Hot Mix Asphalt Research Investigation For Connecticut: Part C – Permeability/Porosity Testing of HMA Mix Designs

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Report Number CT-2250-2-10-9

July 30, 2014

SPR 2250 – Part C Final Report

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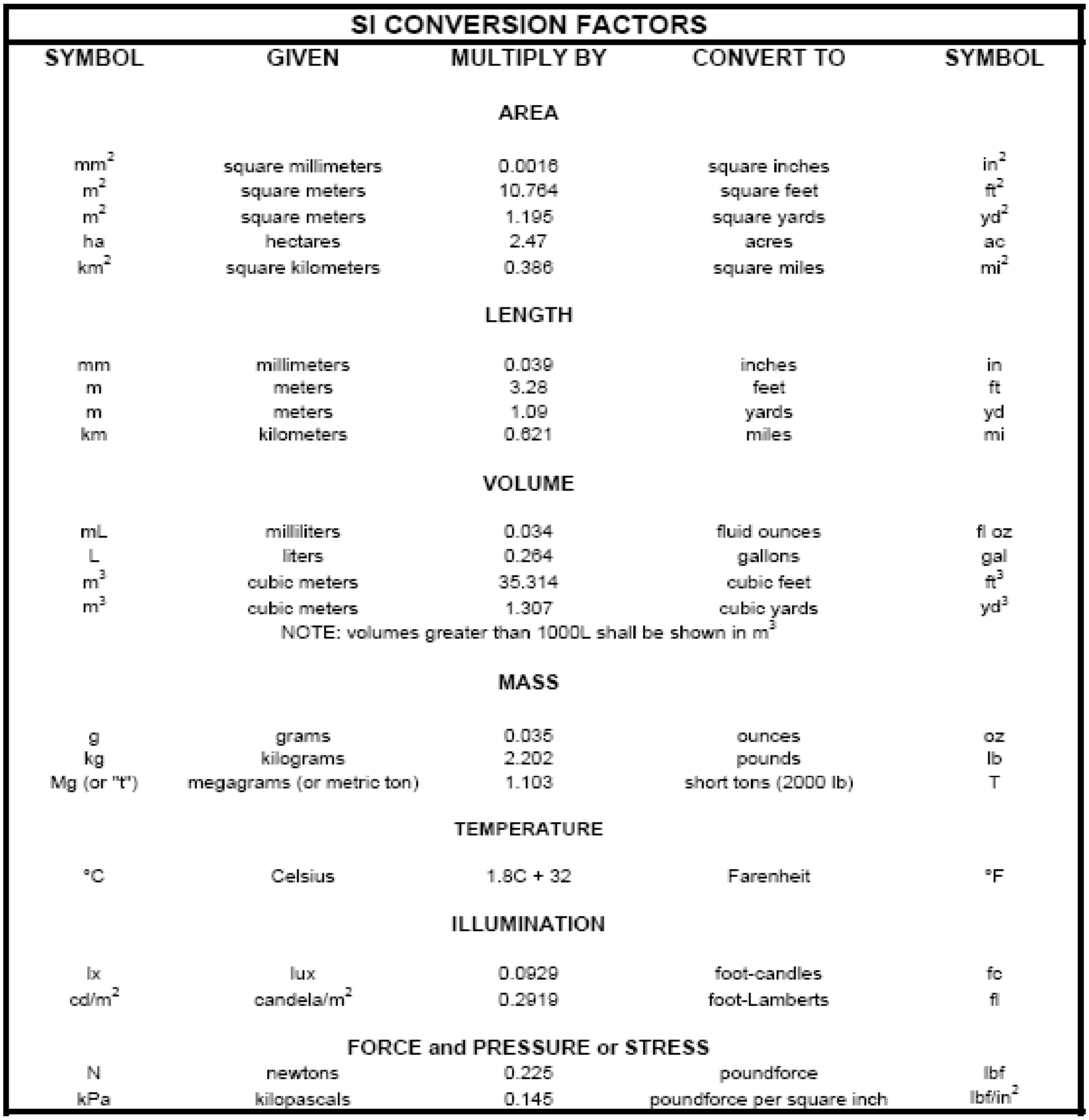
Disclaimer

Standard Metric Conversions



SI CONVERSION FACTORS

SYMBOL	GIVEN	MULTIPLY BY	CONVERT TO	SYMBOL
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
	NOTE: volumes greater than 1000L shall be shown in m^3			
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or metric ton)	1.103	short tons (2000 lb)	T
		TEMPERATURE		
°C	Celsius	1.8C + 32	Farenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

Technical Report Documentation Page

1. Report No. CT-2250-2-10-9	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Hot Mix Asphalt Research Investigation for Connecticut: Part C - Permeability/Porosity Testing of HMA Mix Designs		5. Report Date July 16, 2014 6. Performing Organization Code SPR-2250
7. Author(s) Eric Jackson, James Mahoney		8. Performing Organization Report No. CAPLAB 02-2010
9. Performing Organization Name and Address University of Connecticut Connecticut Transportation Institute 270 Middle Turnpike, U-202 Storrs, Connecticut 06269-5202		10 Work Unit No. (TRAIS) 11. Contract or Grant No. SPR-2250
12. Sponsoring Agency Name and Address Connecticut Department of Transportation Division of Facilities and Transit 2800 Berlin Turnpike, Newington, CT 06131-7546		13. Type of Report and Period Covered Final Report 2006 - 2010 14. Sponsoring Agency Code SPR-2250
15. Supplementary Notes This study conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.		

16. Abstract

The presence of water in asphalt pavements is detrimental to the life of the pavement. Most construction specifications require the pavement to be compacted to a specific air void content. As an asphalt pavement's air void contents increase, the permeability of that pavement will typically increase. Therefore, measuring the air voids during construction is an indirect way to control the permeability for that pavement. The objective of Part C of this research project is to determine permeability rates for current Superpave mixes used in Connecticut. The data collected and analyzed for this research indicates there is an exponential growth in permeability as the% air voids increase. This relationship can be modeled with reasonable accuracy and could be used as a surrogate for density. However, additional testing would be required to develop equations for each of Connecticut's HMA mixes and to improve the sample size (i.e. accuracy). In terms of Connecticut, it appears the CT mixes tested have a lower permeability than those reported in other published research. However, a larger sample size would be necessary to determine if this finding is broadly applicable.

