EVALUATION OF PAVEMENT PERMEABILITY IN MISSISSIPPI

by

L. Allen Cooley, Jr.

July 2003

TABLE OF CONTENTS

EVALUATION OF PAVEMENT PERMEABILITY IN MISSISSIPPI

L. Allen Cooley, Jr.
National Center for Asphalt Technology

INTRODUCTION

The proper compaction of hot mix asphalt (HMA) pavements is vital for a stable and durable pavement. For dense-graded mixtures, it has been recommended that the initial in-place air voids at the time of construction should not be below 3 percent or above approximately 8 percent (1). Low initial in-place air voids have been shown to increase the potential for rutting and shoving, while high initial in-place air voids allow water and air to penetrate into the pavement. When air and water penetrate into a pavement, there is an increased potential for moisture damage, oxidative aging, raveling, and cracking (1).

Research has indicated that increases in in-place air voids result in an increased potential for permeability within a pavement. Zube (2) performed a study in the 1960's that concluded that Hveem designed HMA pavements become excessively permeable at about 8 percent in-place air voids. This finding was later confirmed on Marshall designed pavements by Brown et al (3). However, due to problems associated with coarse-graded (gradations passing below maximum density line and restricted zone) Superpave designed mixes, the size and interconnectivity of air voids have been shown to greatly influence permeability (4). A study conducted by the Florida Department of Transportation (FDOT) indicated that coarse-graded Superpave mixes can be excessively permeable to water at in-place air voids less than 8 percent (4).

Numerous factors can potentially affect the permeability of HMA pavements. In a study by Ford and McWilliams (5), it was suggested that aggregate particle size distribution, aggregate particle shape, and pavement density (air voids or percent compaction) can affect permeability. Hudson and Davis (6) concluded that permeability is dependent on the size of air voids within a pavement, not just the percentage of voids. Recent work in Maine by Mallick et al. (7) has also shown that the nominal maximum aggregate size (NMAS) and lift thickness for a given NMAS affects permeability.

After the adoption of the Superpave mix design technology, the Mississippi DOT also experienced permeability problems. Therefore, a study was needed to evaluate the permeability characteristics of pavements in Mississippi. Included within this research should be analyses to identify the factors that affected permeability.

OBJECTIVE

The primary objective of this study was to evaluate the permeability characteristics of HMA pavements constructed in Mississippi. A secondary objective was to compare the AASHTO T166 and vacuum-sealing methods for determining bulk specific gravity of field compacted samples.

RESEARCH APPROACH

In order to evaluate the relationships between in-place air voids, lift thickness, and permeability, 13 on-going HMA construction projects were visited and field permeability tests conducted. The field permeameter has been described previously by Cooley (8) and Cooley and Brown (9).

For each field project visited, field permeability tests were conducted at a total of fifteen randomly selected locations. At each test location, two replicate permeability tests were conducted. Because the field permeameter uses a silicone-rubber caulk to help seal the device to the pavement, replicate tests could not be conducted on the same spot of the pavement. Therefore, after the first replicate at a given test location was completed, the device was lifted off the pavement and re-sealed immediately beside the first replicate to conduct the second replicate test. The device was moved longitudinally down the pavement during these replicate tests because pavement density tends to be more uniform longitudinally than transversely.

For each of the fifteen test locations, a core was cut from the pavement within the region field permeability tests were conducted. The core was used to measure pavement density and to determine the actual lift thickness on the roadway. For most projects, the bulk specific gravity of the cores were measured using AASHTO T 166 (water displacement method) and the vacuum sealing method (Corelok) described by Buchanan

(10). Theoretical maximum specific gravity (G_{mm}) measurements were obtained from testing of plant produced mix and used to calculate in-place air void contents.

Project Descriptions

A total of 13 on-going HMA construction projects were tested for this study. For the purposes of this study, coarse-graded Superpave gradations were defined as those gradations passing below the Superpave defined maximum density line at the 2.36 mm (No. 8) sieve and fine-graded mixes passed above.

Table 1 presents design information about the 14 projects tested for this study. This table shows that three different NMASs were investigated: 9.5, 12.5, and 19.0 mm. Gradations for the 13 mixes are illustrated in Figures 1 through 3, by NMAS from 9.5 to 19.0 mm. The design gradation for Project 11 was not available and therefore is not shown on Figure 3. However, Project 13 utilized a coarse-graded 19.0 mm NMAS mix. Figures 1 through 3 shows that all of the 9.5 mm NMAS mixes were coarse-graded. Four of the five 12.5 mm NMAS gradations shown in Figure 2 were fine-graded while the fifth gradation was coarse-graded. Figure 3 shows that all of the 19.0 mm NMAS mixes utilized coarse gradations. Design compactive efforts (N_{design}) ranged from a low of 86 to a high of 96 gyrations with a Superpave gyratory compactor. Also included within Table 1 are the design asphalt content (A.C.), voids in mineral aggregate (VMA),and voids filled with asphalt (VFA) and the design lift thickness.

Table 1
Project Information

Project No.	NMAS, mm	N_{design}	A.C., %	VMA, %	VFA, %	Lift Thickness, mm
1	12.5	96	5.7	14.2	72	50
2	12.5	96	4.9	14.3	72	50
3	12.5	96	5.3	14.5	72	50
4	9.5	96	5.9	15.5	74	38
5	19.0	96	5.6	13.2	69	63
6	19.0	86	5.4	13.7	70	50
7	9.5	96	6.2	15.1	74	38
8	19.0	96	5.5	13.2	69	75
9	12.5	96	5.7	14.1	71	38
10	19.0	86	5.3	13.3	69	63
11	19.0	NA	NA	NA	NA	63
12	12.5	86	5.3	14.2	71	50
13	12.5	NA	NA	NA	NA	43

NA – Not Available.

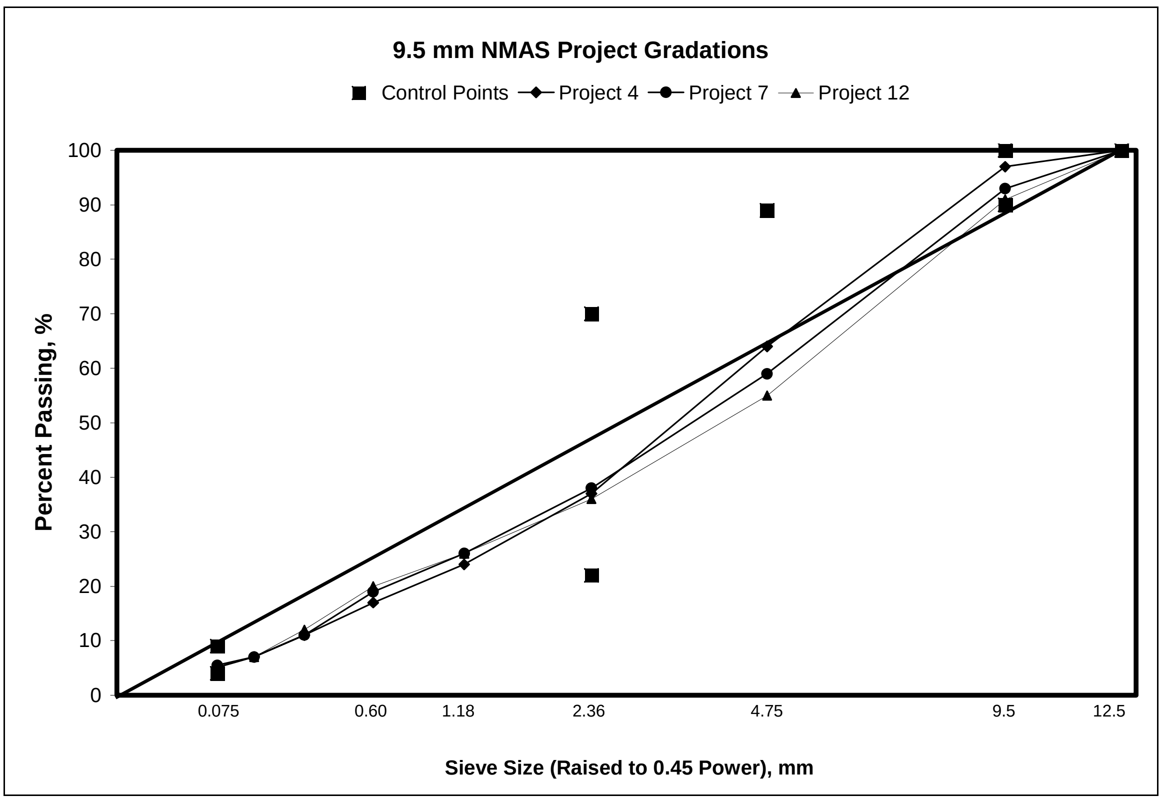

Figure 1: 9.5 mm NMAS Gradations Evaluated

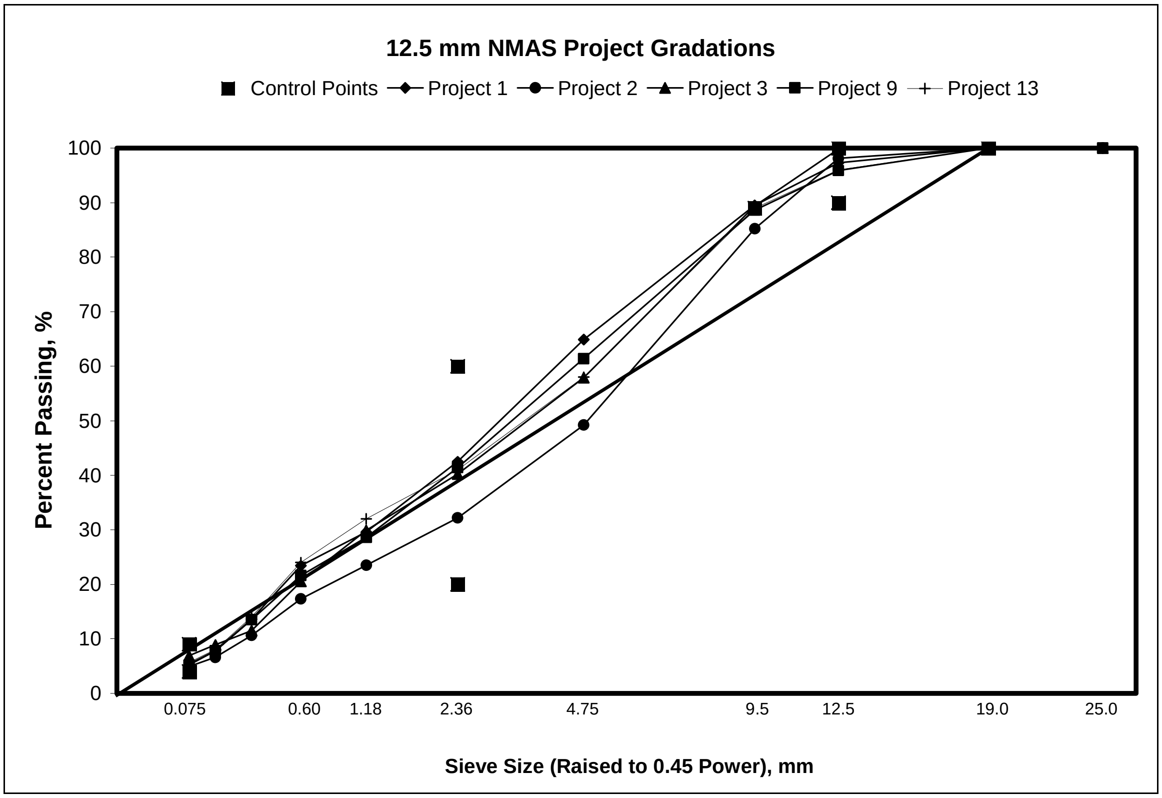

Figure 2: 12.5 mm NMAS Gradations Evaluated

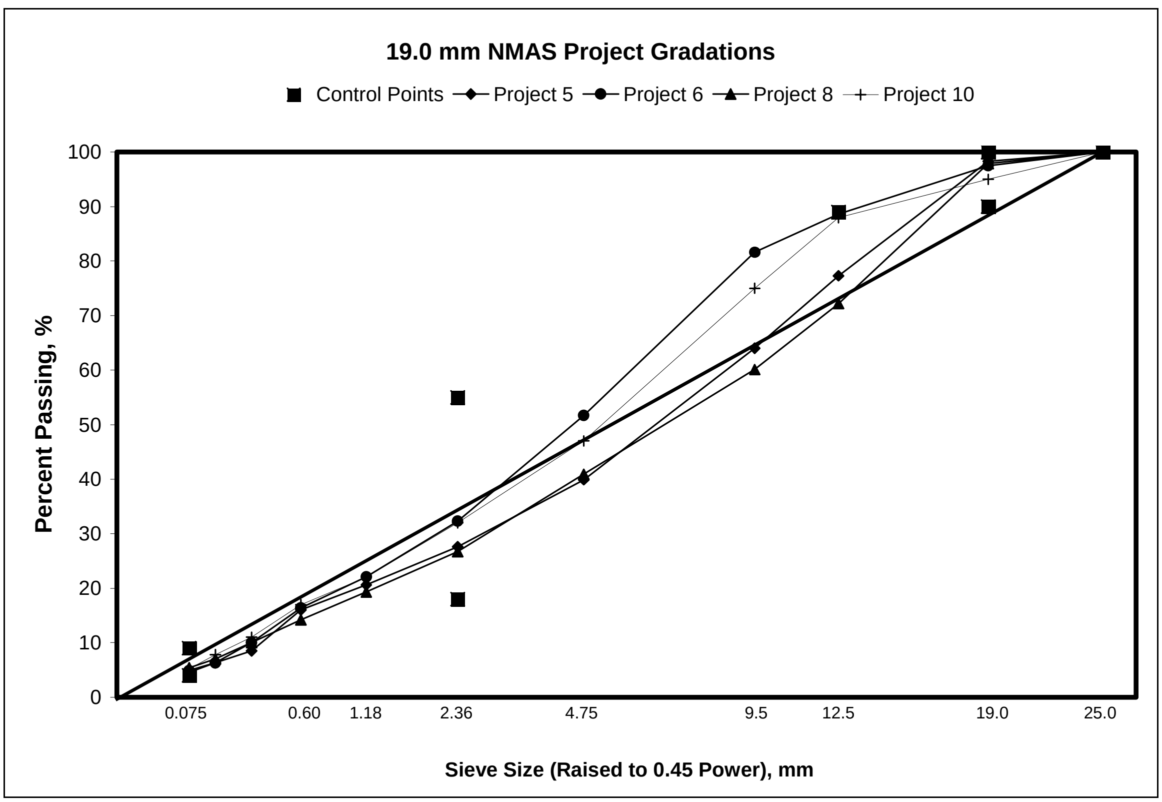

Figure 3: 19.0 mm NMAS Gradations Evaluated

Test Methods

Core densities for all projects were measured using AASHTO T166. For projects in which the Corelok was used (12 of the 13), core densities were first determined with the Corelok device and then in accordance with AASHTO T166. The Corelok device is designed to aid in the density determination of asphalt cores or pills with water absorption greater than 2%. AASHTO T 166, Standard Specification for Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens, specifies that the specimens with greater than 2 percent absorption be tested with paraffin or parafilm (AASHTO T 275). Both of these procedures are extremely time consuming. The Corelok device was developed to vacuum seal a specimen in a plastic bag, which can in turn be measured in a manner similar to parafilm.

The field permeability device utilized in this study was developed by the National Center for Asphalt Technology (8). This device uses a three tier standpipe with each standpipe having a different diameter. The standpipe with the smallest diameter is at the top and the largest diameter standpipe is at the bottom. This configuration was designed in an effort to make the permeameter more sensitive to the flow of water into a pavement. For pavements that are relatively impermeable, the water will fall within the top tier standpipe very slowly. Additionally, because of the small diameter of the top standpipe, the device is very sensitive to water draining from the permeameter.

For pavements of “medium” permeability, the water flows through the top-tier standpipe quickly but slows down when it reaches the larger diameter middle standpipe. Likewise, for a very permeable pavement, the water will flow quickly through the top and middle tiers and slow down in the larger diameter bottom standpipe.

The device is sealed to the pavement surface using silicon-rubber caulk. At the bottom of the device is a square base plate. A flexible rubber mat with a hole cut to the diameter of the lowest tier standpipe is placed below the metal base plate. The silicon-rubber caulk is placed onto the bottom of the rubber mat. A weight is then placed onto the top of the base plate. The weight was designed to resist the hydrostatic uplift forces when the permeameter is filled with water and to provide a downward force to help seal the device. The rubber mat was incorporated into the sealing system because, being flexible, the mass of the weight would push the silicon-rubber caulk into the surface voids of the pavement. This results in a repeatable seal to the pavement surface which prevents water from escaping through the surface texture of the pavement.

Based upon NCAT's work with the field permeability device, a standardized test procedure was developed. This procedure can be found in (8).

It should be stated that results from the field permeability device are not a true measure of permeability, but rather an index of permeability. Water exiting the field device can flow vertically and/or horizontally and, therefore, can have three-dimensional flow. However, for simplicity, the flow rate, or index of permeability, measured by the field device is referred to as permeability within this report since the measured units are the same as typical permeability tests (cm/sec). The strength of the data presented herein is that results of field tests were conducted with similar devices, utilizing identical test methods.

TEST RESULTS AND ANALYSIS

As stated previously, a total of 13 field projects were evaluated for their relationship between in-place density and permeability. This section presents the test results and analyses conducted to accomplish the objective of the study. The first part of this section discusses each of the projects individually. The second part of this section combines the data from the different projects in an effort to identify factors affecting the permeability of pavements in Mississippi.

Individual Projects

Project 1

The HMA tested for Project 1 was a fine-graded 12.5 mm nominal maximum aggregate size (NMAS) mix. The lift was to be placed at a thickness of 50 mm. Table 2 presents results of testing conducted at each of the 15 test locations for this project. Within this table are actual lift thickness, the lift thickness to NMAS ratio (t/NMAS), in-place air voids as determined using the results of both the Corelok and AASHTO T166 methods, field permeability values, and water absorption values determined during AASHTO T166 testing.

