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Relationships of HMA In-Place Air Voids, Lift Thickness, and Permeability
Volume Three

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RELATIONSHIPS OF HMA IN-PLACE AIR VOIDS, LIFT THICKNESS, AND PERMEABILITY

NCHRP 9-27

Task 5

1.0 INTRODUCTION

The presence of water in a pavement is detrimental to its life. Therefore, in the construction of hot mix asphalt (HMA), it is important that there is adequate compaction so the initial permeability is low and there will not be any significant densification under traffic loading. Numerous studies have shown that, for dense-graded mixes, the initial in-place air void content should not be less than approximately 3 percent or greater than 8 percent (1). Low in-place air voids tend to result in rutting, bleeding, and shoving, while high in-place air voids allow air and water to penetrate into the pavement, leading to an increased potential for oxidation, water damage, raveling, and cracking.

For many years it has been believed that high in the in-place air void content of dense graded mixes results in increased permeability of these pavements. During the 1960's, Zube (2) reported that dense-graded pavements became excessively permeable at in-place air voids above 8 percent. This was later confirmed in the 1980's by Brown et al (3). However, recent experience with coarse-graded Superpave mixes has shown that the size and interconnectivity of air voids greatly influence permeability.

Several studies have shown that numerous factors affect the permeability of HMA pavements. Ford and McWilliams (4) suggested that the aggregate particle size distribution (gradation), aggregate particle shape, and pavement density affect permeability. A study by Hudson and Davis (5) concluded that permeability is dependent on both the size of air voids and the total percentage of voids in a pavement.

Recent findings by Mallick et al (6) in Maine demonstrate that the nominal maximum aggregate size (NMAS) of a pavement and the lift thickness for a given NMAS affect permeability. Thicker lift thicknesses reduce the possibility of interconnected voids. Additional work by the Florida Department of Transportation indicated that the lift thickness also has an effect on in-place air voids, which in turn affects permeability (7). This was determined by constructing pavement test sections with different NMASs and lift thicknesses. Results indicated that increased lift thicknesses lead to more desirable in-place air void contents, which lead to lower permeability.

2.0 OBJECTIVES

As previously stated in the report, the overall objectives of NCHRP 9-27 are as follows:

1. Determine the in-place density needed to achieve an impermeable and durable pavement;
2. Determine the minimum lift thickness needed to achieve desirable pavement density levels and thus, impermeable pavements; and
3. Recommend improvements to AAHSTO T166 in order to achieve a more precise, uniform, and accurate determination of bulk specific gravity for compacted HMA mixtures.

The main objective of the field portion of NCHRP 9-27 (Task 5) was to provide a field validation of the relationships between permeability, lift thickness, and in-place density found in earlier tasks so the overall objectives of the study could be accomplished.

3.0 RESEARCH APPROACH

In order to field validate the relationships between air voids, lift thickness, and permeability, twenty HMA construction projects were visited. Testing at these projects included tests on plant-produced mix and on the compacted pavement. Testing of the plant-produced mix included compacting samples to both the design compactive effort and to a specified height. Testing on the compacted pavement included performing field permeability tests with the NCAT Field Permeameter. Selection of the twenty projects was based upon the following factors: NMAS, gradation type (fine- graded, coarse-graded, and SMA), and the lift thickness to NMAS ratio (t/NMAS). Table 1 summarizes the characteristics of the twenty projects evaluated.

Table 1 shows that both fine- and coarse-graded Superpave designed mixes were investigated for each of four NMAS (ranging from 9.5 to 25.0 mm NMAS). Stone matrix asphalt (SMA) mixes were investigated for 12.5 and 19.0 mm NMASs. The effect of lift thickness was evaluated for the 9.5, 12.5, and 19.0mm NMASs. At each of the twenty projects, NCAT utilized its mobile laboratory. This laboratory has equipment to compact samples for evaluating volumetric properties, determine bulk specific gravities (water displacement), theoretical maximum specific gravities, and other miscellaneous HMA tests. Figure 1 presents a flowchart of the field work conducted for each project. In Figure 1, the abbreviation VTM stands for voids in the total mix, and will be used throughout the report. At each project, NCAT obtained truck samples from trucks transporting the HMA to the location that NCAT tended to conduct permeability testing. From here on, the individual truck samples will be referred to as “sublots”.

Table 1: Projects Evaluated for Task 5 – Field Validation

		Lift Thickness/NMAS Ratio			
NMAS	Gradation Shape	2:1	3:1	4:1	5:1
9.5mm	Fine Graded			X (3)	X
	Coarse Graded		X		
	Stone Matrix Asphalt		X		
12.5mm	Fine Graded		X (2)		X
	Coarse Graded		X	X (2)	
	Stone Matrix Asphalt				
19.0mm	Fine Graded				
	Coarse Graded	X	X (3)	X	X
	Stone Matrix Asphalt				
25.0mm	Fine Graded		X		
	Coarse Graded				
	Stone Matrix Asphalt	X			

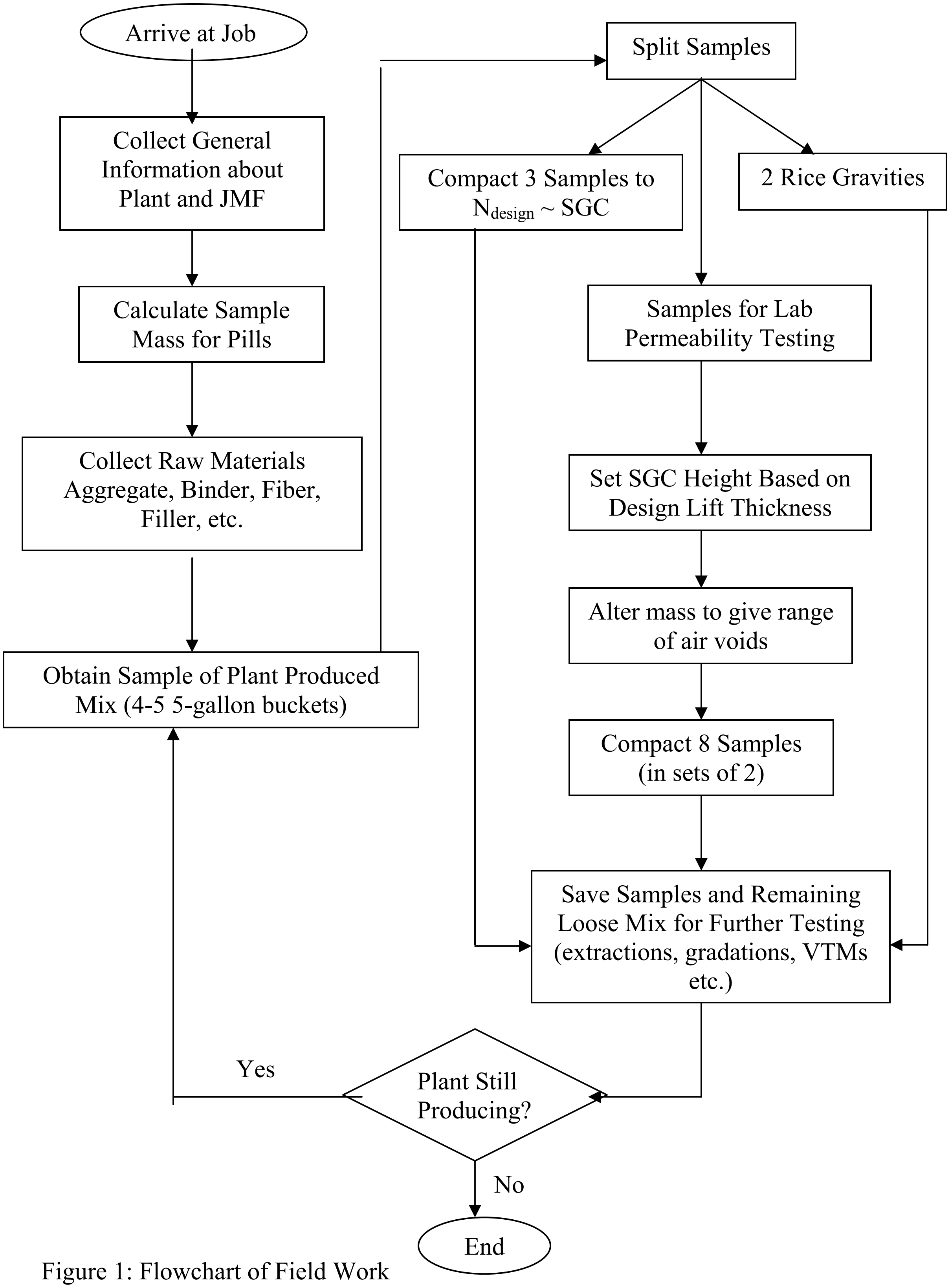

Figure 1: Flowchart of Field Work

For each sublot, NCAT compacted three replicate samples to the design number of gyrations in a Superpave gyratory compactor. Samples of the plant-produced mix were also compacted over a range of sample masses to a height equal to the target lift thickness in the field, in order to provide a range of air void levels. This was accomplished by setting the gyratory compactor to compact samples to the design lift thickness, then determining an initial mass (calculated by multiplying the mix bulk specific gravity from the contractor and the volume of the sample) that would provide the design percent air voids at the design lift thickness. The sample mass was then decreased by a given amount to provide different air void contents above the design percent air voids. Each sublot had four sets of two samples, each set having a different mass. These samples were brought back to the NCAT lab and used for laboratory permeability testing so that comparisons could be made with field results. These comparisons included relationships between (1) air voids (in-place for cores and from AASHTO T166 for the lab compacted samples), (2) permeability (both field and lab), (3) lift thickness (from cores) and field permeability, and (4) field permeability and lab permeability (conducted on cores and lab compacted samples).

NCAT also determined the theoretical maximum specific gravity of each sublot. A portion of each sublot was brought back to the NCAT laboratory to determine asphalt content and gradation. Samples of the mixture components (aggregates, binders, and stabilizing additives) were also brought back to the NCAT laboratory. Laboratory and field quality control data were obtained from each project for the days on which NCAT conducted field permeability testing. This data, which is summarized in the Appendix, included: volumetrics of lab compacted samples, theoretical maximum specific gravity measurements, pavement densities (both core and nuclear gauge), and mixture gradations. The information gathered from each of the projects was also used to evaluate the effect of material constituents, mixture properties, and construction practices on permeability characteristics.

