NCAT Report 02-06

ISSUES PERTAINING TO THE PERMEABILITY CHARACTERISTICS OF COARSE-GRADED SUPERPAVE MIXES

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ABSTRACT

In order to evaluate the relationships between in-place air voids, lift thickness, and permeability, 23 on-going HMA construction projects were visited and field permeability tests conducted. Field permeability tests were conducted at 15 randomly determined locations for each project. Cores were taken at each of the 15 locations to determine pavement density using AASHTO T166. In addition, for some of the projects, cores taken from roadway were tested with the Corelok device and a laboratory permeameter.

As agencies begin to include permeability specifications, mix designers need tools they can use during the mix design process to evaluate the permeability characteristics of a given aggregate structure. Two techniques were evaluated: laboratory permeability measurements on samples compacted using the Superpave gyratory compactor and water absorption determined with AASHTO T 166 or the Corelok device.

Results of testing within this study indicated a good relationship between permeability (measured in the field and lab) and pavement density. Both the gradation's nominal maximum aggregate size (NMAS) and the lift thickness placed in the field were shown to affect the permeability-density relationship. Increasing the NMAS requires higher densities to ensure an impermeable pavement. Also, as the lift thickness of a given pavement (and mixture) increases, permeability decreases at a given density level.

Some reasonable relationships were found between the permeability of samples compacted using the gyratory compactor and field samples. Reasonable relationships were also found between permeability and water absorption regardless of nominal maximum aggregate size.

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INTRODUCTION

It is important in the construction of hot mix asphalt (HMA) that the mix be adequately compacted in-place so that the initial permeability is low and there will not be significant additional densification under traffic. For dense-graded mixes, numerous studies have shown that initial in-place air void content should not be below approximately 3 percent or above approximately 8 percent (*1*). Low in-place air voids have been shown to result in rutting, bleeding, and shoving, while high air voids allow water and air to penetrate into the pavement leading to an increased potential for water damage, oxidation, raveling, and cracking.

In the past, it has been thought that for most conventional dense-graded HMA, increases in in-place air void contents have meant increases in the permeability of pavements. Zube (*2*) indicated during the 1960s dense-graded pavements become excessively permeable at in-place air voids above 8 percent. This value was later confirmed by Brown et al. (*3*) during the 1980s. However, due to problems associated with coarse-graded (gradation 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.

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 total volume 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.

Work by FDOT also indicated that lift thickness can have an influence on density, and hence permeability (*8*). FDOT constructed numerous pavement test sections on Interstate 75 that included mixes of different NMAS and lift thicknesses. Results of this experiment suggested that increased lift thicknesses can lead to better pavement density and, hence, lower permeability.

The three items discussed, density, lift thickness, and permeability, are all interrelated. Permeability has been shown to be related to pavement density. Increased lift thickness has been shown to allow desirable density levels to be more easily achieved. Based upon these confounding factors, the objectives of this study were to characterize the effect of typically specified values (density, NMAS, and lift thickness) on the permeability of coarse-graded Superpave mixes. In addition, the paper examines water absorption from water displacement bulk specific gravity measurements and permeability of gyratory compacted samples as predictors of field permeability. This would allow a mix designer to evaluate various mix properties for permeability potential.

REVIEW OF LITERATURE

A brief review of literature on the permeability of HMA pavements suggested that a significant amount of work has been conducted. Primarily, this work has been to evaluate the relationship between permeability and pavement density. Permeability testing in the literature has been done in both the laboratory and field. Laboratory testing has usually been done using water and a falling head approach (4, 9, 10, 11, 12, 13, 14). Field permeability testing has been conducted using both air (15, 16, 17) and water (2, 7, 10, 14, 18).

Numerous researchers have shown that permeability (both lab and field) is related to pavement density (2, 3, 4, 7, 9, 10, 11, 13, 17, 18, 20). Several factors have been shown to affect the relationship between permeability and density. First, Mallick et al. (7) have shown that nominal maximum aggregate size of a mix can significantly affect this relationship. Work by Cooley and Brown (19) and Maupin (13) has also shown similar trends in the relationship between NMAS and permeability of dense-graded HMA mixes. Cooley and Brown (20) have also shown a similar relationship for SMA mixes.

Research by Mallick et al. (7) and Musselman et al (8) has shown that lift thickness on the roadway can also affect density and permeability. Westerman (10), Choubane et al. (4), and Musselman et al. (8) have suggested that a lift thickness to NMAS ratio (t/NMAS) of 4.0 is preferred. Most guidance recommends that a minimum t/NMAS of 3.0 be used (21).