Table 2
Test Results for Project 1

Test Location	Lift Thickness, mm	t/NMAS	VTM, % (Corelok)	VTM, % (T166)	Field Perm. 10^{-5} cm/sec	Water Abs., % (T166)
1	37.2	2.98	13.9	12.7	697	2.1
2	34.7	2.78	9.5	8.4	76	0.9
3	42.3	3.38	6.5	6.5	5	0.6
4	48.8	3.91	6.6	5.6	10	0.4
5	47.7	3.82	7.5	6.1	22	0.7
6	52.5	4.20	7.0	7.0	37	0.5
7	60.9	4.87	4.4	4.4	1	0.3
8	48.5	3.88	5.6	5.6	1	0.3
9	56.1	4.49	6.8	6.8	1	0.3
10	61.2	4.90	5.0	4.6	1	0.3
11	46.8	3.74	5.6	5.4	1	0.9
12	65.6	5.25	6.8	6.4	7	1.0
13	65.5	5.24	5.5	5.2	1	0.9
14	52.3	4.18	3.8	3.8	1	0.5
15	48.1	3.85	6.1	5.8	22	0.8

Pavement thickness within the 15 test locations ranged from a low of 34.7 mm to a high of 65.6 mm. The average lift thickness for Project 1 was 51.2 mm and the standard deviation of lift thickness was 9.4 mm. In-place air voids as determined using results from the Corelok method ranged from a low of 3.8 percent to a high of 13.9 percent. Thirteen of the 15 test locations had in-place air voids (Corelok) of less than 8 percent. The average in-place air void content as determined using the Corelok method was 6.7 percent with a standard deviation of 2.4 percent.

In-place air voids as determined using the AASHTO T166 method ranged from a low of 3.8 percent to a high of 12.7 percent. The average in-place air void content for the AASHTO T166 results was 6.3 percent with a standard deviation of 2.1 percent. For Project 1, in-place air voids by both the Corelok and AASHTO T166 methods appear to be somewhat similar except for test locations 1 and 2, which were the locations with the highest in-place void levels. For both of these locations, air voids as determined from the Corelok method were higher.

Field permeability results for Project 1 were relatively low except for test location 1, which had a field permeability value of 697×10^{-5} cm/sec. Cooley et al (10) have suggested a critical field permeability value of 125×10^{-5} cm/sec to define excessive field permeability. Except for test location 1, all of the other test locations fell below this value. The relationship between field permeability and in-place air voids is illustrated in Figure 4. Within this figure, two relationships are shown: one with in-place air voids based upon Corelok testing and the other with in-place air voids based upon AASHTO T166 testing. As shown in Table 2, all but one of the data points had relatively low permeability values. Both methods of measuring bulk specific gravity yielded strong relationships with field permeability values as the coefficients of determination (R^2) were both above 0.70. Also included on Figure 4 are the analysis of variances (ANOVAs) for both relationships. Based on the ANOVAs, both relationships were significant at a level of significance of 5 percent (p-values less than 0.05). Based upon both relationships shown in Figure 4, this mixture did not become excessively permeable (permeability level greater than $125x10^{-5}$ cm/sec) until in-place air voids were above 10 percent.

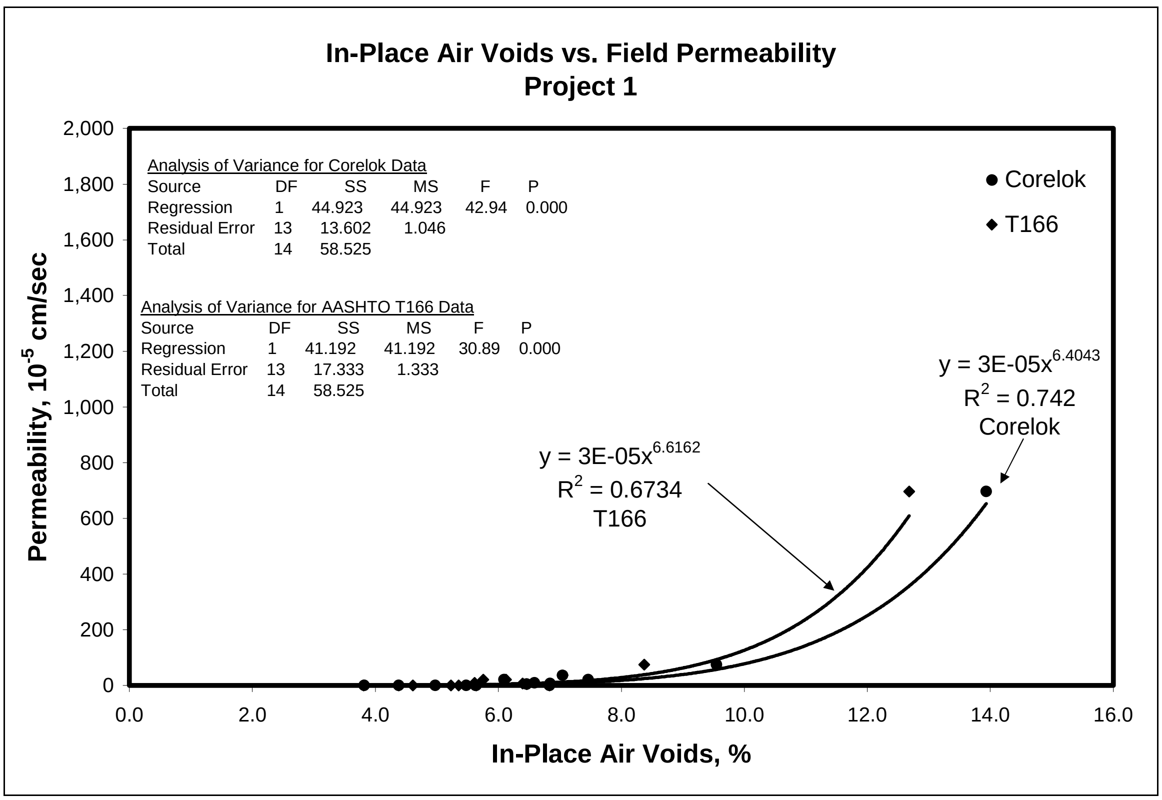

Figure 4: Relationship Between Permeability and In-place Air Voids, Project 1

Project 2

The HMA mixture tested at Project 2 was a fine-graded 12.5 mm NMAS mix. For this project, the design lift thickness was 50 mm. Table 3 presents the results of tests conducted at the 15 test locations for Project 2.

Table 3
Test Results for Project 2

Test Location	Lift Thickness, mm	t/NMAS	VTM, % (Corelok)	VTM, % (T166)	Field Perm. 10^{-5} cm/sec	Water Abs., % (T166)
1	33.0	2.64	4.6	4.2	1	0.2
2	46.6	3.73	6.0	5.5	11	0.3
3	47.1	3.77	4.9	4.5	2	0.2
4	46.3	3.70	6.0	5.5	68	0.2
5	42.9	3.43	5.8	5.3	1	0.4
6	50.7	4.06	5.3	5.3	1	0.2
7	45.4	3.63	5.7	5.4	49	0.3
8	51.2	4.09	5.6	5.6	47	0.4
9	50.2	4.02	7.1	7.1	76	0.5
10	53.6	4.29	5.7	5.3	33	0.2
11	53.3	4.27	6.9	6.0	119	0.3
12	50.0	4.00	8.2	6.9	236	0.7
13	51.6	4.13	5.9	5.0	29	0.3
14	46.4	3.71	6.2	5.2	42	0.3
15	52.4	4.19	7.4	6.1	149	0.6

Pavement thickness ranged from a low of 33.0 mm to a high of 53.6 mm. The average placed thickness was 48.1 mm with a standard deviation of 5.3 mm. This average value is very close to the design lift thickness of 50 mm. In-place air voids determined by the Corelok method ranged from a low of 4.6 percent to a high of 8.2 percent. The average in-place air void content for Project 2 was 6.1 percent which was slightly lower than for Project 1. In-place air voids obtained using AASHTO T166 results ranged from a low of 4.2 percent to a high of 7.1 percent. The average in-place air void content by AASHTO T166 was 5.5 percent. Collectively, in-place air voids were less for Project 2 than for Project 1. Also, in-place air voids were collectively higher using the results from Corelok testing.

Field permeability results for Project 2 ranged from a low of $1x10^{-5}$ cm/sec to a high of $236x10^{-5}$ cm/sec. Project 2 had two test locations that had field permeability values above the recommended maximum value of 125 x10^{-5} cm/sec (locations 12 and 15).

The relationship between field permeability and in-place air voids is illustrated in Figure 5. Again, two relationships are shown representing the two methods of measuring bulk specific gravity (and, thus, air voids). The figure shows that both methods yielded somewhat similar relationships. Collectively, the R^2 values were reasonable as both were above 0.52. Both relationships were significant as shown by the p-values from the ANOVAs being less than 0.05. Based upon both trend lines, this mixture became excessively permeable at an in-place air void content of approximately 7 percent.

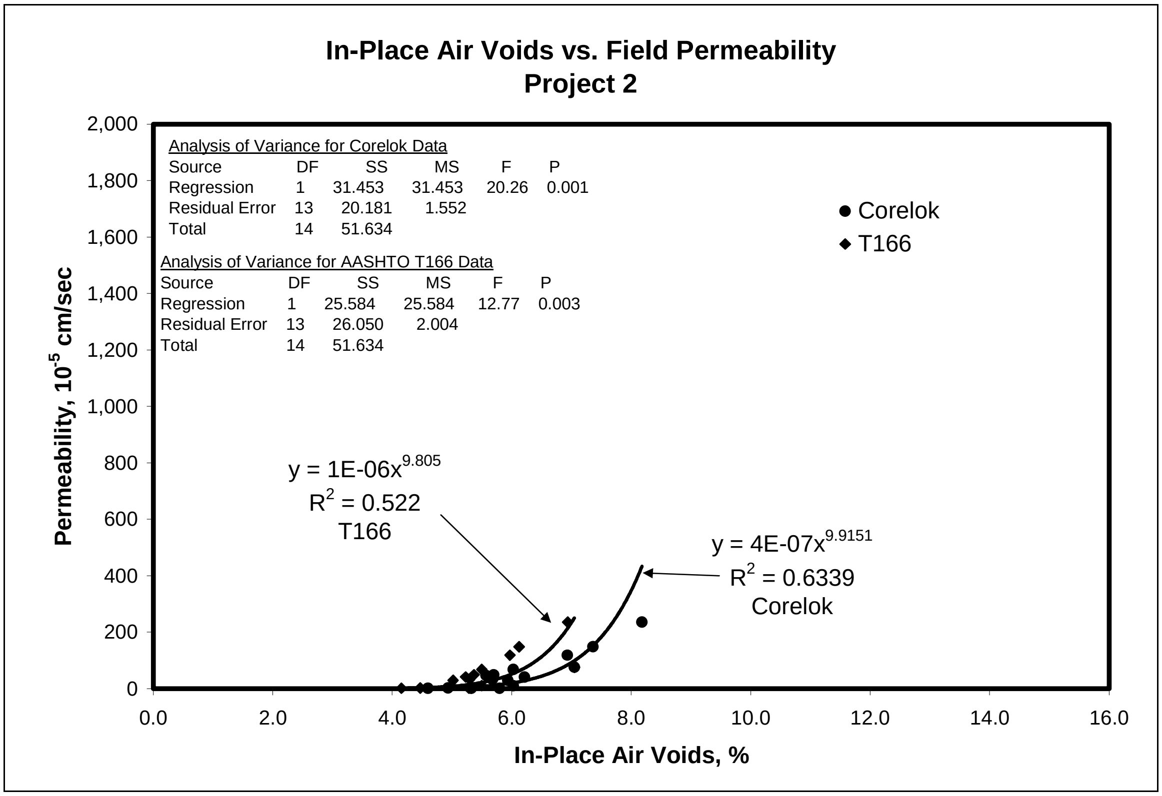

Figure 5: Relationship Between Permeability and In-Place Air Voids, Project 2

Project 3

For Project 3, a fine-graded 12.5 mm NMAS gradation was utilized for the HMA. The design lift thickness for this project was 50 mm. Table 4 provides results of testing conducted at the 15 test locations on Project 3.

Table 4
Test Results for Project 3

Test Location	Lift Thickness, mm	t/NMAS	VTM, % (Corelok)	VTM, % (T166)	Field Perm. 10^{-5} cm/sec	Water Abs., % (T166)
1	43.5	3.48	6.3	5.5	24	0.4
2	49.0	3.92	5.9	5.5	20	0.4
3	47.5	3.80	7.6	6.7	131	1.2
4	48.7	3.90	7.0	6.4	217	0.6
5	49.7	3.98	9.8	8.6	186	2.0
6	62.3	4.99	6.1	5.7	74	0.7
7	39.5	3.16	10.5	10.0	447	1.2
8	36.0	2.88	8.5	7.2	36	0.8
9	55.3	4.42	6.5	5.6	17	1.0
10	41.9	3.35	6.8	5.4	44	0.3
11	50.9	4.07	8.0	7.2	99	0.8
12	53.1	4.24	5.7	5.1	37	0.9
13	43.2	3.45	7.6	6.8	396	0.9
14	46.0	3.68	9.1	7.8	38	1.4
15	56.5	4.52	8.0	7.4	192	0.9

Table 4 shows that the average lift thickness (48.2 mm) was very close to the design lift thickness of 50 mm. Lift thickness values ranged from a low of 36.0 mm to a high of 62.3 mm and had a standard deviation of 6.9 mm. In-place air void contents as determined using the Corelok method ranged from 5.7 to 10.5 percent with an average of 7.6 percent. The standard deviation for the Corelok in-place air voids was 1.5 percent. In-place air voids determined using the AASHTO T166 method had a lower average (6.7 percent) than the Corelok results. In-place air voids ranged from a low of 5.1 percent to a high of 10.0 percent. Collectively, the in-place air void contents for Project 3 were higher than Projects 1 and 2. Field permeability results for Project 3 were collectively higher than for Projects 1 and 2. The average field permeability value was 131×10^{-5} cm/sec. Six of the 15 test locations exhibited permeability results greater than the recommended critical value of 125×10^{-5} cm/sec.

Figure 6 illustrates the relationships between field permeability and in-place air voids. The best fitted lines for the relationships have less correlation (lower R^2 values) than the previously discussed projects; however, the relationships are still significant at a 5 percent level of significance. The two relationships also differ slightly with respect to an air void content defining excessive permeability. For the Corelok relationship, an in-place air void content of 8.5 percent resulted in a permeability value of 125x10^{-5} cm/sec. For the AASHTO T166 relationship, an air void content of 7.5 resulted in excessive permeability.

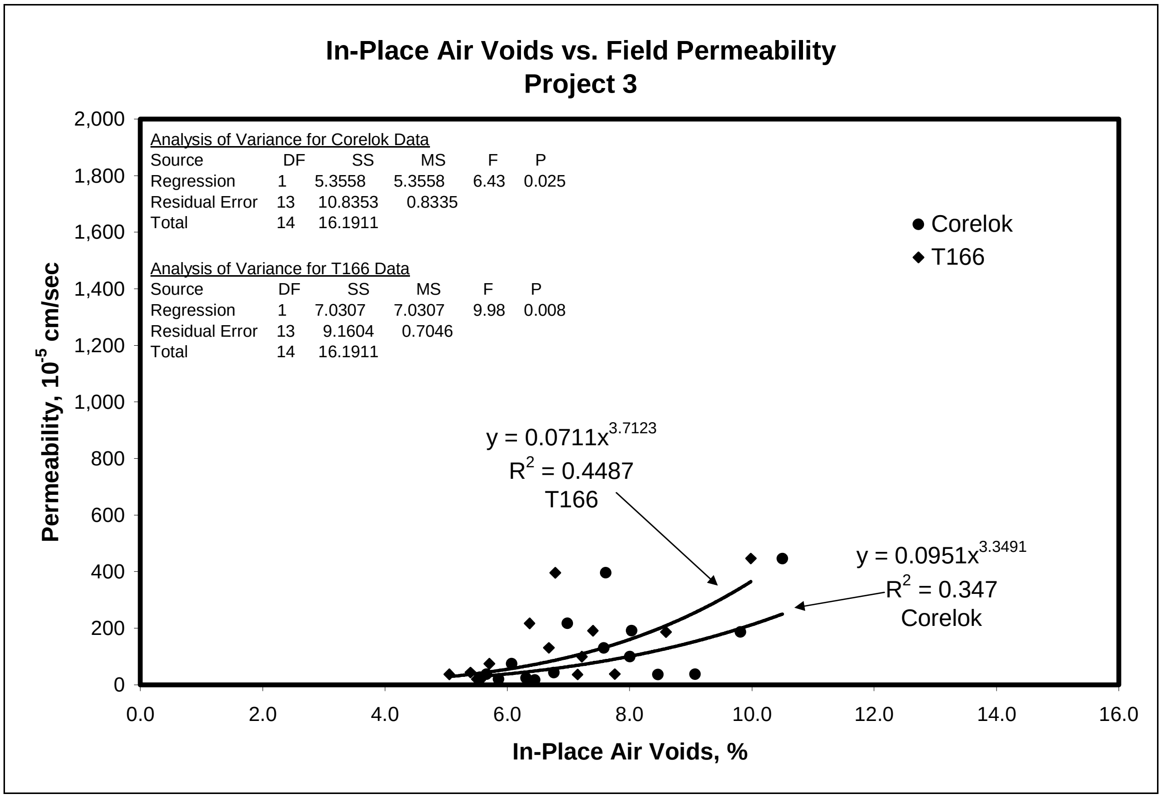

Figure 6: Relationship Between Permeability and In-Place Air Voids, Project 3

Project 4

The mixture tested for Project 4 was a coarse-graded 9.5 mm NMAS mixture. The design lift thickness for the pavement was 38 mm. Results of testing conducted on Project 4 are presented in Table 5.

The thickness of the pavement for Project 4 ranged from a low of 28.1 mm to a high of 41.4 mm. The average thickness was 35.1 mm, which was slightly lower than the design lift thickness. The standard deviation on pavement thickness was 4.5 mm. In-place air void contents determined using the Corelok results ranged from 7.7 to 13.2 percent. The average in-place air void content was 9.3 percent with a standard deviation of 1.5 percent. In-place air void contents by the AASHTO T166 method ranged from 6.7 to 11.7 percent. The average in-place air void content was 8.1 percent with a standard deviation of 1.3 percent. Collectively, the in-place air voids for this pavement were much higher than for the previous projects. Results of air void content determinations using the Corelok method resulted in higher in-place air voids on an average of about 1 percent for Project 4. Field permeability values were also higher than the previously discussed projects as they ranged from 36 to 1000x10^{-5} cm/sec. The average field permeability value was 221x10^{-5} cm/sec.