For each of the twenty projects, field permeability tests were conducted at 10-15 randomly (transversely and longitudinally) selected test locations per project. Figure 2 presents testing conducted at each of the project test locationss. This figure shows that three field permeability tests were conducted and that one core was obtained within each test location. Three field permeability tests were utilized for each location to provide an indication of variation within test results. Replicate tests could not be performed on the same spot of the pavement because of the sealant that sealed the device to the pavement. Also, pavement density measurements were made with the PQI (Pavement Quality Indicator) device: at each location where field permeability tests were conducted or field cores taken. This testing was conducted to identify changes in density to potentially explain outlier data between the three field permeability measurements. The cores obtained were used to determine in-place density, laboratory permeability (ASTM PS-129, Standard Provisional Test Method for Measurement of Permeability of Bituminous Paving Mixtures Using a Flexible Wall Permeameter), and lift thickness.

Field testing conducted on the compacted pavement included field permeability testing and an evaluation of the paving procedures. The evaluation of the paving procedures included documenting the makes and models of the paving equipment, recording pavement temperatures from initial laydown to the finish roller, and documenting the rolling patterns for the individual compactors on each project. Also documented was the haul distance to the paving site and the weather conditions for the day on site. For the field permeability testing, each sublot consisted of a 500-foot section of the pavement. Within this section, five randomly determined (longitudinally and transversely) test locations were marked. It was within these test locations that the field permeability testing took place, as previously discussed.

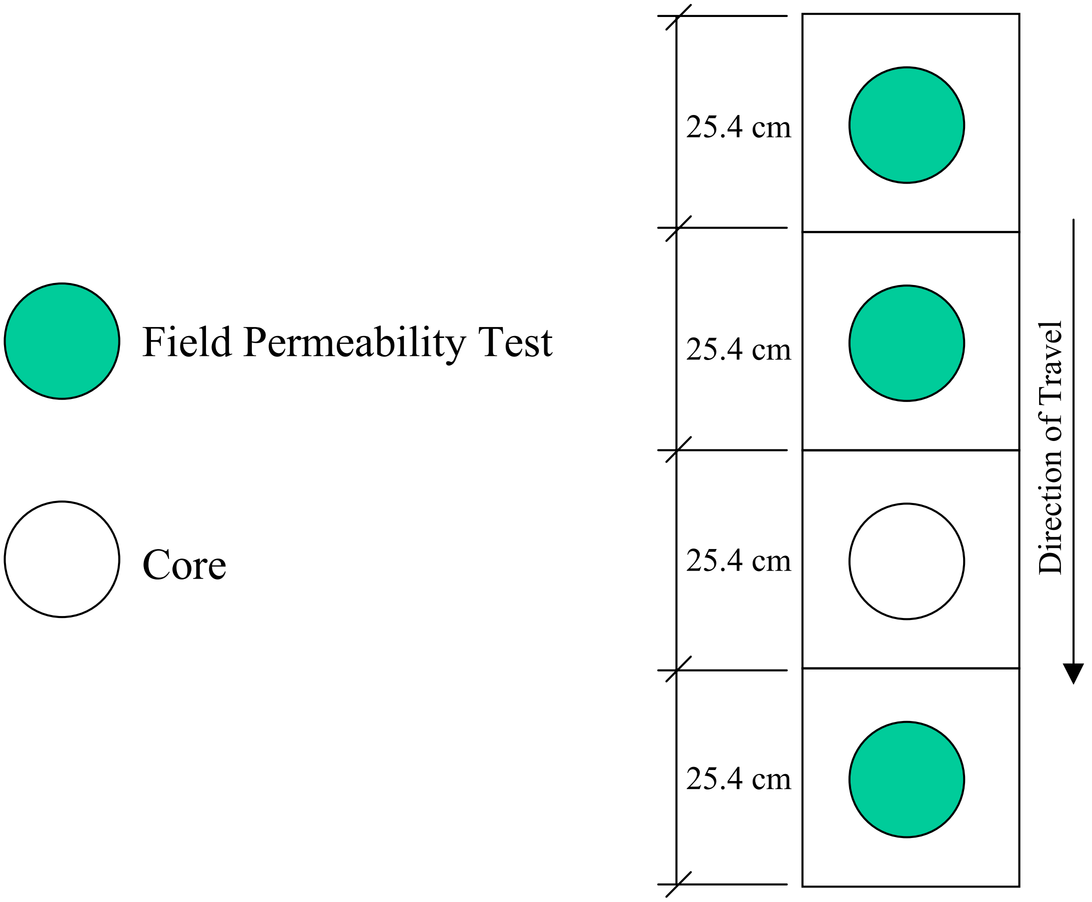

Figure 2: Testing conducted at each test location.

4.0 MATERIALS AND TEST METHODS

For the twenty projects evaluated, a total of 213 cores and 342 lab-compacted height samples were tested. Cores were cut at each of the field permeability test locations prior to traffic. Of the twenty projects, six utilized a 9.5-mm NMAS gradation, six utilized a 12.5-mm NMAS gradation, six utilized a 19.0-mm NMMAS gradation, and the remaining two utilized a 25.0-mm NMAS gradation. Average lift thickness ranged from 20.7 to 104.1 mm. The calculated lift thickness to NMAS ratio (t/NMAS) ranged from 1.7 to 9.4 and the N_{design} ranged from 50 to 125 gyrations with a Superpave gyratory compactor. A brief description of the testing that was performed on the compacted pavement and on the samples brought back to NCAT follows.

4.1 Bulk Specific Gravity Measurements

In order to recommend improvements to AASHTO T166 that would provide a more precise and accurate determination of the bulk specific gravity, five test methods for determining the bulk specific gravity of compacted hot mix asphalt mixtures were evaluated. These included: the water displacement method (AASHTO T166), dimensional analysis, vacuum sealing (using the Vacuum seal method, ASTM PS 131), gamma ray (using the CoreReader), and effective (using the Vacuum seal method). Brief test descriptions are as follows.

4.1.1 AASHTO T166 – In this method, a sample is weighed in air, then weighed under water after a period of soaking for three to five minutes, and finally weighed after being removed from water and blotted (SSD condition). Bulk specific gravity is then calculated using the following equation:

$$G_{mb} = \frac{\text{Dry Mass (grams)}}{\text{SSD Mass (grams) - Mass (grams)}}$$

where,

Dry mass = mass of the HMA sample without any water;

SSD mass = mass of the HMA sample in saturated surface-dry condition; and

Mass = mass of HMA sample submerged in water.

4.1.2 Dimensional Analysis – This method uses a calculated volume of a cylindrical sample, determined by multiplying the area of the sample by its height. To determine the bulk specific gravity using the dimensional analysis procedure, the dry mass of the sample is divided by its calculated volume.

4.1.3 Vacuum Sealing – This method utilizes a puncture resistant, resilient plastic bag to seal the test specimen and prevent water intrusion. The sample is placed in the bag and sealed with a vacuum device, which collapses the bag tightly around the sample, allowing the bag to conform to the surface voids and irregularities. The sample is then weighed in both air and under water. Bulk specific gravity is then calculated using the following equation (13):

$$G_{mb} = \frac{A}{B - E - ((B - A) / F_t)}$$

where,

A = mass of dry specimen in air, grams

B = mass of dry, sealed specimen, grams

E = mass of sealed specimen underwater, grams

F_t = apparent specific gravity of plastic bag at 25°C, provided by the manufacturer

Figure 3: Vacuum Sealing Device

4.1.4 Gamma Ray – This method uses a nondestructive gamma ray transmission method for measuring the specific gravity of an HMA specimen. This method is based on the scattering and absorption properties of gamma rays in matter. The number of gamma rays that penetrate the sample and reach the detector is inversely proportional to the density of the material. The device converts the gamma-ray count to the specific gravity of the sample (8).

Figure 4: Gamma Ray Device (CoreReader)

4.2 Lab Permeability

Laboratory permeability testing was conducted on each core and lab compacted sample in accordance with ASTM PS 129-01, Standard Provisional Test Method for Measurement of Permeability of Bituminous Paving Mixtures Using a Flexible Wall Permeameter. This method utilized a falling head approach in measuring permeability. Each sample was saturated during the determination of the effective air void procedure. Water from a graduated standpipe was allowed to flow through the saturated sample and the time to reach a known change in the height of the head was recorded. Saturation was considered sufficient when four consecutive time interval measurements did not differ by more than ten percent of the mean. In this method, Darcy's Law was then applied to determine the permeability of the sample.

Figure 5: Lab Permeability Device

4.3 Field Permeability

Testing on the compacted pavement was conducted using the NCAT Field Permeameter. This device has been shown to compare reasonably well with the Florida DOT lab permeameter and produce good relationships with in-place air voids in a pavement. It used a silicone-rubber sealant and a flexible rubber base in conjunction with a metal base plate to secure the device to the pavement surface. It also incorporated a three-tier system to make the permeameter more sensitive to the flow of water into the pavement.

Figure 6: Field Permeability Device

5.0 OVERALL ANALYSIS OF FIELD PROJECT TEST RESULTS

As stated above, twenty projects were evaluated during construction. A description of the projects evaluated is provided in Table 2. Projects are labeled as fine-graded, coarse-graded, or Stone Matrix Asphalt (SMA) based on the definition given by the National Asphalt Paving Association (NAPA)(9). This definition uses the percent passing certain sieve sizes for a given NMAS (Table 3) to define fine- and coarse-graded mixes.

Table 2: Field Project Summary Information

Project ID	NMAS	Fine or Coarse Gradation	Average Lift Thickness (mm)	Actual Lift Thickness/ NMAS Ratio	AC Performance Grade	Ndesign
1	9.5	Fine	48.7	5.1:1	70-22	65
2	19.0	Coarse	65.7	3.5:1	64-22	65
3	9.5	Coarse	32.3	3.4:1	64-22	65
4	12.5	Fine	68.6	5.5:1	*	75
5	9.5	Fine	41.0	4.3:1	70-22	100
6	12.5	Coarse	50.3	4.0:1	58-28	75
7	9.5	Fine	40.6	4.3:1	64-28	75
8	19.0	Coarse	58.9	3.1:1	64-22	100
9	19.0	Coarse	96.4	5.1:1	64-22	100
10	19.0	Coarse	70.9	3.7:1	64-34	100
11	19.0	Coarse	38.0	2.0:1	64-34	125
12	25.0	SMA	42.6	1.7:1	76-22	50
13	25.0	Fine	70.0	2.8:1	67-22	100
14	9.5	SMA	26.8	2.8:1	76-22	75
15	19.0	Coarse	50.4	2.7:1	76-22	100
16	12.5	Coarse	43.8	3.5:1	67-22	86
17	12.5	Fine	43.3	3.5:1	64-22	75
18	12.5	Coarse	44.5	3.6:1	67-22	75
19	9.5	Fine	41.5	4.4:1	67-22	75
20	12.5	Fine	34.5	2.8:1	67-22	80

* : Designated RA295 by the agency

Table 3: Definition of Fine- and Coarse-Graded Mixes (9)

Mixture NMAS	Coarse-Graded	Fine-Graded
37.5mm (1 1/2")	< 35% Passing 4.75mm Sieve	> 35% Passing 4.75mm Sieve
25.0mm (1")	< 40% Passing 4.75mm Sieve	> 40% Passing 4.75mm Sieve
19.0mm (3/")	< 35% Passing 2.36mm Sieve	> 35% Passing 2.36mm Sieve
12.5 (1/2")	< 40% Passing 2.36mm Sieve	> 40% Passing 2.36mm Sieve
9.5mm (3/8")	< 45% Passing 2.36mm Sieve	> 45% Passing 2.36mm Sieve
4.75mm (No. 4 Sieve)	N/A (No Standard Superpave Gradation)	

All projects are referenced in the generic terminology as “Project a”. The “a” is a numeric integer that is assigned to a specific project, usually in the order that the project was evaluated. The original test plan called for one project for each location in the test matrix, but due to the difficulty in locating certain projects, several mix types were evaluated twice.