Another factor that can affect the relationship between permeability and density is the gradation shape for a given NMAS. Choubane et al. (4) suggested that fine-graded (passing above maximum density line and restricted zone) Superpave mixes tend to be less permeable than coarse-graded mixes at similar air void levels.

Work by Cechetini (16) has suggested that the type of roller and rolling pattern during construction can affect pavement permeability. Based upon Cechetini, vibratory rollers reduce the potential for permeability.

Zube (2) has suggested that the time of construction can also affect permeability characteristics over time. Pavements constructed during the summer can be expected to “seal up” due to traffic and thus reduce pavement permeability quickly. Pavements constructed in the fall may not “seal up” due to cooler weather and lead to permeability problems for an extended time period.

The permeability characteristics of an HMA pavement are important because a number of researchers have shown that permeability is directly related to durability (9, 12, 17). When a pavement is permeable, both air and water can permeate into the void structure of a pavement. Water entering the pavement can lead to moisture-induced damage, while air penetrating into a pavement can lead to excessive age hardening of the binder and, thus, premature cracking.

SCOPE

In order to evaluate the relationships between in-place air voids, lift thickness, and permeability, 23 on-going HMA construction projects were visited and field permeability tests conducted. The field permeameter has been described previously by Cooley (14) and Cooley and Brown (18).

For each field project visited, field permeability tests were conducted at a total of fifteen randomly selected locations. At each test location, replicate permeability tests were conducted (single tests were performed for six projects in one state). 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 single 150 mm 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 placed lift thickness on the roadway. For all projects, the bulk specific gravity of the cores was measured using AASHTO T 166 (water displacement method). For some projects, the bulk specific gravity of the cores was also measured using the vacuum sealing method (Corelok) described by Buchanan (*22*). Theoretical maximum specific gravity (G_{mm}) measurements were obtained from the testing of plant produced mix and used to calculate in-place air void contents.

PROJECT DESCRIPTIONS

A total of 23 on-going HMA construction projects were tested during this study. The common thread between all 23 projects was that mix from each project was designed using Superpave protocols and that the gradations of each mix passed below the maximum density line at the 2.36 mm (No. 8) sieve. For the purposes of this study, coarse-graded Superpave gradations were defined as gradations passing below the Superpave defined maximum density line at the 2.36 mm (No. 8) sieve.

Tables 1 though 4 present design information for the 23 projects tested during this study. Table 1 shows information on six 9.5 mm NMAS mixes. Design compactive efforts for the six mixes ranged from a low of 75 gyrations to a high of 100 gyrations. Binder contents ranged from 5.5 percent to 7.9 percent. Project 5, which had the 7.9 percent binder content, was actually an SMA mix. Design lift thicknesses for the six projects were all similar ranging from 38 to 40 mm. Voids in mineral aggregate (VMA) values ranged from 15.0 to 20.1 percent. Besides the one stone matrix asphalt (SMA) project (Project 5), all of the gradations are also similar except the percent passing the 0.075 mm sieve was a lower at 3.8 percent (Project 1).

Table 1. Design Information on 9.5 mm NMAS Mixes

Project	1	2	3	4	5	6
Ndesign	96	86	96	96	100	75
Pb, %	5.5	5.7	5.9	6.2	7.9	5.9
VMA, %	15.0	15.4	15.5	15.1	20.1	15.4
VFA, %	73	74	74	74	82	84
Lift Thickness, mm	40	38	38	38	38	38
Sieve Size	**% Passing Sieve**					
12.5 mm	100	100	100	100	100	100
9.5 mm	93	94	97	93	94	96
4.75 mm	56	63	64	59	36	66
2.36 mm	33	38	37	38	22	45
1.18 mm	26	21	24	26	19	31
60 mm	20	15	17	19	17	21
0.30 mm	12	11	11	11	16	12
0.15 mm	8	8	7	7	14	8
0.075 mm	3.8	4.9	5.1	5.5	10.4	5.2

Table 2 presents design information for the eight 12.5 mm NMAS mixes. Design compactive efforts for these eight mixes ranged from a low of 75 gyrations to a high of 125 gyrations. Optimum binder contents ranged from 4.6 to 6.2 percent. VMA ranged from 13.6 to 17.4 percent. Unlike the 9.5 mm mixes (Table 1), there was some variation in design lift thickness for the 12.5 mm NMAS mixes. Lift thicknesses ranged from a low of 38 mm to a high of 64 mm. Gradations for the different mixes were more variable than the 9.5 mm NMAS mixes. On the

2.36 mm sieve, values of percent passing ranged from 28 to 39 percent. On the 0.075 mm sieve, values of percent passing ranged from 4.1 to 6.1 percent passing. the 12.5 mm NMAS gradations are illustrated in Figure 2.