Table 5
Test Results for Project 4

Test Location	Lift Thickness, mm	t/NMAS	VTM, % (Corelok)	VTM, % (T166)	Field Perm. 10^{-5} cm/sec	Water Abs., % (T166)
1	39.1	4.12	9.1	7.8	126	1.1
2	39.1	4.12	9.1	7.9	191	0.6
3	37.3	3.93	8.8	7.4	97	0.5
4	41.4	4.36	11.0	9.6	291	1.6
5	38.9	4.09	9.3	8.1	179	0.5
6	30.5	3.21	8.4	7.2	71	0.7
7	32.8	3.45	8.8	7.2	120	0.4
8	40.1	4.22	8.2	7.1	92	0.3
9	28.1	2.96	10.3	8.7	212	1.3
10	30.8	3.25	7.8	6.7	192	0.6
11	28.6	3.01	8.2	7.2	54	0.7
12	31.6	3.32	13.2	11.7	1,000	3.1
13	33.4	3.51	7.7	7.9	36	0.4
14	38.7	4.07	9.0	7.5	291	0.7
15	36.3	3.82	10.7	9.3	377	1.0

Figure 7 illustrates the relationships between permeability test results and in-place air voids. The best fitted line for the Corelok relationship had a higher R^2 (0.73) than the regression line for the AASHTO T166 determined air voids (0.53). However, both of the relationships were significant at a 5 percent level of significance. The approximately 1 percent higher air voids determined by the Corelok method are evident on Figure 7 in that the regression line for the Corelok data is shifted toward higher air voids. Both relationships do, however, have similar shapes. Similar to Project 4, there was an approximately 1 percent difference on an in-place air void content that defined excessive permeability, depending upon the method of measuring bulk specific gravity. In-place air void contents of 8.8 and 7.6 percent for the Corelok and AASHTO T166 methods, respectively, resulted in excessive permeability.

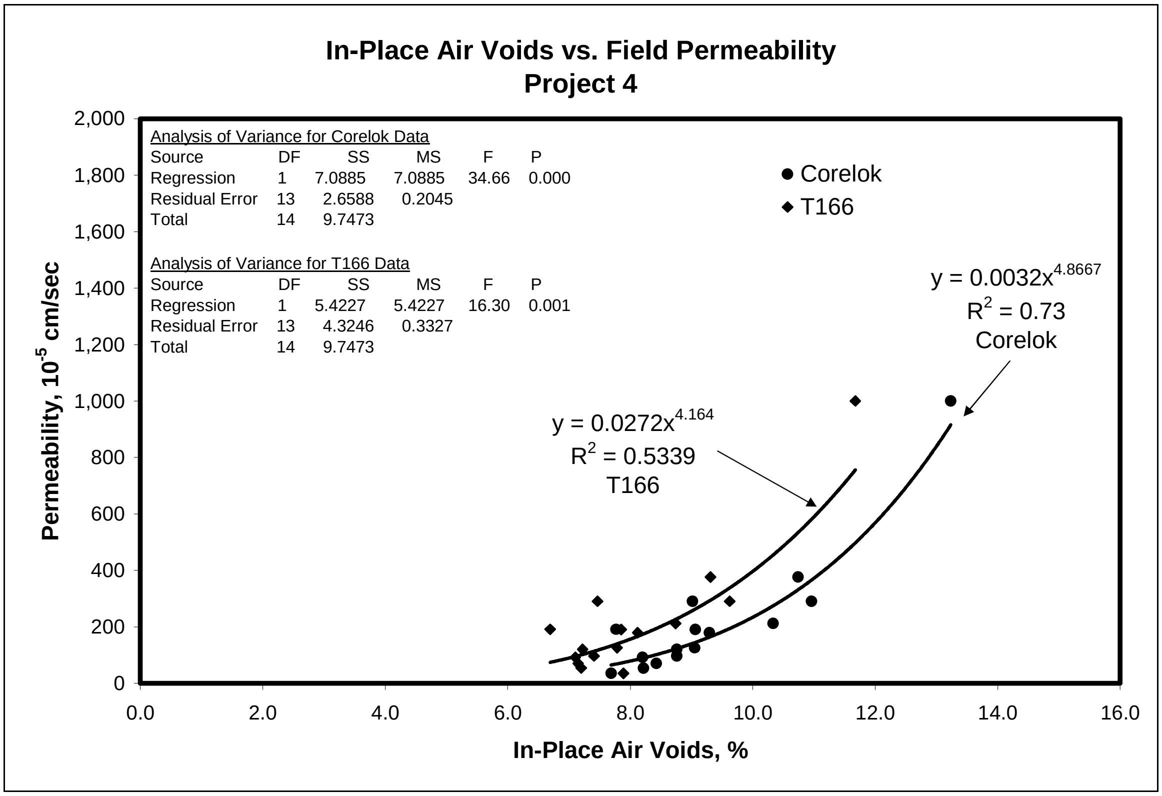

Figure 7: Relationship Between Permeability and In-Place Air Voids, Project 4

Project 5

Project 5 consisted of a coarse-graded 19.0 mm NMAS mix to be placed at a thickness of 63 mm. Results of testing conducted on the 15 test locations from Project 5 are provided in Table 6.

The average thickness for the test locations (57.8 mm) was slightly less than the design thickness of 63 mm. Lift thicknesses ranged from a low of 50.4 mm to a high of 73.1 mm. The standard deviation for lift thickness was 5.6 mm. In-place air voids determined using the Corelok method ranged from a low 5.4 percent to a high of 12.6 percent. The average void level using the Corelok was 8.8 percent and the standard deviation was 2.1 percent. In-place air void contents determined using the AASHTO T166 method ranged from a low of 4.1 percent to a high of 10.4 percent. The average in-place air void content determined using AASHTO T166 was 7.2 percent with a standard deviation of 1.9 percent. On average there was a 1.5 percent difference between air void contents determined using the Corelok and AASHTO T166 methods for Project 5. Permeability values for Project 5 were very high. The average permeability value was 1951x10^{-5} cm/sec. This level of permeability is much higher than the first four projects discussed.

Table 6
Test Results for Project 5

Test Location	Lift Thickness, mm	t/NMAS	VTM, % (Corelok)	VTM, % (T166)	Field Perm. 10^{-5} cm/sec	Water Abs., % (T166)
1	57.74	3.04	7.4	6.3	2,222	1.8
2	64.66	3.40	7.8	6.2	425	1.7
3	73.09	3.85	5.4	4.1	175	1.2
4	55.08	2.90	8.5	7.2	232	1.9
5	53.98	2.84	12.6	10.4	4,407	3.5
6	51.64	2.72	6.4	5.0	288	1.6
7	54.75	2.88	7.8	6.5	374	1.5
8	62.10	3.27	7.8	6.6	1,218	1.7
9	58.17	3.06	11.8	9.5	4,989	4.2
10	56.74	2.99	10.9	9.3	211	4.7
11	55.23	2.91	10.6	9.2	4,200	3.9
12	58.31	3.07	7.2	5.9	207	1.8
13	50.35	2.65	7.6	6.3	218	1.6
14	58.21	3.06	11.2	9.6	1,651	3.5
15	56.16	2.96	8.3	6.5	32	1.9

Figure 8 illustrates the relationships between field permeability and in-place air voids. Four data points are not illustrated on Figure 7. To keep the scale similar to the previously presented relationships between permeability and air voids, the upper limit on the y-axis of Figure 8 was set at a permeability value of 2,000x10^{-5} cm/sec. Test locations 1, 5, 9, and 11 are not shown because permeability values were in excess of 2,000x10^{-5} cm/sec; however, these data were included to develop the regression equations and statistics. The relationships shown in Figure 8 are not strong as the R^2 values were 0.33 (Corelok) and 0.35 (AASHTO T166); however, the relationships were significant. The difference in measured air voids by the two methods used in this study is evident on the figure in that the relationship utilizing the Corelok results are shifted toward higher air void contents. Based upon the regression lines shown in the figure, there is also a difference in what would be considered an in-place air void level that defines excessive permeability. For the Corelok relationship, an in-place air void content of 5.5 percent would provide a 125×10^{-5} cm/sec permeability value. However, for the AASHTO T166 relationship, an in-place air void content of approximately 4.4 percent would provide a permeability level of 125×10^{-5} cm/sec.

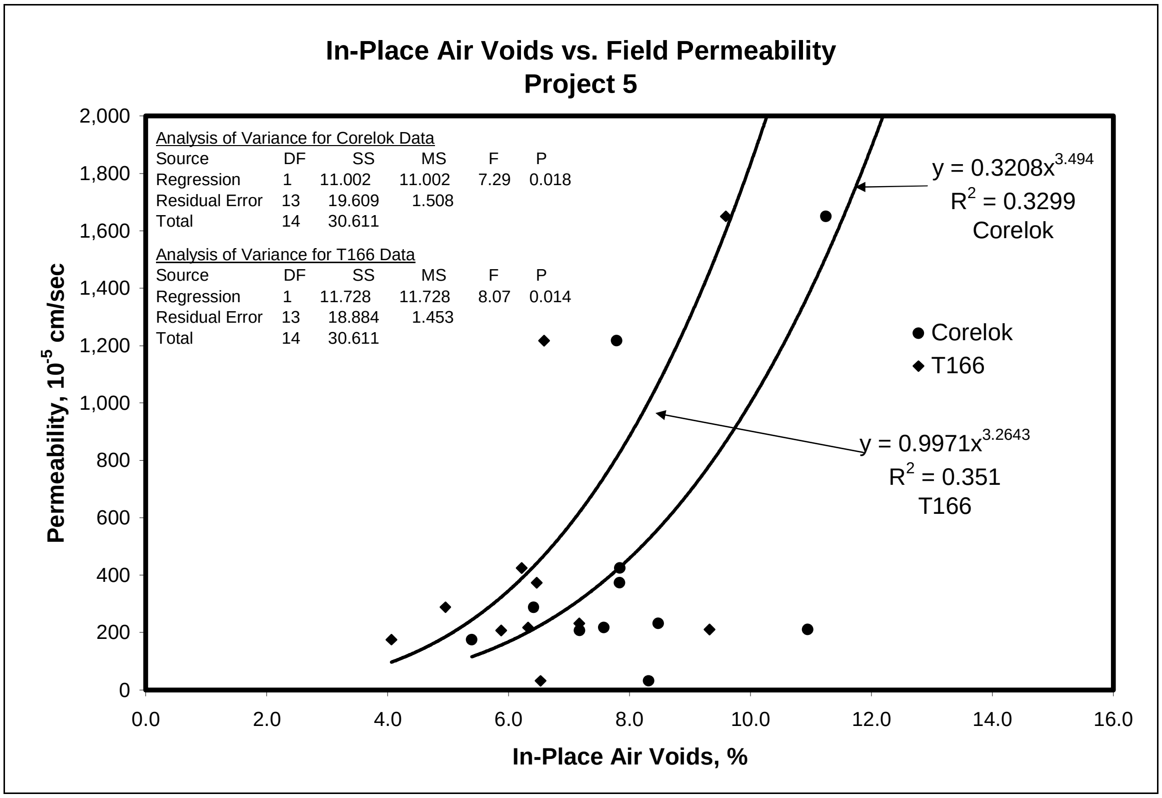

Figure 8: Relationship Between Permeability and In-Place Air Voids, Project 5

Project 6

Project 6 was the second project evaluated that utilized a 19.0 mm NMAS. The HMA for this project had a coarse gradation (passing below the maximum density line at the 2.36 mm sieve) and was to be placed at a lift thickness of 50 mm. Table 7 presents results of testing conducted at the 15 test locations for Project 6.

In-place lift thicknesses for Project 6 ranged from 31.5 mm to 58.8 mm. The average lift thickness was 49.1 mm with a standard deviation of 7.9 mm. This average lift thickness was close to the target of 50 mm. In-place air void contents for project 6 ranged from 6.0 to 13.1 percent as determined using the Corelok method for bulk specific gravity. The average in-place air void content was 9.3 percent and the standard deviation was 2.0 percent. Using the AASHTO T166 method of determining bulk specific gravity, in-place air voids ranged from 4.2 percent to 11.1 percent. The average was 7.5 percent with a standard deviation of 1.8 percent. Based upon the results from the two bulk specific gravity methods, there was an average difference in in-place air voids of 1.8 percent with the Corelok method providing higher values. Field permeability values for Project 6 were high having an average of 898×10^{-5} cm/sec. The range in permeability values was 1 to $4{,}279 \times 10^{-5}$ cm/sec. Only two of the 15 test locations had permeability values less than the 125×10^{-5} cm/sec (locations 1 and 13).

Table 7
Test Results for Project 6

Test Location	Lift Thickness, mm	t/NMAS	VTM, % (Corelok)	VTM, % (T166)	Field Perm. 10^{-5} cm/sec	Water Abs., % (T166)
1	49.50	2.61	7.4	6.0	115	1.2
2	31.52	1.66	13.1	11.1	4,279	4.2
3	58.84	3.10	8.7	6.1	459	1.4
4	53.52	2.82	8.9	7.3	395	1.6
5	44.26	2.33	13.0	9.7	961	2.5
6	52.58	2.77	8.7	6.9	269	1.5
7	45.23	2.38	11.0	9.6	1,386	2.4
8	59.21	3.12	9.6	8.3	656	2.2
9	51.07	2.69	10.5	8.2	813	2.3
10	58.47	3.08	9.8	8.0	1,590	2.0
11	48.15	2.53	8.5	7.0	1,856	1.7
12	51.54	2.71	8.2	6.7	287	1.2
13	40.18	2.11	6.0	4.2	1	0.9
14	52.54	2.77	7.5	6.0	178	1.2
15	39.09	2.06	8.6	6.7	226	1.5

Figure 9 presents the relationships between field permeability and in-place air voids for Project 6. In order to maintain the scale of previous figures showing the relationship between permeability and in-place air voids, a data point is not shown on Figure 9 (test location 2). This test location had a permeability value of $4{,}279 \times 10^{-5}$ cm/sec and would be considered excessively permeable. The regressions equations and statistics shown on Figure 9 do include test location 2. The relationships between permeability and in-place air voids were relatively strong as both had R^2 values above 0.66. Based upon the regression statistics, both regressions were significant. Utilizing the trend lines, the in-place air void content representing a critical field permeability value (125x10^{-5} cm/sec) is different depending upon the method of measuring bulk specific gravity. Corelok results suggest an in-place air void content of 7.7 percent led to excessive permeability. AASHTO T166 results suggest a permeability value near 6.2 percent.

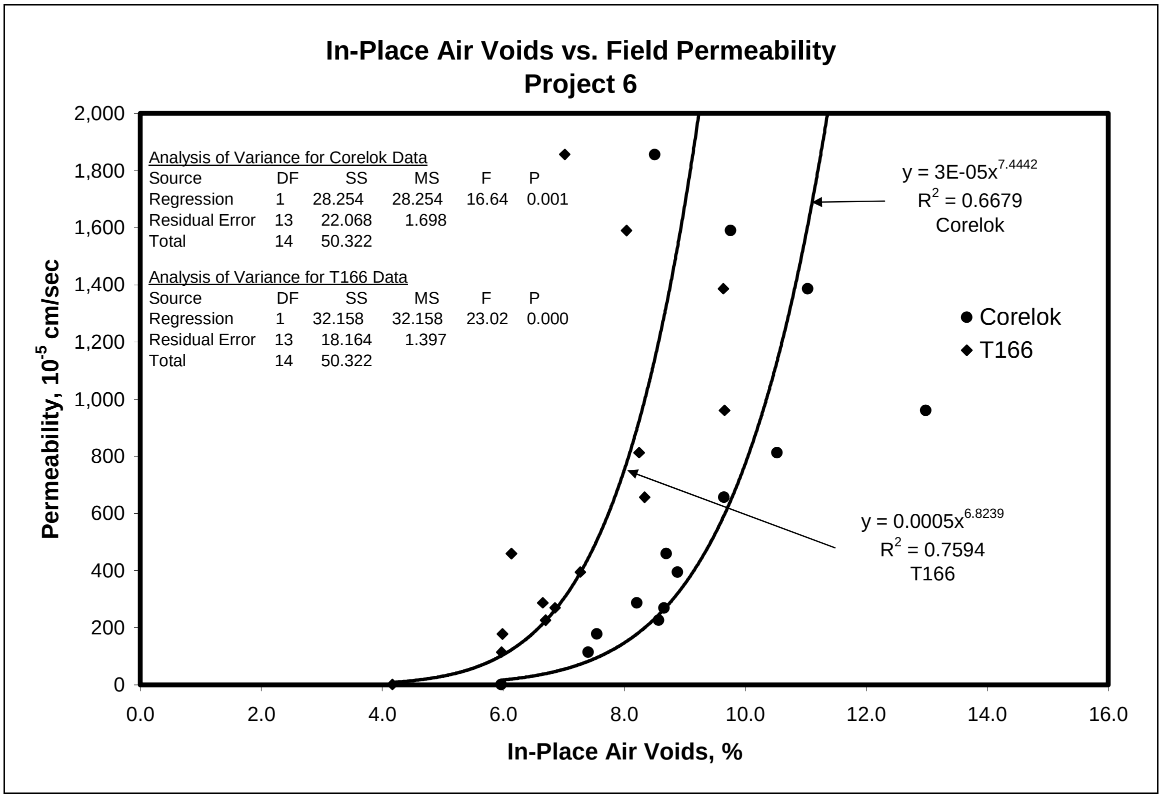

Figure 9: Relationship Between Permeability and In-Place Air Voids, Project 6

Project 7

The mixture used on Project 7 was a coarse-graded 9.5 mm NMAS mix. This mix was to be placed at a lift thickness of 38 mm. Table 8 presents results of testing conducted at the 15 test locations from Project 7.

Based upon the results of testing on Project 7, the placed thicknesses ranged from a low of 31.9 mm to a high of 61.2 mm. The average thickness was 46.1 mm and the standard deviation was 7.3 mm. This average thickness was approximately 8 mm higher than the design lift thickness of 38 mm. In-place air void contents as determined using the Corelok method ranged from a low of 4.5 percent to a high of 15.1 percent. The average in-place air void content using the Corelok bulk specific gravity method was 8.4

percent and the standard deviation was 3 percent. Using the AASHTO T166 bulk specific gravity method, in-place air voids ranged from 3.7 percent to 12.4 percent. The average void content was 7.1 percent and the standard deviation was 2.6 percent. The average difference in in-place air voids for the two methods of measuring bulk specific gravity was approximately 1.3 percent with the Corelok method again providing a higher value. Field permeability values ranged from no measurable flow to a high of 940x10^{-5} cm/sec.