17. Key Words Pavement, hot mix asphalt, permeameter, permeability, porosity density, asphalt,	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 report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 29	21. Price N/A
Form DOT F 1700.7 (8-72)	Reproduction of completed page authorized		

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Introduction

The presence of water in asphalt pavements is detrimental to the life of the pavement. Most construction specifications require the pavement to be compacted to a specific air void content. As an asphalt pavement's air void contents increase, the permeability of that pavement will typically increase. Therefore, measuring the air voids during construction is an indirect way to control the permeability for that pavement.

Asphalt pavements with high permeability are vulnerable to binder oxidation and stripping of binder from aggregate (Mohammad et al. 2003; Mogawer et al. 2002). In addition to stripping, Allen et al. (2003) also indicated asphalt emulsification, frost heaving, and water emerging from lower pavement layers and then freezing at the surface were related to permeability. Many research studies have investigated methods to measure and quantify permeability to extend the life and durability of asphalt pavements. As a result, maximum permeability limits have been established for HMA pavements (Maupin, 2000). The objective of Part C of this research project was to determine permeability rates for current Superpave mixes used in Connecticut. Ultimately, permeability limits were compared to those in the literature and recommendations were made for Connecticut.

Background

Permeability in asphalt pavements is related to aggregate size, shape and gradation, but most importantly, air void content (Maupin, 2000). Previous research efforts have investigated the relationship between aggregate, compaction and permeability. This section will review the current research on the parameters that impact permeability and the methods used to collect permeability data.

Isotropic Permeability refers to the rate at which water flows through a specimen in a single direction. *Porosity* is defined as the percentage of air voids in the compacted HMA sample that are accessible to water. The term *porosity* is the ability to absorb fluid while the term *permeability* is the ability to transmit fluid. Note that there is a big difference between permeability and porosity. A substance may be quite porous, but unless the voids are inter-connected so that a liquid can flow through the material, it is not permeable. Some research suggests porosity may be a better measure of a pavement's resistance to air and water infiltration, when compared to permeability, because it is easier to measure porosity as compared permeability (Mogawer et al. 2002). However, a specimen can be porous, but not permeable, but cannot be permeable unless it has porosity. Therefore, measuring only porosity is not an effective indicator of the ability of water and air to move through the pavement. Permeability is the focus of this research as well as the majority of previous research.

Laboratory Permeability Testing

A pavement or mix design's permeability can be measured in the laboratory or in the field. Laboratory permeability tests are considered to be a more true indication of the flow of water (or air) through a pavement specimen since lateral flow through the specimen is restricted. The testing of pavement specimens in the lab requires specimens that are obtained using one of two methods. The first method involves manufacturing a specimen in the lab using a specific mix design and representative aggregate. The limitation of this method is that the compaction methods and densities obtained in the lab may not be truly representative of placed pavements. The second method used to obtain specimens involves the cutting of cores from in-place pavements. This method ensures the pavement is representative (mix design, compaction method and density) of what is actually being placed in the field. However, this method does not allow for rapid changes to the mix designs before placement begins in order to limit permeability.

Once test specimens are obtained, permeability can be measured using a flexible wall lab falling head permeameter. There are several different makes and models of permeameters, but they all function in a similar manner. The specimen is placed between two caps (upper and lower caps) in a cell filled with water. A flexible latex membrane lines the sides of the cell and separates the water in the cell from the specimen. The water pressure in the cell is then increased to apply lateral stress to the specimen (coated with petroleum jelly) to ensure the membrane is sealed tightly to the specimen. Without an adequate seal, water can leak through the outside edge of the specimen (between the membrane and specimen interface) instead of through the actual specimen. The coefficient of permeability is then calculated using Darcy's law:

$$k = (aL/At)\ln(h2/h1) \qquad \textbf{Equation 1}$$

where:

k = coefficient of permeability
a = cross sectional are of the standpipe
L= thickness of the test specimen
A = cross sectional area of the test specimen
t = time between h1 and h2
h1 = head at end of test
h2 = head at start of test

Field Permeability Testing

Field testing involved the use of a falling head permeameter. The field permeameter is sealed to the pavement being tested and then filled with water. Graduated markings on the side of the permeameter allow for a head reading at timed intervals. As a result, pavement permeability can be estimated based on the change in head readings over time.

Lateral flow through in-place pavement is a major limitation of field testing. As mentioned previously, permeability is defined as the flow through a specimen. In field testing, lateral flow cannot be restricted and the permeability calculated from this is referred to "anisotropic" permeability. Therefore, field permeability values collected may not be a true measure of isotropic (uniaxial) permeability. There have been efforts to correlate field permeability with laboratory results. Allen et al. 2003 noted that testing location within the mat had an impact on variations in field permeability rates. Sections tested closer to the joints had higher permeability than tests conducted at the center of the mat (Allen et al. 2003).

Mallick et al. 2003 found that mix design impacted the correlation of field-to-laboratory permeability. The 9.5-mm fine, 9.5-mm coarse, and the 12.5-mm coarse mixes had little variation between lab and field results. However, for the 19-mm coarse and 25-mm coarse mixes, the differences were significant (Mallick et al. 2003).

Cooley and Brown (2000) found the two different models of field permeameters used in their experiment had no significant difference between laboratory and field obtained permeability values. However, the measured field permeability was higher than laboratory permeability due to lateral flow. Cooley and Brown (2000) also noted that discrepancies between lab and field values were most likely mix specific. They indicated that the degree of the difference was dependent upon nominal maximum aggregate size (NMAS), interconnectivity of air voids and coarseness of the mix gradation.

Previous research indicates mix design and aggregate size play a role in permeability of pavements (Cooley and Brown, 2000; Maupin, 2000; Mallick et al. 2003). Since aggregate type and mix design are state specific, this research is aimed at identifying specific lab-to-field correlations and acceptable permeability rates for Connecticut mixes.