Table 2. Design Information for 12.5 mm NMAS Mixes

Project	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
N_{design}	96	96	125	125	96	75	75	75
Pb, %	5.2	6.2	4.8	4.6	5.7	5.4	5.3	6.1
VMA, %	14.6	14.1	13.6	14.1	14.2	16.5	17.4	16.7
VFA, %	73	73	69	71	72	76	75	78
Lift Thickness, mm	50	50	34	38	50	50	50	64
Sieve Size	**% Passing Sieve**							
19.0 mm	100	100	100	100	100	100	100	100
12.5 mm	96	96	95	94	97	100	96	99
9.5 mm	88	89	83	84	89	84	87	84
4.75 mm	60	61	52	51	65	47	56	44
2.36 mm	55	39	35	32	39	32	33	28
1.18 mm	24	29	25	23	30	25	22	22
0.6 mm	19	22	19	17	23	19	16	18
0.3 mm	14	13	14	12	14	13	11	13
0.15 mm	8	8	9	7	8	8	8	8
0.075 mm	4.8	6.1	4.8	4.1	5.4	5.3	5.3	5.5

Table 3 presents the information for six 19.0 mm NMAS mixes encountered in this study. for the six 19.0 mm NMAS mixes, design compactive efforts ranged from a low of 65 gyrations to a high of 96 gyrations. Optimum binder contents ranged from 4.6 to 5.6 percent. Values of VMA ranged from 13.2 to 15.6 percent. The lowest design left thickness encountered for the 19.0 mm NMAS mixes was 50 mm while the highest was 75 mm. Gradations were only available for five of the six mixes and are illustrated in Figure 3.

Table 4 presents design information for three 25.0 NMAS mixes. Design compactive efforts for these three mixes were 76 and 109 gyrations. Optimum asphalt contents ranged from 4.3 to 4.8 percent. VMA values ranged from 12.7 to 14.1 percent. All three of the projects utilized a design lift thickness of 75 mm. However, for Project 23 two separate lifts were tested. The first lift tested had a design lift thickness of 75 mm. This lift was placed directly on an aggregate base. The second lift tested had a design lift thickness of 50 mm and was placed over the initial 75 mm lift. Percent passing the 4.75 mm sieve ranged from 28 to 41 percent. On the 0.075 mm sieve, the percent passing ranged from 5.2 to 6.0 percent. The 25.0 mm NMAS project gradations are illustrated in Figure 4.

Table 3. Design Information for 19.0 mm NMAS Mixes

Project	**15**	**16**	**17**	**18**	**19**	**20**
N_{design}	95	96	96	96	86	65
Pb, %	4.9	5.6	5.4	5.5	5.3	4.6
VMA, %	15.4	13.2	13.7	13.2	13.4	15.6
VFA, %	71	69	70	69	70	64
Lift Thickness, mm	50	75	50	75	64	57
Sieve Size	**% Passing Sieve**					
25.0 mm	100	100	100	100	100	100
19.0 mm	98	98	98	98	95	97
12.5 mm	89	77	89	72	88	85
9.5 mm	79	64	82	60	75	72
4.75 mm	48	40	52	41	47	42
2.36 mm	32	28	32	27	32	32
1.18 mm	21	21	22	19	22	28
0.60 mm	13	16	16	14	17	21
0.3 mm	7	9	10	10	11	10
0.15 mm	5	6	6	7	8	6
0.075 mm	3.3	4.6	4.9	5.4	5.2	4.2

Table 4. Design Information for 25.0 mm NMAS Mixes

Project	**21**	**22**	**23**
N_{design}	109	76	76
Pb, %	4.4	4.8	4.3
VMA, %	13.1	12.7	14.1
VFA, %	70	80	75
Lift Thickness, mm	75	75	75 and 50 used
Sieve Size	**% Passing Sieve**		
37.5 mm	100	100	100
25.0 mm	96	92	99
19.0 mm	81	81	86
12.5 mm	50	67	62
9.5 mm	40	62	54
4.75 mm	28	41	38
2.36 mm	21	27	29
1.18 mm	15	19	22
0.60 mm	10	15	18
0.3 mm	8	12	14
0.15 mm	7	9	12
0.075 mm	6.0	5.2	5.2