Table 8
Test Results for Project 7

Test Location	Lift Thickness, mm	t/NMAS	VTM, % (Corelok)	VTM, % (T166)	Field Perm. 10^{-5} cm/sec	Water Abs., % (T166)
1	61.15	6.44	4.5	3.7	NF	0.1
2	50.98	5.37	5.6	5.1	NF	0.2
3	50.77	5.34	4.7	4.0	NF	0.2
4	38.48	4.05	8.2	6.7	143	0.3
5	45.91	4.83	6.2	5.1	NF	0.3
6	48.09	5.06	7.2	6.4	28	0.3
7	35.92	3.78	14.0	12.0	625	2.8
8	48.52	5.11	6.6	5.5	43	0.4
9	52.85	5.56	10.6	9.1	527	2.0
10	31.91	3.36	15.1	12.4	940	2.9
11	45.85	4.83	8.3	6.8	161	0.4
12	49.06	5.16	7.3	6.3	38	0.4
13	48.26	5.08	9.5	8.1	327	1.1
14	40.86	4.30	8.0	7.0	91	0.9
15	43.18	4.55	9.9	8.4	382	1.3

NF- No Measurable Flow

The relationships between field permeability and in-place air voids are illustrated in Figure 10. Both regression lines shown on this figure provided strong relationships as the R^2 values were above 0.79. Both relationships were also highly significant (based on ANOVAs) indicating the relationship between permeability and in-place air voids for this project. The two best-fitted lines shown on Figure 10 were very similar up to an in-place air void content of approximately 7 percent. Above this void level, the Corelok method of measuring bulk specific gravity corresponded to higher air void contents at a given permeability level. Based upon the Corelok trendline, the mixture for Project 7 became excessively permeable at 9.5 percent air voids while results using the AASHTO T166 methods indicated a critical in-place air void content of 8 percent.

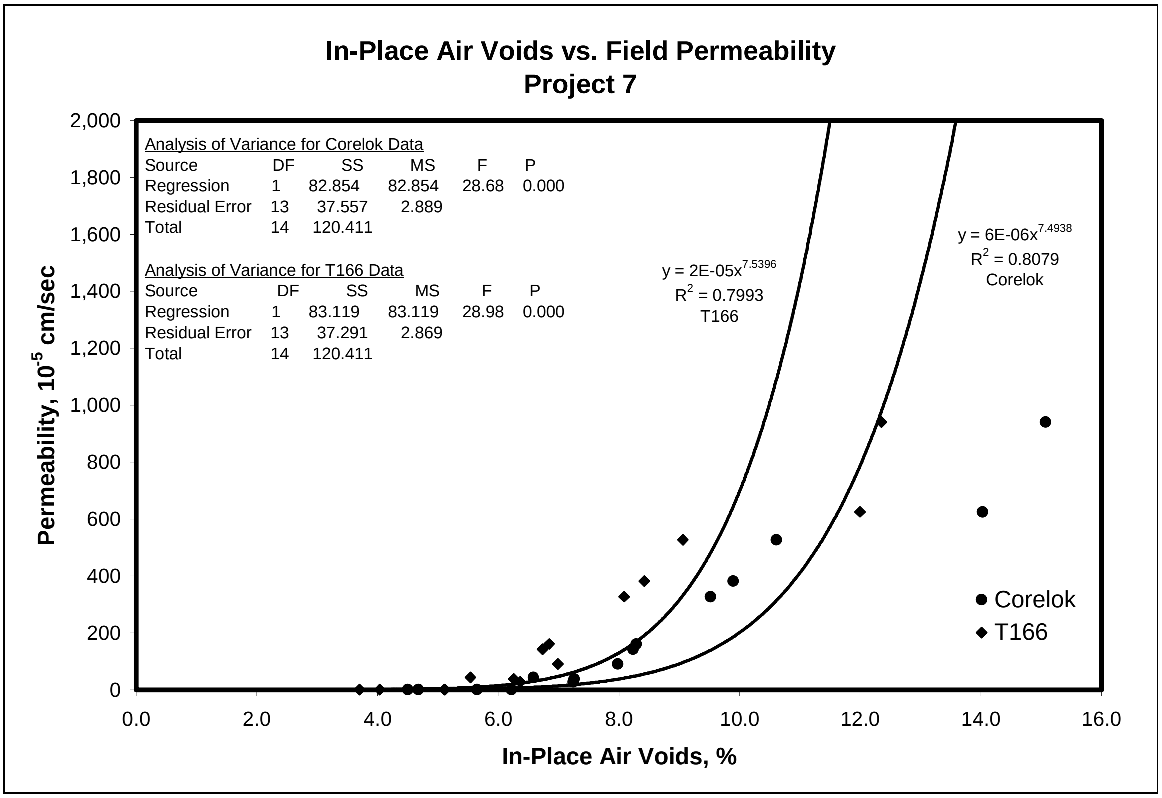

Figure 10: Relationship Between Permeability and Air Voids, Project 7

Project 8

The HMA utilized for Project 8 was a coarse-graded 19.0 mm NMAS mix. A design lift thickness of 75 mm was to be used for this project. Results of testing conducted at the 15 test locations are presented in Table 9.

The average placed thickness for Project 8 was 70.0 mm, which is 5 mm less than the design lift thickness. Lift thickness values ranged from a low of 41.3 mm to a high of 98.4 mm. The standard deviation for lift thickness was 15.5 mm. In-place air voids as determined using the Corelok method ranged from 6.4 to 12.6 percent. The average in-place air voids was 9.4 percent with a standard deviation of 1.6 percent. The range of in-place air voids using the AASHTO T166 method was 5.9 to 9.6 percent. In-place air voids averaged 7.8 percent and had a standard deviation of 1.0 percent. Based upon the two methods of measuring bulk specific gravity, there was an average difference in air void contents of 1.7 percent with the Corelok method again providing larger values. Field permeability results for Project 8 were all very high. All 15 results had values above the recommended critical value of 125x10^{-5} cm/sec. Permeability values ranged from a low of 943 to a high of 17,789x10^{-5} cm/sec with an average value of 7,375x10^{-5} cm/sec.

Table 9
Test Results for Project 8

Test Location	Lift Thickness, mm	t/NMAS	VTM, % (Corelok)	VTM, % (T166)	Field Perm. 10^{-5} cm/sec	Water Abs., % (T166)
1	98.42	5.18	10.1	8.9	4,702	3.8
2	89.57	4.71	9.1	8.2	5,123	3.3
3	80.66	4.25	6.4	5.9	1,103	1.2
4	68.32	3.60	9.2	7.1	7,425	3.0
5	80.69	4.25	8.3	7.2	3,838	2.6
6	72.93	3.84	7.8	6.8	943	1.2
7	64.73	3.41	10.8	8.3	13,342	4.4
8	63.75	3.36	10.7	8.6	13,766	4.8
9	81.59	4.29	8.3	7.2	2,540	2.6
10	75.68	3.98	10.6	8.5	13,477	4.2
11	67.18	3.54	9.6	7.2	16,307	3.8
12	66.71	3.51	7.6	6.8	1,619	1.5
13	47.82	2.52	12.6	9.6	17,789	4.9
14	50.87	2.68	10.2	8.4	7,261	3.5
15	41.28	2.17	10.1	7.7	1,403	2.2

The relationships between field permeability and in-place air voids are illustrated in Figure 11. It should be noted that the scale for Figure 11 is different than the previously presented relationships between permeability and air voids. In the previous figures, the y-axis was limited to 2,000x10^{-5} cm/sec; however, for Project 8 only four of the 15 test locations had permeability results less than 2,000x10^{-5} cm/sec. The relationship between permeability and in-place air voids (for the Corelok data) was reasonably strong as the R^2 value was 0.63. For the relationship using air void contents determined using the AASHTO T166 method, the R^2 was much lower (0.48). This was the first project that such a wide difference in the R^2 values for the two relationships was encountered. One possible reason that the AASHTO T166 relationship had a lower R^2 value is because of the insensitivity of this method when water absorption values are high. As shown in Table 9, water absorption values were generally above 2 percent. Both of the relationships shown in Figure 11 were significant. Based upon the trend lines, it is difficult to determine the in-place air void content at which the pavement became excessively permeable as all 15 data points had high permeability values. However, the in-place air void content at which the pavement provided a permeability value of 125x10^{-5} cm/sec was below 6 percent for both data sets. Extrapolation of the two trendlines toward lower in-place air void contents indicates that the mixes became permeable at 4 percent air voids.

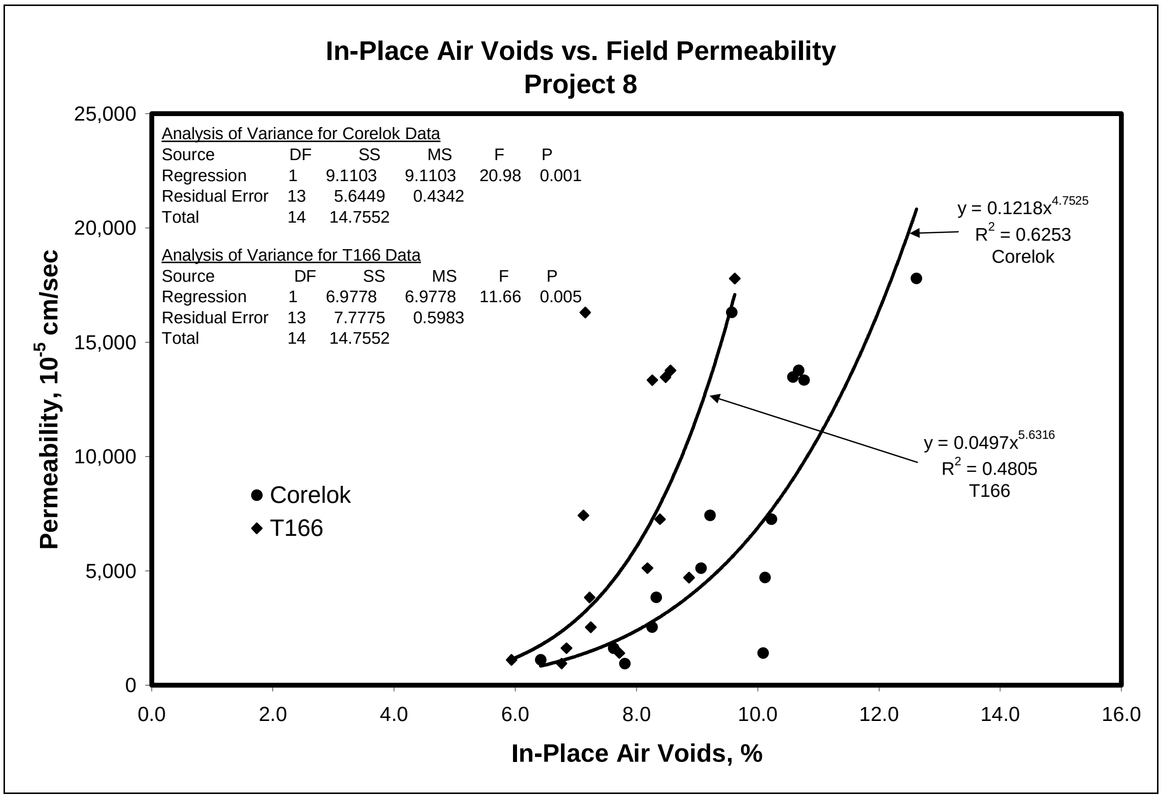

Figure 11: Relationship Between Permeability and Air Voids, Project 8

Project 9

Project 9 entailed the placement of a fine-graded 12.5 mm NMAS mixture. The target lift thickness for this project was 50 mm. Results of testing conducted at the 15 test locations are presented in Table 10.

Results in Table 10 show that the pavement lift thickness ranged from 40.5 to 76.6 mm. The average lift thickness was 56.9 mm and the standard deviation was 10.0 mm. The average lift thickness on the roadway was about 7 mm thicker than the design lift thickness. In-place air voids as determined using the results of Corelok testing ranged from a low of 5.6 to a high of 12.1 percent. The average in-place air void content was 8.5 percent while the standard deviation was 2.0 percent. Bulk specific gravity testing by AASHTO T166 yielded a range of in-place air void contents of 5.5 to 10.0 percent with an average of 7.4 percent and standard deviation of 1.6 percent. Permeability values for the 15 test locations ranged from 1 to 337×10^{-5} cm/sec. The average permeability value was 79×10^{-5} cm/sec.

Table 10
Test Results for Project 9

Test Location	Lift Thickness, mm	t/NMAS	VTM, % (Corelok)	VTM, % (T166)	Field Perm. 10^{-5} cm/sec	Water Abs., % (T166)
1	43.03	3.44	6.5	6.2	5	0.9
2	40.54	3.24	5.6	5.5	1	0.6
3	76.57	6.13	9.1	8.3	101	2.5
4	60.20	4.82	6.7	6.4	23	0.7
5	63.40	5.07	10.4	8.8	86	1.8
6	50.74	4.06	8.1	5.6	6	0.6
7	47.90	3.83	8.9	5.9	34	0.9
8	65.90	5.27	7.0	6.8	76	0.6
9	46.78	3.74	11.5	10.0	337	2.7
10	59.09	4.73	7.1	6.8	27	0.8
11	55.07	4.41	12.1	9.1	200	3.2
12	56.11	4.49	8.4	6.9	24	1.1
13	69.54	5.56	6.4	6.5	23	2.3
14	58.04	4.64	11.1	9.9	218	3.2
15	61.13	4.89	8.9	8.8	22	1.7

Figure 12 illustrates the relationships between permeability and in-place air voids. Both relationships are reasonably strong as the R^2 values are above 0.66. Both relationships were also significant at a 5 percent level of significance (p-value less than 0.05). The best-fitted lines shown on Figure 12 indicate that the pavement tested for Project 9 did not become excessively permeable until the in-place air voids were above 8 percent. This was true for both relationships.

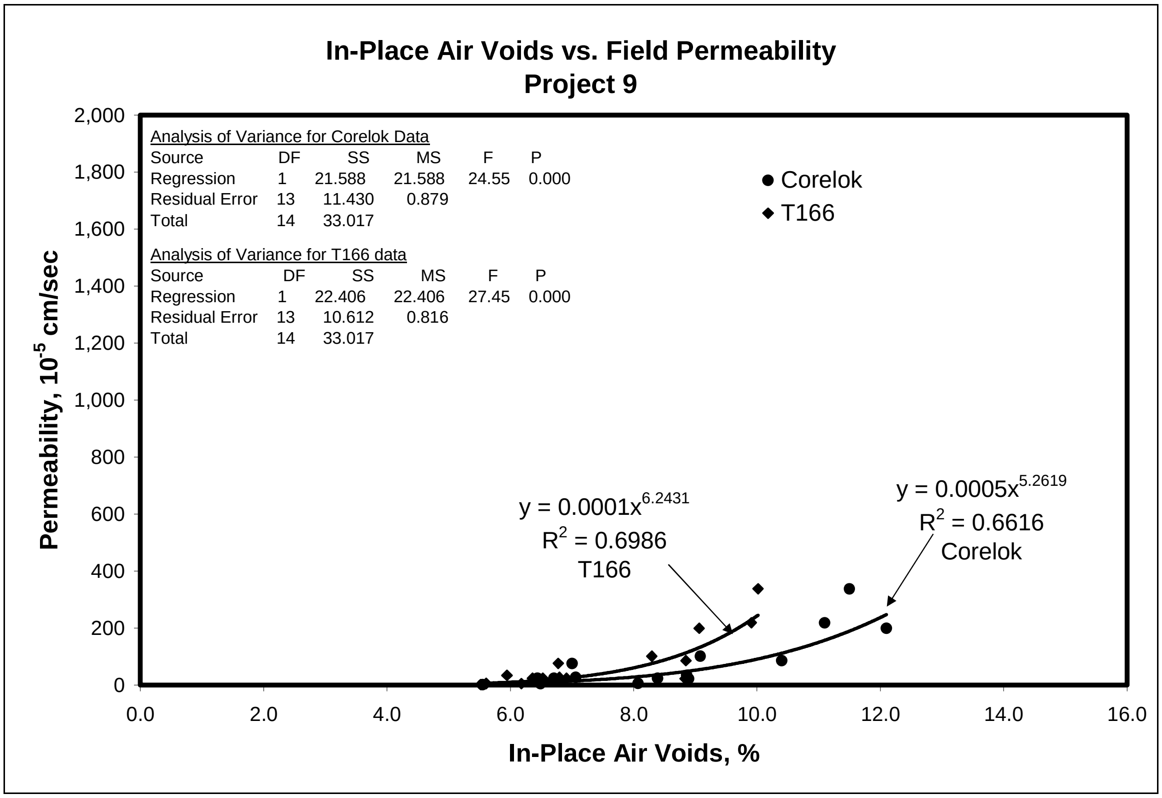

Figure 12: Relationship Between Permeability and Air Voids, Project 9

Project 10

Table 11 presents the results of testing conducted for Project 10. The HMA mixture utilized for this project was a coarse-graded 19.0 mm NMAS. The design lift thickness for this project was 63 mm.

Pavement thickness for Project 10 ranged from 53.9 to 95.9 mm. The average pavement thickness was 70.3 mm while the standard deviation was 10.0 mm. This average thickness was about 7 mm greater than the design lift thickness of 63 mm. In-place air voids determined using the Corelok results ranged from 4.1 to 12.1 percent. The average in-place air void content using the Corelok results was 7.6 percent and the standard deviation was 2.0 percent. In-place air voids determined using the results of AASHTO T166 ranged from a low of 4.3 percent to a high of 9.3 percent. The average air void content was 6.5 percent while the standard deviation was 1.5 percent. For Project 10, the average difference in air void content between the Corelok and AASHTO T166 methods was 1.1 percent with the Corelok results providing higher results. Field permeability results for Project 10 ranged from 2 to 2,285x10^{-5} cm/sec. On average, the field permeability results were 530x10^{-5} cm/sec. Only five of the 15 test locations had permeability values less than the suggested critical value of 125x10^{-5} cm/sec.