Factors that Impact Permeability

The underlying factor that determines permeability is the amount of air voids contained in the specimen. In asphalt pavements, air void content is reduced using compaction to increase the density of the pavement. Therefore, the degree of compaction (density) should be related to the permeability of the pavement. Early work on permeability indicated a pavement with air voids greater than 8% was susceptible to excessive permeability (Zube, 1962). This threshold of 8% was also confirmed by Brown et al. (1998) almost three decades later. However, the development and implementation of Superpave mixes warrants a second look at the permeability/density relationship. Connecticut's first large-scale Superpave project was placed on State Route 2 in the towns of Colchester, Bozrah and Lebanon, between May and September 1997 (FHWA, 2008). Furthermore, as of January 1, 2004, all new projects awarded by ConnDOT utilize Superpave.

Investigations into Superpave permeability indicate fine-graded mixes are relatively impermeable even at air voids significantly higher than 7% (Choubane et al. 1998). The fine particles in these mixes reduce the interconnectivity of air voids, thus limiting permeability. Kanitpong et al. 2005, researched permeability in fine graded mixes and recommended the minimum density should be set at 93.8% (6.2% air voids) to control permeability in fine graded Superpave mixes.

In addition to fine mixes, Choubane et al. (1998) also studied coarse mixes and concluded course mixes with air voids greater than 6% are susceptible to excessive permeability. A study by Cooley et al. (2001) studied a range of course mixes. This study used in-place field testing of coarse-graded Superpave mixes to conclude there is a range of acceptable air void contents which is based on the aggregate size. 9.5-mm and 12.5-mm NMAS mixtures became excessively permeable at approximately 7.7% in-place air voids, 19.0-mm NMAS mixtures became excessively permeable at 5.5% in-place air voids, and 25.0 mm NMAS mixtures became excessively permeable at 4.4% air voids (Cooley et al. 2001). Therefore, as the NMAS increases the acceptable air void% needs to decrease in order to avoid permeability issues with the pavement.

In addition to testing different gradations of Superpave mixes, a study conducted by Allen et al. (2003), indicated location within the mat has a significant impact on permeability. Test locations located near a longitudinal joint had greater permeability rates when compared to locations near the center of the mat. This trend in permeability follows the density profiles of the mat. Joints and edges of the pavement mat are typically less dense than the center of the mat. This lack of density at the longitudinal joints of mat may be attributed to the lack of lateral support during the compaction process. The studies reviewed above indicate that as density increases permeability decreases. The objective of this research is to investigate the permeability of Connecticut Superpave mix designs. Laboratory and field testing will be used to develop correlations between density and permeability. Furthermore, correction factors will be developed for the field test procedure in an effort to reduce error in the field tests due to the lack of constraints on lateral flow.

Data Collection

Data for this research were collected from 3 paving projects, for 4 different asphalt mixes, which were produced and placed by 2 different contractors, during the summer of 2008. Table 1 outlines the contractor, location and mix used for data collection. For each of these locations measurements were taken from both the mat and on the hot side of the longitudinal joint. The original objective was to focus exclusively on mat locations, but current concerns have been raised about the density and permeability of joints in the state. Therefore, a few measurements were taken at joint locations to provide insight on potential problems with longitudinal joint densities.

Table 1: Data Collection Summary

Contractor	Route	Location	Mix	Traffic level	Longitudinal Joint	# Mat	# Joint
A	Route 85	Hebron	12.5 mm (1/2 in)	2	Butt	10	1
A	I-91 N&S	Wallingford to Middletown	12.5 mm (1/2 in)	4	Notched Wedge	10	10
B	I-95 Rest Area	Milford	12.5 mm (1/2 in)	4	Butt	5	0
B	I-95 Rest Area	Milford	9.5 mm (3/8 in)	4	Butt	5	0

Field Testing

At each location, the non-destructive field measurements consisted of 2 nuclear density measurements and a field permeability measurement. For nuclear density testing, the CAP Lab’s gage was placed on the exact location where the ConnDOT field inspector's gage was placed. The density readings from both gages were recorded and the% compaction was calculated based on the maximum theoretical densities (G_{mm}) provided by a ConnDOT field inspector. Field permeability measurements were taken using the Gilson AP-1B field permeameter that is based on the National Center for Asphalt Technology (NCAT) field permeameter. The falling head principal of the permeameter allowed for a calculation of the coefficient of permeability using Darcy's law as described in Equation 1 above. Finally, cores were cut from the exact locations of the nuclear density readings and field permeability tests for further testing back in the laboratory.

Field Permeability Testing Observations

Conducting the field permeability tests presented a few challenges that were overcome but should be noted for future testing. The main issue that arose with the field permeameter was the ability to make and maintain a good water-tight seal with the pavement. In order to create a good seal the following three observations were made 1) the pavement must be warm (≈ > 100 F). The heat makes the plumber's putty tacky and malleable to fill any surface voids. 2) The weights included with the permeameter were not sufficient; therefore the person conducting the test stood on the base of the permeameter to add the necessary weight to maintain a good seal. 3) After a few minutes, there was what appeared to be leakage from under the permeameter. However, after investigation it was concluded this was water traveling laterally through the top layer of voids in the pavement, and then, resurfacing out of the pavement once past the seal of the plumber's putty. With trial and error, these challenges were overcome and a satisfactory bond was achieved between the permeameter and pavement for the data collected and analyzed below.

Laboratory Testing

Laboratory testing of the cored specimens consisted of determining the bulk specific gravity,% air voids and laboratory permeability testing. The bulk specific gravity and% air voids were calculated using AASHTO T269. Laboratory permeability testing was conducted using a lab permeameter and the methods described in ASTM PS 129-01. The collection of laboratory and field density, along with permeability allowed for an analysis of the validity of the non-destructive test methods when compared to the actual values obtained from a core in the lab.

Data Analysis

The data analysis in this section will be divided into two main sections; mat data analysis and joint data analysis. Mix type, permeability vs. density, and field vs. laboratory comparisons were conducted.

