was selected as a model for its simplicity and effectiveness. Through repeated testing and evaluation, the final device (Figure 2) was developed with three tiers, a flexible base, and two donut shaped weights. A scale was attached to the top two tiers for reading off the level of water. The three tiers were recommended (5) for testing pavements with a wide range of permeability, and hence different rates of water flow. A flexible closed-cell sponge rubber was selected as the base because of its non-absorptive nature and its ability to prevent flow of water. The dimensions were selected on the basis of repeated tests on different types of surfaces (HMA and concrete) to ensure practicality, ease of use, and prevent any leakage of water between the permeameter and the base, and the base and the pavement surface. Initially, caulking used for household need was used between the permeameter and the flexible base, and the flexible base and the pavement to seal water. However, this process involved considerable amount of time (required for repeated caulking at each location) and also prevented the researchers from obtaining cores at the test location. To solve this problem, three more weights were fabricated, and a total of five weights (total 47 kg) were found to be adequate for sealing off the permeameter without using any caulking. The final model is shown in Figure 2. Water for the permeameter was supplied by a 50-gallon tank, which was mounted on the back of a pickup truck. The testing setup is shown in Figure 3.

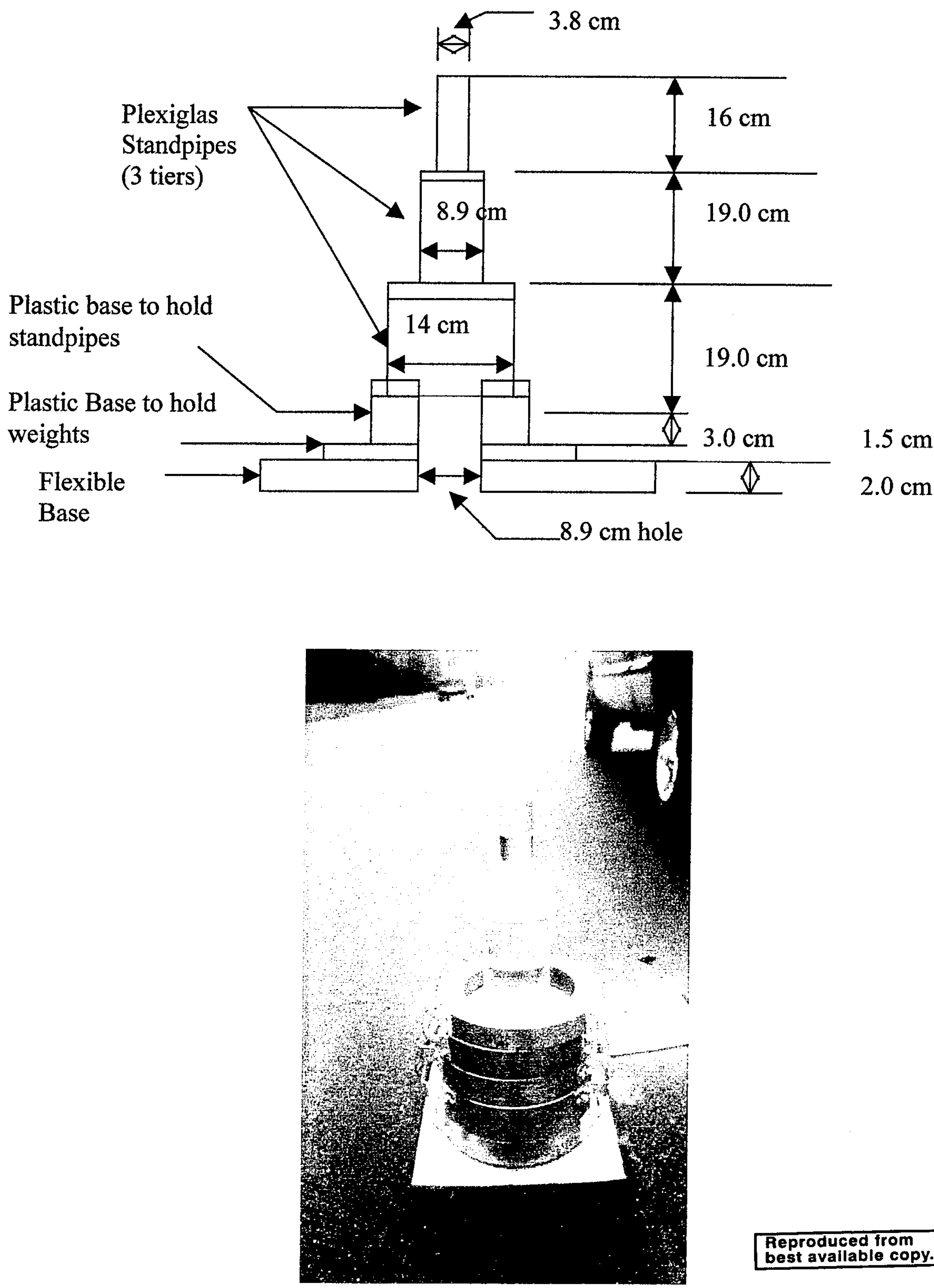
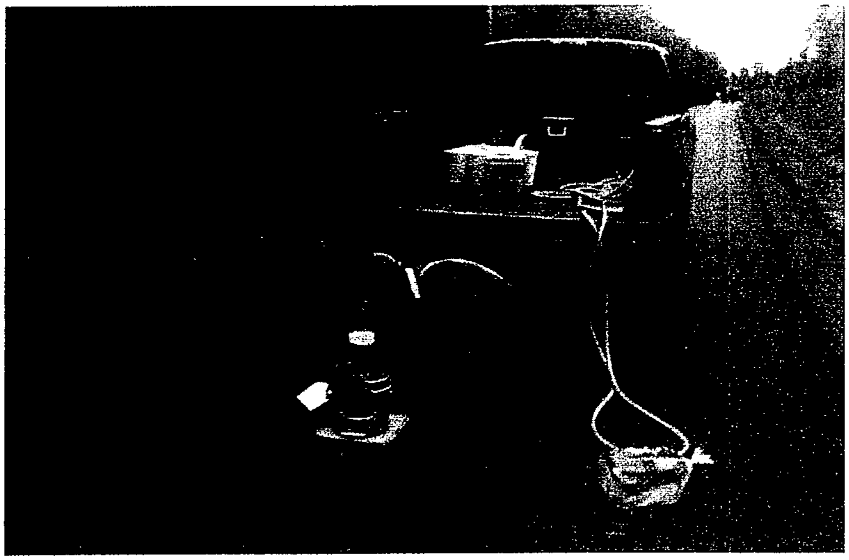