Table 11
Test Results for Project 10

Test Location	Lift Thickness, mm	t/NMAS	VTM, % (Corelok)	VTM, % (T166)	Field Perm. 10^{-5} cm/sec	Water Abs., % (T166)
1	63.10	3.32	7.4	7.2	518	1.8
2	72.62	3.82	7.2	6.0	31	1.2
3	75.22	3.96	4.1	4.3	2	0.8
4	80.35	4.23	8.4	6.5	425	1.7
5	71.45	3.76	7.0	5.8	514	1.0
6	84.45	4.44	7.0	6.4	332	1.4
7	70.77	3.72	7.3	6.5	339	1.5
8	84.35	4.44	5.2	4.9	10	0.9
9	61.97	3.26	7.4	5.0	73	1.6
10	58.64	3.09	9.9	9.3	2,285	3.5
11	59.67	3.14	8.6	8.4	910	2.3
12	53.86	2.83	12.1	8.4	2,025	2.8
13	56.85	2.99	8.4	6.6	197	2.0
14	95.88	5.05	5.0	4.8	65	0.9
15	71.79	3.78	9.0	6.7	217	1.5

The relationships between permeability and in-place air void content for Project 10 are illustrated in Figure 13. Two data points are not shown on this figure, test locations 10 and 12, as they had permeability values in excess of 2,000x10^{-5} cm/sec. The relationships shown in Figure 13 both have strong correlations as the R^2 values were above 0.73 and both relationships are significant (ANOVA results). The relationships between permeability and in-place air voids have a similar trend for both methods of measuring bulk specific gravity. However, the relationship using the Corelok data is shifted toward higher air voids. Based upon the Corelok data, the in-place air void content at which the pavement became excessively permeable was approximately 7 percent. For the AASHTO T166 data, the pavement became excessively permeable between 6.2 percent air voids.

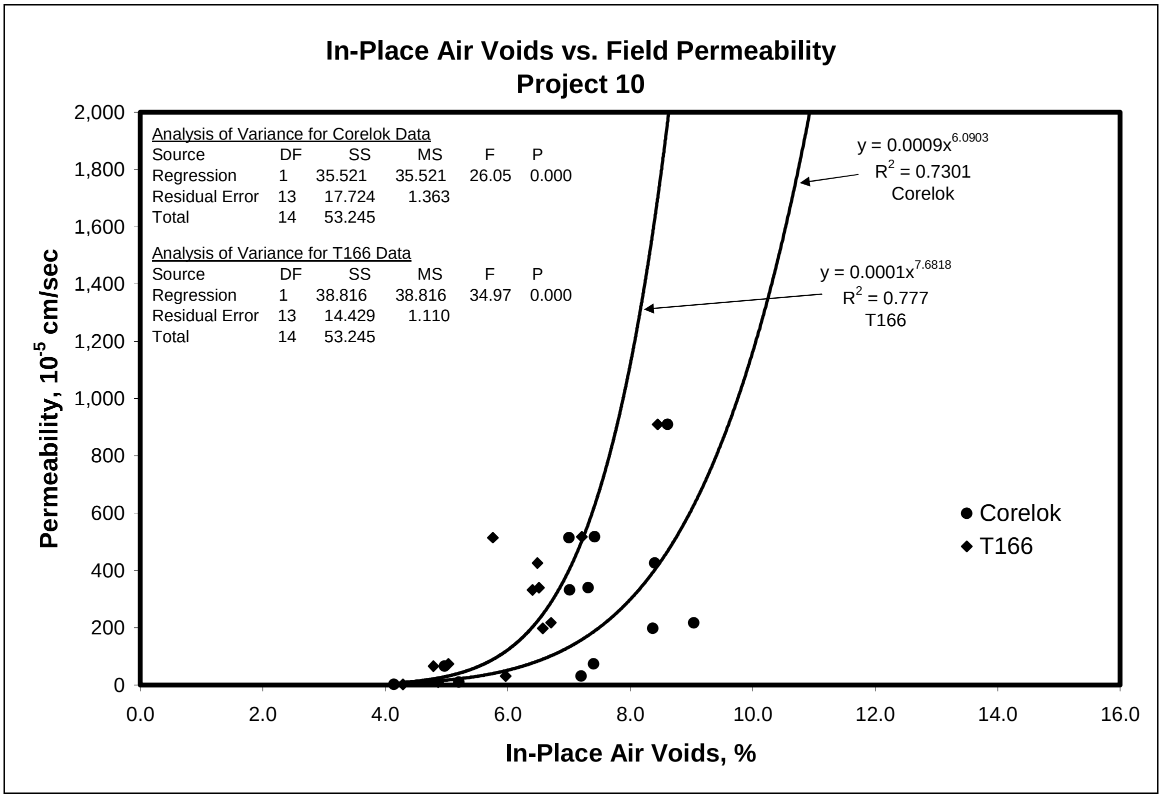

Figure 13: Relationship Between Permeability and Air Voids, Project 10

Project 11

A coarse-graded 19.0 mm NMAS mixture was utilized for Project 11. The mixture was to be placed at a thickness of 63 mm. Table 12 presents results of testing conducted at the 15 test locations for Project 11.

Based upon results of testing conducted on Project 11, the thickness of the placed pavement ranged from 31.9 mm to 61.2 mm. The average lift thickness was 46.1 mm and the standard deviation was 7.3 mm. These results indicate that the mix was placed approximately 17 mm thinner than design. In-place air voids determined using the results from Corelok testing ranged from a low of 6.2 percent to a high of 11.3 percent. The average in-place air void content was 8.7 percent with a standard deviation of 1.3 percent. Based upon AASHTO T166 testing, the in-place air void content ranged from 4.6 to 9.1 percent. The average void content was 6.3 percent while the standard deviation was 1.1 percent. Average voids by the two bulk specific gravity methods differed by 2.4 percent for this project. Permeability values for Project 11 were collectively very high and ranged from 705 to 4,496x10^{-5} cm/sec.

Table 12
Test Results for Project 11

Test Location	Lift Thickness, mm	t/NMAS	VTM, % (Corelok)	VTM, % (T166)	Field Perm. 10^{-5} cm/sec	Water Abs., % (T166)
1	61.15	3.22	9.4	6.2	2,064	3.1
2	50.98	2.68	7.0	4.6	1,003	1.3
3	50.77	2.67	6.2	5.0	1,124	2.0
4	38.48	2.03	8.0	5.9	1,619	2.0
5	45.91	2.42	8.7	7.0	2,816	2.1
6	48.09	2.53	8.5	5.4	1,054	1.8
7	35.92	1.89	9.3	6.8	2,162	2.0
8	48.52	2.55	11.3	9.1	4,496	3.1
9	52.85	2.78	9.8	6.6	3,008	2.1
10	31.91	1.68	8.4	5.9	2,461	1.8
11	45.85	2.41	8.4	6.1	2,874	1.8
12	49.06	2.58	9.3	7.2	3,203	2.2
13	48.26	2.54	9.4	6.7	2,799	2.2
14	40.86	2.15	9.5	7.4	2,497	2.2
15	43.18	2.27	6.9	5.2	705	1.3

Figure 14 illustrates the relationships between permeability and in-place air void content for Project 11. Similar to the figure developed for Project 8 (Figure 11), the y-axis scale is different than for the remaining figures showing permeability versus air voids. For project 11, only five of the 15 test locations had permeability values below 2,000x10^{-5} cm/sec. The two relationships representing the two methods of measuring bulk specific gravity were both relatively strong as the R^2 values were above 0.69. Results of the ANOVAs on the two data sets also showed that the relationships were significant. The best fitted lines shown on Figure 14 both had similar shapes; however, the trendline representing the Corelok data was shifted toward higher air void contents. Based on the two trend lines, it is difficult to determine the in-place air void content that represents permeability value of 125x10^{-5} cm/sec. However, both trendlines suggest that the in-place air void content where the pavement becomes excessively permeable is below 5 percent. Extrapolation of the regression lines indicated that the pavement became excessively permeable at in-place air voids less than 4 percent for both methods of measuring bulk specific gravity.

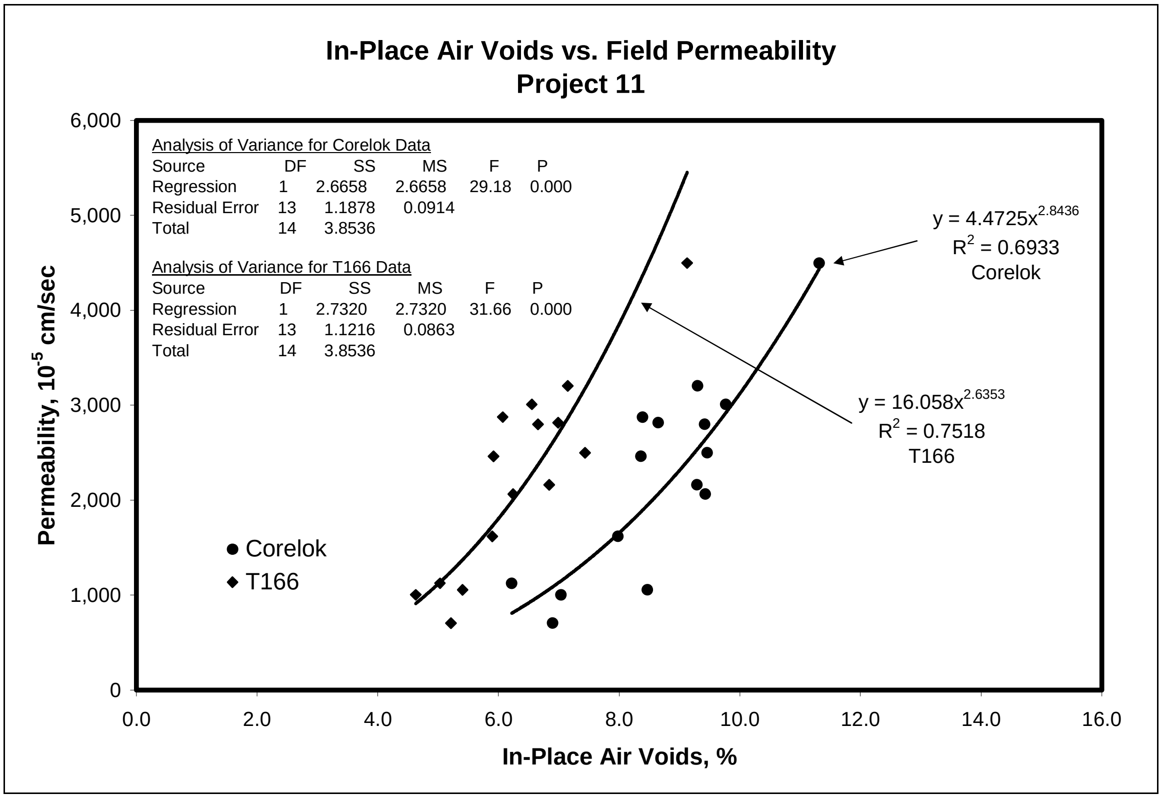

Figure 14: Relationship Between Permeability and Air Voids, Project 11

Project 12

Project 12 utilized a coarse-graded 9.5 mm NMAS mixture that was to be placed 50 mm. For this project, only ten test locations were evaluated. Results of testing on these ten locations are presented in Table 13.

Table 13
Test Results for Project 12

Test Location	Lift Thickness, mm	t/NMAS	VTM, % (Corelok)	VTM, % (T166)	Field Perm. 10^{-5} cm/sec	Water Abs., % (T166)
1	43.60	3.49	8.9	6.8	72	1.4
2	48.90	3.91	10.7	9.0	805	2.9
3	44.50	3.56	7.4	5.5	58	1.1
4	45.70	3.66	13.5	11.6	1712	4.2
5	44.20	3.54	12.3	9.3	725	3.7
6	38.00	3.04	7.8	6.8	266	1.6
7	45.20	3.62	11.4	9.6	2345	3.5
8	43.80	3.50	7.3	6.1	125	1.0
9	42.80	3.42	8.0	6.7	126	1.8
10	40.80	3.26	9.3	8.4	677	1.3

For Project 12, the thickness of the lift placed on the roadway ranged from a low of 38.0 mm to a high of 48.9 mm. The average lift thickness was 43.8 mm while the standard deviation was 2.9 mm. The average lift thickness of 43.8 mm was approximately 6 mm thinner than the design lift thickness of 50 mm. In-place air voids as determined using the results of the Corelok testing ranged from 7.3 to 13.5 percent. The average void level was 9.7 percent and the standard deviation was 2.2 percent. Based upon the AASHTO T166 testing, in-place air voids ranged from 5.5 to 11.6 percent with an average of 8.0 percent and standard deviation of 1.9 percent. Results from Corelok testing resulted in approximately 1.7 percent higher air voids than did results from AASHTO T166 testing. Field permeability results from Project 12 ranged from 58 to $2{,}345 \times 10^{-5}$ cm/sec. The average level of permeability was 691×10^{-5} cm/sec.

Figure 15 illustrates the relationships between permeability and in-place air voids for the ten test locations sampled from Project 12. The data for test location 7 is not shown on the figure in order to maintain the scale at an upper permeability value of $2{,}000 \times 10^{-5}$ cm/sec. Both of the relationships shown on this figure had relatively strong correlations as the R^2 values were above 0.71. Both relationships were also significant as the p-values were less than 0.05. Similar to other data sets, the shapes of the two trend lines were similar; however, the trend line for the Corelok data set is shifted toward higher void levels. Based upon the Corelok data, the mixture became excessively permeable at 7.7 percent air voids. For the AASHTO T166 data set, an in-place air void content of 6.4 percent would define where the pavement had a permeability level of 125×10^{-5} cm/sec.

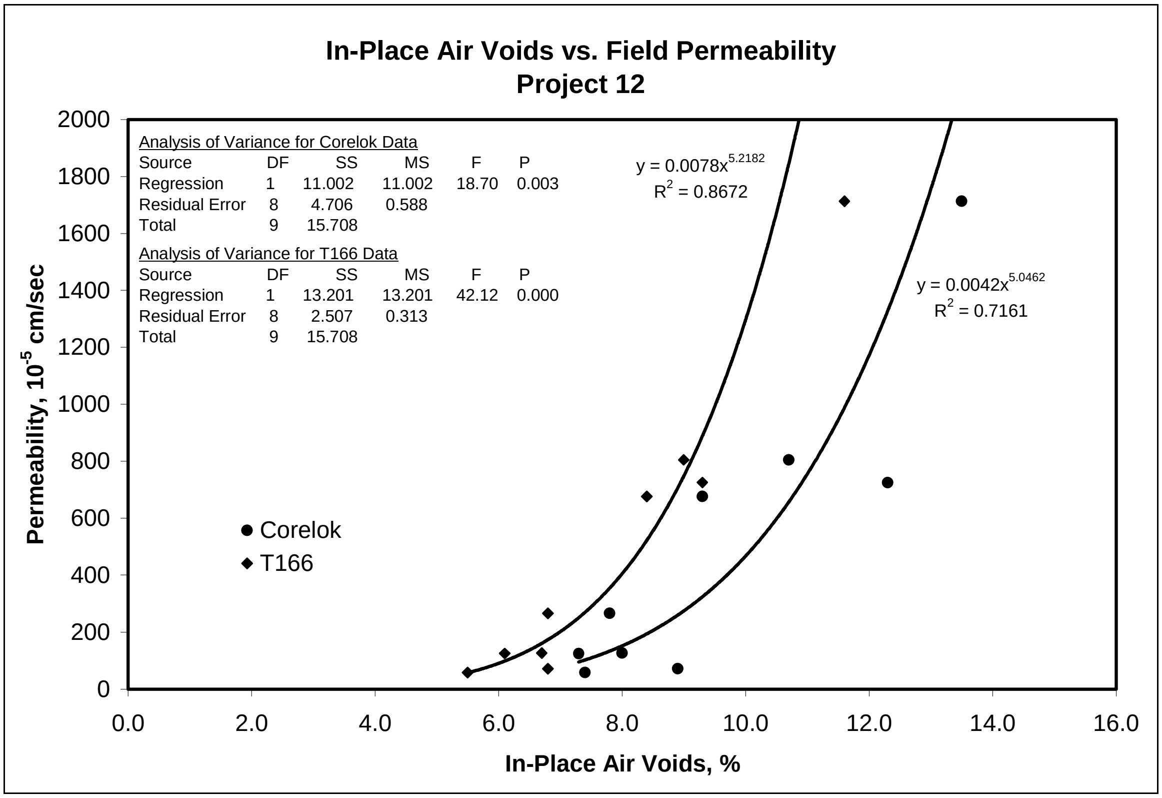

Figure 15: Relationship Between Permeability and Air Voids, Project 12

Project 13

Project 13 was tested as part of NCAT's original field permeability study conducted as a pooled-fund study through the Southeastern Superpave Center. The mixture tested for Project 13 was a coarse-graded 12.5 mm NMAS mix. At the time this study was conducted, the Corelok device was not available. Therefore, bulk specific gravity measurements for the cores obtained from the roadway were only measured using the AASHTO T166 method. Also, no measurements were obtained on the cores in order to determine actual lift thicknesses. Table 14 present the results of testing conducted at the 15 test locations for Project 13.

Table 14
Test Results for Project 13

Test Location	VTM, % (T166)	Field Perm. 10^{-5} cm/sec	Water Abs., % (T166)
1	8.5	140	1.7
2	15.0	2503	5.8
3	7.0	77	1.4
4	7.7	448	2.0
5	4.8	1	0.8
6	4.5	4	0.7
7	8.5	84	2.1
8	5.8	5	0.9
9	3.9	10	0.6
10	8.0	169	1.6
11	4.6	3	0.7
12	5.3	55	0.8
13	5.9	11	0.8
14	6.3	32	0.7
15	3.9	2	0.6

As stated previously, only the AASHTO T166 method was used to determine the bulk specific gravity of cores cut from the roadway. Air void contents based on the AASHTO T166 method ranged from 3.9 to 15.0 percent with an average of 6.6 percent and standard deviation of 2.8 percent. Permeability values ranged from 1 to $2{,}503 \times 10^{-5}$ cm/sec with an average of 236×10^{-5}cm/sec. For the most part, the permeability values were relatively low except for the very high value for test location 2 ($2{,}503 \times 10^{-5}$ cm/sec).

The relationship between permeability and in-place air voids is illustrated in Figure16. The relationship illustrated shows a good correlation between permeability and in-place air voids as the R^2 was 0.79. As would be expected with this high R^2, the relationship was also significant at a 5 percent level of significance. Based upon the trend line, the mixture for Project 13 had a permeability level of 125×10^{-5} cm/sec at an in-place air void content at 8.2 percent.