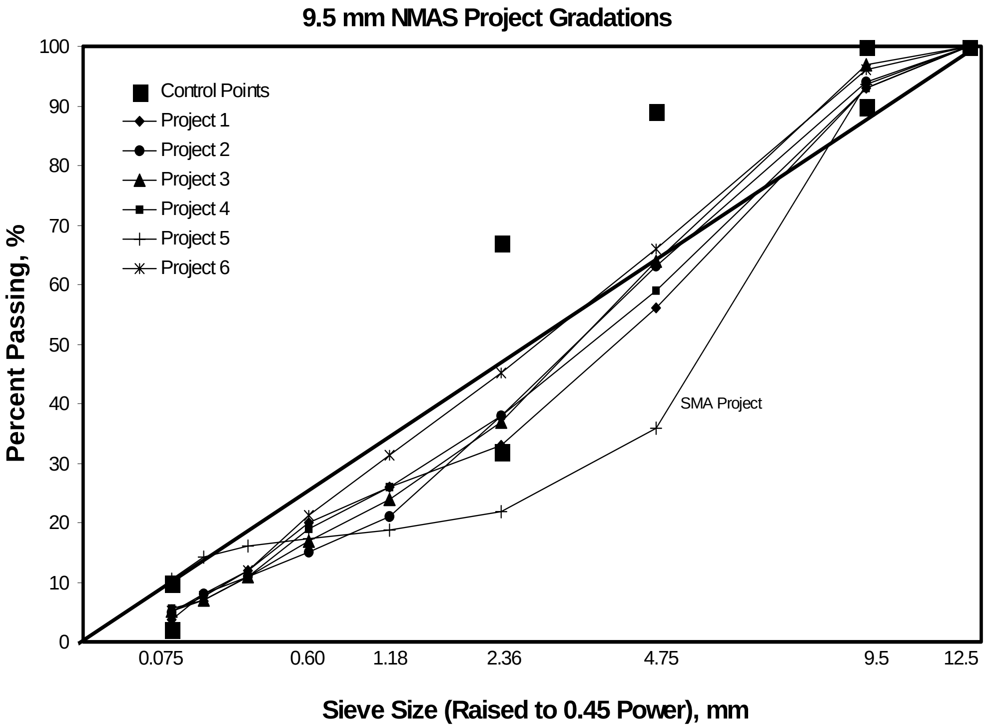

Figure 1. 9.5 mm NMAS Gradations

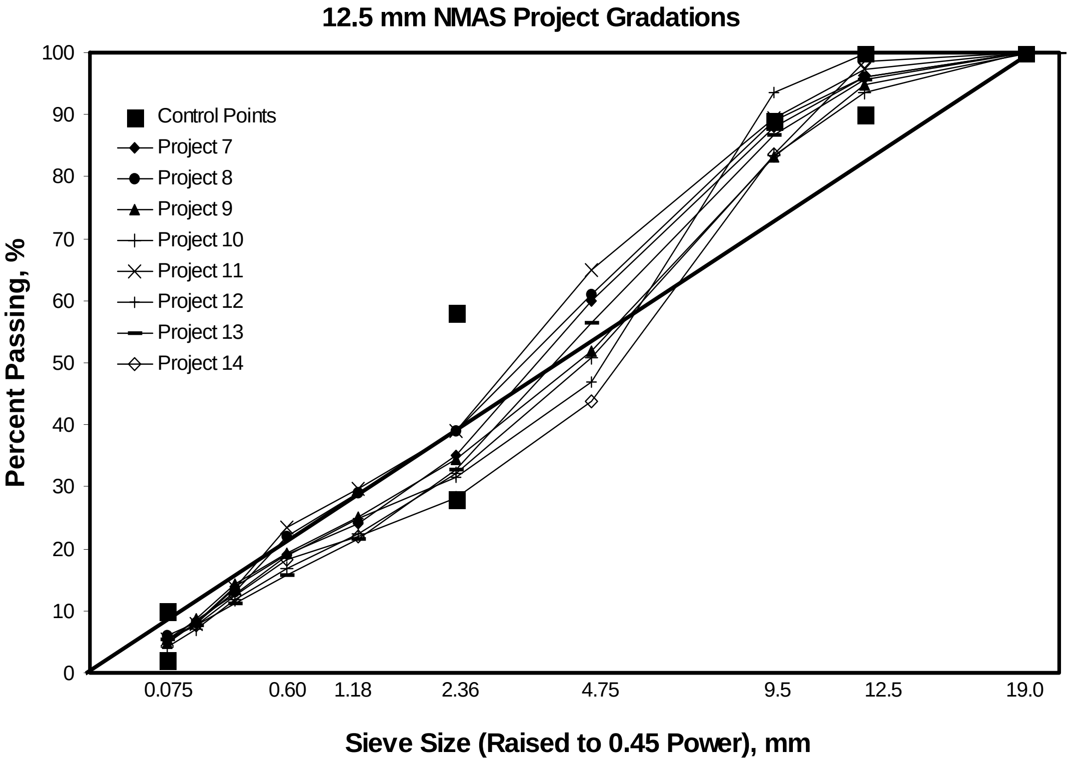

Figure 2. 12:5 mm NMAS Gradations

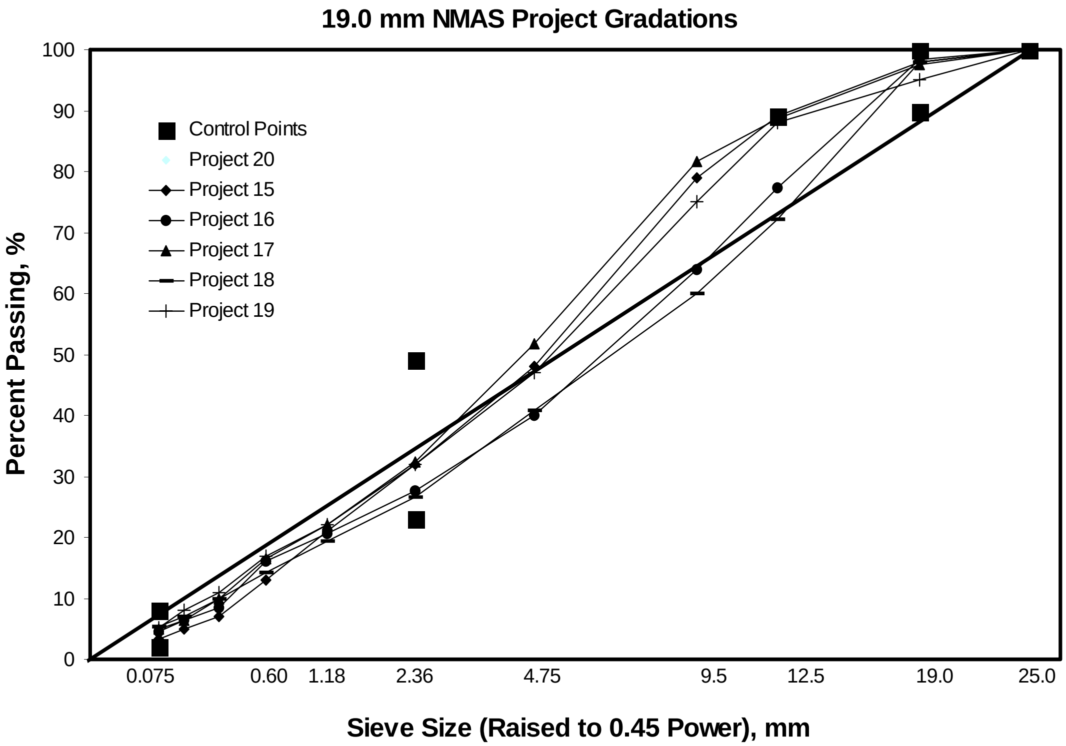

Figure 3. 19.0 mm NMAS Gradations

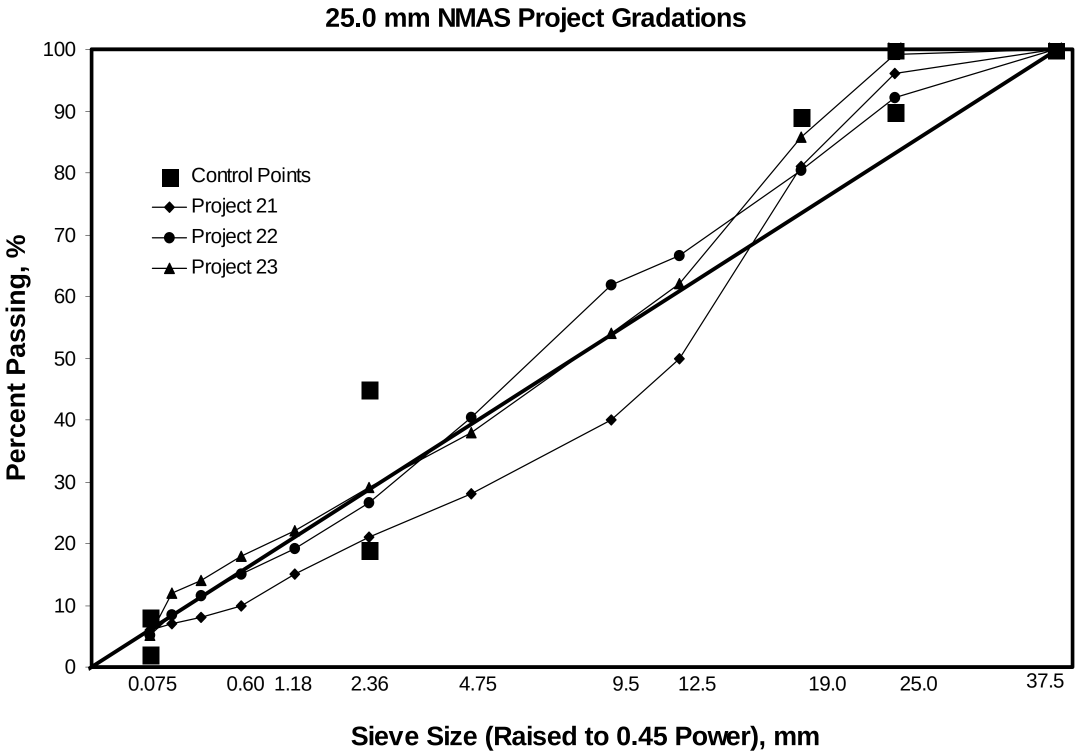

Figure 4. 25.0 mm NMAS Gradations

Test Methods

Core densities for all projects were measured using AASHTO T166. For projects in which the Corelok was used, core densities were first determined with the Corelok device and then in accordance with AASHTO T-166. The Corelok device was designed to aid in the density determination of HMA samples with water absorption greater than 2 percent. AASHTO T166, Standard Specification for Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens, specifies that the specimens with greater than 2 percent water 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 maximum specific gravity, used to calculate percent density (or in-place air voids), was conducted on plant-produced material in accordance with AASHTO T209.

The field permeability device utilized in this study was developed by the National Center for Asphalt Technology (*14*). 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 device.