Permeability Comparison

The primary objective is to evaluate the permeability of Connecticut Superpave mixes with those published in literature. Allen et al. (2003) reported field and lab permeability values ranging from a maximum of 0.035 cm/s down to a minimum of 0 cm/s. The average permeability for the pavements tested by Allen et al. (2003) was approximately 0.005 cm/s. The mean permeability for the data collected in this research was 0.0016 cm/s. Mallick et al. (2003) also reported a typical permeability value of 0.00040 cm/s for 12.5 mm mixes at 6 % air voids. An analysis of the data collected for this research indicates that a mean permeability for the 12.5-mm mixes at 6% air voids is approximately 0.00024 cm/s. The literature also suggests there is a strong relationship between permeability and density. While the statistical summary of permeability is of a similar magnitude as reported in the literature, permeability is relative to the densities of the pavement samples collected. Therefore, a direct comparison between the summary of permeability values between our data and the literature is not sufficient due to the different range of densities tested.

Mat Data Analysis

To fully understand the relative permeability of Connecticut mixes, this analysis includes an investigation of the relationship between density and permeability. Table 2 contains a summary of G_{mm}, permeability and density for the mat samples obtained in this research. The large range of G_{mm} values (2.495-2.259) is due to the different mixes and producers used for the data collected in this study. The middle two rows indicate there are substantial differences between the field-obtained and laboratory-obtained coefficient of permeability. The lab permeability has a standard deviation that is about half that of the field permeability. The differences in these two methods to measure permeability are the focus of this report and will be investigated further in subsequent analysis. The last two rows in Table 2 present the lab vs. field% air void measurements.

Table 2: Mat Data Summary

	Mean	Max	Min	Std. Dev.
Bulk Specific Gravity (g/cm3)	2.376	2.495	2.259	0.057
Lab Permeability (cm/s)	0.0016	0.0100	0	0.0024
Field Permeability (cm/s)	0.0024	0.0202	0	0.0045
Lab % Air Voids	8.6	13.1	5.0	2.0
Field % Air Voids	8.5	13.3	4.2	1.9

One of the goals of this research was to investigate the relationship between density and permeability. A plot of field permeability vs. field density (percent air voids obtained from field cores) is presented in Figure 1. This figure indicates there is an exponential growth in permeability as the%age of air voids increase in the pavement mat. A plot of the laboratory test results indicated a similar trend (Figure 2). The difference between the laboratory and field test results is evident in looking at the magnitude of the coefficient of permeability. The field test samples have a much larger value for permeability when compared to the laboratory test samples. This is hypothesized to be due to the lack of lateral flow constraint in the field device. The laboratory permeameter prevents lateral flow through the core therefore giving a more accurate measure of material isotropic permeability.