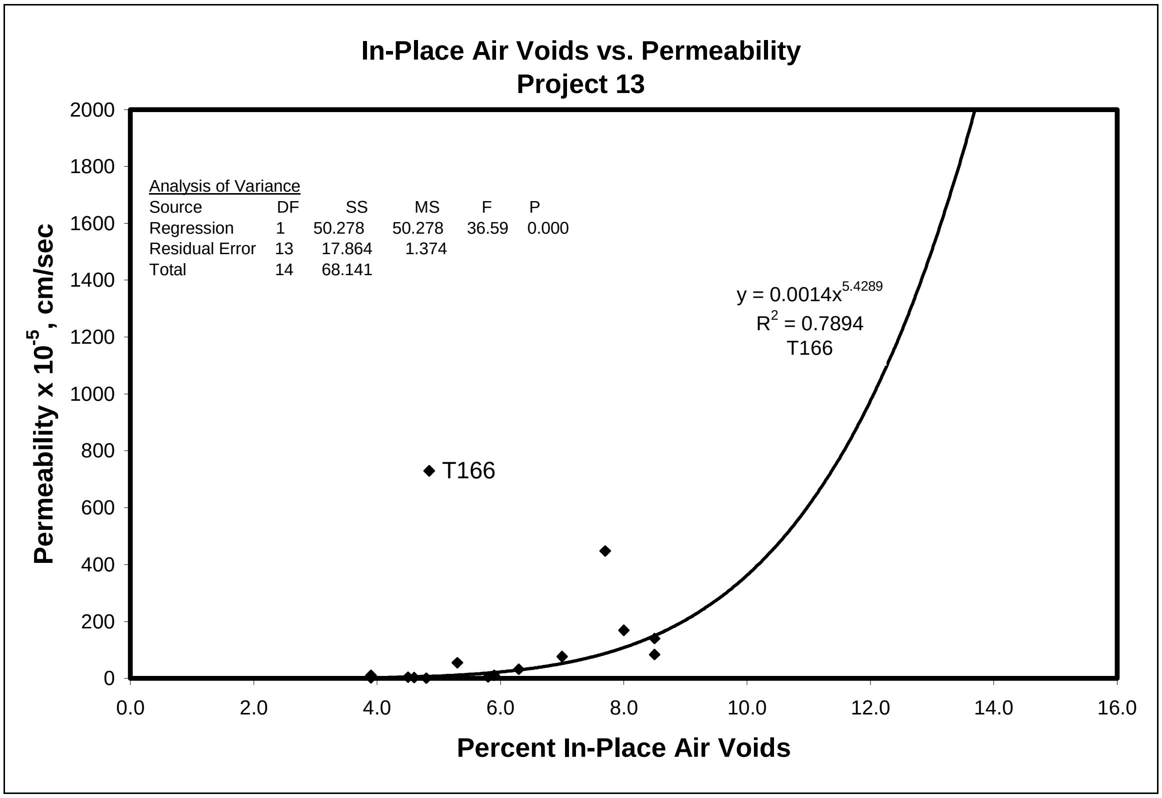

Figure 16: Relationship Between Permeability and Air Voids, Project 13

Combined Data

Within this section, the data was combined to evaluate trends in the permeability characteristics of the pavements tested. Figure 17 illustrates the relationship between permeability and in-place air voids for the 9.5 mm NMAS mixes tested. This figure represents the combined data from three different projects. The common thread between the projects was that all had a 9.5 mm NMAS and all had gradations passing below the maximum density line at the 2.36 mm sieve. Similar to the analyses conducted on the individual projects, this figures shows two relationships (trendlines). One trendline represents air void contents determined using the Corelok method to measure bulk specific gravity and the other trendline represents air voids determined using AASHTO T166. Also similar to previous analyses, the two regression lines had similar shapes; however, the trend line representing the Corelok data was shifted towards higher air void contents. Both relationships had reasonably strong R^2 values as both were above 0.74. Based upon the two trendlines, the in-place air void content at which the combined pavements had a permeability level of 125x10^{-5} cm/sec was between approximately 7.5 and 9.0 percent. For the Corelok trendline, the void level was 8.8 percent and for the AASHTO T166 trend line the void level was 7.6 percent.

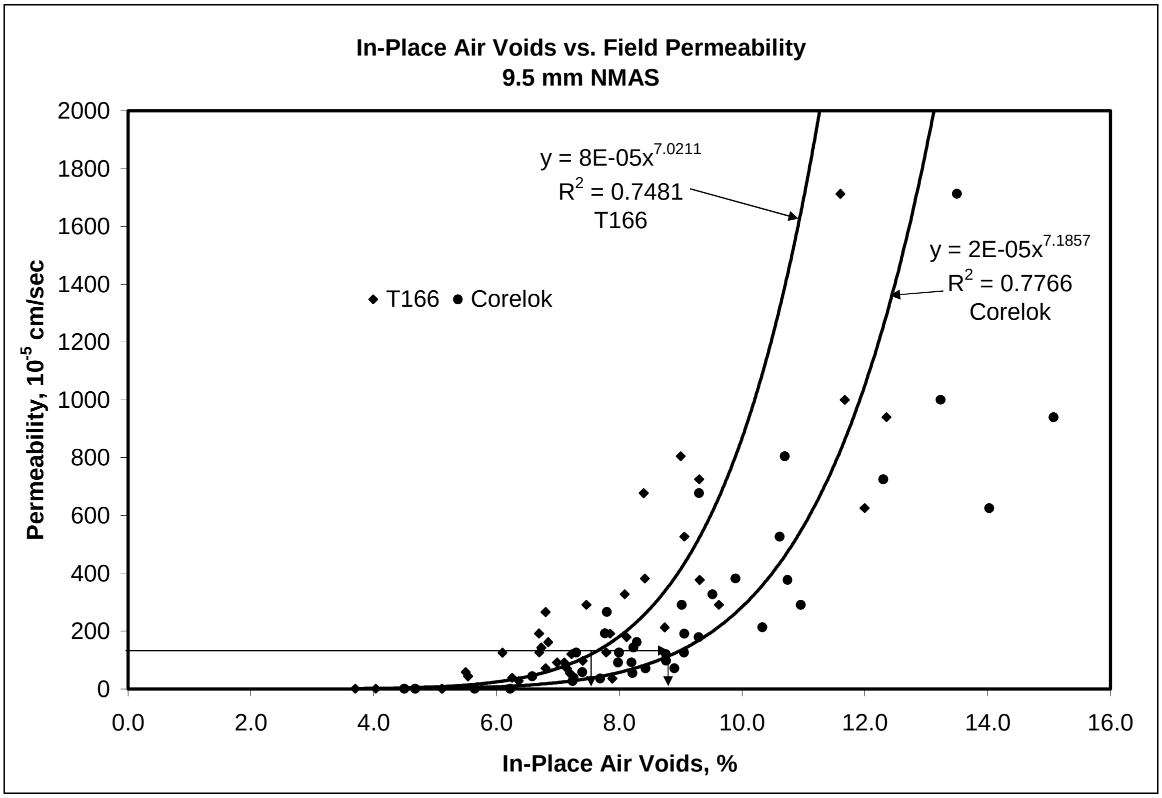

Figure 17: Relationship Between Permeability and Air Voids, 9.5 mm NMAS Mixes

The combined relationships between permeability and air voids for mixes having a NMAS of 12.5 mm are illustrated in Figure 18. Data on this figure represent five different projects. Four of the projects utilized mixes having gradations on the fine side of the maximum density line while the remaining project utilized a coarse-graded mixture. Corelok data were available for only four of the projects. The fifth project (Project 13) was tested prior to the Corelok being developed. Similar to Figure 17, the two trend lines have similar shapes; however, the Corelok trendline is shifted toward higher air void levels. The R^2 values shown in Figure 18 were lower than for the 9.5 mm NMAS mixes (Figure 17) but still represent significant relationships. Based upon the two trend lines, the 12.5 mm NMAS mixes became excessively permeable at an in-place air void content of between 8.5 and 9.5 percent. For the Corelok data, the mixture became excessively permeable at 9.3 percent air voids and for the AASHTO T166 data the mixture became excessively permeable at 8.5 percent.

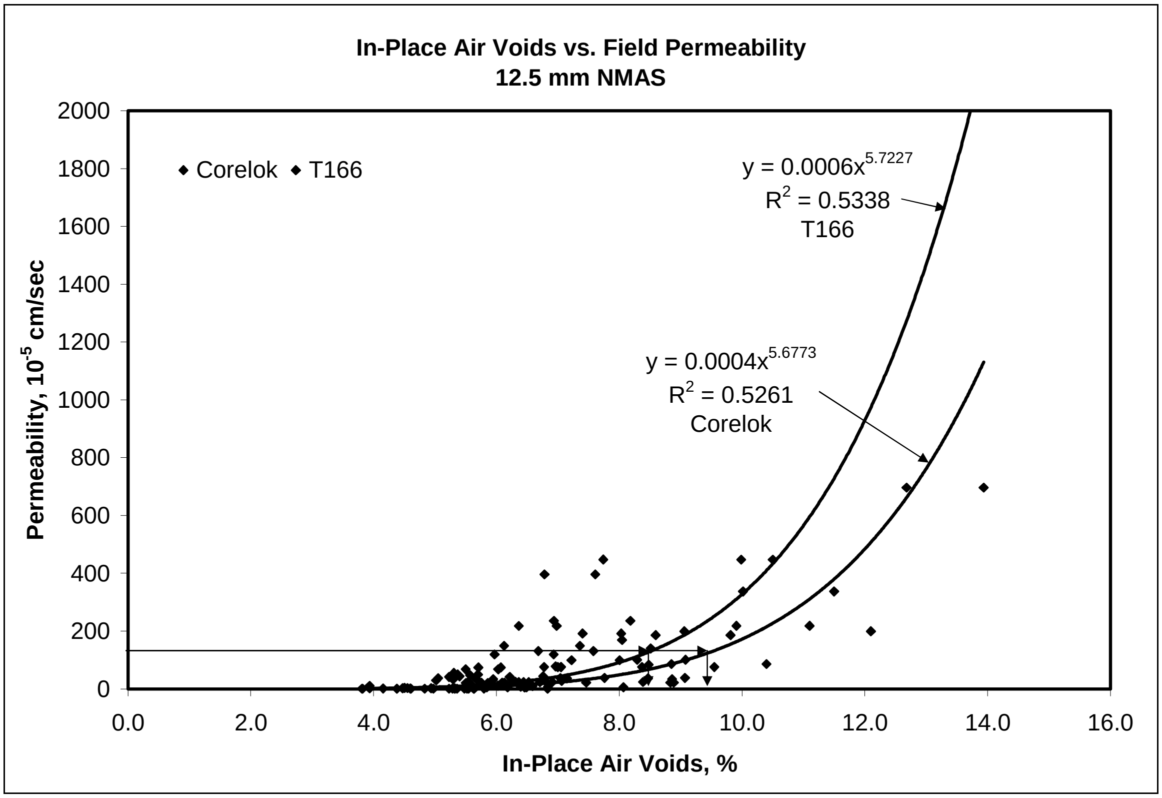

Figure 18: Relationship Between Permeability and Air Voids, 12.5 mm NMAS Mixes

Unlike the 9.5 mm NMAS mix data, the 12.5 mm NMAS mix data allowed for a comparison between the permeability characteristics of coarse- and fine-graded mixes. One project used a coarse-graded mix (Project 13) while there were four projects utilizing fine-graded mixes (Projects 1, 2, 3, and 9). Figure 2 presented the different gradation shapes. This comparison is illustrated in Figure 19. As stated previously, only AASHTO T166 was used to determine bulk specific gravity of the cores from Project 13. Therefore, results shown in Figure 19 only represent air void contents determined using AASHTO T166. Based upon Figure 19, the permeability characteristics were similar for both gradation types. The trendlines representing the two gradation types fell almost on top of each other indicating similar permeability characteristics. It should be pointed out; however, that this is a limited comparison as only one coarse-graded mix was included.

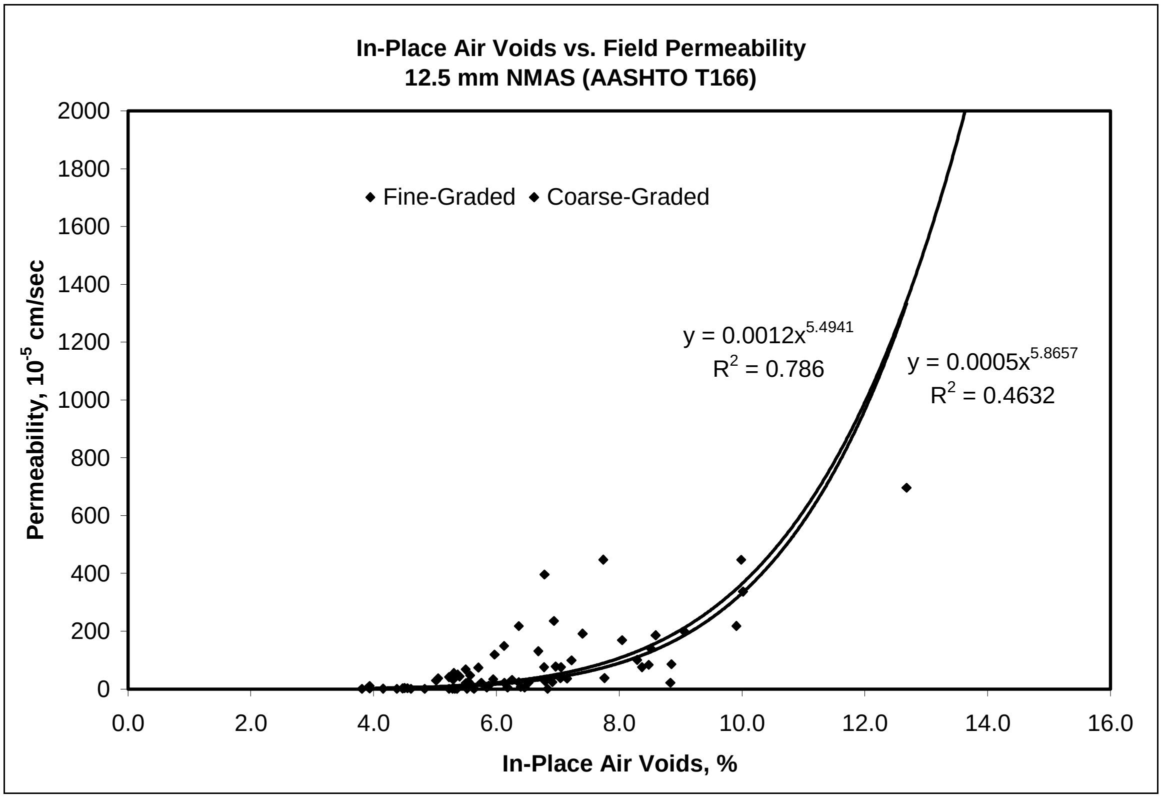

Figure 19: Comparison Between Coarse- and Fine-Graded Mixes, 12.5 mm NMAS

Five 19.0 mm NMAS mixes were tested during the course of this study. All five of the mixes were coarse-graded. The combined relationships between permeability and air voids for these five mixes are illustrated in Figure 20. Both Corelok and AASHTO T166 testing were conducted for all five projects. Again, the shapes of the trendlines shown in Figure 20 were similar, but the Corelok data was shifted toward higher air voids. Based on the relationships, the 19.0 mm NMAS mixes became excessively permeable (greater than $125x10^{-5}$ cm/sec) at in-place air voids between about 5 and 6 percent. The Corelok data suggests an in-place air void content of 6.2 percent to define excessive permeability, while the AASHTO T166 data indicates 4.8 percent in-place air voids.

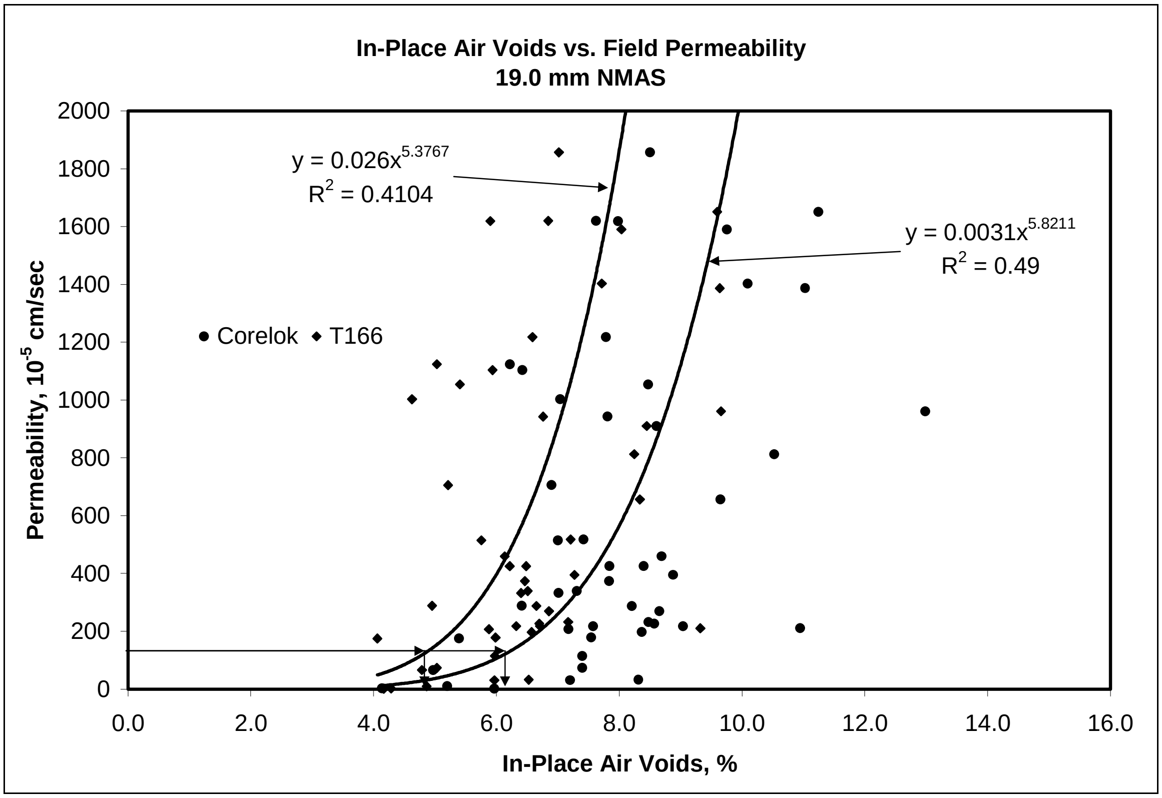

Figure 20: Relationship Between Permeability and Air Voids, 19.0 mm NMAS Mixes

Based upon Figures 17, 18 and 20, there was an obvious effect of NMAS on the permeability characteristics of the pavements. Figure 21 summarizes this effect as it illustrates the combined data for the 9.5, 12.5, and 19.0 mm NMAS mixes. In-place air voids determined using the Corelok method are illustrated on this figure. Based upon this figure, the 9.5 and 12.5 NMAS mixes had a similar relationship between permeability and air voids up to in-place air voids of about 9 percent. At a given air void level, the 19.0 mm NMAS mixes were much more permeable than the 9.5 and 12.5 mm NMAS mixes. Therefore, it can be concluded from the data that NMAS does have an effect on the permeability characteristics of a pavement.