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 *14*.

It should be stated that results from the field permeability device are not a true measure of permeability (hydraulic conductivity), 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 paper 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.

The laboratory permeameter used for this study is commercially sold and is essentially the second generation of the lab device developed by the Florida DOT (4). The device is a flexible wall, falling head permeameter that applies a confining seal via air pressure. Currently, no national standardized procedure is available for the lab device; however, a task group under the ASTM Subcommittee D04.23 is in the process of developing a standardized test method. A standardized test procedure was developed for use in this study based upon the work of the task group and can be found in (*14*).

RESULTS AND DISCUSSION

This section provides the results of analyses conducted to accomplish the objectives of this study.

Relationship Between Field Permeability and In-Place Density

One of the primary goals of this research was to evaluate the relationship between field permeability and in-place density. Figures 5 through 8 illustrate the relationship between field permeability and in-place density. For each of these plots, in-place air void contents are located on the x-axis. These void contents were determined based upon the bulk specific gravity of cores measured by the water displacement method and maximum theoretical specific gravities determined on plant-produced mix.

Figure 5 illustrates the relationship for 9.5 mm NMAS mixes. A total of six projects are illustrated on this figure, all of which are coarse-graded Superpave mixes except Project 5, which was SMA. The overall coefficient of determination (R^2=0.69) for Figure 5 was fairly strong considering: 1) the only common thread between the six mixes was that each gradation was a 9.5 mm NMAS and passed below the maximum density line at the 2.36 mm (No. 8) sieve; 2) the mixes were from four different states; 3) four different operators conducted the testing; 4) different materials (aggregates and binders) were used; and 5) each project likely utilized different construction techniques.