Figure 2. Sketch and photo of permeameter



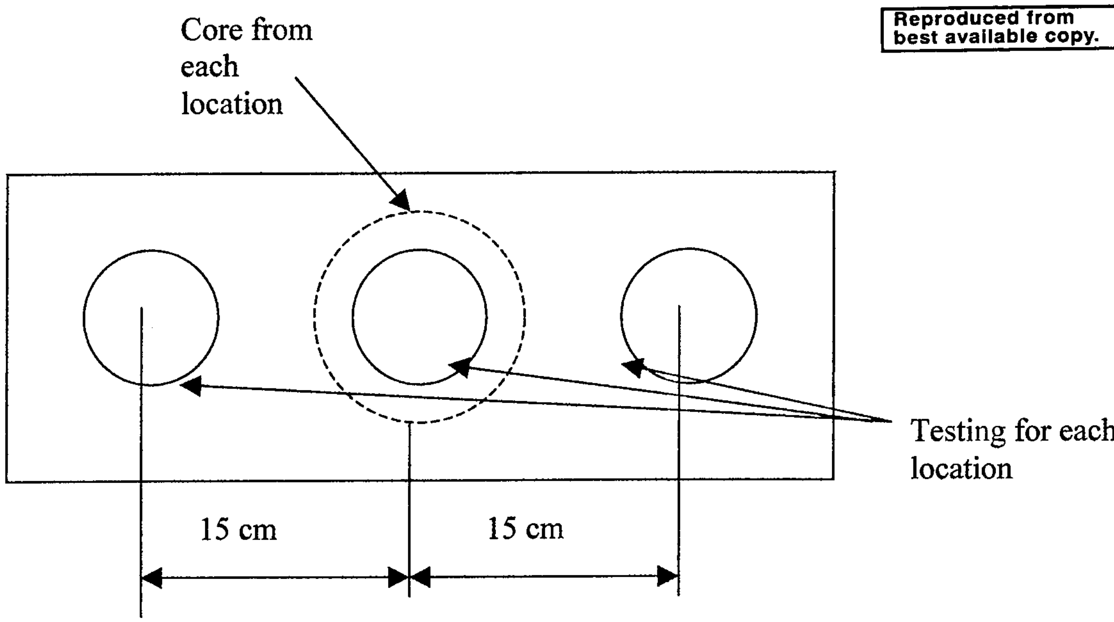


Figure 3. Testing and testing location

Field Testing

The field permeameter was used as a falling head device to record the drop in water level in the standpipe at a specified time. The standpipe was filled up to a specific mark, and the drop in water was noted for 60 seconds. If the pavement was highly permeable, the time to drop a specific interval was taken. For most of such cases, a drop of one inch (2.54 cm) was noted. In a few cases where the pavement was highly permeable, a drop of 2 inch (5 cm) was noted for practicality. In the case of the 25 mm base mix, the permeameter was filled up to the top of the second tier, and the drop was noted in the second tier. Because of the larger diameter, the drop in the tier was slow enough for efficient recording of data. For each location, three measurements were made at 150 mm apart. For each measurement, the average of three individual measurements was used. Each time the water dropped, the standpipe was filled up to the same starting level. In a few cases, due to scarcity of water, water was let drop through three successive inch mark, and the data was collected without filling up the standpipe to the original level.

A typical set of data obtained during field permeability testing is shown in Table 1. In most cases, the dropping time (or the drop in 60 seconds) was different for three readings. Usually, the first drop took less time than the second (or the drop was higher for the first reading), and the second drop took less time than the third (or the drop was higher for the second reading compared to the third). One possible explanation is that during the first test, the water fills up the voids, including some which are not interconnected, and during the second and third reading the water cannot go through

Table 1. Typical data from field permeability testing

Location	Test	Replicate	Initial Head, cm	Final Head, cm	time, s	Area of standpipe, cm^2	Thickness of layer L, cm	Area through which water enters pavement A, cm^2	Permeability k, cm/s	Average Permeability k, average
2	A	1	54.42	46.8	19	11.33	4	62.18	5.79E-03	0.006552
2	A	2	54.42	46.8	20	11.33	4	62.18	5.50E-03	
2	A	3	54.42	46.8	20	11.33	4	62.18	5.50E-03	
2	B	1	54.42	46.8	12	11.33	4	62.18	9.16E-03	
2	B	2	54.42	46.8	15	11.33	4	62.18	7.33E-03	
2	B	3	54.42	46.8	15	11.33	4	62.18	7.33E-03	
2	C	1	54.42	46.8	17	11.33	4	62.18	6.47E-03	
2	C	2	54.42	46.8	18	11.33	4	62.18	6.11E-03	
2	C	3	54.42	46.8	19	11.33	4	62.18	5.79E-03	

Note: $k = (aL)*\ln(h_1/h_2)/(AT)$

these non-connected voids, and only flows through the interconnected voids. Since in the case of rainstorm, the pavement may not be saturated, and the non-connected voids may not be filled with water, it was decided to use all three readings for specific measurements. A core was obtained at the center of the three reading locations. A typical testing and coring location are show in Figure 3.

Laboratory Sample Preparation and Testing

Loose mix obtained for each project was compacted to 5 percent VTM and at different thickness. The 5 percent VTM was selected because that is the average specified construction VTM for Maine DOT. The different thickness were selected so as to give sample thickness to nominal maximum aggregate size ratios of 2.5:1, 3:1, 3.5:1 and 4:1. The intent was to evaluate the effect of lift thickness on permeability. These samples as well as the field cores were tested for laboratory permeability, using a Karol-Warner laboratory permeameter. Falling head tests were conducted according to Florida DOT specification (FM 5-565). The cores and laboratory samples were saturated before testing by applying a vacuum under water for ten minutes. A typical set of data is shown in Table 2. As noted in the case of field permeability testing, the drop in water was faster initially, compared to the drop in successive testing. However, the data did not differ significantly during successive testing of the same sample.

Table 2. Typical data from laboratory permeability testing

Core:	2 (Uncut)		
Avg. Height:	35.25mm		
Weights:	Sub:	686.5	
		SSD:	1217.5
		Dry:	1206.1
BSG:	2.271		
Permeability Measurements: Time (s)	Start = 60 cm / Finish = 50 cm		
		00:04.3	
		00:03.8	
		00:03.8	
		00:03.9	
		00:03.8	
		00:03.9	
		00:03.9	

Sample	**Area of burette,**	**Thickness of sample**	**Area of sample**	**Time between h1 and h2**	**Initial head**	**Final head**	**Temperature correction factor for water**	**Permeability**
(Core)	**a**	**L**	**A**	**t**	**h_1**	**h_2**	**t_c**	**K**
	cm^2	**cm**	**cm^2**	**s**	**cm**	**cm**		**cm/s**
2	7.065	3.525	176.625	3.9	60	50	1	6.59E-03

Note: $k = (aL)*\ln(h_1/h_2)/(AT)$

RESULTS AND ANALYSIS

Permeability testing was done in the field for mixes with 9.5 mm fine (surface), 9.5 mm coarse (surface), 12.5 mm coarse (surface), 19 mm coarse (base), and 25 mm coarse (base) mixes. Gradation, design asphalt content, and lift thickness of these mixes are shown in Table 3. The 9.5 mm fine mix has a gradation, which goes above the restricted zone and the maximum density line, and the other four mixes have gradations passing below the restricted zone and the maximum density line. The air voids and coefficient of permeability determined from data obtained from field testing and laboratory testing (of cores) are given in Table 4. The air voids and coefficient of permeability determined from data obtained from laboratory testing of laboratory compacted samples are given in Table 5. The results of analyses carried out to answer the different questions about factors affecting permeability of dense graded HMA are given in the following paragraphs. The term permeability is used for "coefficient of permeability" in the rest of the report.

The flow of water in HMA pavements occur through interconnected air voids. Since there is always some interconnected air voids, there always exists some degree of permeability in a HMA pavement. However, since there is a critical permeability beyond which the pavement lets in excessive amount of water, the question is at what VTM do dense graded HMA become highly permeable? There is also a need to define how much permeability is too much. To answer these questions, Figure 4 is shown with the data of VTM versus field permeability. Figure 4 shows that for the different mixes, permeability increases significantly with VTM beyond a threshold VTM, and that the threshold VTM is dependent on the mix properties. The 25 mm coarse mix shows significantly high

Table 3. HMA Mix Information

Mix	Gradation		Asphalt Content, %	Lift Thickness, cm
9.5 mm fine	Sieve Size (mm)	Percent Passing	5.8	4
	12.5	100		
	9.5	99		
	4.75	65		
	2.36	51		
	1.18	45		
	0.6	35		
	0.3	21		
	0.15	9		
	0.075	5		
9.5 mm coarse	Sieve Size (mm)	Percent Passing	6.2	3
	12.5	100		
	9.5	99		
	4.75	64		
	2.36	45		
	1.18	31		
	0.6	18		
	0.3	10		
	0.15	6		
	0.075	4		
12.5 mm coarse	Sieve Size (mm)	Percent Passing	5.5	4
	19.0	100		
	12.5	91		
	9.5	73		
	4.75	53		
	2.36	36		
	1.18	24		
	0.6	14		
	0.3	8		
	0.15	5		
	0.075	4		
19 mm coarse	Sieve Size (mm)	Percent Passing	4.7	5
	25.0	100		
	19.0	100		
	12.5	86		
	9.5	66		
	4.75	44		
	2.36	30		
	1.18	19		
	0.6	13		
	0.3	9		
	0.15	7		
	0.075	4.9		

Table 3. HMA Mix Information (continued)

Mix	Gradation		Asphalt Content, %	Lift Thickness, cm
25 mm coarse	Sieve Size (mm)	Percent Passing	5.1	8.9
	37.5	100		
	25.0	99		
	19.0	93		
	12.5	78		
	9.5	72		
	4.75	41		
	2.36	25		
	1.18	18		
	0.6	12		
	0.3	8		
	0.15	6		
	0.075	5		