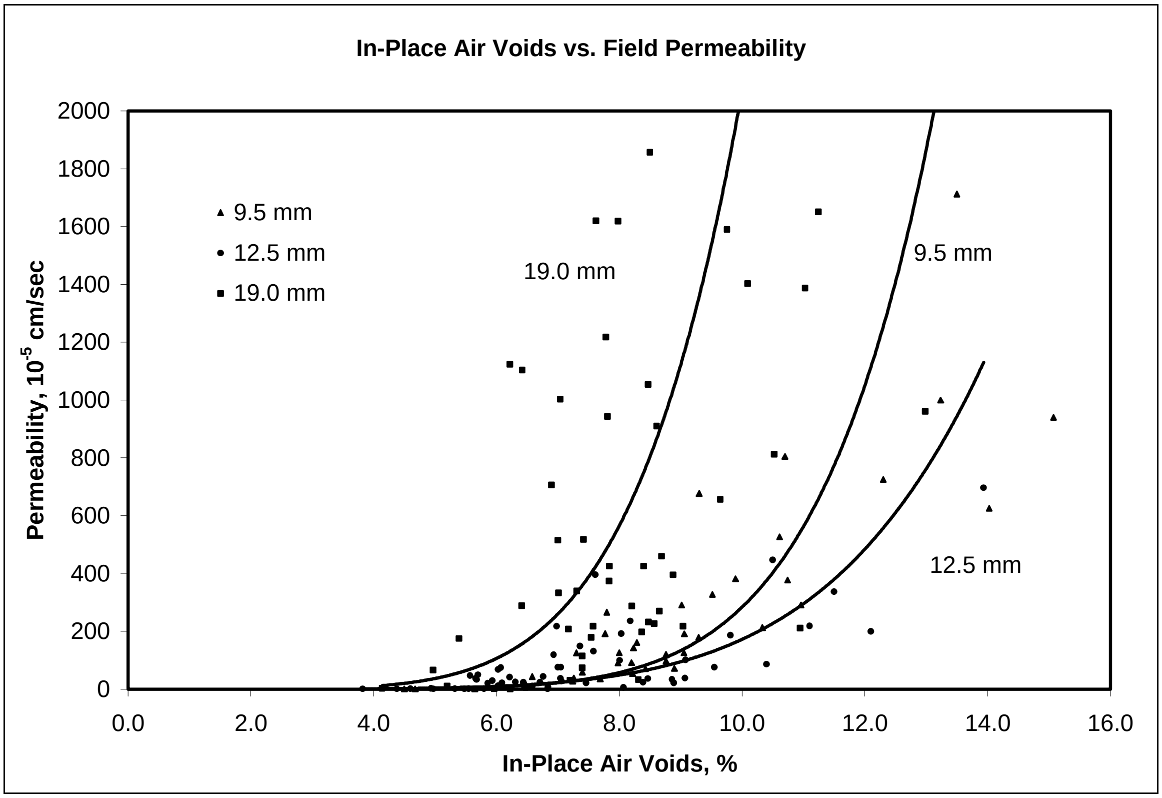

Figure 21: Effect of Nominal Maximum Aggregate Size on Permeability

Based upon the discussions of the individual and combined projects, it is obvious that a number of the pavements evaluated during the course of this study were permeable. Therefore, it would be beneficial to the Department to have a method to identify when a pavement may be too permeable without the need for running permeability tests. One possible method would be to evaluate the amount of water absorption during AASHTO T166 testing to provide an indication of permeability.

Figure 22 illustrates the relationship between permeability and water absorption (by volume) for all of the data obtained from this study. This figure indicates that there is a relationship between permeability and water absorption. The R^2 for this relationship is reasonable (0.60) and the results of the ANOVA for the regression indicate that the relationship is significant (p-value less than 0.05). Based upon the trend line, once the water absorption value reaches approximately 1 percent the pavement became excessively permeable (125×10^{-5} cm/sec).

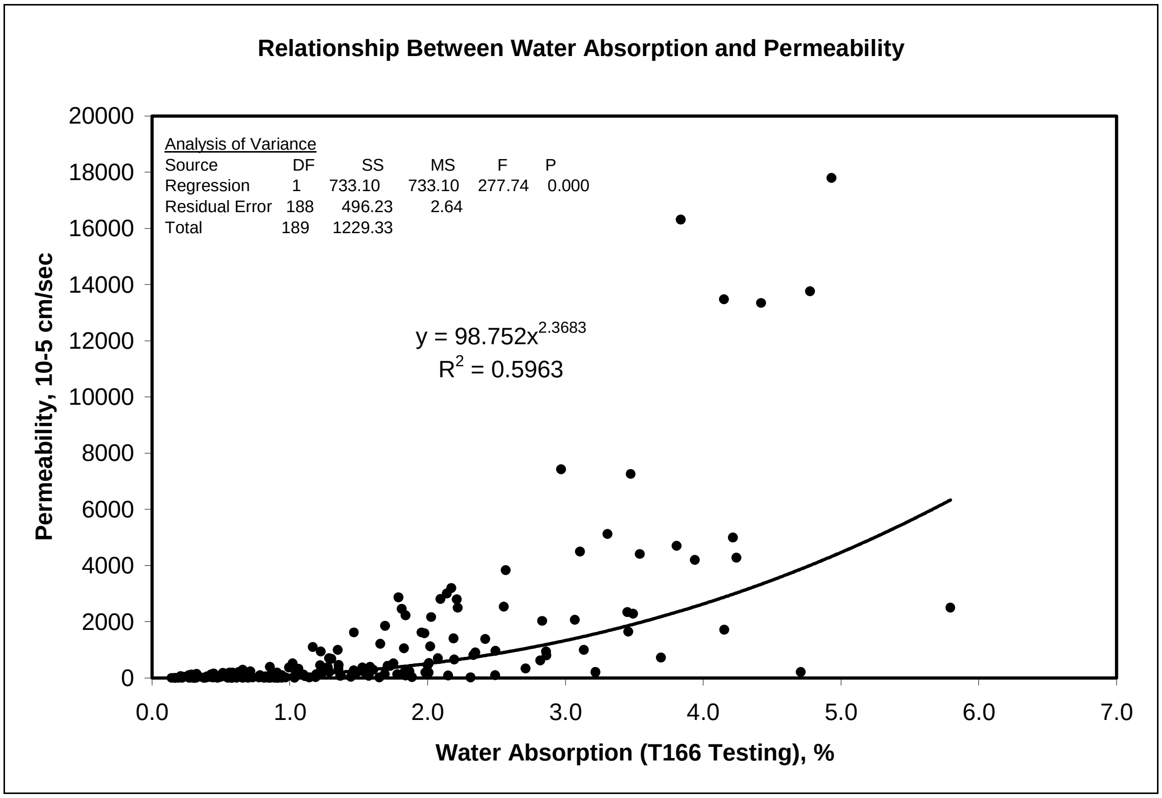

Figure 22: Relationship Between Permeability and Water Absorption

Two factors that may affect this relationship between permeability and water absorption are NMAS and gradation shape (coarse- and fine-graded mixes). Within this study, three different NMAS gradations were tested; however, there was not a sufficient number of mixes having the same NMAS with differing gradation shapes. Figures 23, 24, and 25 present the relationships between permeability and water absorption for the 9.5, 12.5, and 19.0 mm NMAS projects. The regression lines developed for all three NMASs were significant. However, the R^2 values for the 9.5 and 19.0 mm NMAS mixes were higher (0.66 and 0.58, respectively) than for the 12.5 mm NMAS mixes (0.30). Also, there was a much wider range in absorption values for the 9.5 and 19.0 mm NMAS mixes which was likely an effect of gradation shape. Figure 24 shows that for the 12.5 mm NMAS mixes, the majority of absorption values were below 1 percent. This would be expected since most of these mixes were fine-graded. All of the 9.5 and 19.0 mm NMAS mixes had coarse gradations resulting in larger individual air voids. The larger individual air voids increase the potential for the interconnected voids that allow water to penetrate into the sample (or flow through the sample).

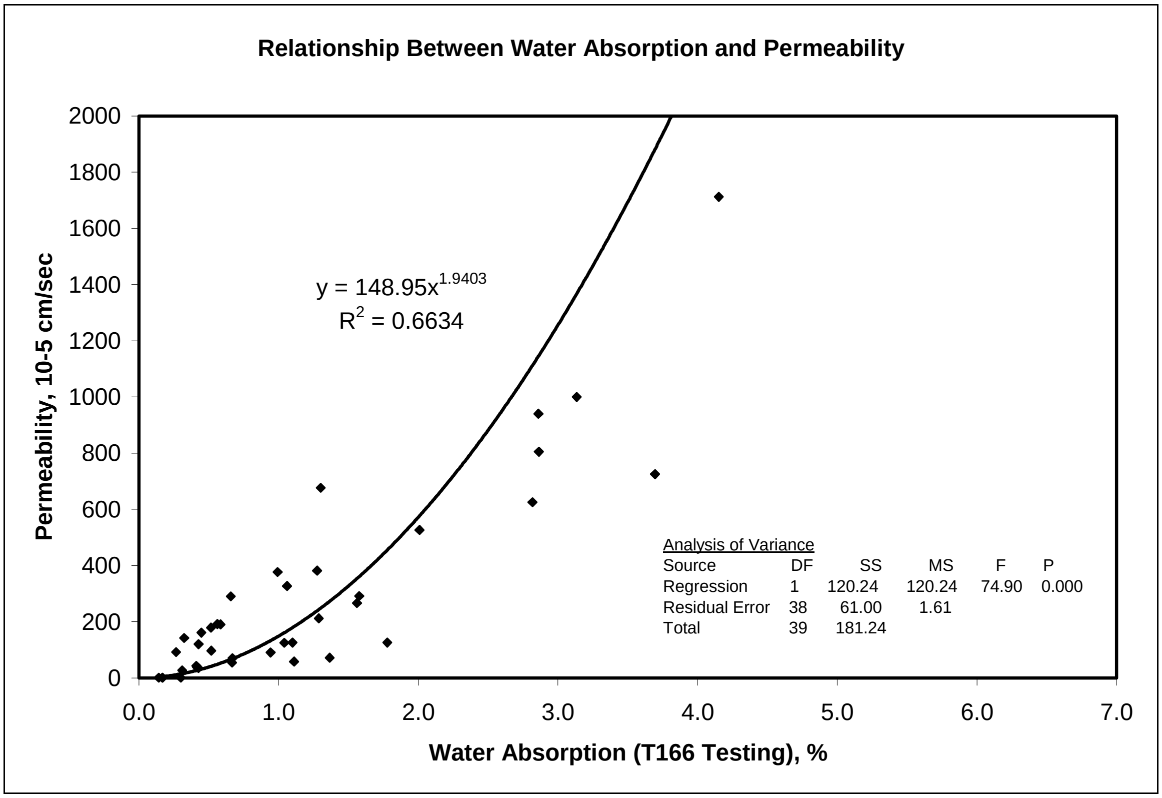

Figure 23: Relationship Between Permeability and Water Absorption, 9.5 mm NMAS Mixes

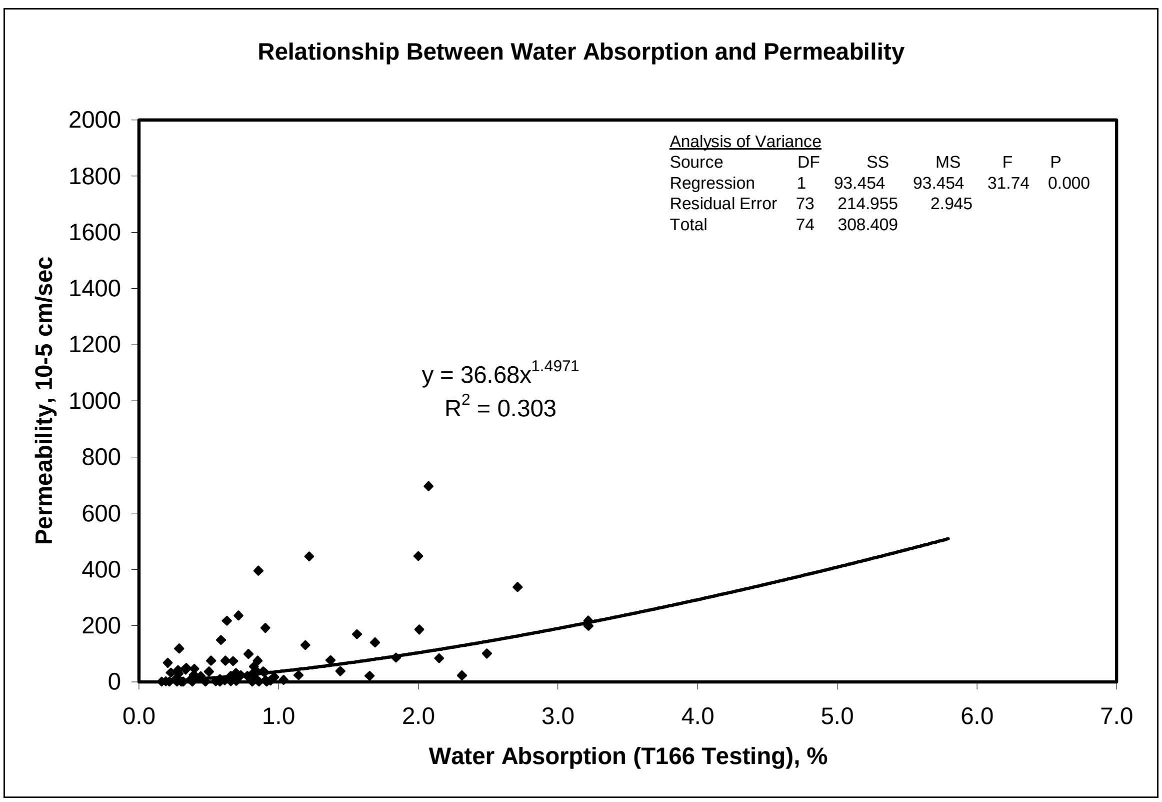

Figure 24: Relationship Between Permeability and Water Absorption, 12.5 mm NMAS Mixes

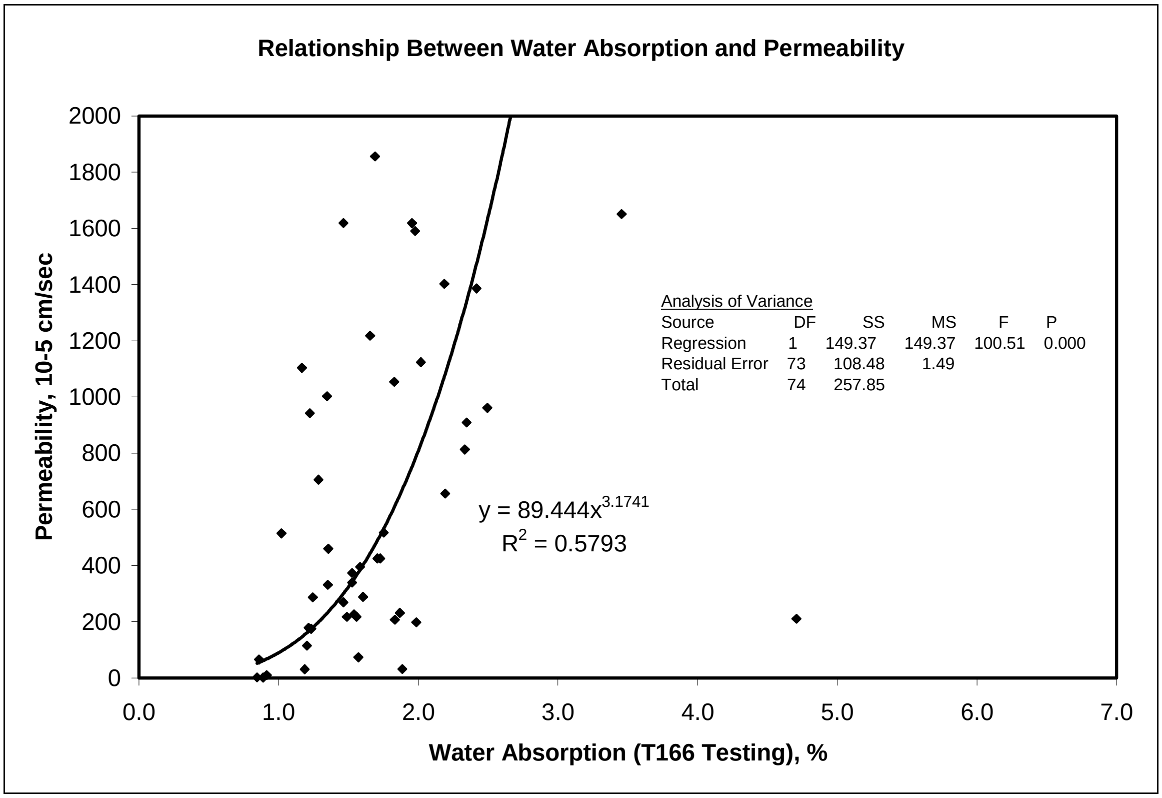

Figure 25: Relationship Between Permeability and Water Absorption, 19.0 mm NMAS Mixes

Based upon the regression lines in Figures 23 through 25, the value of water absorption related to a permeability value of 125×10^{-5} cm/sec was dependent on the NMAS and gradation shape. For 9.5 mm coarse-graded mixes (Figure 23), a water absorption value of 0.9 percent would define when a pavement becomes excessively permeable. Therefore, if cores were cut from a 9.5 mm coarse-graded mix, the bulk specific gravity measured in accordance with AASHTO T166, and the resulting water absorption value was 0.9 percent or higher, then it would be reasonably expected the pavement was excessively permeable. A similar value was obtained for the 19.0 mm NMAS mixes (Figure 25) which were also all coarse-graded (1.1 percent absorption). For the 12.5 mm NMAS mixes (Figure 24), four of the five mixes being fine-graded, a water absorption value of 2.3 percent would define when a pavement becomes excessively permeable. Therefore, use of a water absorption value to identify excessively permeable pavements should be used with caution as gradation shape does affect the relationship.