In this section of the report, various items are discussed relating to the field project results obtained in the study (the individual results for each of the 20 projects is provided in the appendix provided in volume 4 of this report). Included is a discussion of the relationship between in-place air voids and field permeability, the effect of NMAS on permeability, the effect of gradation shape on permeability, the effect of lift thickness on permeability, and a comparison of field and lab permeability test results.

5.1 Relationship Between Field Permeability and In-place Air Voids

A primary objective of this study was to evaluate the relationship between field permeability and in-place air voids. Figure 7 illustrates that relationship for the twenty projects tested in this study. The overall R^2 value was 0.20, which is poor, but likely attributed to the wide variability of nominal maximum aggregate size, gradation shape (coarse-graded, fine-graded, SMA), and lift thickness. An ANOVA was conducted on the regression to determine if the relationship was significant even though the R^2 value was low; the p-value of 0.000 confirmed that the relationship was indeed significant. Since there are obviously other factors besides voids affecting the permeability, these factors were further evaluated.

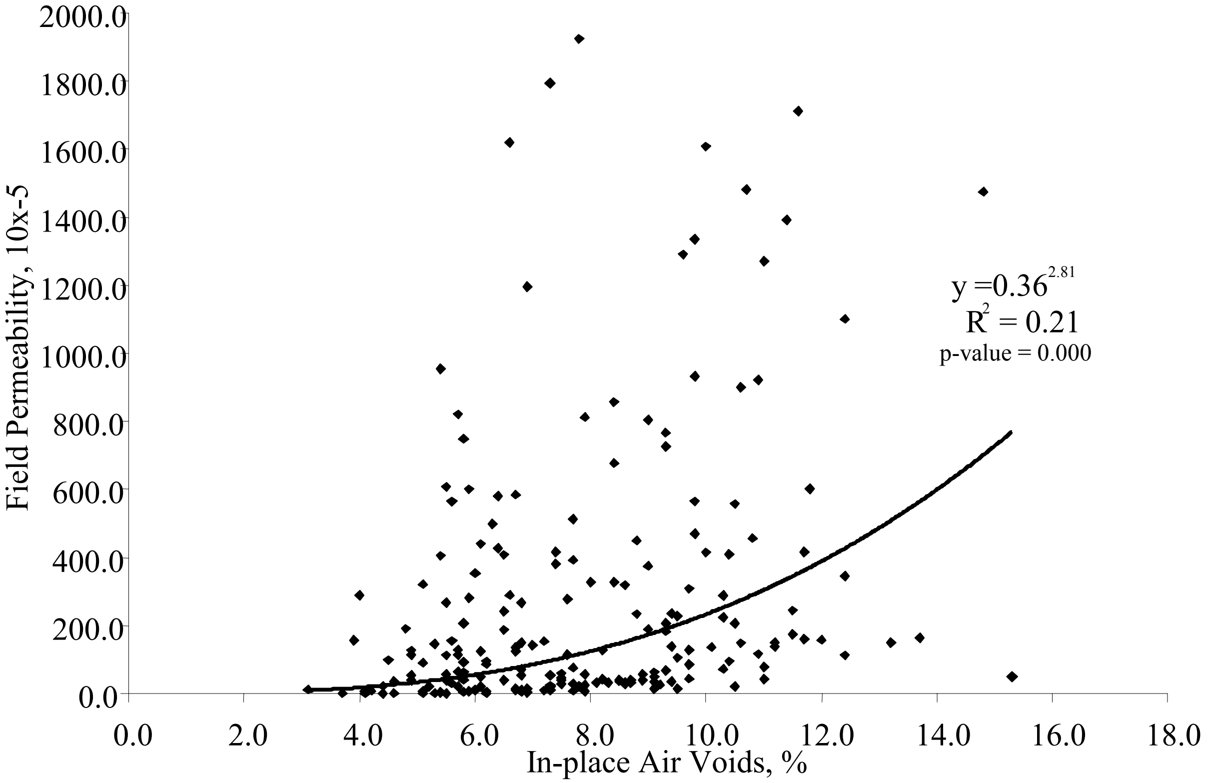

Figure 7: Relationship Between Field Permeability and In-place Air Voids, All Projects

Figures 8 through 11 illustrate the relationship between field permeability and in-place air voids for the different NMAS's tested. For each of the plots, in-place air void contents are located on the x-axis. These air void contents were determined using the water displacement method and maximum theoretical specific gravities determined on the plant-produced mix. The projects were analyzed according to the NMAS determined form the average gradation data produced from the extracted material

Figure 8 illustrates the relationship between field permeability and in-place air voids for the 9.5 mm NMAS mixes. Results from six projects are included in this figure; four were fine-graded Superpave mixes (Projects 1, 5, 7, and 19), one was a coarse-graded mix (Project 3), and the last one was an SMA mix (Project 14).

The overall coefficient of determination (R^2) for Figure 8 was reasonably strong (0.65), suggesting that 65 percent of the variation in field permeability measurements for the 9.5 mm NMAS mixes can be attributed to changes in in-place air voids. An ANOVA was conducted for the regression and showed that the relationship between field permeability and in-place air voids for the 9.5 mm NMAS mixes was significant (p-value for the regression was 0.000). From the regression equation produced on the combined data, the 9.5 mm NMAS mixes became permeable at approximately 10.0 percent in-place air voids, based on a critical field permeability value of 125×10^{-5} cm/s. However, some of the projects became permeable at air voids between 7 and 8 percent.

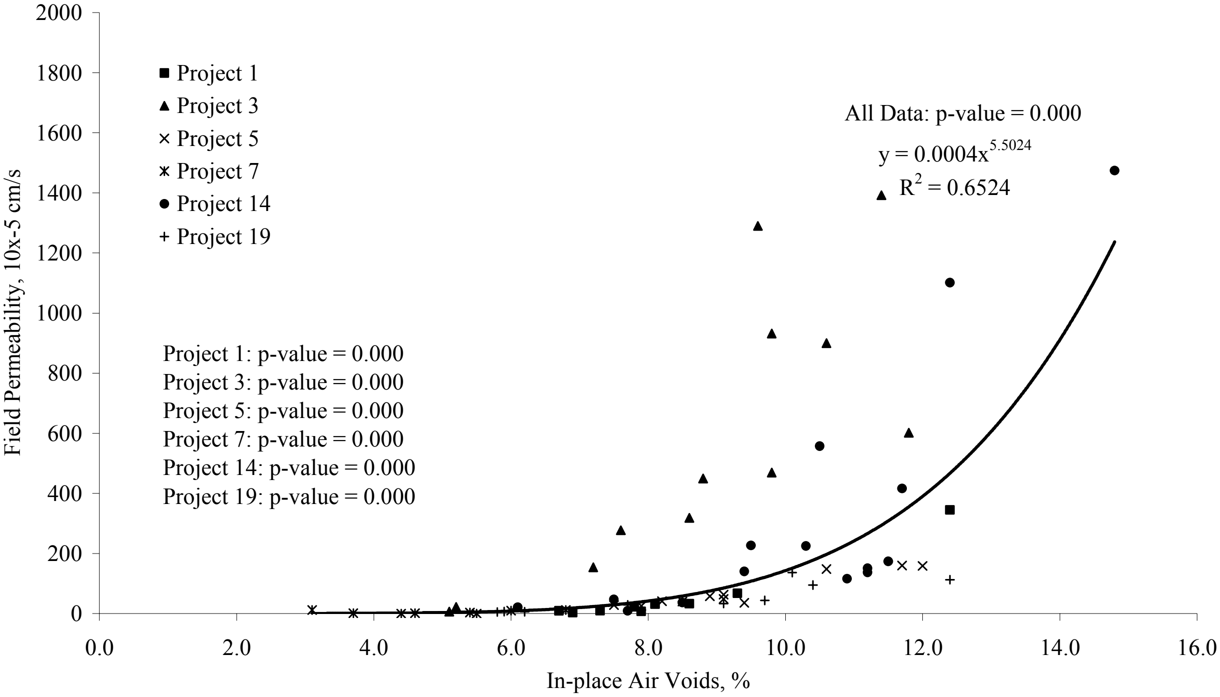

Figure 8: Relationship Between Permeability and In-place Air Voids – 9.5 mm NMAS

In addition to the p-value value for the combined data, the p-values for the individual projects are also presented in Figure 8. The p-value for all six projects indicated that the relationship between field permeability and in-place air voids was significant for each of the 9.5 mm NMAS mixes evaluated.

Figure 9 illustrates the relationship between field permeability and in-place air voids for the 12.5 mm NMAS mixes. A low R^2 value (0.06) was found for the combined data set for the 12.5 mm NMAS mixes. The data set included six HMA mixes from five different states and test results by three different operators. Based on the regression line equation produced from the combined data, the 12.5 mm NMAS mixes became permeable at an in-place air void content of approximately 10 percent. An ANOVA conducted on the regression showed that the relationship between field permeability and in-place air voids for the 12.5 mm NMAS mixes was significant (p-value = 0.000). When an ANOVA was conducted for the individual projects, the p-values determined showed that each project had a significant relationship. These p-values are shown in Figure 9.