Table 4. Air Voids and Permeability of Field Cores

Mix	Lift thickness, cm	VTM, %	Field Permeability, cm/s	Lab Permeability, cm/s
9.5 (fine)	4	8.3	1.0838E-03	9.7499E-04
		6.3	1.3443E-04	2.7014E-04
		6.7	2.8635E-04	4.9118E-04
		12.3	6.3481E-03	9.8072E-03
		5.8	1.2072E-04	3.7335E-04
		8.4	1.8246E-04	4.0176E-04
		8.4	6.4517E-04	8.0461E-04
		8.1	6.7204E-04	1.3329E-03
		7.6	4.2636E-04	1.3616E-03
		10.6	3.6161E-03	3.5850E-03
9.5 (coarse)	3	3.1	9.1749E-06	8.0143E-05
		5.4	6.6733E-05	9.0595E-05
		6.3	6.3873E-05	1.1297E-04
		5.5	7.7628E-06	0.0000E+00
		2.9	6.3502E-06	1.3901E-04
		8.1	1.0073E-03	1.8793E-03
		4.7	1.6242E-05	6.5697E-05
		6.3	2.7559E-05	1.4204E-04
		5.5	6.3054E-05	9.4517E-05
		7.4	3.2238E-04	1.3434E-03
12.5 (coarse)	4	3.5	5.7183E-05	0.0000E+00
		8.4	6.5517E-03	6.5916E-03
		6.7	1.1618E-03	1.0851E-03
		4.0	4.8518E-05	0.0000E+00
		4.0	9.4083E-06	5.5650E-05
		2.2	6.0353E-05	9.7985E-06
		4.7	1.3460E-04	1.3835E-04
		5.8	2.9604E-04	1.1175E-03
		3.1	8.4669E-06	0.0000E+00
		7.3	7.7538E-04	1.1588E-03
19 (coarse)	5	6.5	2.3413E-03	1.3265E-04
		6.8	5.5854E-03	7.1780E-04
		8.4	2.3629E-02	6.7643E-03
		8.3	1.8440E-02	5.9969E-03
		7.2	2.3528E-03	4.6177E-04
		7.9	2.0039E-02	4.7073E-03
		5.8	1.3512E-03	2.1065E-04
		Destroyed	5.9815E-04	
		6.4	1.6120E-03	1.1689E-03
		6.9	5.0150E-03	9.2987E-04

Table 4. Air Voids and Permeability of Field Cores (continued)

Mix	Lift thickness, cm	VTM, %	Field Permeability, cm/s	Lab Permeability, cm/s
25 (coarse)	8.9	6.8	2.7677E-02	0
		5.7	9.4550E-03	1.2155E-05
		7.3	6.4893E-02	4.8978E-04
		7.1	1.6911E-02	2.4105E-05
		5.5	7.9700E-03	2.1694E-05
		8.4	2.7452E-02	5.1882E-04
		4.8	7.0200E-03	8.6849E-05
		7.0	5.9678E-03	5.8678E-05
		4.5	8.0188E-03	0
		9.2	1.2263E-01	9.8173E-04

Table 5. Thickness, Air Voids and Permeability of Laboratory Compacted Samples

Mix	**Lift thickness, cm**	**Sample thickness, cm***	**VTM**	**Lab Permeability**
		(lift thickness to NMAS ratio of 4, 3.5, 3, 2.5)	**%**	**cm/s**
9.5 (fine)*	4	3.8	5.0	1.05E-03
		3.3	5.9	6.45E-03
9.5 (coarse)	3	3.8	5.1	1.7150E-04
		3.3	4.9	1.1458E-04
		2.9	5.1	5.3596E-04
		2.4	4.9	4.9641E-04
12.5 (coarse)	4	5	4.9	7.4840E-04
		4.4	5.3	1.6326E-03
		3.8	5.0	1.1358E-03
		3.3	5.2	1.7009E-03
19 (coarse)	5	7.6	5.0	8.93E-03
		6.7	4.9	1.01E-02
		5.7	4.7	1.15E-02
		4.7	5.1	1.57E-02
25 (coarse)	8.9	10	5.0	2.59E-03
		8.7	5.1	7.86E-04
		7.5	5.0	1.30E-03
		6.2	5.1	2.24E-03

* It required more than 300 gyrations to bring the voids down to 6 percent for sample thickness to NMAS ratio of 3 and lower. It was suspected that the aggregates were being crushed during compaction of these samples. Hence these samples were not compacted and not used for permeability testing.

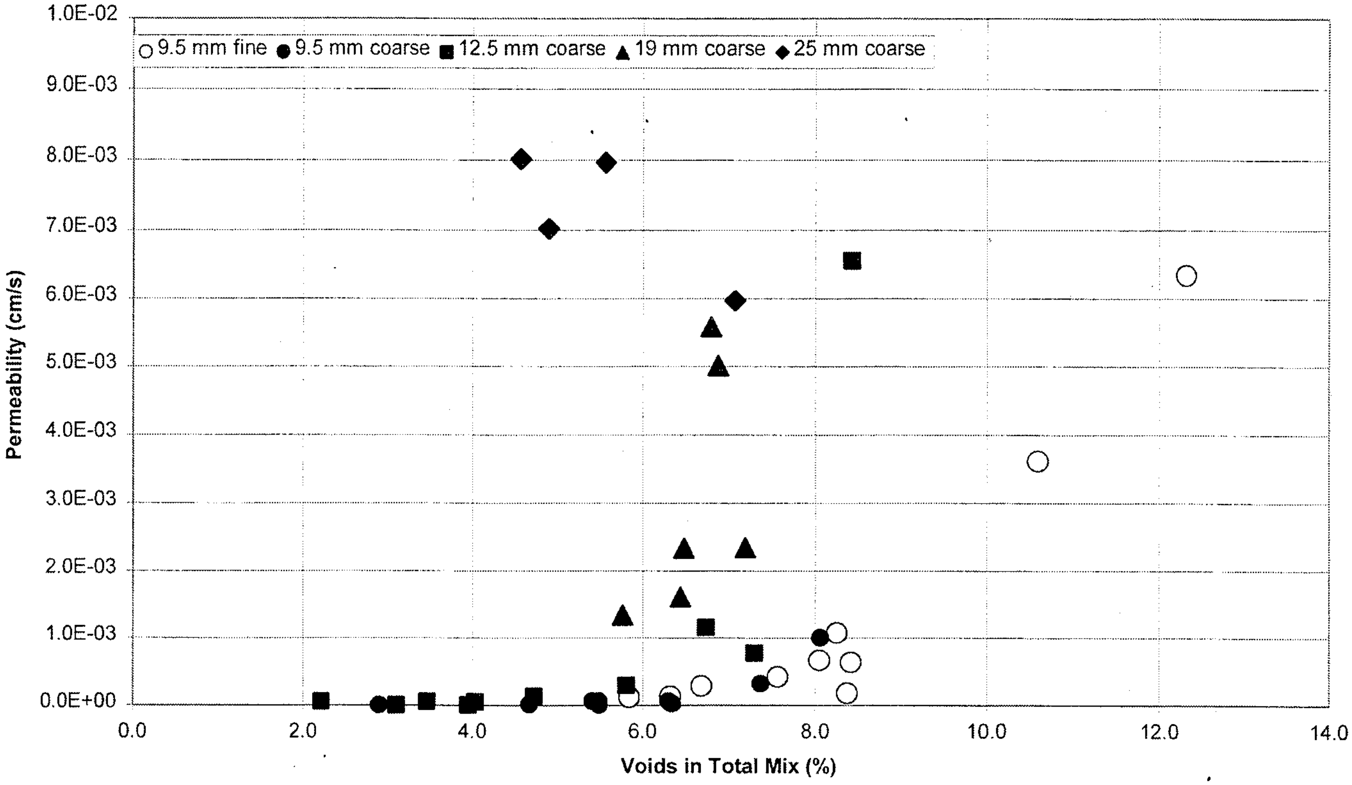


Figure 4. Voids in total mix versus field permeability

permeability at 5 % VTM, the 19 mm coarse mix shows high permeability at 6 % VTM, the 12.5 mm coarse mix shows a significant increase in permeability at VTM greater than 6 %, the 9.5 mm coarse mix shows a significant increase in permeability at VTM greater than 7 %, whereas the 9.5 mm fine mix shows a significant increase in permeability at VTM greater than 8 %. It seems that coarser the mix, lower is the VTM at which there is a significant increase in permeability.