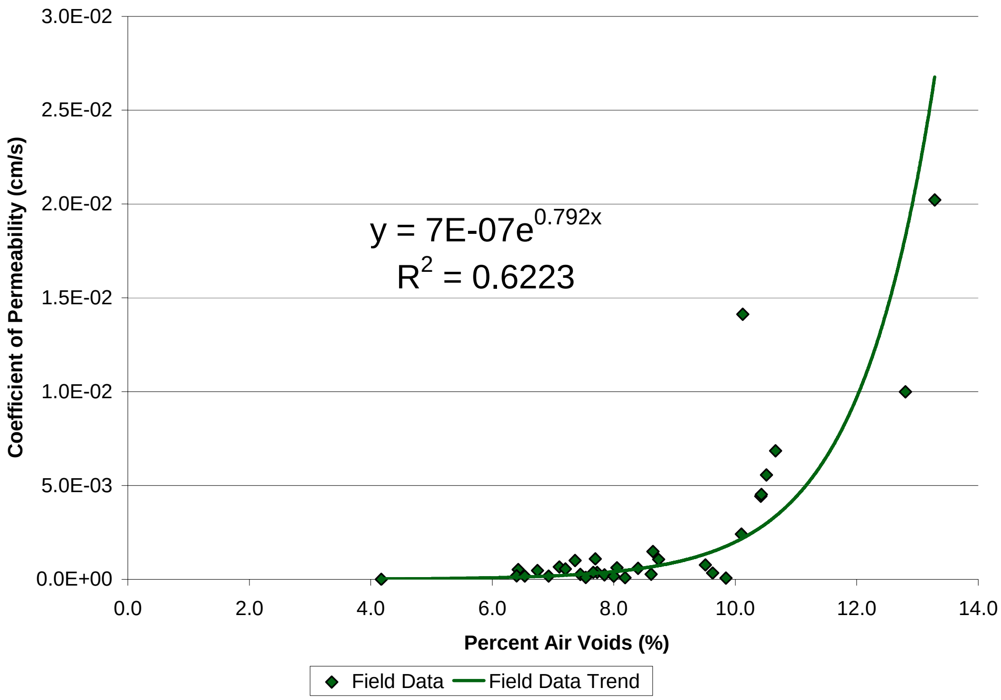


Figure 1: Field Measured Permeability/Density Relationship

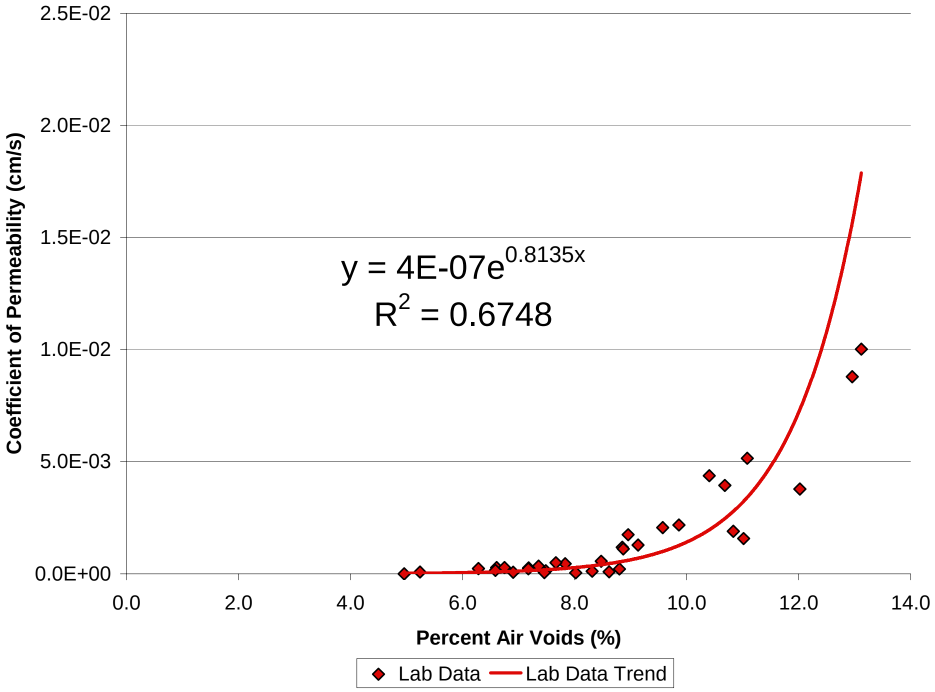
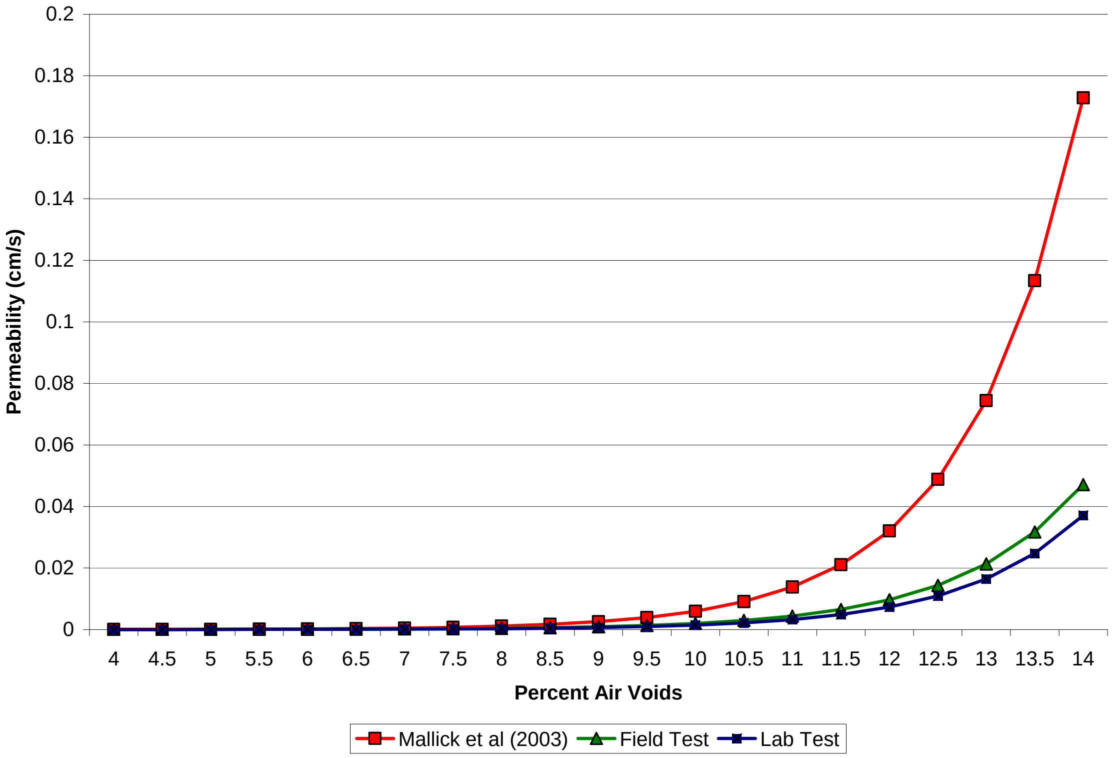


Figure 2: Laboratory Measured Permeability/Density Relationship

When comparing the models developed above to those in the literature there are slight differences in the coefficients and exponents. Mallick et al (2003) report the relationship between permeability and air voids to be $y = (13.0x10^{-7})e^{0.8427x}$ and for the data collected in this research the modeled relationship is $y=(7x10^{-7})e^{0.792x}$ for field permeability and $y=(4\ x10^{-7})e^{0.8135x}$ for lab permeability. Comparison of these three equations can be found in Figure 3. The results of this plot indicate that the Connecticut mixes are less permeable, as air voids increase, when compared to the pavements studied in Mallick et al (2003).



<u>Figure 3: Comparison of Published and Derived Permeability/Density Relationships</u>

Figure 4 plots the field-measured permeability vs. the laboratory-measured permeability. Linear regression techniques were used to develop an equation to represent the relationship between field-measured permeability and laboratory-measured permeability. The results of this regression are displayed on the chart in the lower right-hand corner. The coefficient of X indicates that the permeability values obtained from the field permeameter will be 1.5 times that of the laboratory-measured permeability. This elevated permeability in the field tests can be attributed to the excess water that is allowed to permeate into the pavement during the field test due to the lack of lateral flow constraints. Therefore, if field permeameters are to be used for future field testing, correction factors need to be developed to obtain an accurate coefficient of isotropic permeability. The limited amount of data obtained and small number of mixes tested in this study limits our ability to accurately determine this correction factor.