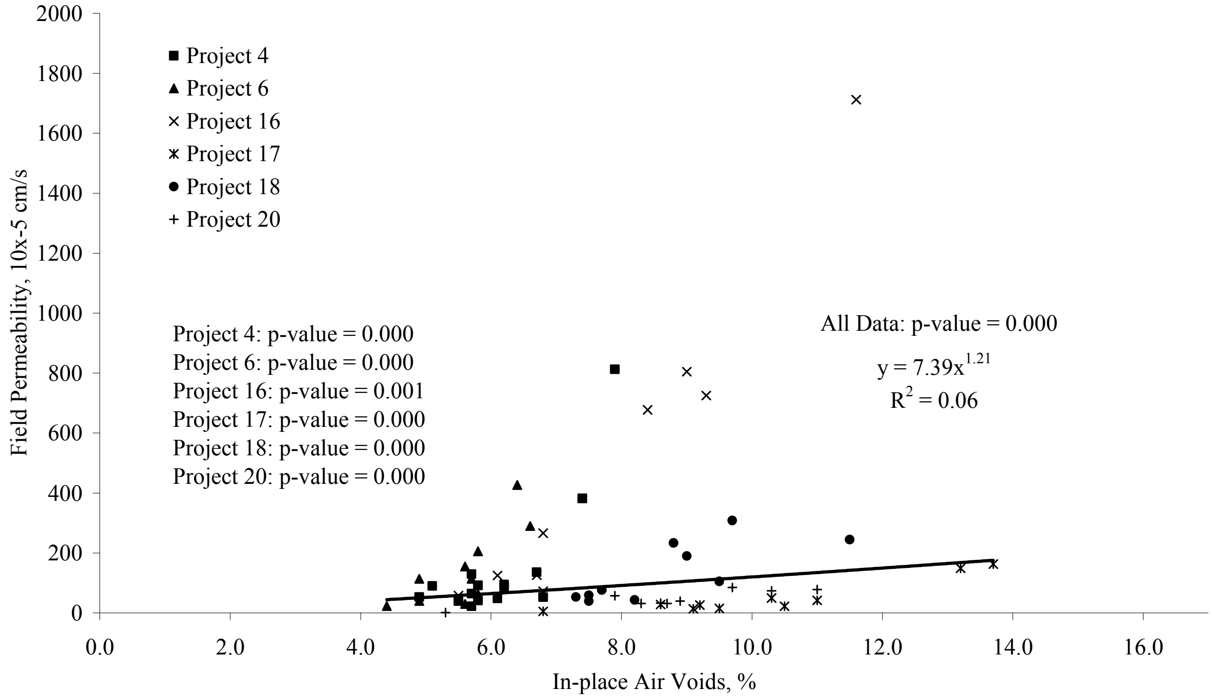

Figure 9: Relationship Between Permeability and In-place Air Voids – 12.5 mm NMAS

Figure 10 illustrates the relationship between field permeability and in-place air voids for the 19.0 mm NMAS mixes. The six 19.0 mm NMAS mixes were all coarse-graded mixes (Projects 2, 8, 9, 10, 11, and 15). These mixes were from four different states and were tested by four different operators.

The R^2 value for the 19.0 mm NMAS combined data (0.23) was higher than the R^2 for the 12.5 mm NMAS mixes (0.06) but was lower than the R^2 for the 9.5 mm NMAS mixes (0.65). An ANOVA was conducted for the regression and showed that the relationship between field permeability and in-place air voids for the 19.0 mm NMAS mixes was significant (p-value = 0.000). When evaluated at a given in-place air void content, the 19.0 mm NMAS mixes tended to be more permeable than the 9.5 and 12.5 mm NMAS mixes. For instance, at an in-place air void content of 6 percent, the 19.0 mm regression line equation yields a field permeability of 128×10^{-5} cm/s. At the same in-place air void content (6 percent), the 9.5 and 12.5 mm NMAS mixes had field permeability values of 8 and 65×10^{-5} cm/s, respectively.

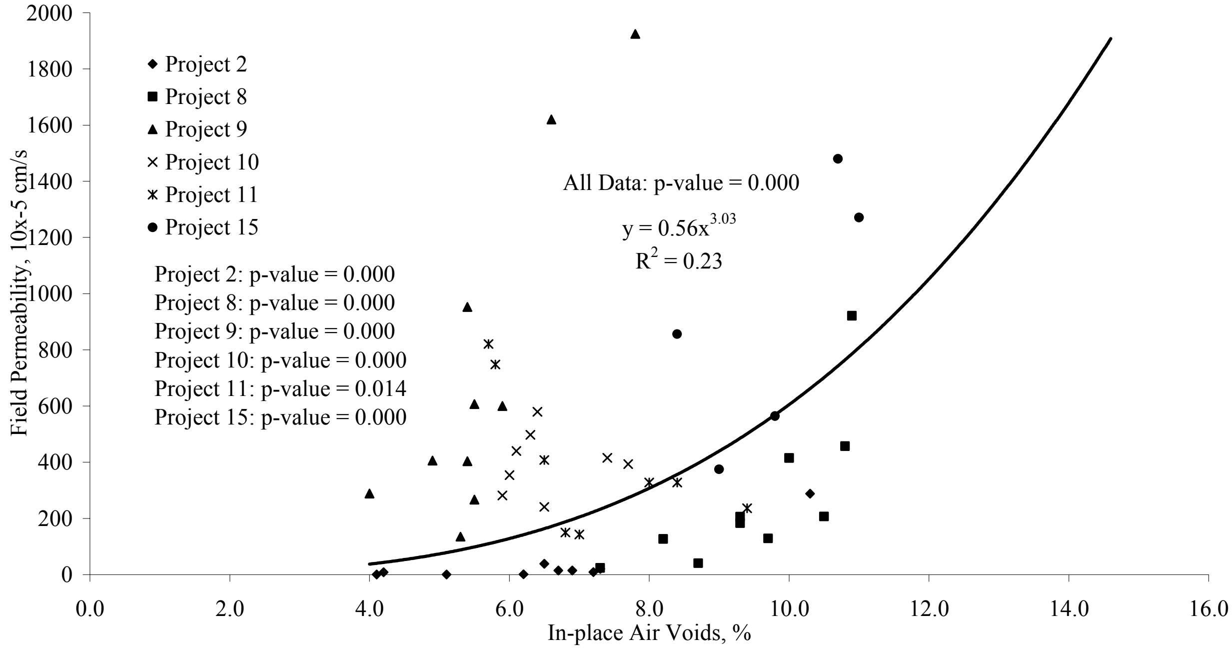

Figure 10: Relationship Between Permeability and In-place Air Voids – 19.0 mm NMAS

The relationship between field permeability and in-place air voids for the 25.0 mm NMAS mixes is illustrated in Figure 11. The two projects that are included in the figure came from two different states and were tested by three different operators. One mix was a fine-graded Superpave mix (Project 13) and the other was an SMA mix (Project 12).

A fair R^2 value was determined for the 25.0 mm NMAS mixes (0.56). From the regression equation, the 25.0 mm NMAS mixes became permeable at approximately 4.9 percent in-place air voids. An ANOVA was conducted to see if a significant relationship existed between field permeability and in-place air voids for the 25.0 mm NMAS mixes; the p-value for the combined data was 0.000, which indicated the relationship was significant. The relationship was significant for both individual projects as well (p-values of 0.000 and 0.007 for Projects 12 and 13, respectively).

When evaluated at a given in-place air void content (six percent, to compare with the previous permeability values for the other NMAS's), the 25.0 mm NMAS mixes had a field permeability of 240x10^{-5} cm/s. This permeability value was twice as high that for the 19.0 mm NMAS mixes (128x10^{-5} cm/s).

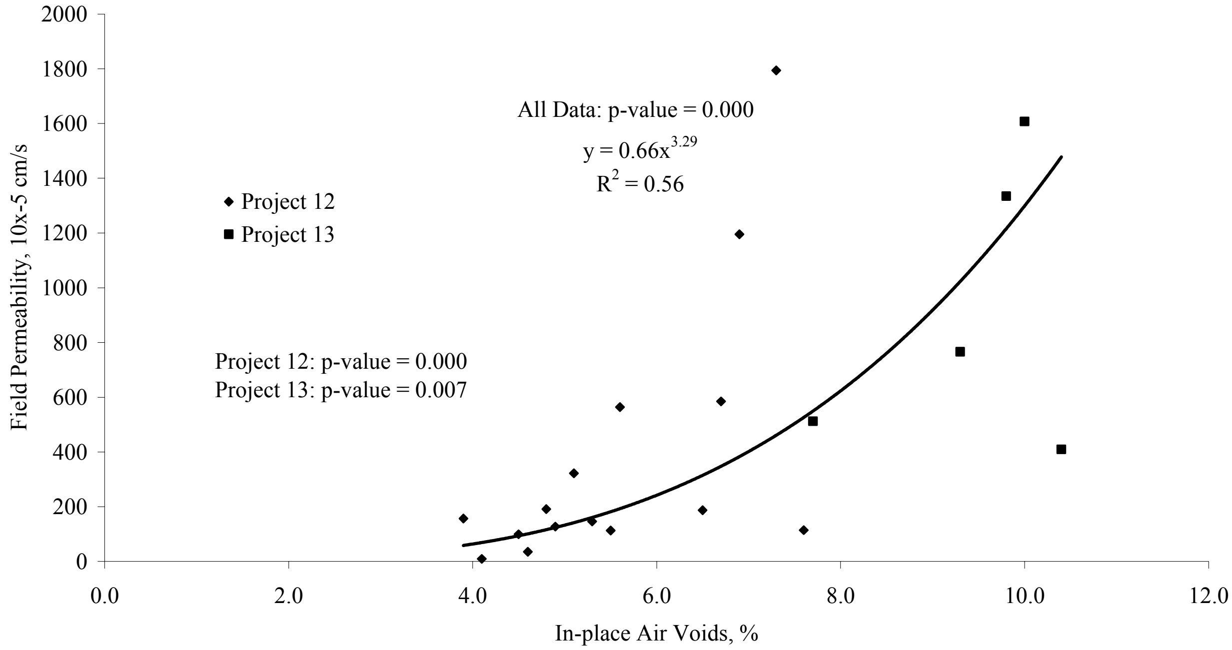

Figure 11: Relationship Between Permeability and In-place Air Voids – 25.0 NMAS

Figure 12 further illustrates the effect that NMAS has on field permeability, based on the regression line equations developed in Figures 8 through 11. Observation of Figure 12 suggested that the permeability characteristics for the 9.5 and 12.5 mm NMAS mixes are similar. It can also be seen that NMAS clearly affected the permeability characteristics of a pavement.