Selection of a critical permeability value is required for comparison of permeability of different mixes or permeability of same mix at different densities, and help in deciding whether the HMA material has excessive permeability or not. Considering mixes that have performed well in the past is the best place to start even though there is no actual in-place permeability data available for these older mixes. The 9.5 mm fine graded mix used in this project is similar in gradation and asphalt content to older Marshall mixes that have performed very well in resisting permeability-induced damage such as stripping. These Marshall mixes were typically compacted to a density of approximately 92 percent of theoretical maximum density (8 percent air voids). Also, work performed by Zube (6) has shown that dense graded HMA pavements (constructed with fine mixes) become excessively permeable to water at approximately 8 percent air voids. Therefore, the permeability of the 9.5 mm fine graded mix at 8 percent air voids can be used to serve as a suitable baseline for comparing the permeability of the other four mixes used in this study. The permeability values between 7.5 and 8.5 percent air voids were averaged, yielding the following:

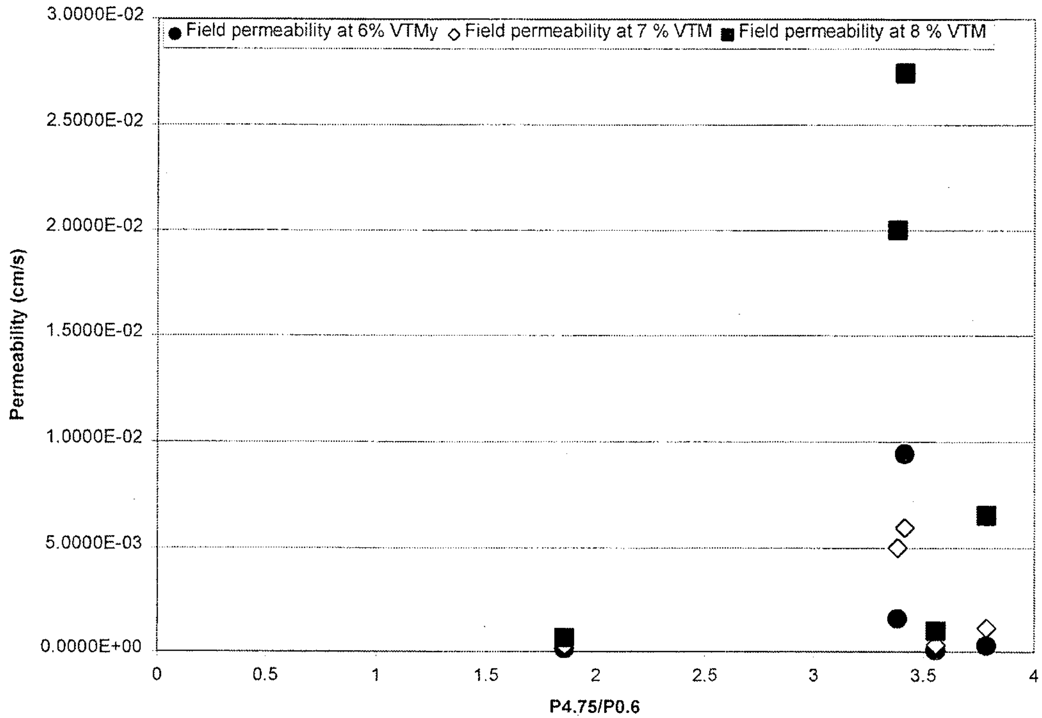
Field: $k_{average} = 6.02 \times 10^{-4}$ cm/s at 8 % voids

Laboratory: $k_{average} = 9.75 \times 10^{-4}$ cm/s at 8 % air voids

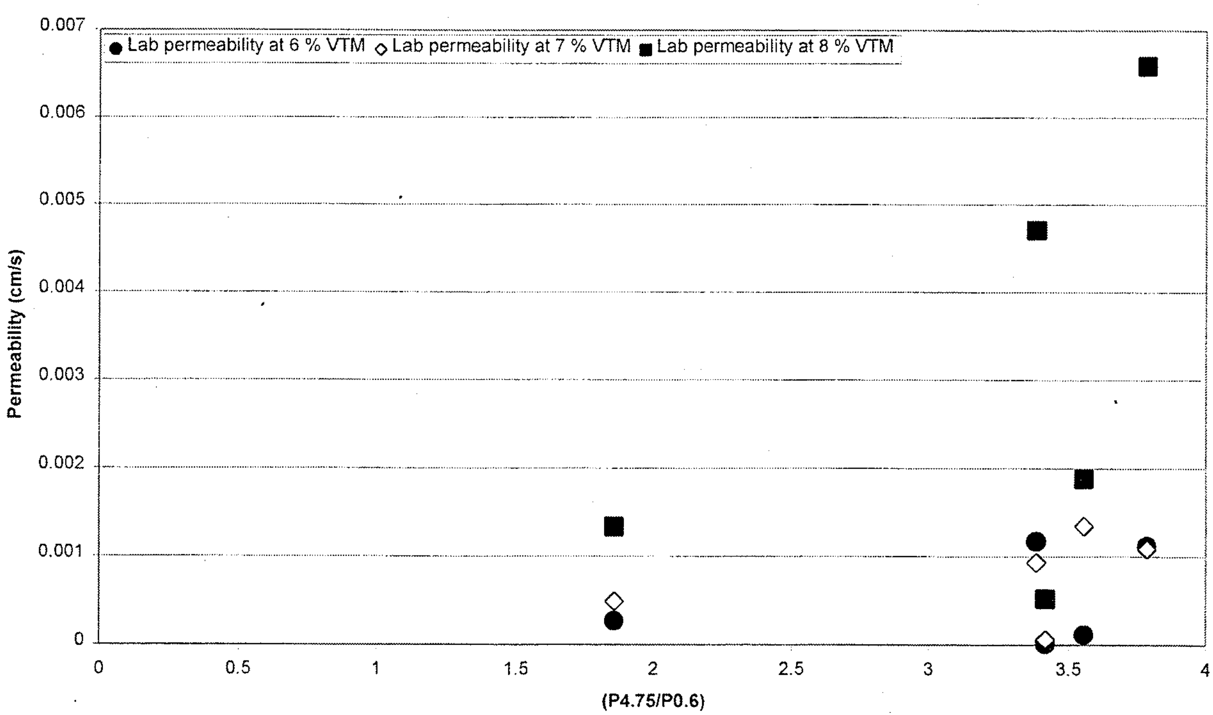
Taking the larger of the two numbers, a value of $k = 9.75 \times 10^{-4}$ cm/s was selected. This number was rounded to $k = 1.0 \times 10^{-3}$ cm/s for simplicity, and selected as a critical permeability. Note that at a permeability level in the order of 10^{-4} cm/s, use of 6 or 9 or 10 does not have a significant effect on the actual numerical value.

The different gradation curves for the five mixes could also be represented by a shape factor - some way of distinguishing the difference in which the materials are graded in different mixes. In order to do this, a ratio of P4.75 to P0.6 was calculated for the different mixes. These values are greater than 3 in all cases except the 9.5 mm fine mix, in which case it is 1.8. Field and laboratory permeability of the different mixes was plotted against the (P4.75/P0.6) ratios at 6, 7 and 8 % VTM. Figure 5 shows these plots for field and laboratory permeabilities. It can be seen that the effect of higher VTM is significantly greater at higher (P4.75/P0.6) ratios than the effect at low (P4.75/P0.6) ratio. This seems to support the idea that coarse graded mixes have a higher permeability than fine graded mixes at similar void levels. The use of (P4.75/P0.6) parameter seems to indicate the difference in the effect of voids on permeability.

Hence, it appears to be that for coarse graded Superpave mixes, the VTM should be less than 6 or 7 to keep the same permeability level as is expected from a fine graded mix at 8 % VTM. Most likely, a VTM of 5 % is desirable for a 25 mm coarse mixes, 6 % is appropriate for 12.5 mm coarse mixes, whereas a VTM level of 7 % is acceptable for a 9.5 mm coarse mix.