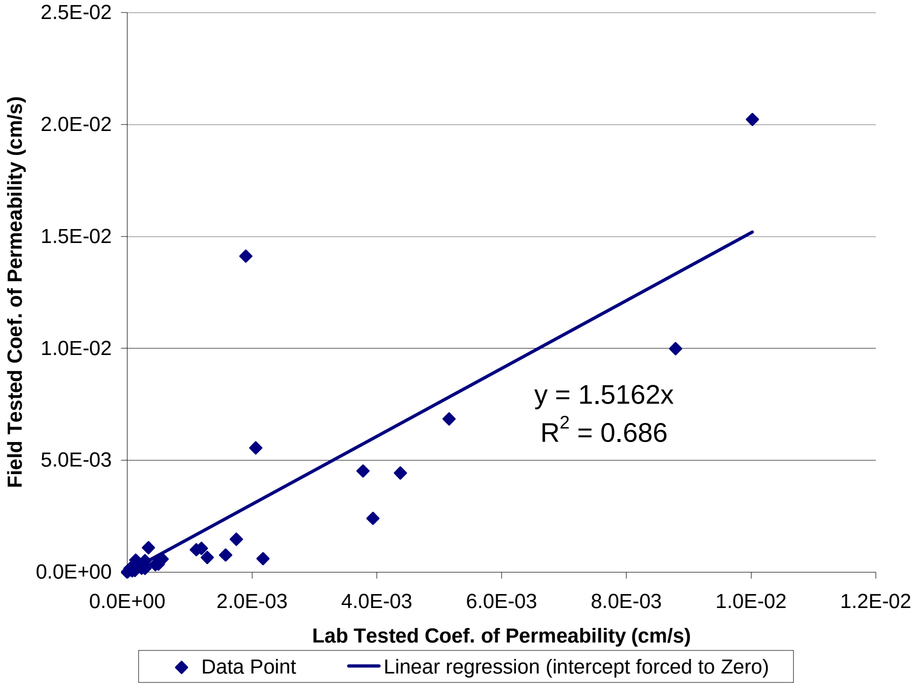


Figure 4: Laboratory vs. Field Permeability

Joint Data Analysis

Analysis of the Data collected along longitudinal joints only uses data collected from the I-91 project. This project used a notched wedge joint and a 12.5-mm (1/2-in) Superpave Traffic Level 4 mix. Table 3 contains a summary of the field and laboratory metrics. The range of G_{mm} values for this analysis is much more consistent than for the mat analysis since only one mix is being analyzed. The lab and field permeability values have a much smaller range than the mat samples. However this could be due the fact that there are only 10 samples in this dataset where the mat analysis was comprised of 30 samples. For the joint data, on average, the field-obtained coefficient of permeability values were less than lab-obtained values. This is opposite that of the mat samples, where the field results indicated higher field permeability values than lab results. The% air voids in the last two rows indicate the nuclear gage readings are over-estimating the density of the material on the joint when compared to the lab density results (cores).

Table 3: Joint Data Summary

	Mean	Max	Min	Std. Dev.
Bulk Specific Gravity (g/cm3)	2.310	2.367	2.217	0.041
Lab Permeability (cm/s)	0.011	0.047	0.027	0.129
Field Permeability (cm/s)	0.098	0.036	0.025	0.0111
Lab % Air Voids	11.4	15.5	8.3	2.0
Field % Air Voids	9.1	11.4	7.0	1.3

Figures 5 and 6 plot the density vs. coefficient of permeability for the joint data. These figures indicated there is an exponential relationship between density and permeability, similar to that seen in the mat data. However, the range of% air voids for the joint data is smaller than the mat data. This limited range makes the regression equations less accurate than the mat data. These plots indicate the relationship between density and permeability is the same, or similar, for mat and joint locations.

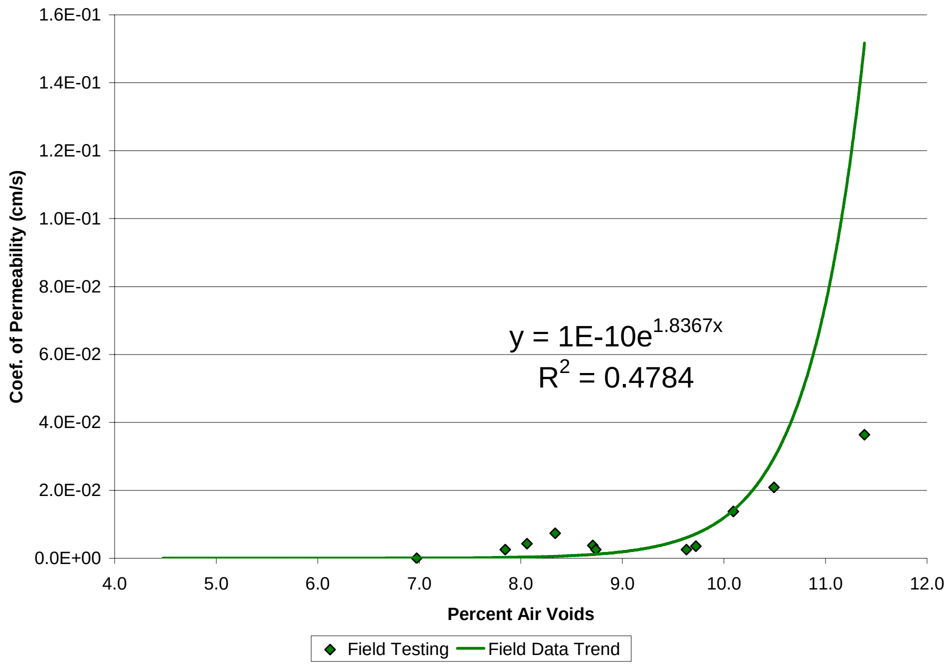


Figure 5: Field-Measured Permeability/Density Relationship (Joint Data)