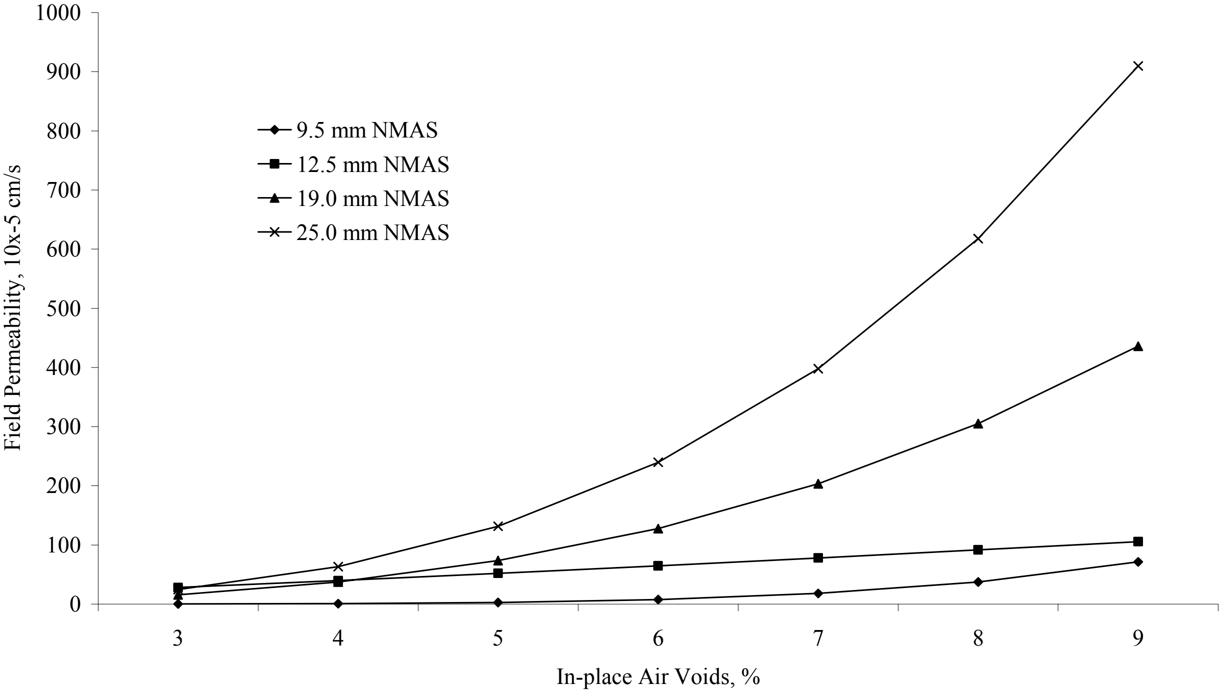

Figure 12: Effect of NMAS on Field Permeability

5.2 Effect of Gradation on Field Permeability

Figure 13 illustrates the comparison between fine-graded and coarse-graded mixes when evaluated for field permeability for the 9.5mm mixes. For all three type mixes (fine-graded, coarse-graded, and SMA) strong R^2 values were produced (0.67, 0.89, and 0.74, respectively). From the regression, the fine-graded mixes became permeable at an in-place air void content of 11.4 percent, based on a permeability value of $125x10^{-5}$ cm/s. At air void levels less than 11.4 percent, some samples were permeable. For the coarse-graded mixes, this air void content decreased to 7.3 percent. The SMA mix became permeable at 9.8 percent in-place air voids. The void level at which the mixes became permeable for the fine-graded mixture and for the SMA mixture were higher than normally recommended.

An ANOVA conducted on the regression showed that the relationship was significant for the combined data as well as each type mix (p-values of 0.000 for all regressions).

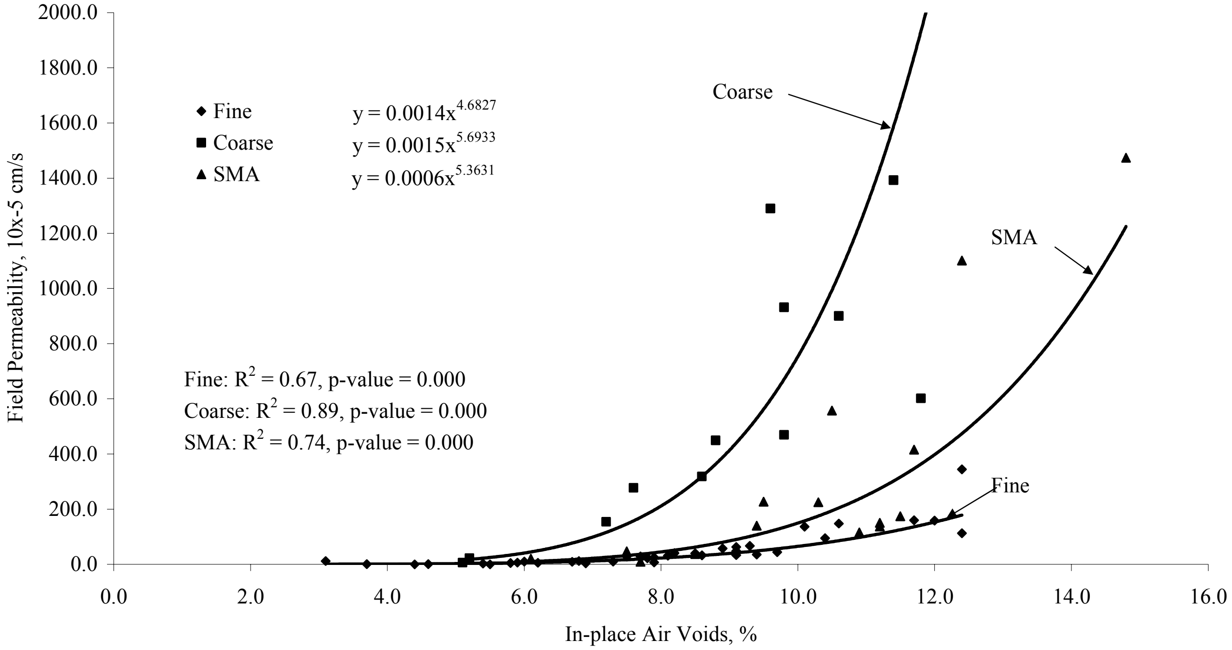

Figure 13: Fine-graded, Coarse-graded and SMA 9.5mm NMAS mixes

For the 12.5mm NMAS mixes, the comparison between the fine-graded and coarse-graded mixes is shown in Figure 14. For the 12.5mm NMAS mixes, the R^2 values were low for both the fine-graded mixes (0.06) and the coarse-graded mixes (0.38). A small range of field permeability values may have influenced the R^2 for the fine-graded mixes. An ANOVA conducted on the regressions showed that even though low R^2 values were found, both type mixes had a significant relationship between field permeability and in-place air voids (p-values of 0.001 for fine-graded and 0.000 for coarse-graded). Based on the regression equations and a critical permeability value of $125x10^{-5}$ cm/s, the coarse-graded mixes became permeable at an in-place air void content of 6.7 percent. The flatness of the regression line for the fine-graded mixes did not allow for a reasonable in-place air void content to be determined for which the mixes became permeable.

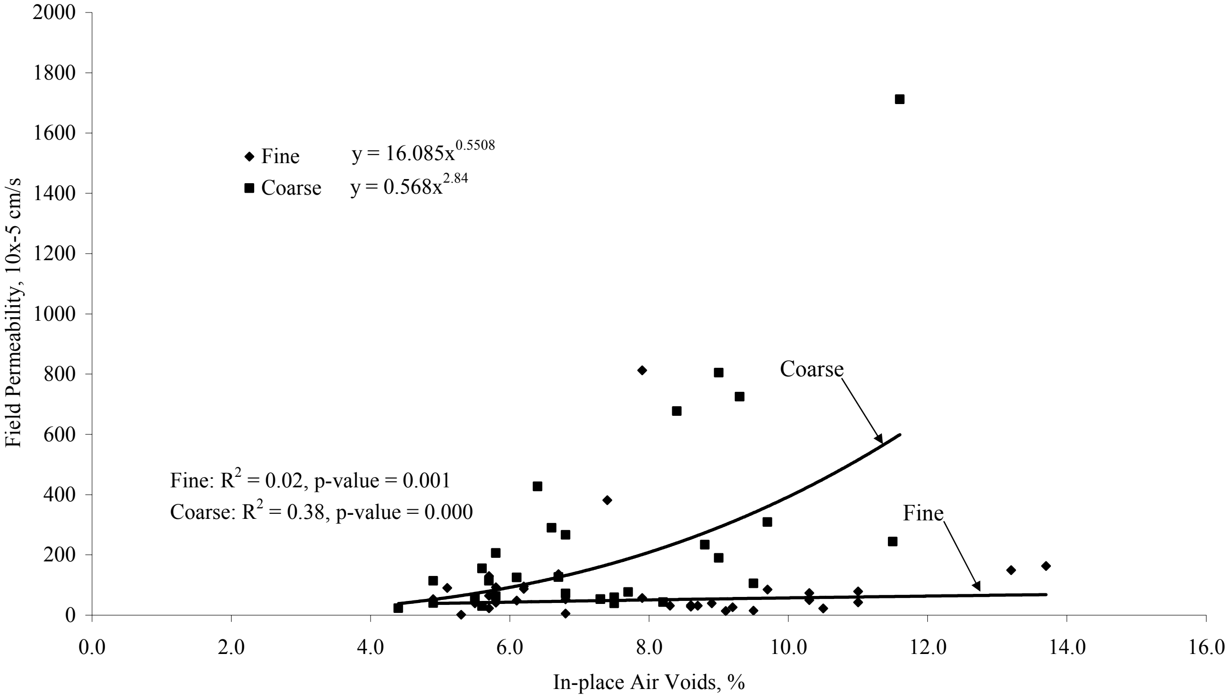

Figure 14: Fine-graded and Coarse-graded 12.5mm NMAS mixes

Since all six of the 19.0mm NMAS mixes were coarse-graded Superpave mixes, no gradation comparison could be made. Based on the regression equation in Figure 10, the 19.0 mm NMAS mixes became permeable at 6.0 percent in-place air voids.

The comparison between the fine-graded and SMA mixes for the 25.0 mm NMAS is illustrated in Figure 15. Some of the voids for the SMA mixtures and especially for the fine-graded mixtures were very high indicating poor compaction for many projects. The fine-graded mix produced a low R^2 value (0.09), but the relationship was significant based on the p-value produced from an ANOVA conducted on the regression (0.007). A fair R^2 value was found for the SMA mix (0.42). The SMA mix also had a significant relationship between field permeability and in-place air voids (p-value of 0.000). The fine-graded 25.0 mm mix became permeable at 3.1% in-place air voids, while the SMA mix became permeable at 4.9%.