Field permeability



Laboratory permeability

Figure 5. Permeability versus (P4.75/P0.6) for different VTM

Figure 6 shows the results of laboratory permeability testing of cores from different projects. The trend seems to be the same as that shown by the results of field permeability testing – a significant increase in permeability beyond threshold VTM content. However, there are differences at the levels of VTM at which the permeability increases significantly for the different mixes. The 9.5 mm fine and coarse mixes show a significant increase in permeability beyond 8 % VTM, whereas the 12.5 coarse and the 19 mm coarse mix shows significant increase in permeability beyond 7 % VTM.
The 25 mm coarse mixes does not seem to show a significant increase even beyond 8 % VTM. The question is which method – field or laboratory, gives true indication of permeability of a mix? Obviously, field test is more realistic than the laboratory test, even though the ideal conditions, which are assumed for calculation of coefficient of permeability (assuming Darcy's law of one-dimensional flow), are not present in the field. Figure 7 shows a plot of difference between field and laboratory (field permeability – laboratory permeability) permeability for the different mixes and for different VTM. For the 9.5 mm fine, 9.5 mm coarse, and the 12.5 mm coarse mixes, the differences are not very significant, and in most cases the laboratory permeability is slightly higher than field permeability. However, for the 19 mm coarse and 25 mm coarse mixes, the differences are very significant, all of the differences are positive (which indicates field permeability is higher), and the differences tend to increase with an increase in VTM. It is believed that permeability is strongly influenced by the macrostructure of the mix. The 19 mm and the 25 mm coarse mixes were 5 and 9 cm thick, respectively, and most likely had horizontal permeability many times more than the vertical permeability. The overall

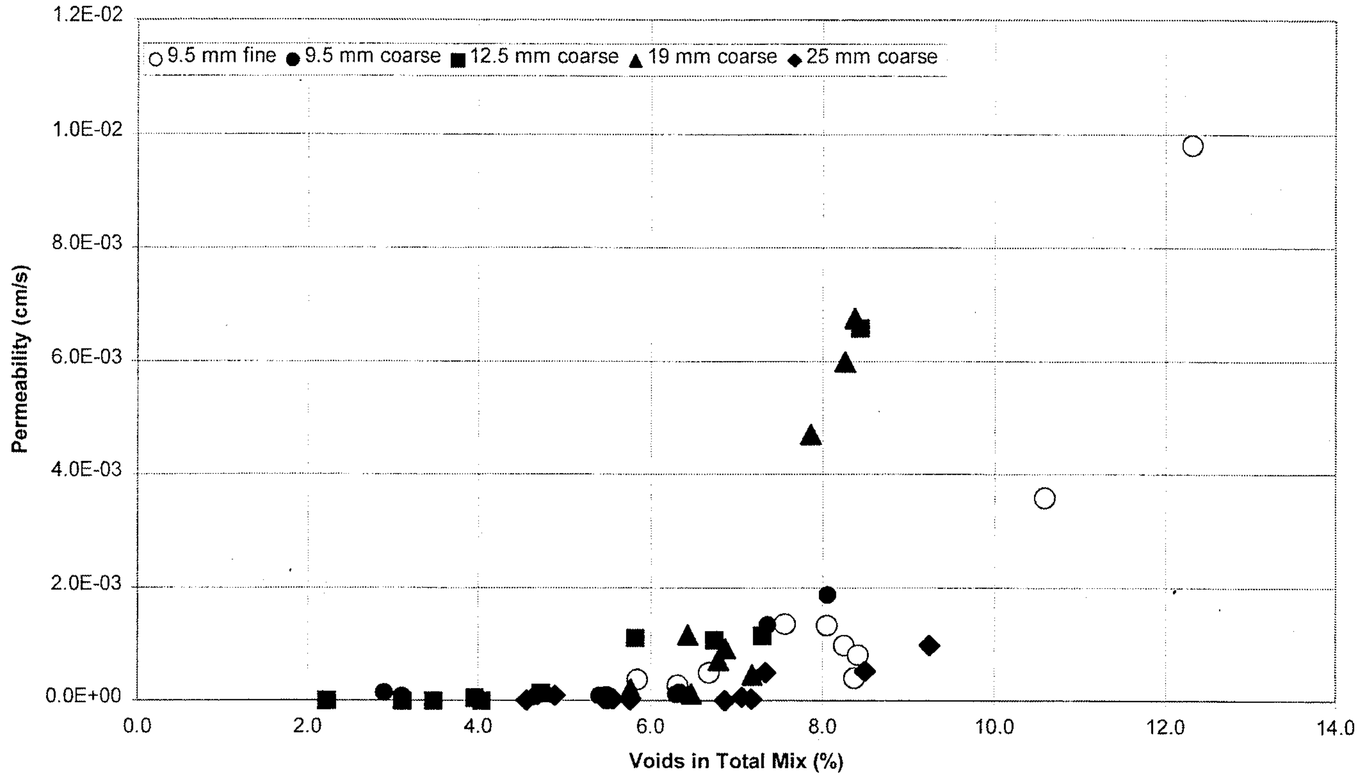


Figure 6. Voids in total mix versus laboratory permeability

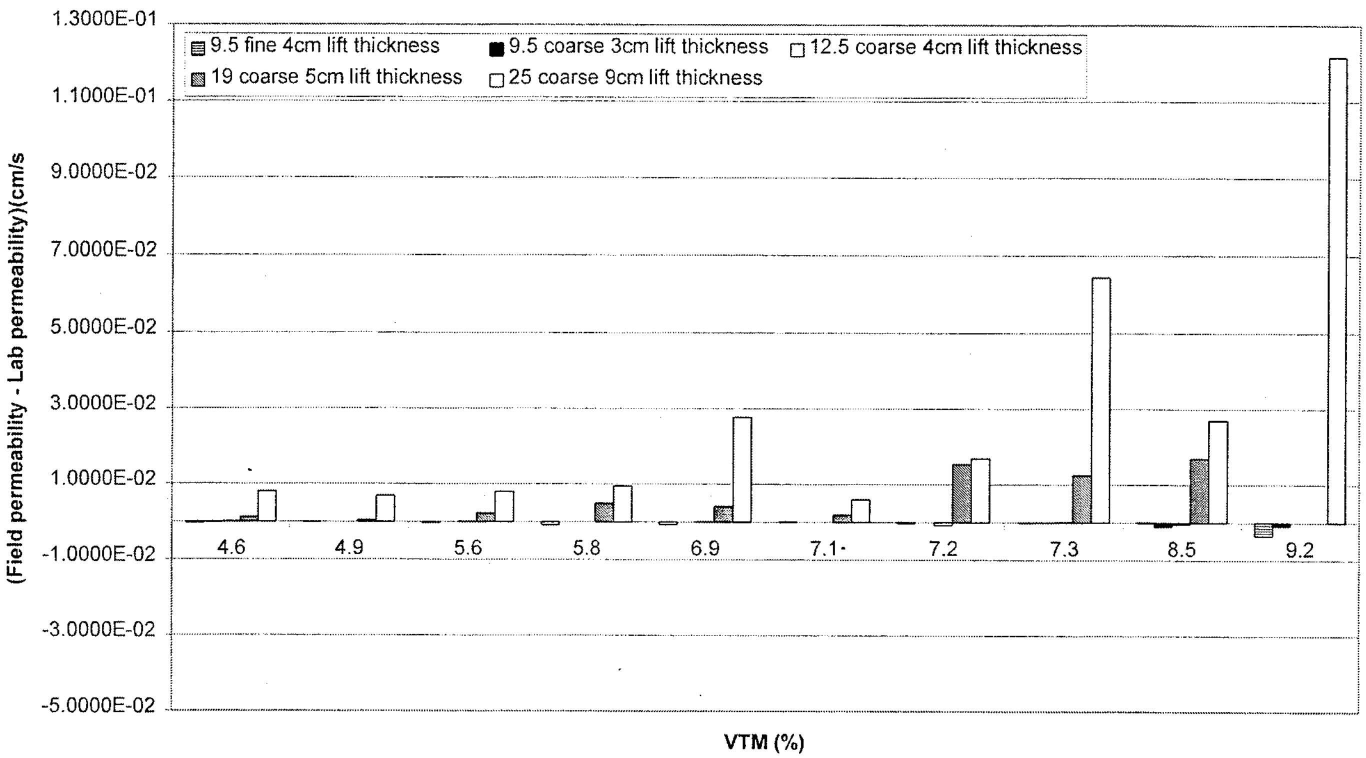


Figure 7. Difference between field and laboratory permeability

permeability could be approximately equal to the horizontal permeability. The high difference between the field and the laboratory permeability for the 19 mm and 25 mm mixes gives an indication of horizontal permeability, since in the laboratory the flow of water is restricted in the vertical direction. It seems that a large amount of flow in the coarser mixes with thick lifts occurs in the horizontal direction, whereas finer mixes with thinner lifts tend to have more of a vertical flow. For the 9.5 and 12.5 mixes, water was observed to come up through the mat a few cm away from the permeameter (Figure 8). This was not observed in the case of 19 or 25 mm mixes. Hence, laboratory testing with falling head permeameter using vertical flow of water may not give a true indication of permeability of mixes with pronounced macrostructure. The horizontal permeability of some mixes may be much higher and hence of overriding importance in such cases.