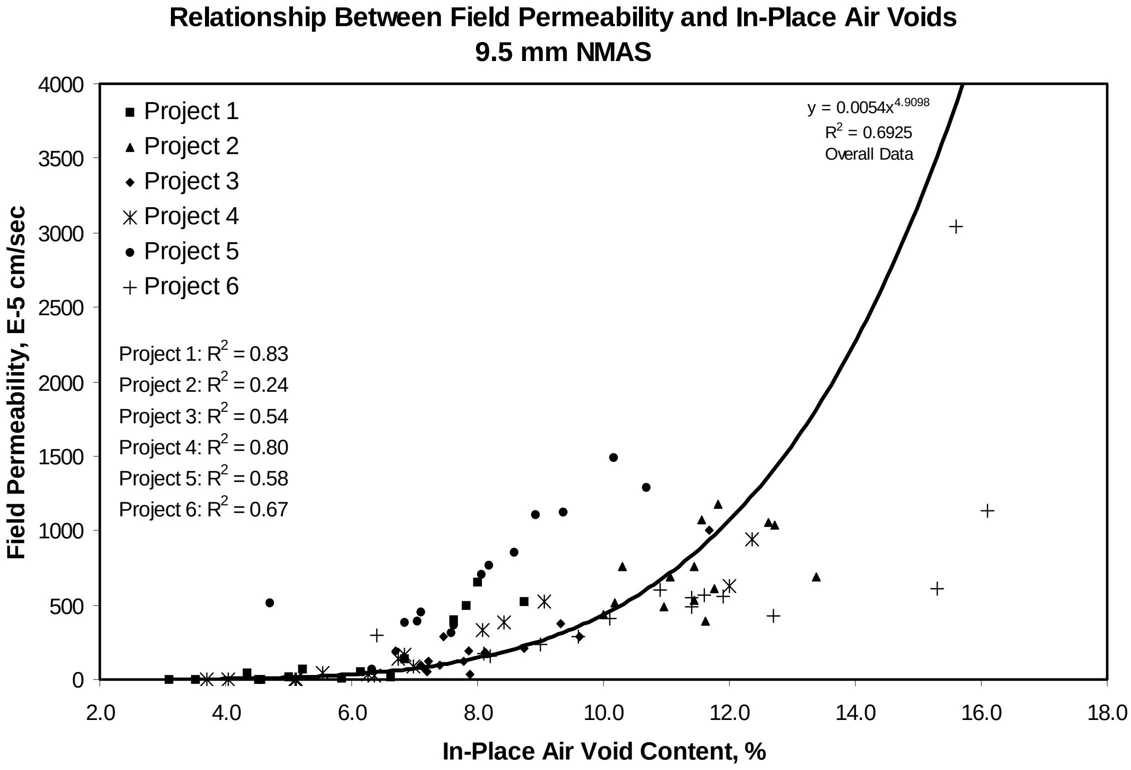

Figure 5. Relationship Between Permeability and Density ~ 9.5 mm NMAS Mixes

The R^2 value of 0.69 indicates that 69 percent of the variation in field permeability measurements for 9.5 mm NMAS mixes can be attributed to changes in in-place air voids. Therefore, a pavement's permeability is greatly influenced by the total number of air voids within the pavement. Based upon the relationship, permeability is very low at low in-place air void contents below 5 percent. From 5 to 7 percent voids, the permeability begins to increase at a greater rate with changes in in-place air voids. These results are very similar to those presented by Choubane et al. (*4*). At voids above approximately 8 percent, small changes in density resulted in large increases in field permeability.

For Figure 5, two of the six projects appear to be influencing the overall R^2 value (Projects 5 and 6). Interestingly, Project 5 utilized a SMA gradation and Project 6 utilized the finest gradation (Figure 1). Data points for the SMA (Project 5) all fall above the best-fit trend line while the data for Project 6 fell below the best-fit line. This suggests that SMA mixes may have a higher potential for permeability than dense-graded mixes, at a given void level. (Note that eleven of the fifteen data points for the SMA have in-place air void contents above 6 percent. Numerous researchers have suggested that SMA mixes should be compacted to at least 94 percent of Rice density. The data in Figure 5 seems to support this conclusion.)

Most of the data points for Project 6 fall below the overall trend line. Since this project utilized the finest of the 9.5 mm NMAS gradations (follows near maximum density line), it appears that finer gradations may reduce the potential for permeability in the field as suggested by Choubane et al. (*4*).

Based upon the relationship between field permeability and in-place air voids, Cooley et al. (*19*) have suggested that 9.5 mm NMAS mixes become excessively permeable at in-place air void contents above 7.7 percent, which corresponded to a field permeability value of 100×10^{-5} cm/sec. The data in Figure 5 seems to also suggest that 9.5 mm NMAS mixes become excessively permeable at in-place air void contents above 7.5 to 8 percent.

The relationship between field permeability and in-place density for 12.5 mm NMAS mixes is illustrated in Figure 6. Again, a fairly strong R^2 value was found (0.64). A total of eight HMA mixes are shown on Figure 6. These mixes came from four different states and were tested by three different operators.

The relationship shown in Figure 6 is similar to that shown in Figure 5. At in-place air void contents below approximately 6 percent, the field permeability values were very low. Between 6 and 7 percent the slope of the relationship begins to change. Above approximately 8 percent, permeability begins to increase at a greater rate with small changes in in-place air void contents.

Figure 6 appears to show one project that has a permeability-density relationship that is slightly different from the others (Project 14). Data points for this project fall above the best-fit trend line. Referring back to Figure 2, the gradation for Project 14 is the coarsest of the eight 12.5 mm NMAS gradations within this study. The gradation falls near the lower control point on the 2.36 mm (No. 8) sieve. Again, it appears that gradation shape may influence the permeability-density relationship.