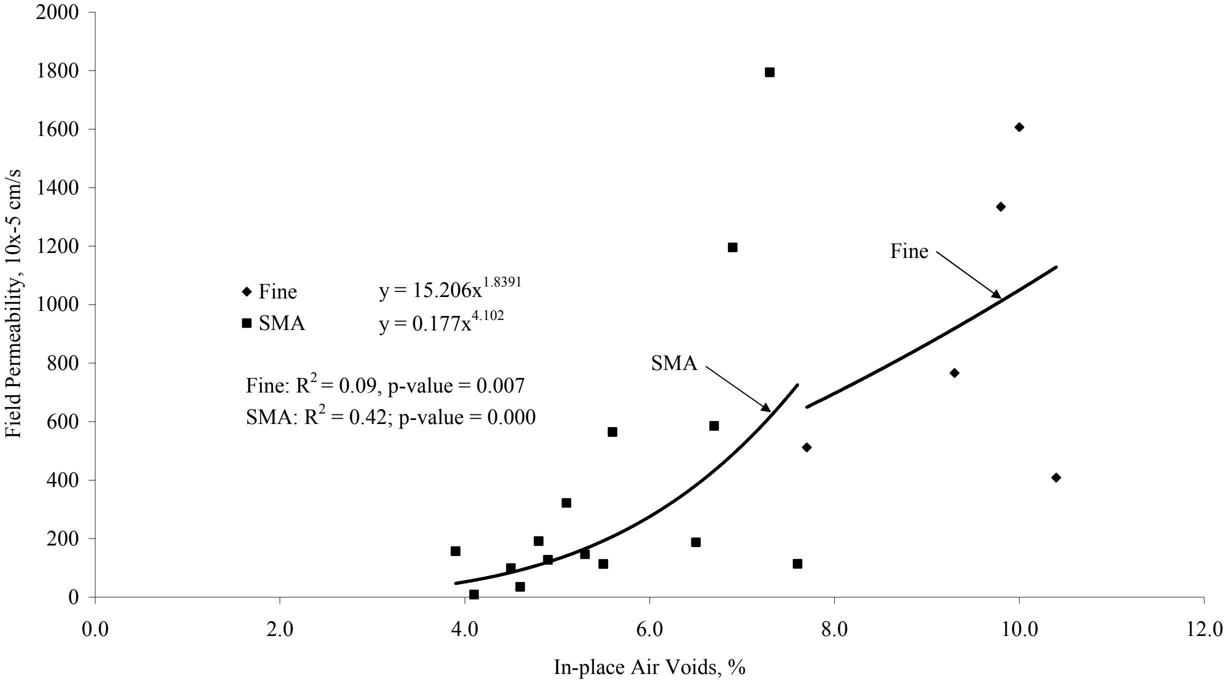

Figure 15: Fine-graded and SMA 25.0 mm NMAS mixes

The field and laboratory permeability tests generally provided results that were not very similar. This was expected since the two methods really have different approaches that really don't make the same measurements. For this study the laboratory permeability test was considered to be the preferred method. One thing that is noticed is that there is a lot of variability in the permeability between different mixtures. The voids did not explain all of the variability in permeability but low voids always resulted in very low or no permeability. A review of the 20 projects shown in the appendix in Volume 4 of this report indicates that the 9.5mm mixes always had low permeability (below 125 x 10-5 cm/s) when the air voids was at 7 percent or lower. The 12.5, 19.0, and 25.0mm mixtures always had low permeability when the air voids were at approximately 6 percent or lower. Hence, every effort should be made to compact mixtures close to these lower void levels to ensure that water permeability is not a problem.

5.3 Relationship Between Lift Thickness and In-place Air Voids

In order to evaluate the relationship between lift thickness and in-place air voids, in-place air voids were plotted against the ratio of lift thickness and NMAS (t/NMAS). Figure 16 illustrates the relationship between lift thickness and t/NMAS for 9.5 mm NMAS mixes (6 projects). Initial observation of Figure 16 indicates that the lift thickness for a particular project can be very sporadic. Lift thickness for the 9.5 mm NMAS mixes ranged from 20.7 to 66.9 mm.

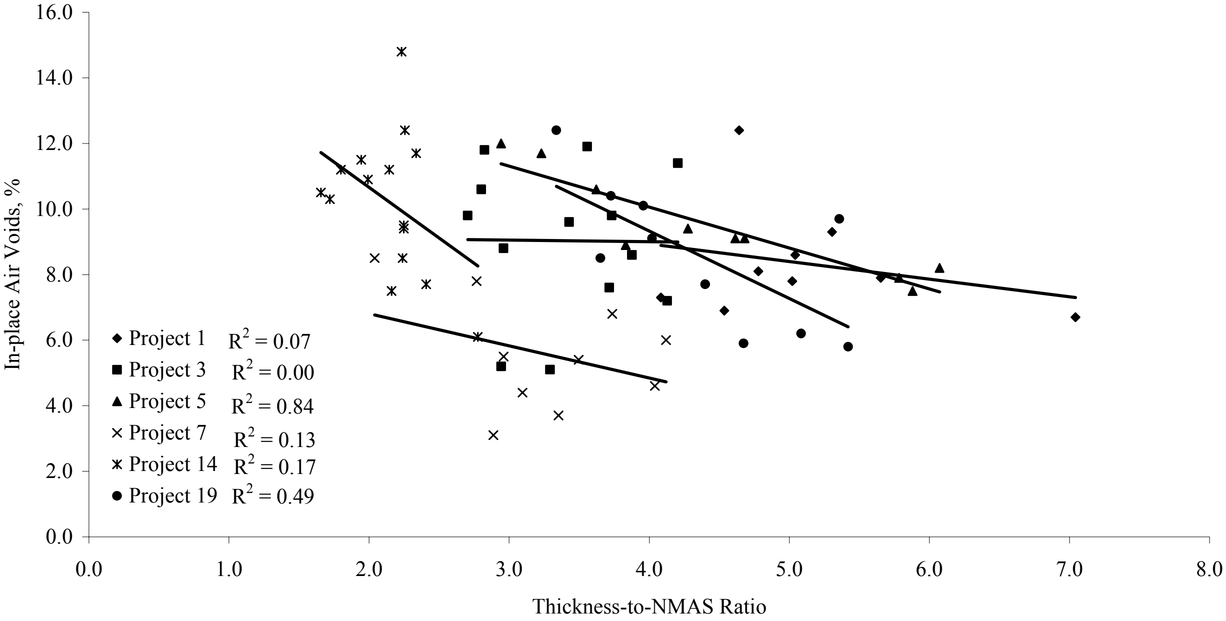

Figure 16: Relationship Between Lift Thickness and In-place Air Voids – 9.5 mm NMAS

The R^2 values for the six projects were all fair to low, ranging from 0.0001 to 0.49. For the trend lines, all six were either flat or suggested that as t/NMAS increased, the in-place air voids content decreased.

To determine if a general trend occurred between in-place air voids and t/NMAS, a regression was performed on the combined data. Figure 17 illustrates this general relationship. From this regression, a low R^2 of 0.09 was found. However, the trendline suggested that as the ratio of lift thickness to NMAS increased, in-place air voids decreased.

To determine if the relationship between in-place air voids and the t/NMAS ratio was significant, an ANOVA was conducted on the regression. For the combined data, the p-value was 0.014, which indicated that the overall relationship was significant. Then the data was separated into the three mix types. When an ANOVA was conducted on the regressions for the mix types, it was found that the relationship was not significant for any of the mix types (p-values of 0.956, 0.994, and 0.107 for fine-graded, coarse-graded, and SMA, respectively). It was also observed from Figure 17 that 7 percent in-place air voids was not achieved until the t/NMAS ratio reached approximately 6:1, which is equivalent to 2.2 inches.

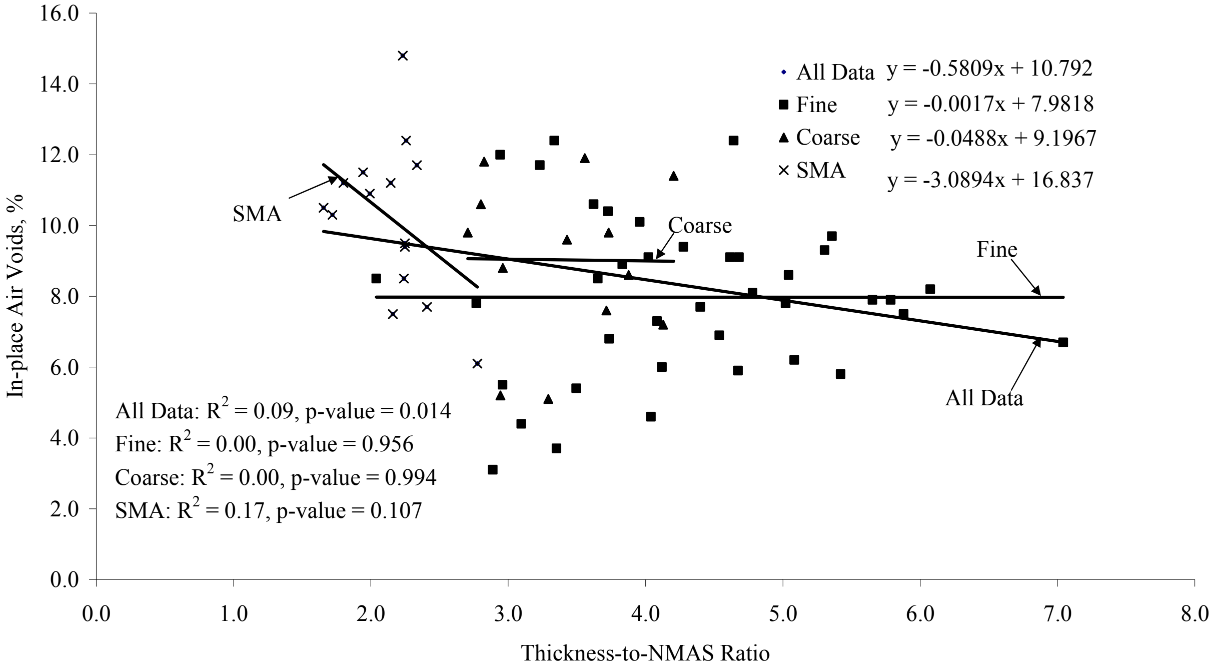

Figure 17: Relationship Between t/NMAS an In-place Air Voids – 9.5 mm All Data

Figure 18 illustrates the relationship between lift thickness and in-place air voids for the six 12.5 mm NMAS mixes. For these projects, the lift thickness ranged from 24.5 to 89.6 mm. The relationships for the six projects again were not strong as the R^2 values ranged from 0.05 to 0.24. Half of the trendlines suggested that as the ratio of lift thickness to NMAS increased, the in-place air void content decreased. The other half suggested the opposite; in-place air voids increased with an increase in the t/NMAS ratio.