Figure 9 shows a plot of sample thickness (from laboratory compacted samples, all sample compacted to 5 % VTM) versus laboratory permeability for different mixes. There is a trend of decreasing permeability with an increase in sample thickness (or increase in thickness to nominal maximum aggregate size ratio) for all of the mixes, except the 25 mm NMAS coarse mix. It should be noted that the voids in total mix of the 9.5 mm fine coarse are about 6 percent for the sample with 3.5:1 thickness to NMAS ratio. This is because it required more than 300 gyrations to bring the voids below 6 percent for a thickness to NMAS ratio of 3.5 and lower. It was suspected that the aggregates were getting crushed at such high number of gyrations. Hence it was possible to use only two thickness to NMAS ratio, 4:1 and 3.5 : 1 (at 6 percent) for this part of the study. The change in permeability per unit change in thickness seems to be increasing

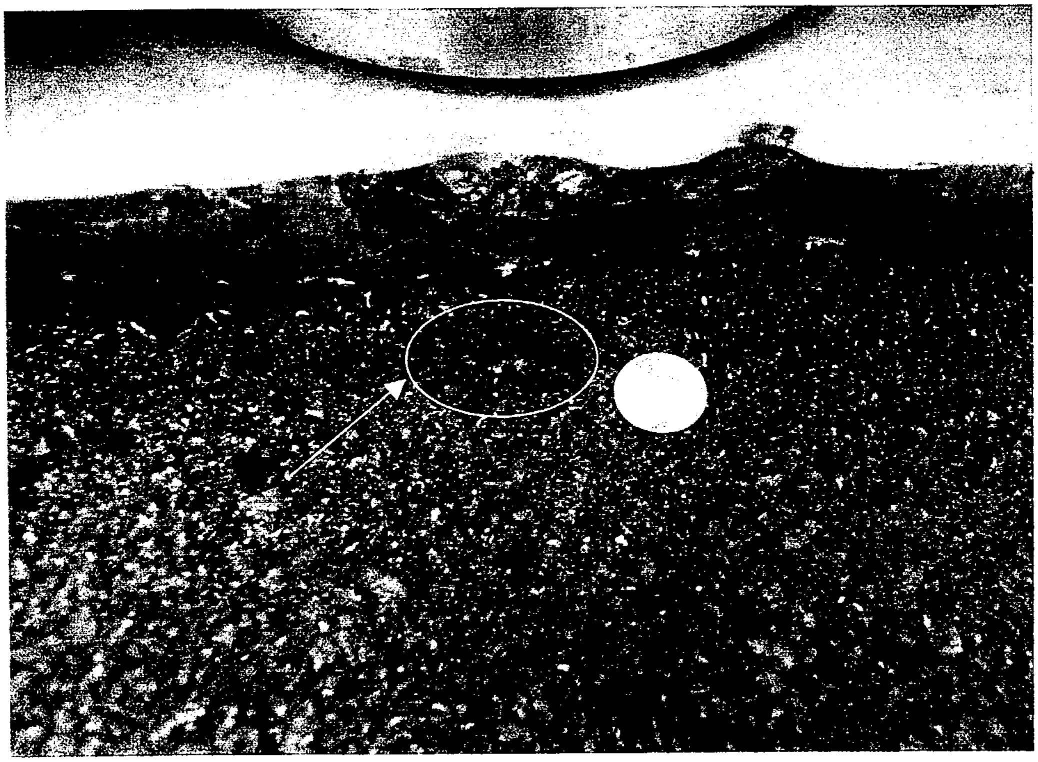


Figure 8. Water popping up near permeameter during field testing

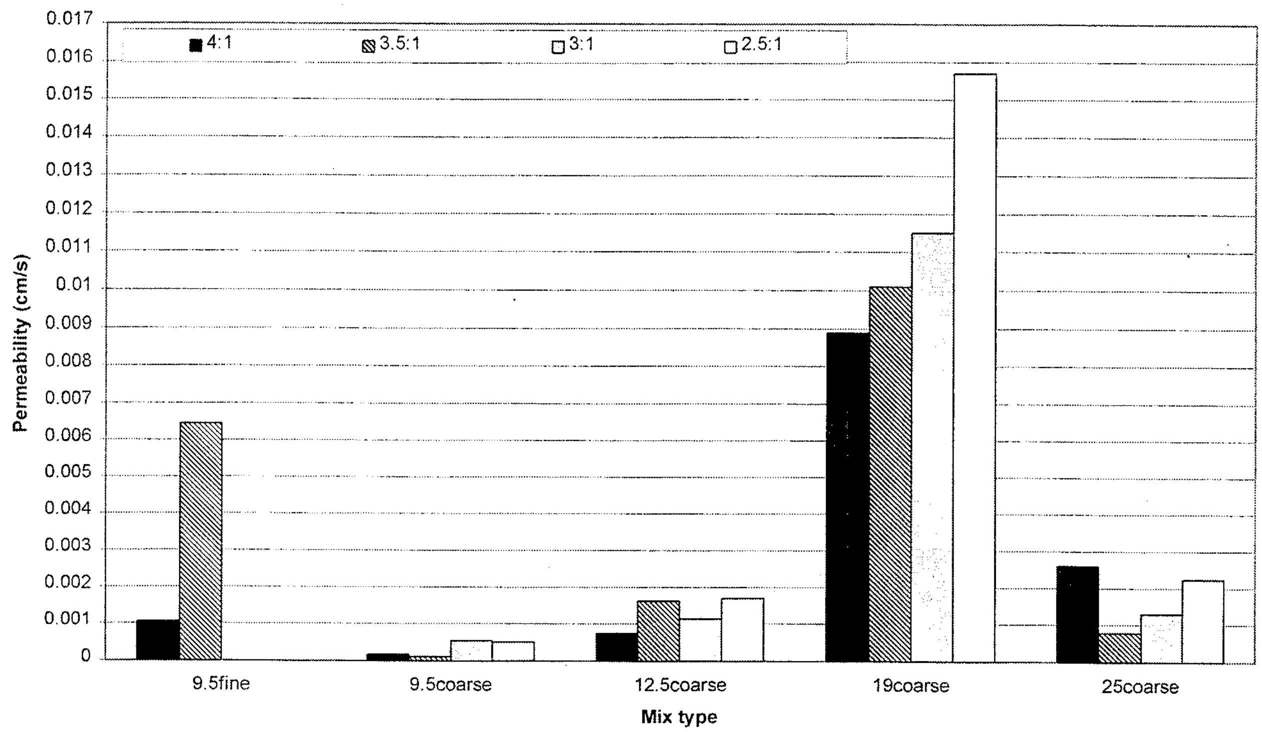


Figure 9. Permeability of samples with different thickness

with an increase in NMAS size. Hence, the effect of lift thickness on laboratory permeability is significantly more in the case of 19.0 mm coarse mix, compared to the 12.5 mm mix, and it is more in the case of 12.5 mm coarse mix compared to a 9.5 mm mix. These results indicate that at the same VTM, a mix with NMAS of 9.5 mm or 12.5mm or 19 mm would have a lower permeability value at a higher thickness. This can be explained by the fact that higher the thickness, more path the water has to flow through, and probably, greater is the chance of existence of not connected flow paths. The laboratory permeability results for the 25 mm coarse mix shows that there is no significant difference between the values for samples with different thickness to NMAS ratio. This is probably because the mix is very coarse, and the number of interconnected flow paths is very high.