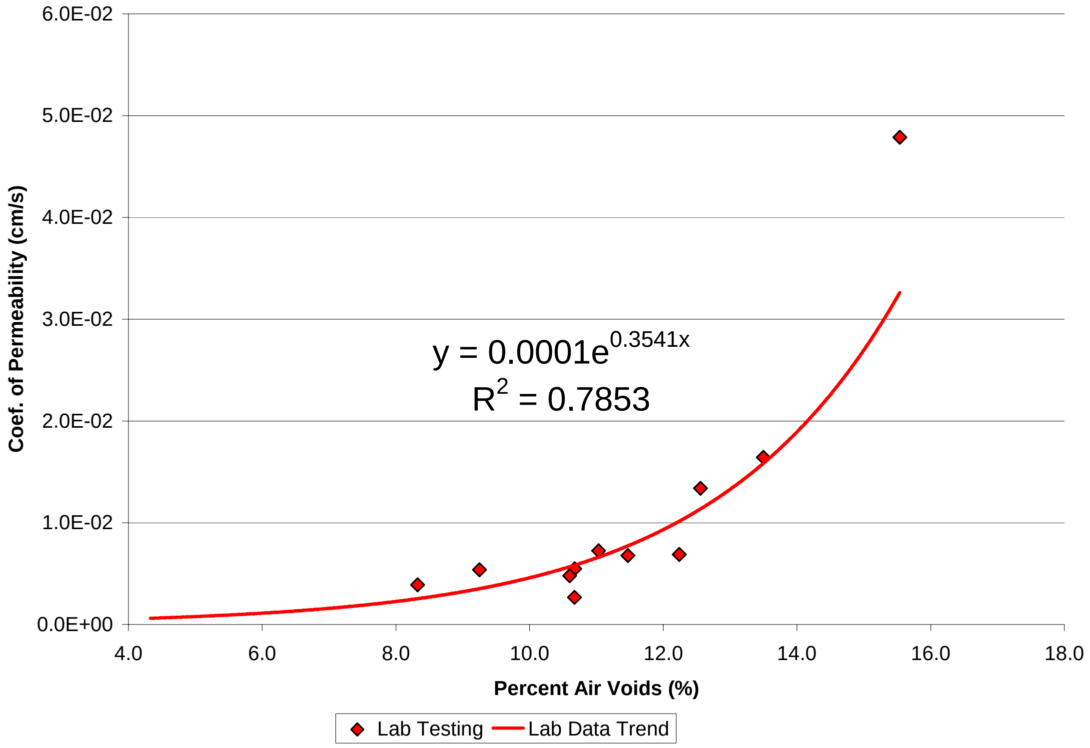


Figure 6: Lab-Measured Permeability/Density Relationship (Joint Data)

Figure 7 displays a plot of lab permeability vs. field permeability. A linear regression was preformed to describe the relationship between the two measures of permeability. From this plot, it appears that the field permeability values are approximately 81% of the lab permeability values. This relationship is inverse to that of the mat sample analysis where the field permeability values were larger than the lab-obtained values. This indicates there could be a need to develop different permeability correction factors for mat locations and joint locations. The obvious difference between the two sampling locations is the use of the notched wedge. Sampling on the notched wedge means the upper portion of the asphalt layer is the warm side and the lower portion of the sample is the cold side (Figure 8). These two layers are then bonded using tack coat. Therefore this could create issues when attempting to accurately measure field and lab permeability.

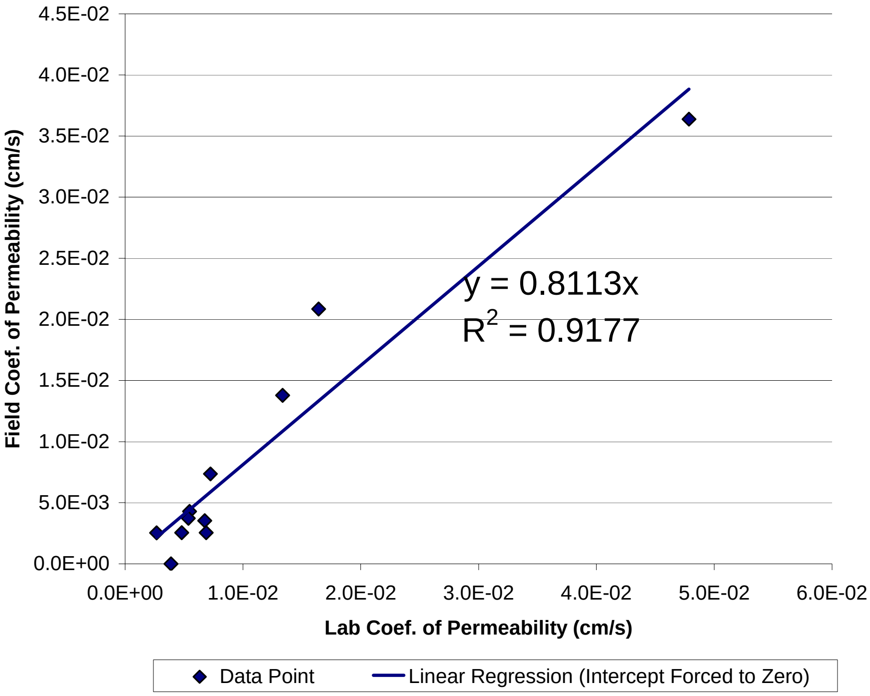


Figure 7: Laboratory vs. Field Permeability (Joint Data)

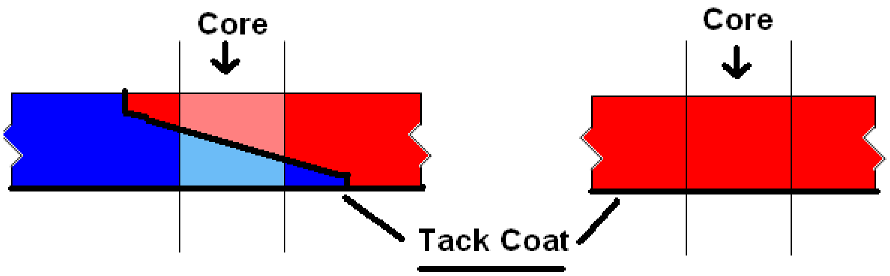


Figure 8: Notched Wedge Joint and Mat Cross Sections

A second set of longitudinal joint data were collected on I-91 in Windsor during the 2007 paving season. Laboratory permeability testing was conducted on 37 cores taken from the longitudinal joints; however, field permeability tests were not performed in this instance. Table 4 contains a summary of the data collected. This supplemental data contains a larger range of joint densities and permeability values than in the joint analysis above.