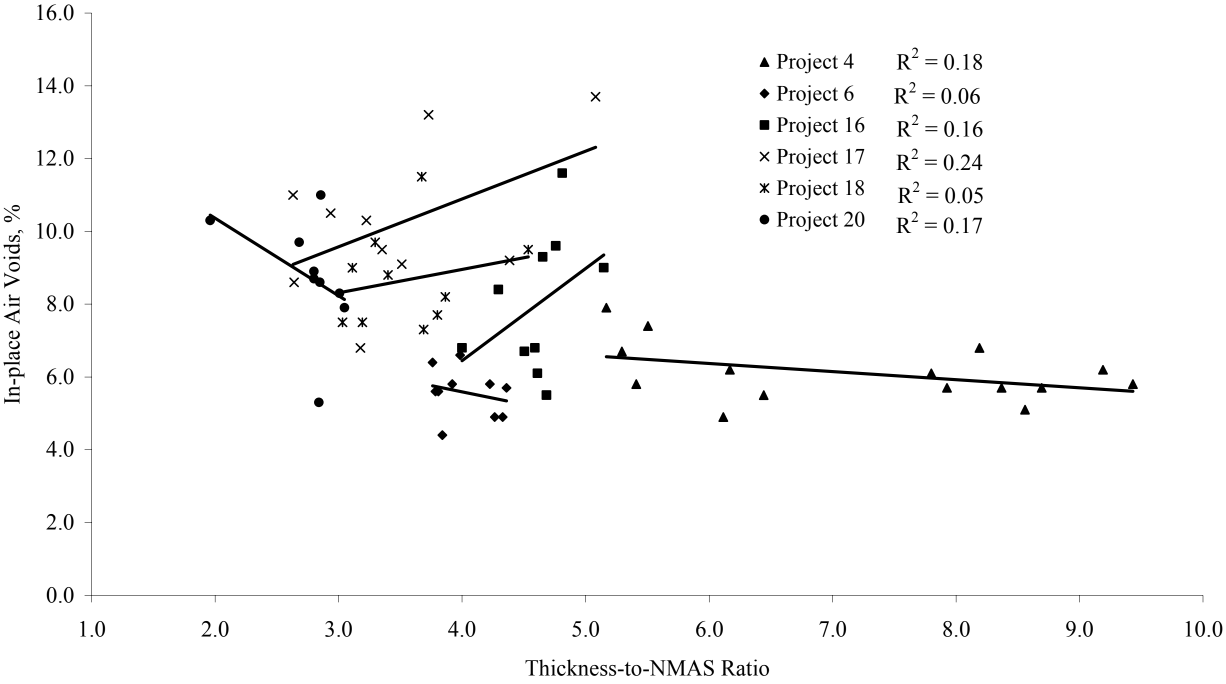

Figure 18: Relationship Between Lift Thickness and In-place Air Voids – 12.5 mm NMAS

For Figure 19, a best fit line was produced on the combined data for the 12.5 mm NMAS mixes. A low correlation was found from this regression (0.19), but the general trend suggested that as the lift thickness increased, in-place air voids decreased. An ANOVA conducted for the combined regression indicated that the relationship was significant (p-value = 0.001). The data was then separated into the different mix types to see if the relationship was significant for each mix type. For the fine-graded mixes, the relationship was significant (p-value = 0.000). The coarse-graded mixes did not have a significant relationship between in-place air voids and t/NMAS (p-value = 0.932). Figure 60 also indicated that 7 percent in-place air voids was not achieved until the t/NMAS ratio reached approximately 6:1, or about 3 inches.

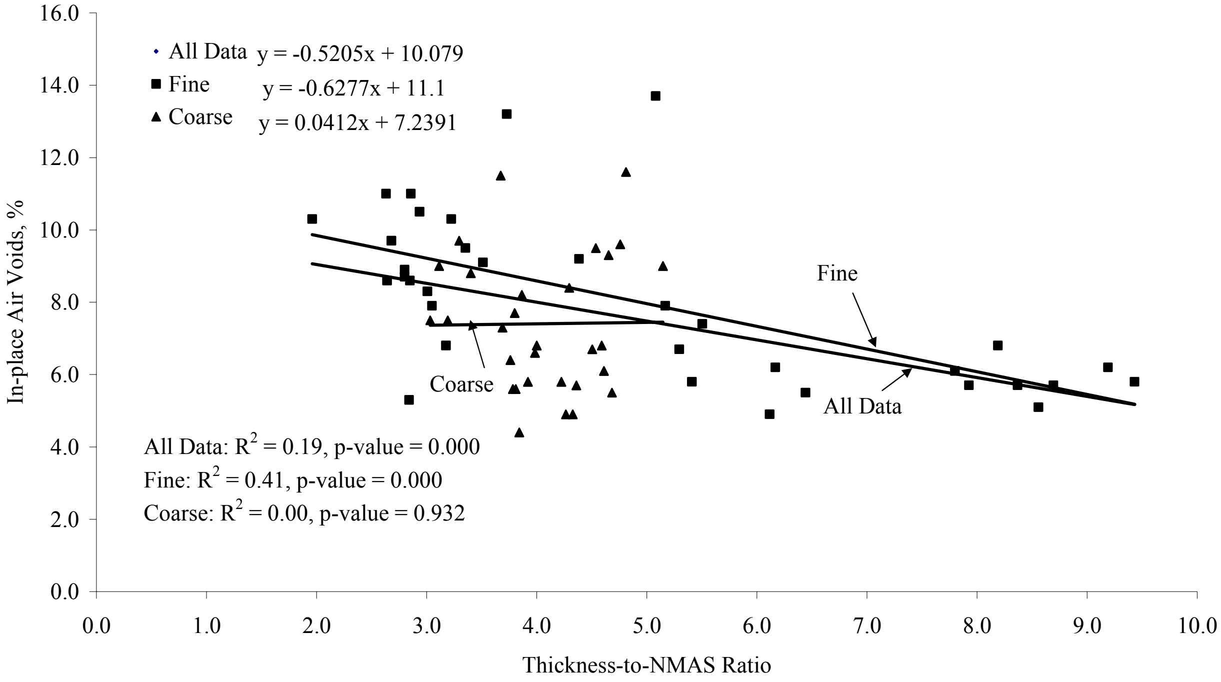

Figure 19: Relationship Between Lift Thickness and In-place Air Voids – 12.5 mm NMAS All Data

The relationship between lift thickness and in-place air voids for the 19.0 mm NMAS mixes is shown in Figure 20. Lift thicknesses for the six projects ranged from 33.7 mm to 104.1 mm. All best fit lines produced small R^2 values (0.03 for Project 2 to 0.23 for Project 9). Five of the six best fit lines suggested increasing in-place air voids with increasing lift thickness, while the sixth project showed the opposite trend.

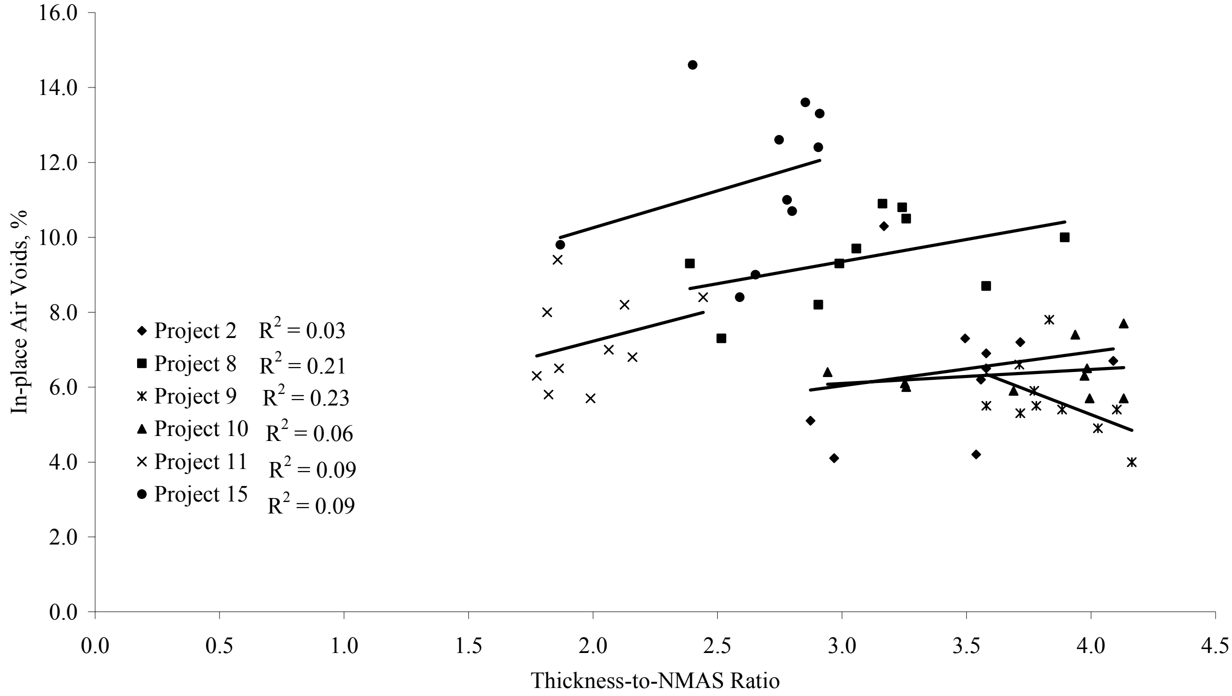

Figure 20: Relationship Between Lift Thickness and In-place Air Voids – 19.0 mm NMAS

Figure 21 shows the relationship between lift thickness and in-place air voids for the combined data set for the 19.0 mm NMAS mixes, as well as for the individual mix types. For the combined data, the regression produced a low R^2 value (0.09). An ANOVA performed on the regression determined that the relationship between t/NMAS and in-place air voids for the 19.0 mm NMAS mixes was significant (p-value of 0.000). Also, Figure 21 indicated that 7 percent in-place air voids was not achieved from the regression until the t/NMAS ratio reached approximately 4:1, or about 3 inches. However, there was so much scatter in the data that this plot cannot be used to select the minimum t/NMAS needed to obtain a given void level.