Comparison of Air Voids Determined Using Corelok and AASHTO T166 Methods

Recently, there has been a lot of discussion about potential problems in measuring the bulk specific gravity of compacted HMA mixes having coarse gradations using the AASHTO T166 method. The potential problem in measuring the bulk specific gravity of mixes having coarse gradations comes from the internal air void structure within these mix types. These types of mixes tend to have larger internal air voids than finer graded mixes, at similar overall air void contents. Mixes with coarser gradations have a much higher percentage of large aggregate particles. At a certain overall air void volume, which is mix specific, the large internal air voids of the coarse mixes can become interconnected. This was shown in the previous discussions within this report on the permeability characteristics of pavements. During bulk specific gravity testing with the AASHTO T166 method, water can quickly infiltrate into the sample through these interconnected voids. However, when removing the sample from the water bath to obtain the saturated-surface dry condition the water can also drain from the sample quickly. This draining of the water from the sample is what causes errors when using the SSD method. The net result when the water drains from the sample is that the bulk volume of the sample is underestimated.

Buchanan (*10*) recently reported on a comparison between the Corelok vacuum sealing device and other more conventional G_{mb} methods that included: AASHTO T166, parafilm, and dimensional methods. This comparison indicated that the vacuum-sealing method could be used to determine G_{mb} with greater accuracy than the conventional methods when samples are at low densities (i.e., high air voids). This vacuum-sealing device utilizes an automatic vacuum chamber (shown in Figure 26a) with a specially designed plastic bag, which tightly conforms to the sides of the sample (shown in Figure 26b) and prevents water from infiltrating into the sample.

Figure 26a. Vacuum-Sealing Device **Figure 26b. Sealed Sample**

In addition to Buchanan (_10_), Hall *et al* (_11_) and Cooley et al (_12_) have also indicated that the Corelok method is a viable option for determining the bulk specific gravity of compacted HMA. Hall *et al* indicated that the within-lab (operator) variability for the Corelok method was less than the SSD method. Based on two separate round-robin studies, Cooley *et al* (_13_) and Spellerberg *et al* (_14_) both suggested that the vacuum-sealing method was slightly more variable than AASHTO T166; however, both round-robin studies noted that a portion of the participating laboratories had little experience with the Corelok equipment and test procedure prior to the round-robin. A provisional ASTM test method, ASTM PS131-01, "Bulk Specific Gravity and Density of Compacted Bituminous Mixtures Using Automatic Vacuum Sealing Method," has been developed for the vacuum-sealing test method,

Because of the potential problems in measuring bulk specific gravity using AASHTO T166 for coarse-graded mixes (which included most of the projects evaluated in this study) and the fact that the Corelok method was also used on 12 of the 13 projects, a brief comparison between the methods is provided. A direct comparison between the two bulk specific gravity methods is illustrated in Figure 27. Data within this figure represent all samples obtained during this study except for Project 13 where only the AASHTO T166 method was utilized. The data is presented as air voids to normalize the results based upon different aggregate types, gradations, asphalt contents, etc.

Based upon Figure 27, the two methods appear to provide similar results below about 5 percent air voids. However, once the air void content becomes higher than 5 percent, the Corelok method provided higher air void contents. As the amount of water absorption increased, the difference in air voids determined by the two methods also increased. Interestingly, the R^2 value for the relationship between air voids was high (0.87) even though data from twelve independent projects were included. Another interesting observation about Figure 27 is that the regression line does not provide a slope of 1.0. The slope of the relationship was 0.7503. If the slope term were close to 1.0, then there would be a constant offset between the results of the Corelok and AASHTO T166.

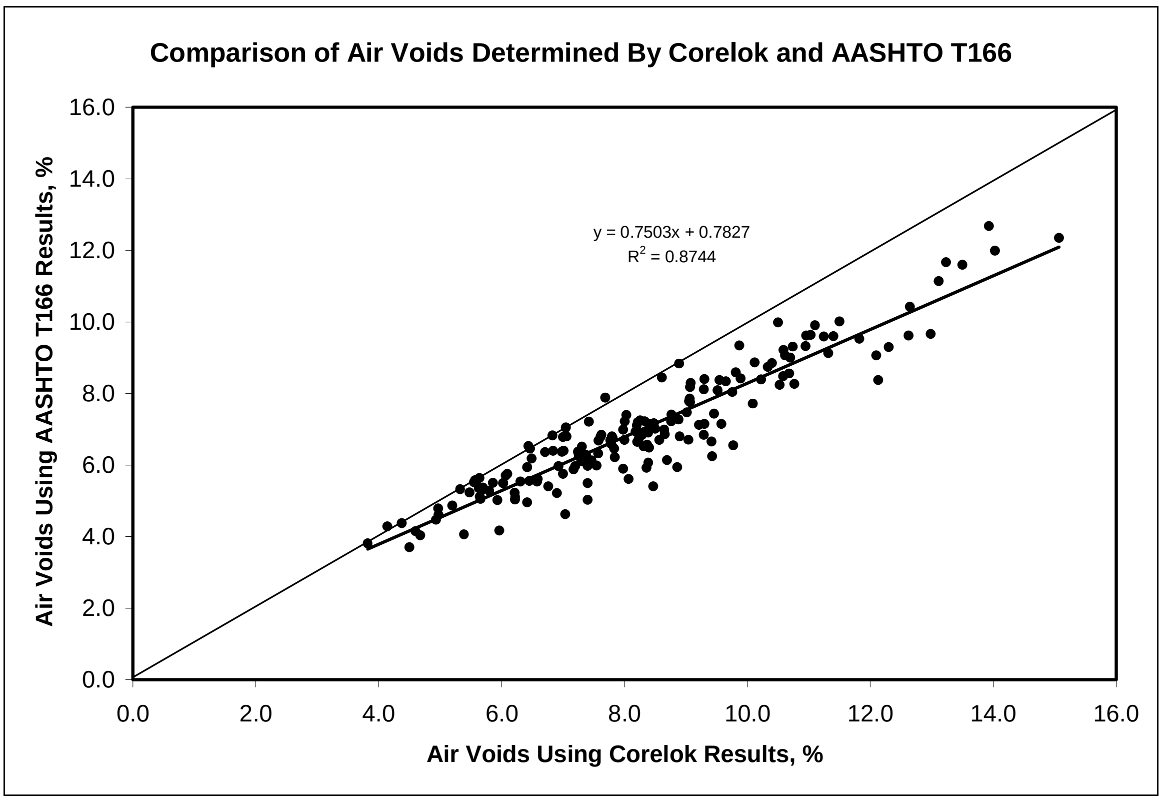

Figure 27: Comparison of Air Voids Determined Using the Corelok and AASHTO T166 Methods

The results shown in Figure 27 are interesting in that as air voids decrease, the two methods provided more similar results. Previously, the potential problems associated with measuring the bulk specific gravity of samples using AASHTO T166 were discussed. Samples having high air void contents likely have large voids interconnected to the sample surface.

To further analyze the field data paired t-tests were conducted to compare air void contents resulting from the two methods of measuring bulk specific gravity, by project. This analysis was conducted for Projects 1 through 12. Results of the paired t-tests are presented in Table 15.

Table 5
Results of Paired t-Tests for Field Projects

Project	NMAS/ Grad.[1]	Avg. T166 Air Voids, %	Avg. Corelok Air Voids, %	Avg. Diff. (Corelok-T166), %	t-Value	p-value	Different?
1	12.5F	6.3	6.7	0.4	3.31	0.005	Yes
2	12.5F	5.5	6.1	0.6	5.27	0.000	Yes
3	12.5F	6.7	7.5	0.8	9.55	0.000	Yes
4	9.5C	8.1	9.3	1.2	10.87	0.000	Yes
5	19.0C	7.2	8.7	1.5	16.78	0.000	Yes
6	19.0C	7.5	9.3	1.8	13.46	0.000	Yes
7	9.5C	7.1	8.4	1.3	8.76	0.000	Yes
8	19.0C	7.8	9.4	1.7	8.41	0.000	Yes
9	12.5F	7.4	8.5	1.1	3.90	0.002	Yes
10	19.0C	6.5	7.6	1.1	4.10	0.001	Yes
11	19.0C	6.3	8.7	3.3	15.62	0.000	Yes
12	9.5C	8.0	9.7	1.7	8.55	0.000	Yes

[1] Nominal Maximum Aggregate Size and Gradation Shape (C- coarse graded, F-fine graded)

Results from the paired t-tests indicated that the two methods of measuring bulk specific gravity yielded significantly different air void contents for each of the 12 projects evaluated. The average differences in air voids were greater for the 9.5 and 19.0 mm NMAS mixes than for the 12.5 mm NMAS mixes. This may have been caused by the gradation shapes of the different mixes. All of the 9.5 and 19.0 mm NMAS mixes were coarse-graded while all of the 12.5 mm NMAS mixes were fine-graded (the one coarse-graded 12.5 mm NMAS mix [Project 13] was not included because Corelok testing was not utilized). This observation supports the hypothesis that coarse-graded mixes have a higher potential for error (if the Corelok method is assumed to be closer to correct) during bulk specific gravity testing using the AASHTO T166 method. The coarser gradations have larger air voids that can become interconnected and allow water to quickly enter and drain from a sample during testing.

One possible method of determining whether an excessive amount of water enters a given sample during AASHTO T166 testing would be to evaluate the amount of water absorbed by the sample during testing. This analysis would not provide an exact measure of the volume of water that enters and exits a sample, but rather would provide a measure of the potential. As water absorption increases, the potential for errors should also increase. Figure 28 presents the relationship between air voids determined by the two bulk specific gravity methods and water absorption. As shown on the figure, both methods of measuring bulk specific gravity produced similar air void contents at low levels of water absorption. As the water absorption level increases, the two bulk specific gravity methods provide larger differences in air voids.

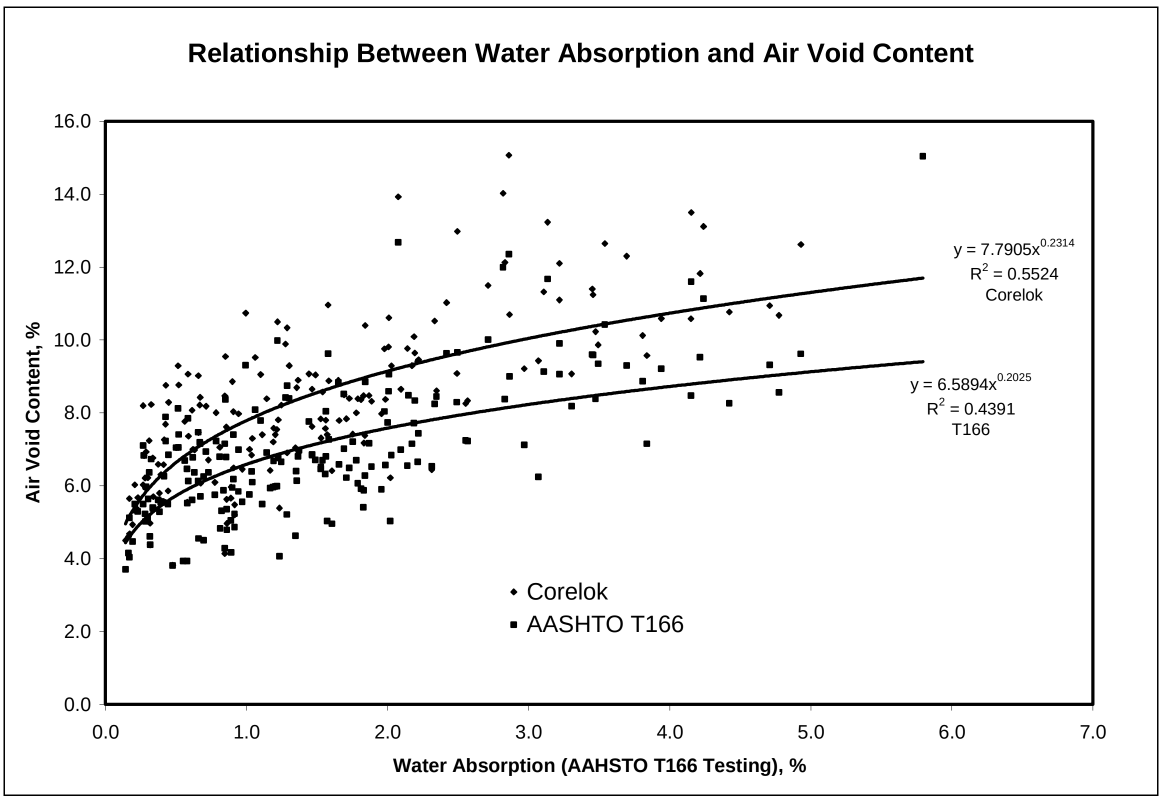

Figure 28: Relationship Between Air Void Content and Water Absorption

CONCLUSIONS AND RECOMMENDATIONS

The primary objective of this study was to evaluate the permeability characteristics of HMA pavements constructed in Mississippi. A secondary objective was to compare the AASHTO T166 and vacuum-sealing methods for determining bulk specific gravity of field compacted samples. Based upon the research results and analyses, the following are concluded:

1. There is a significant relationship between the permeability and pavement density (air voids). This relationship is dependent on both nominal maximum aggregate size and gradation.
2. Mixes having a nominal maximum aggregate size of 9.5 mm became excessively permeable at in-place air voids of 8.8 percent based upon the Corelok data and 7.6 percent for the AASHTO T166 data. Mixes having a 12.5 mm nominal maximum aggregate size became excessively permeable at 9.3 percent air voids based upon Corelok testing and 8.5 percent for the AASHTO T166 data. Mixes having a nominal maximum aggregate size of 19.0 mm became excessively permeable at 6.2 percent based upon Corelok testing, while the AASHTO T166 data indicated 4.8 percent in-place air voids. Of the mix types tested during this study, only the fine-graded 12.5 mm nominal maximum aggregate size mixes would be expected to be impermeable (assuming a critical permeability level of 125×10^{-5} cm/sec) at typical density specifications (8 percent in-place using AASHTO T166 results).
3. There is a significant relationship between permeability and water absorption as measured by AASHTO T166 on cores cut from a roadway. The relationship appears to be more related to gradation shape than nominal maximum aggregate size. For coarse-graded mixes, a water absorption value of approximately 1 percent would define a point where a pavement becomes excessively permeable.
4. Air void contents resulting from the testing of core samples using Corelok and AASHTO T166 bulk specific gravity methods were significantly different. The Corelok method resulted in significantly higher air void contents.

On the basis of the conclusions of this study, it is recommended that field permeability testing be used as a quality control for pavement density on selected HMA projects. This testing should initially shadow current density specifications to determine the usefulness of the field permeability device to control construction practices. It is also recommended that the Department further evaluate the use of the Corelok vacuum-sealing device for measuring the bulk specific gravity of field compacted samples.

REFERENCES

1. F.L. Roberts, P.S. Kandhal, E.R. Brown, D.Y. Lee, and T.W, Kennedy. Hot Mix Asphalt Materials, Mixture Design, and Construction. NAPA Education Foundation, Lanham, MD. Second Ed., 1996.

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

3. E.R. Brown, R. Collins, and J.A. Brownfield. “Investigation of Segregation of Asphalt Mixtures in the State of Georgia.” Transportation Research Record 1217, 1989.

4. B. Choubane, G.C. Page, and J.A. Musselman. “Investigation of Water Permeability of Coarse Graded Superpave Pavements.” Association of Asphalt Paving Technologists, Volume 67 (1998).

5. M.C. Ford, and C.E. McWilliams. “Asphalt Mix Permeability.” University of Arkansas, Fayettville, AR, 1988.

6. S.B. Hudson, and R.L. Davis. “Relationship of Aggregate Voidage to Gradation.” Association of Asphalt Paving Technologists, Volume 34 (1965).

7. R.B. Mallick, L.A. Cooley, Jr., and M. Teto. “Evaluation of Permeability of Superpave Mixes in Maine, Final Report. Technical Report ME-001, November 1999.

8. L.A. Cooley, Jr. “Permeability of Superpave Mixtures: Evaluation of Field Permeameters.” National Center for Asphalt Technology, NCAT Report 99-1, February 1999.

9. L.A. Cooley, Jr. and E.R. Brown. “Selection and Evaluation of a Field Permeability Device for Asphalt Pavements.” Transportation Research Record 1723, 2000.

10. M.S. Buchanan. “An Evaluation of Selected Methods for Measuring the Bulk Specific Gravity of Compacted Hot Mix Asphalt (HMA) Mixes.” Association of Asphalt Paving Technologists, Volume 69 (2000).

11. K. D. Hall, F. T. Griffith, and S. G. Williams. Examination of Operator Variability for Selected Methods for Measuring Bulk Specific Gravity of Hot-Mix Asphalt Concrete. In *Transportation Research Record 1761*, TRB, National Research Council, Washington D. C. 2001.

12. L.A. Cooley, Jr. and B.D. Prowell. "Comparison of the Saturated Surface-Dry and Vacuum Sealing Methods for Determining the Bulk Specific Gravity of Compacted HMA." Prepared for the 2003 Meeting of the Association of the Association of Asphalt Paving Technologists. (To be published in Volume

13. Cooley, Jr., L.A., B.D. Prowell, M.R. Hainin, M.S. Buchanan, and J. Harrington. "Bulk Specific Gravity Round-Robin Using the Corelok Vacuum Sealing Device." FHWA Report No. FHWA-IF-02-044. National Center For Asphalt Technology Report No. 02-11. November 2002.

14. Spellerberg, P., D. Savage, J. Pielert. "Precision Estimates of Selected Volumetric Properties of HMA Using Non-Absorptive Aggregate." National Cooperative Highway Research Program Web Document 54 (Project D9-26): Contractor's Interim Report. February 2003.