It seems that VTM and lift thickness have significant effects on permeability. The data obtained from field and laboratory testing was analyzed to determine the effect of these two factors. Table 6 shows the result of the analysis. In both cases VTM and lift thickness have significant effects, as expected. In both cases, VTM has a positive effect, that is permeability increases with an increase in VTM. However, lift thickness shows a positive effect in the case of field permeability, and shows a negative effect on laboratory permeability. This means that in the field, a mix with higher lift thickness would have a higher permeability, whereas in the laboratory, a mix with higher lift thickness would have a lower permeability. This is most probably due to the fact that during laboratory testing, more thickness means more path of flow, whereas in the field more thickness most likely means more horizontal channels of flow. However, it must be noted that the

Table 6. Analysis of factors

Field permeability

Step 2 Variable VTM Entered R-square = 0.37871145 C(p) = 2.89890121

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	2	0.00739275	0.00369637	14.02	0.0001
Error	46	0.01212805	0.00026365		
Total	48	0.01952079			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-0.03382939	0.00927991	0.00350375	13.29	0.0007
Lift thickness	0.00512753	0.00112202	0.00550613	20.88	0.0001
VTM	0.00254478	0.00118526	0.00121537	4.61	0.0371

Bounds on condition number: 1.012672, 4.050686

Lab permeability

Step 2 Variable LIFTTHCK Entered R-square = 0.46586349 C(p) = 9.57224487

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	2	0.00009790	0.00004895	20.06	0.0001
Error	46	0.00011225	0.00000244		
Total	48	0.00021015			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-0.00241384	0.00089277	0.00001784	7.31	0.0096
Lift thickness	-0.00020587	0.00010794	0.00000888	3.64	0.0627
VTM	0.00070874	0.00011403	0.00009427	38.63	0.0001

Bounds on condition number: 1.012672, 4.050686

Note: Probability >F (Prob>F) less than 0.05 indicates significant effect at 5 % significance level mixes with significantly high thickness are also the mixes with higher nominal maximum size aggregates (19 mm and 25 mm). As Figure 9 shows from laboratory results, there is a significant decrease in permeability of 12.5 and 9.5 mm mixes for an increase in sample thickness. Also, from Figure 7 it is evident that there is no significant difference between laboratory permeability and field permeability in the case of 9.5 mm and 12.5 mm mixes. For these mixes, laboratory data shows that there is a decrease in permeability with an increase in sample thickness. However, there is significant difference between laboratory and field permeability of 19 mm and especially 25 mm mixes. Even though laboratory permeability test data shows that the 19 mm and 25 mm mixes do not become highly permeable before seven and eight percent VTM, in the field these two mixes show a high permeability at around six and five percent VTM, respectively. Obviously, this high field permeability is not only due to gradation (otherwise it would have been reflected in laboratory test), but most likely due to high horizontal permeability. Therefore, in the case of 19 mm and especially 25 mm coarse mixes similar to the mixes studied, it seems that it would be advisable to keep the construction VTM in the 5-6 percent range.

It should be noted that there exists a density gradient in in-place HMA pavements. The center one third typically has a higher density than the top and bottom one third. One explanation of high horizontal permeability is that water simply flows laterally through the low density top of the lift. Since the density gradient becomes more pronounced with an increase in aggregate size, it seems that a higher horizontal permeability should be observed in 19 mm and 25 mm nominal maximum size mixes.

At this time there is no good method for determination of horizontal permeability of HMA in the laboratory. Because of the sealing effect of drill during coring operation, it is not possible to have water flow through the sides of HMA cores in the laboratory. A similar problem arises with testing of laboratory prepared samples, in which case the sides are sealed off by kneading effect during compaction with a Superpave gyratory compactor. However, one possible approach for estimating horizontal permeability is to conduct a permeability test on a constructed in-place pavement, and then saw of one side to observe the flow of water. This method, although time consuming, can help in avoiding the sealing effect of a core drill. The flow of water through the cut face can be measured to get an approximate estimation of horizontal permeability of the in-place mix.

Limitations of Permeability Test

The limitation of the in-place permeability test that was developed and used in this project is that the conditions, which are assumed to be valid in order to calculate the coefficient of permeability from Darcy's law, are not valid. For example, Darcy's law is valid for one dimensional flow, whereas the flow of water through a pavement is partly horizontal and partly vertical. Hence, it is difficult to compare or correlate permeability values that are obtained in the field to the permeability values that are obtained from laboratory testing. However, it must be noted that it is impossible to meet Darcy's law condition during in-place permeability testing, and in the absence of "ideal" conditions, Darcy's law can still be used to get an estimation of water flow through pavements, and more importantly, to make a comparison of permeability of different HMA mixes.

The laboratory test method has less limitations in the sense that the flow conditions are more similar to those assumed for application of Darcy's law, and hence calculating coefficient of permeability.

The use of in-place permeability test, as indicated in this report, is best suited for comparative evaluation of permeability of different mixes, and same mixes with different properties, such as in-place density. Since the limitations of in-place testing will be present in each and every test, as long as a similar equipment and a consistent procedure is maintained, the results should be good enough for comparative evaluation purpose. A suggested method for in-place permeability testing is given in Appendix A.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of results obtained in this study, the following conclusions can be made:

1. Air void content (as measured by voids in total mix) of dense graded HMA has a significant effect on permeability of HMA. The permeability of dense graded HMA increases significantly at VTM greater than a threshold VTM, the threshold VTM being dependent on type of mix.
2. There is a significant effect of gradation on permeability of dense graded HMA. For a coarser mix, there is a significant increase in permeability at a lower VTM, compared to a finer mix. 25 mm, 19 mm, 12.5 mm and a 9.5 mm nominal maximum aggregate size coarse mixes showed significant increase in permeability at 5, 6, 7 and 8 % VTM, respectively. In contrast, a 9.5 mm fine mix showed significant increase in permeability at VTM greater than 8 percent.

3. The use of a ratio, percent passing the 4.75 mm sieve to the percent passing the 0.6 mm sieve, seems to be capable of differentiating the effect of VTM on permeability – a mix with low (P4.75/P0.6) ratio (less than two) indicates a relatively fine mix, and a mix with a higher (P4.75/P0.6) ratio (greater than 3) indicates a relatively coarse mix. A mix with a high (P4.75/P0.6) ratio would have a significant increase in permeability at relatively lower VTM compared to a mix with low (P4.75/P0.6) ratio.
4. A field permeability of 0.001 cm/s (1.00 X 10^{-3} cm/s) was selected to be critical permeability of dense graded HMA, based on historical fine graded mixes.
5. Laboratory tests on samples with different thickness showed that there is a decrease in permeability with an increase in thickness. The decrease in permeability per unit change in thickness is more significant in the case of 12.5 mm mix than a 9.5 mm mix.
6. The difference between field and laboratory density is significant at higher VTM for 19 mm nominal maximum aggregate size and 25 mm nominal maximum aggregate size coarse mixes, but not significant for the 9.5 mm nominal maximum aggregate size fine, 9.5 mm nominal maximum aggregate size coarse and 12.5 mm nominal maximum aggregate size coarse mixes.
7. 19 mm and 25 mm nominal maximum aggregate size mixes seem to have a large number of horizontal flowpaths, and hence significantly high horizontal permeability. The field permeability of these mixes seems to be determined by the horizontal permeability.

Based on the conclusions, the recommendations are:

1. For coarse graded mixes similar to those discussed in this paper, DOTs should specify in-place construction VTM of less than 7 % for 9.5 mm and 12.5 mm nominal maximum aggregate size mixes
2. For 12.5 mm and 9.5 mm nominal maximum aggregate size coarse mixes, an increase in lift thickness can be considered as a way of reducing excessive permeability.
3. For 19 mm and 25 mm nominal maximum aggregate size coarse graded mixes, construction VTM should preferably be kept around 5 percent.
4. As quality control procedures, regular field permeability testing of coarse graded mixes should be done to ensure proper watertightness of the mix. A critical field permeability value of 0.001 cm/s is suggested. However, the value should be checked against the acceptable permeability obtained earlier with fine graded mixes at acceptable voids in total mix content, with the same permeameter.
5. Laboratory tests can be substituted for field test for 9.5 mm and 12.5 mm nominal maximum aggregate size mixes. However, field testing must be done for 19 mm and 25 mm nominal maximum aggregate size mixes in order to get a true indication of permeability of these mixes.
6. Further research should be conducted to fine tune field permeability device.

REFERENCES

1. The Asphalt Institute. Principles of Construction of Hot Mix Asphalt Pavements. Manual Series No. 22 (MS-22), 1983.

2. Fromm., H. J., The Mechanisms of Asphalt Stripping from Aggregate Surfaces. Association of Asphalt Paving Technologists, Volume 43, 1974.