Table 4: Supplemental Joint Data Summary

	Mean	Max	Min	Std. Dev.
Bulk Specific Gravity (g/cm3)	2.396	2.581	2.247	0.070
Permeability (cm/s)	0.011	0.054	0	0.010
% Air Voids	11.2	17.0	3.3	2.6

The supplemental joint data were also analyzed to determine the relationship between density and permeability. Figure 9 contains the data plot and the regression equation for this supplemental data. Figure 10 contains a comparison of the supplemental joints equation to that of the mat analysis and the equations in the literature. The results indicate that the Connecticut mixes analyzed are less permeable than the mixes used in Maine, which were analyzed by Mallick et al (2003). However, the common inflection point on the plot in Figure 10 indicates that, as the air voids approach 9.5 to 10.5%, permeability begins in increase rapidly.

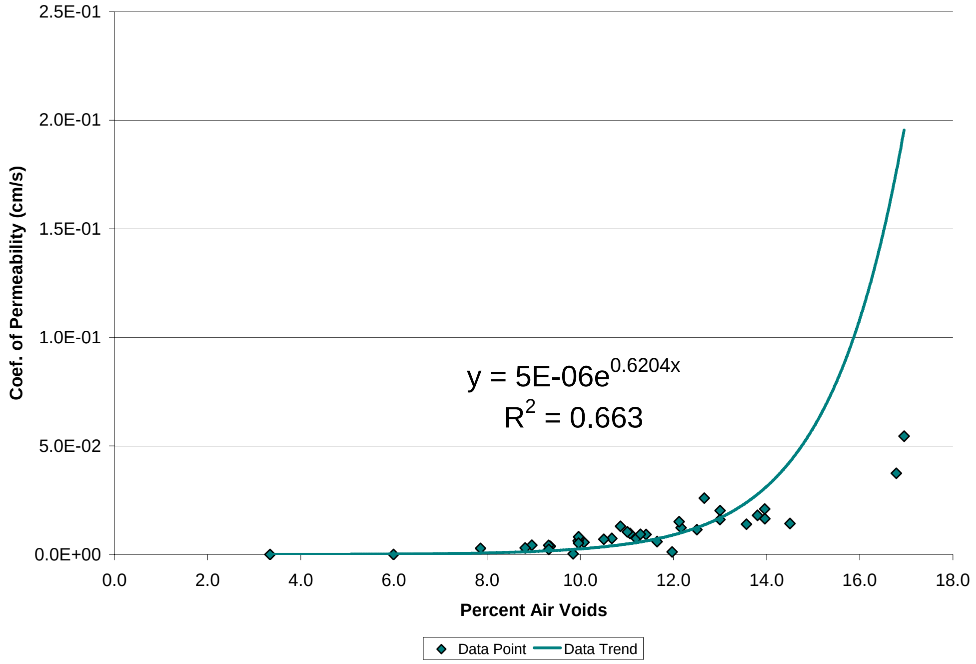


Figure 9: Supplemental Joint Data Plot

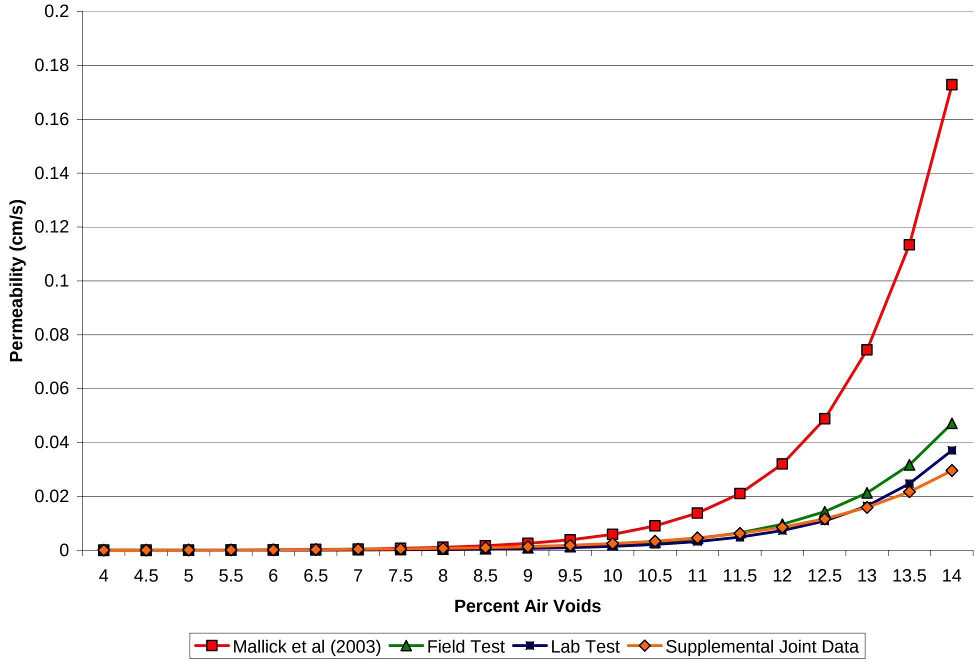


Figure 10: Resulting Equation Plots of Permeability/Density Relationship

Summary and Conclusions

The data collected and analyzed for this research indicates there is an exponential growth in permeability as the% air voids increase. However, the regression models shown in the figures above need to be validated and calibrated before they can be used with any certainty. This procedure will require the collection of a large dataset for each mix type to ensure there are no abnormal permeability results. Furthermore, there is a strong relationship between density and permeability. This relationship can be modeled with reasonable accuracy and could be used as a surrogate for density. However, additional testing would be required to develop equations for each of Connecticut's HMA mixes and to improve the sample size (i.e. accuracy).

It appears Connecticut mixes tested have a lower permeability than those reported in other published research. However, a larger sample size would be necessary to determine if this finding is true. Furthermore, the type of joint used in construction did not have a significant impact on the permeability of the joint. However, it should be noted that cores for the butt joints were not taken directly on the joint. These cores and permeability measurements were taken on the warm side of the joint. If the butt joints were cored directly on the joint there is the potential the vertical seam between the two passes of the paver could serve as a weak point for water to flow through.

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