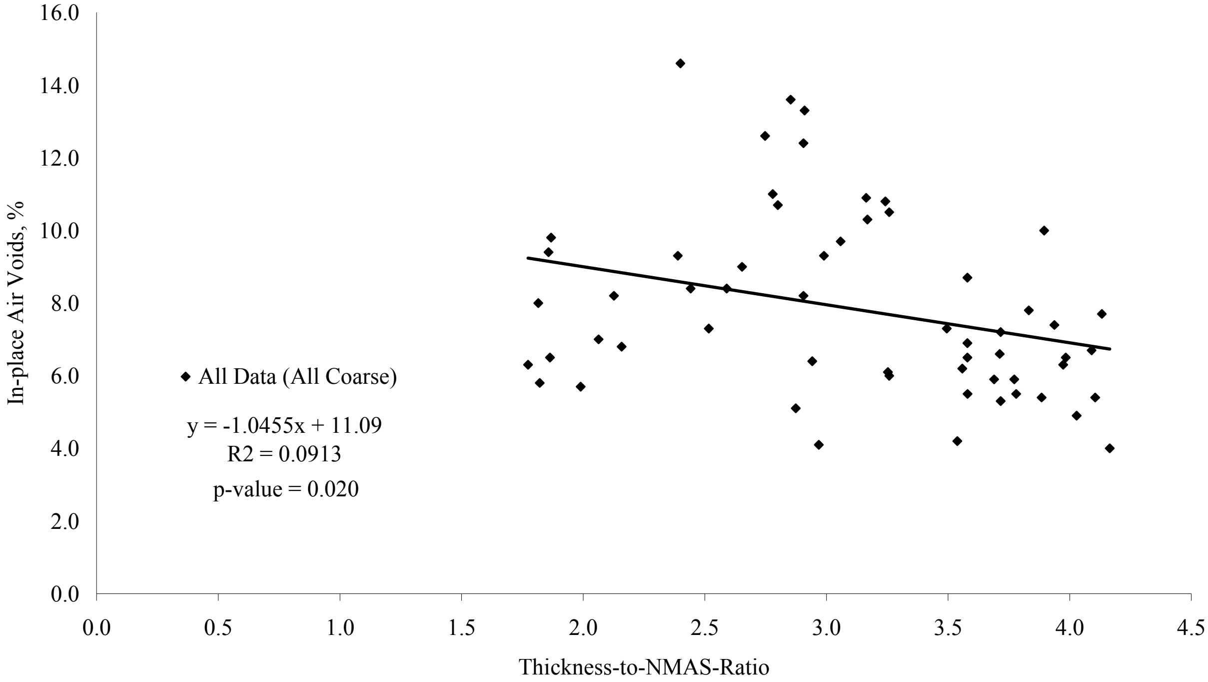

Figure 21: Relationship Between Lift Thickness and In-place Air Voids – 19.0 mm NMAS All Data

The relationship between lift thickness and in-place air voids for the 25.0 mm NMAS mixes is shown in Figure 22. Lift thicknesses for the two projects ranged from 34.1 to 85.4 mm. The R^2 values for the two regressions were both low (0.08 for Project 12 and 0.03 for Project 13). The two trendlines produced were either flat or suggested that as the t/NMAS ratio increased, in-place air voids decreased.

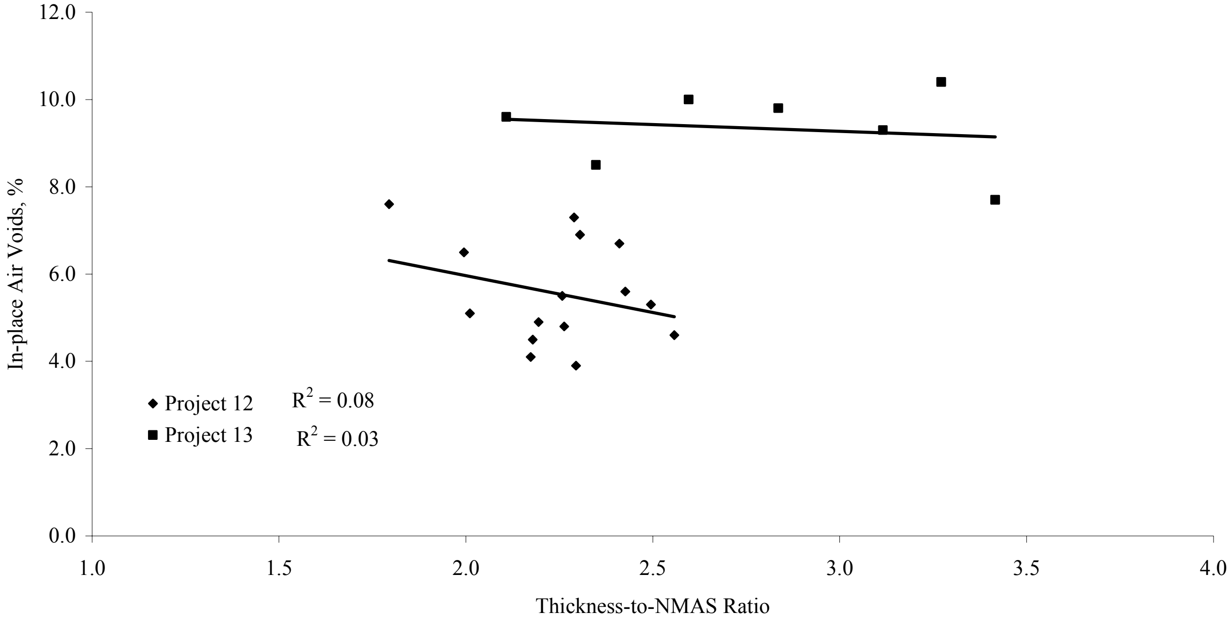

Figure 22: Relationship Between Lift Thickness and In-place Air Voids – 25.0 mm NMAS

5.4 Comparison Between Field and Lab Permeability

Figure 23 illustrates the comparison between field and lab permeability test methods. The lab permeability test results were performed on cores taken at the location of field permeability measurements.

The R^2 value for this relationship was low at 0.29. The relationship between the two test methods is interesting. Figure 23 indicates that the field permeability test method yielded higher permeability values, up to a permeability value of $150x10^{-5}$ cm/s. At that point, the lab permeability test method yielded higher permeability values.

Permeability values of $150x10^{-5}$ cm/s were associated with in-place air voids between nine and thirteen percent for the 9.5, 12.5, and 19.0 mm NMAS mixes and around three percent for the 25.0 mm NMAS mixes. At permeability values higher than $150x10^{-5}$ cm/s, HMA mixtures tend to have a higher percentage of interconnected air voids. In the field, an interconnected air void may or may not be of a length to allow water to pass through the pavement. In the lab, an interconnected air void may extend through the entire sample, making the permeability value for the lab much higher than that in the field.

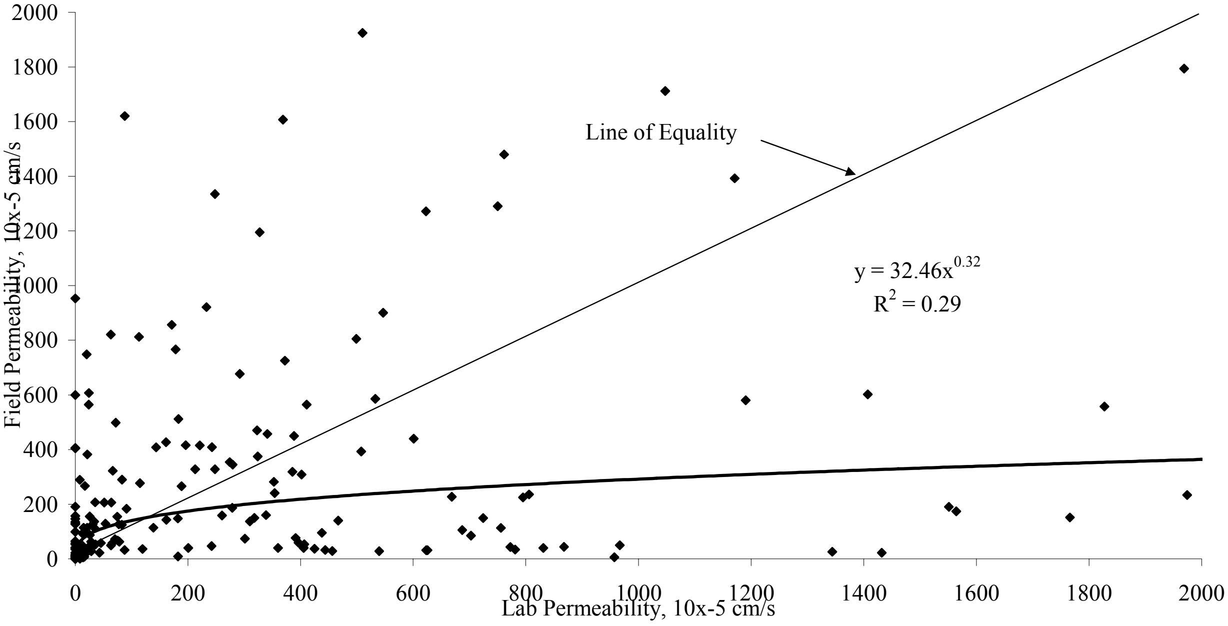

Figure 23: Comparison Between Field and Lab Permeability

6.0 CONCLUSIONS

The primary purpose for the field study was to validate the findings in the earlier part of the study and to validate the relationships between voids, lift thickness, and permeability. Based on the field study of the twenty pavement sections the following conclusions were made:

- The in-place air voids of the twenty projects were high. Fourteen of the twenty mixes tested had average in-place air voids above 8% and seven of the mixes had average air voids over 10% (based on test results with the vacuum-seal method). Five of the seven projects with more than 10% air voids were coarse-graded mixes. This low density on a high percentage of random projects is disturbing since this lower density will most certainly lead to significant loss in pavement life. The poor density obtained on most of these projects makes it very difficult to determine the effect of t/NMAS, grading, and other factors on permeability. In general, much of the loss in pavement life is a direct result of low density. This study along with other recent studies clearly shows that inadequate density is a significant problem on a high percentage of paving projects.

- Some of the twenty projects did not have poor density results. For example, five of the twenty projects had less than 7% average air voids. Three of these projects with less than 7% air voids were coarse-graded mixes. These successful projects show that adequate density can be obtained.
- Even though there is a lot of scatter in the data (within and between projects), most of the results for these twenty projects support the finding that higher t/NMAS ratios generally provide lower void levels.
- Based on these twenty projects coarse-graded mixtures generally have higher permeability values than the fine-graded mixtures for a given air void level.
- Air voids were clearly shown to be a key determinant of permeability. However, many times the air voids were reasonably low (5-7%) and the permeability was still high. Permeability testing needs to be conducted on

local materials to develop an understanding of the effect of air voids, NMAS, and grading on permeability. Consideration should be given to making permeability a part of the specification requirements.

7.0 RECOMMENDATIONS

- More emphasis must be placed on obtaining adequate density. Regardless of the method of density measurement used, some cores have to be taken and tested for calibration. The most reliable way to measure density is to take cores for density testing. If the amount of absorption during density measurement exceeds 1 percent the T166 method will likely provide a higher measured density than the true density. The Vacuum seal method approach is one approach to measure a more accurate density when the water absorption exceeds 1 percent.
- Since the relationship between air voids and permeability was not highly correlated there is a need to adopt some type of permeability test to help ensure that the mixture being produced and placed is not permeable. The laboratory permeability test appears to be more accurate than the field device, however, the laboratory test requires that cores be taken for laboratory testing. Some effort is needed to evaluate and recommend a permeability test to be used as part of QC/QA.

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