3. Brown, E. Ray, Dale Decker, Rajib B. Mallick and John Bukowski. Superpave Construction Issues and Early Performance Evaluations. Presented at the Annual Meeting of the Association of Asphalt Paving Technologists (Chicago, 1999).

4. Cooley, Larry Allen. Permeability of Superpave Mixtures: Evaluation of Field Permeameters. Final Report prepared for Southeastern Superpave Center Pooled Fund Study, NCAT, Auburn University, 1998.

5. Personal communication with Dr. E. Ray Brown, Director, National Center for Asphalt Technology, AL 36849.

6. Zube, E. Compaction Studies of Asphalt Concrete Pavements as Related to the Water Permeability Test. Highway Research Board, Bulletin 358, 1962.

Appendix A: In-Place Permeability Testing Procedure

Test Method for Determining In-Place Permeability

1. **Scope**

1.1 This test method covers the in-place estimation of the water permeability of a compacted hot mix asphalt (HMA) pavement. The estimate provides an indication of water permeability of a pavement.

1.2 The values states in metric (SI) units are regarded as standard. Values given in parenthesis are for information and reference purposes only.

1.3 This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. **Summary of Test Method**

2.1 A falling head permeability test is used to estimate the rate at which water flows into a compacted HMA pavement. Water from a graduated standpipe is allowed to flow into a compacted HMA pavement and the interval of time taken to reach a known change in head loss is recorded. The coefficient of permeability of a compacted HMA pavement is then estimated based on Darcy's Law.

3. **Significance and Use**

3.1 This test method provides a means of estimating water permeability of comapcted HMA pavements. This estimation of water permeability is based upon assumptions that the sample thickness is equal to the immediately underlying HMA pavement course thickness; the area of the tested sample is equal to the area of the permeameter from which water is allowed to penetrate the HMA pavement; one-dimensional flow; and laminar flow of the water. It is assumed Darcy's Law is valid.

4. **Apparatus**

1.1 Field Permeameter – A field permeameter made to the dimensions and specifications shown in Figure 1.

1.2 Gasket – A gasket made of ethyl vinyl acetate (or similar, suitable, closed cell material) to be used for sealing the field permeameter to the pavement surface.

1.3 Weights – Cylindrical weights, a total of 120 lb, constructed to fit over the permeameter and rest on the permeameter base, to aid in sealing the gasket to the pavement surface.

1.4 Timing Device – A stopwatch or other timing device graduated in divisions of 1.0 seconds.

5. **Test Procedure**

5.1 Permeameter Setup

5.1.1 Ensure that both sides of the gasket are free of debris.

5.1.2 Place the gasket on the pavement surface over the desired testing location.

5.1.3 Place the permeameter on the gasket, ensuring the holes in each are properly aligned.

5.1.4 Place the cylindrical weights over the permeameter, letting them rest on the base flange of the permeameter.

5.2 Permeability Test

5.2.1 Fill the standpipe to just above the desired initial head.

Note 1: For most applications, enough water should be introduced to bring the water level to the top of the top tier standpipe.

5.2.2 When the water level has fallen to the desired initial head, start the timing device. (See Note 2) Stop the timing device when the water level within the standpipe reaches the desired head. (See

Note 3) Record the initial head, final head, and time interval between the initial and final head.

Note 2: For relatively impermeable pavements, the water level will drop very slowly within the top tier standpipe. Therefore, the initial head should be taken within the top tier standpipe. For pavements of "medium" permeability, the water level will drop very quickly through the top tier standpipe. Therefore, the initial head should be taken within the middle tier standpipe. For very permeable pavements the water level will drop very quickly through the top and middle tier standpipes but slow down when it reaches the bottom tier standpipe. Therefore, the initial head should be taken in the bottom tier standpipe.

Note 3: The initial and final head determinations should be made within the same standpipe tier.

6. Calculation

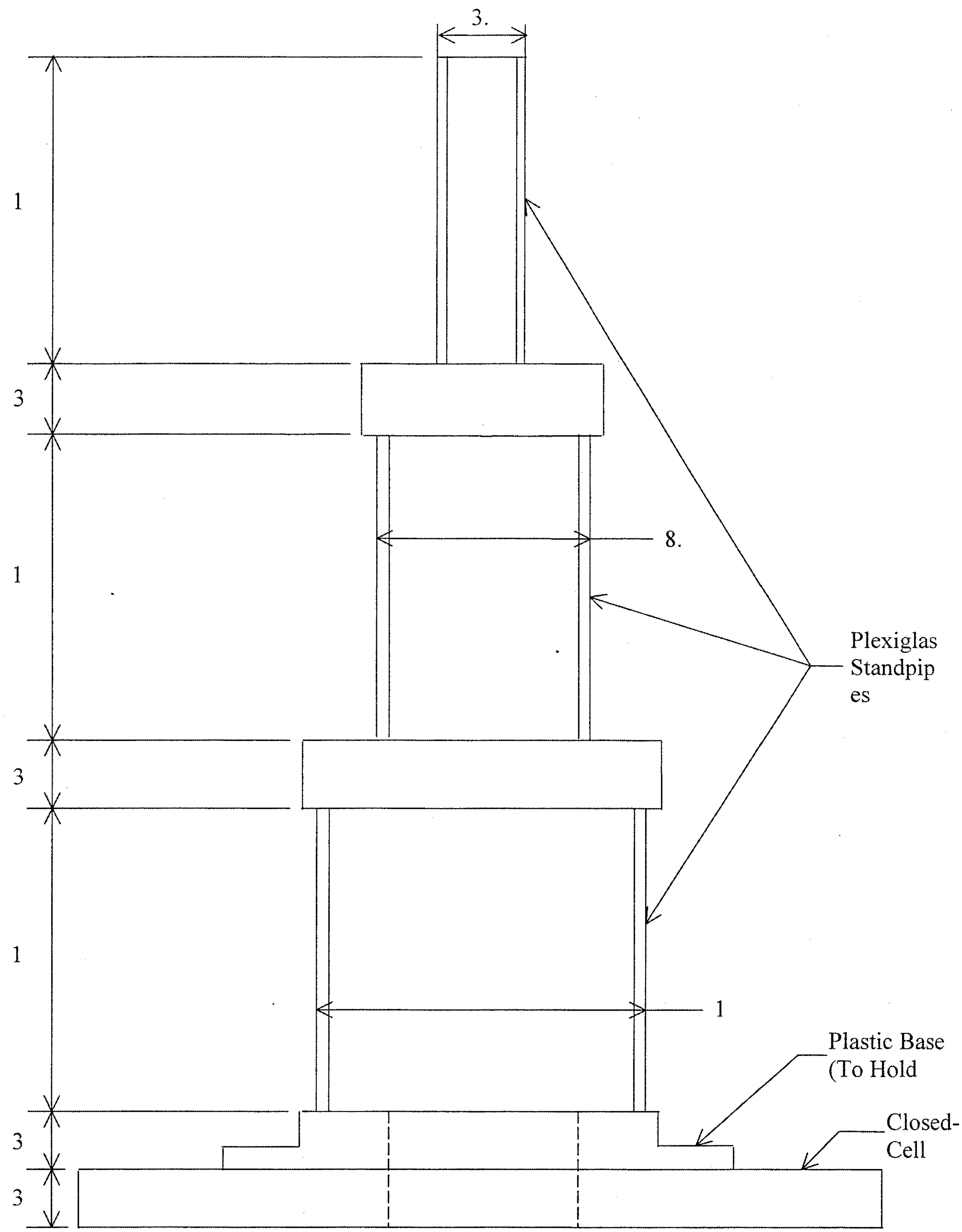
6.1 The coefficient of permeability, k, is estimated using the following equation:

$$k = \frac{a L * \ln (h_1 / h_2)}{A \Delta t}$$

where:

where:	k	=	coefficient of permeability
	a	=	area of stand pipe
	L	=	length of sample
	A	=	cross-sectional area of sample
	Δt	=	time during which the change in head is measured
	h_1	=	water head at beginning of test
	h_2	=	water head at end of test

6.2 Report results for k to the nearest whole units, in cm/s, using scientific notation.



Sketch of the Field Permeameter.

In-Place Permeability Data Form

IN-PLACE PERMEABILITY DATA FORM

Project: Date:

Location: Engineer:

Course:

Thickness:

Nominal Maximum Aggregate Size:

Time (s)	Water Level (cm)	Permeability (cm/s)	Notes