Cooley et al. (*19*) suggested that the permeability of 9.5 and 12.5 mm NMAS coarse-graded mixes were similar and thus recommended a critical in-place air void content of 7.7 percent for both (field permeability value of 100×10^{-5} cm/sec). Figure 6 seems to also suggest that 12.5 mm NMAS mixes become excessively permeable at in-place air void contents above 7.5 to 8 percent.

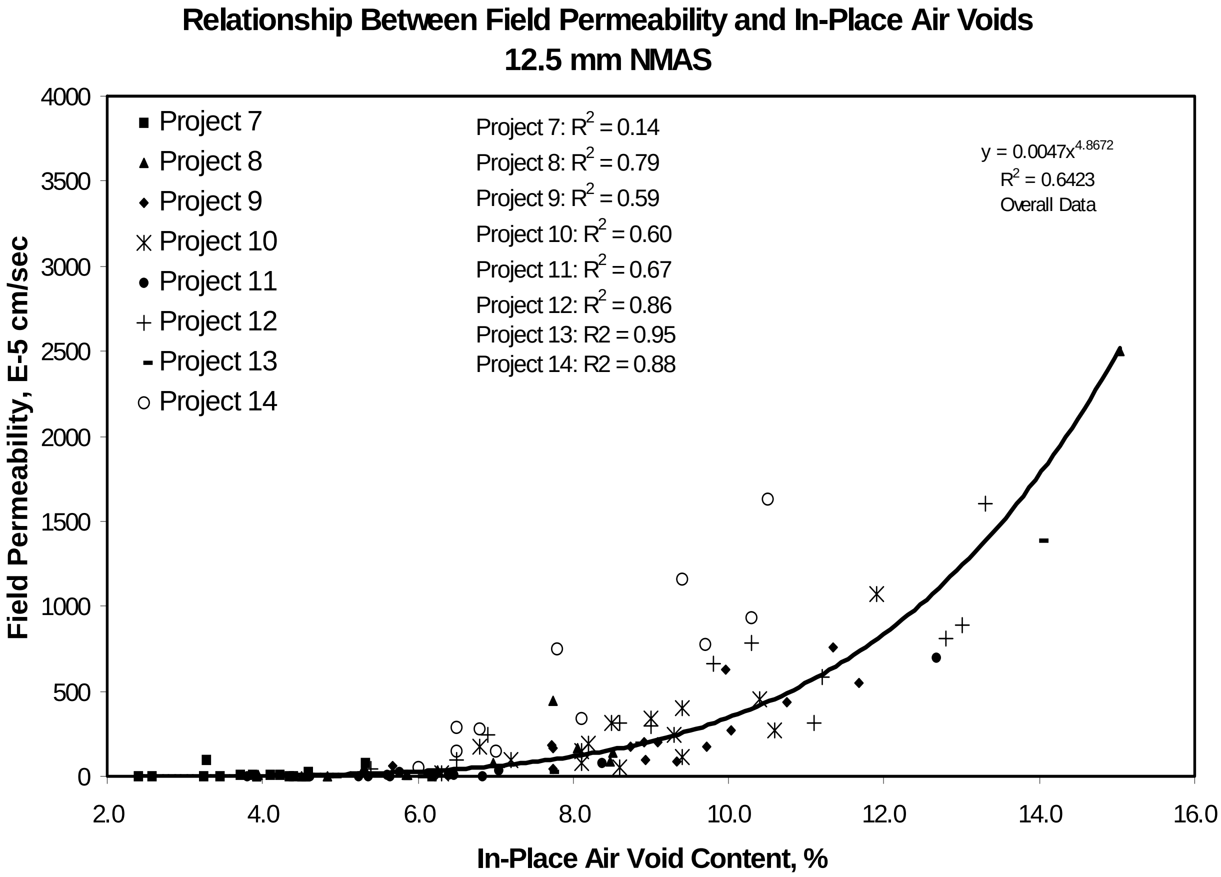

Figure 6. Relationship Between Permeability and Density ~ 12.5 mm NMAS Mixes

Figure 7 illustrates the permeability-density relationship for six 19.0 mm NMAS mixes. The R^2 value for these mixes was much smaller than for the previous two NMASs (0.42). Mixes shown on the figure came from three different states and were tested by five different operators.

In addition to the R^2 value for the overall data set, R^2 values are presented for each of the individual projects. These R^2 values ranged from a low of 0.49 for project 16 to a high of 0.77 for project 20. Except for project 16, all of the R^2 values are reasonably strong. Based upon Figure 7, project 20 appears to be influencing the overall R^2 value. Data from this project are all well below the regression line. Removing project 20 from the data set, the R^2 value increases to 0.58, which is reasonably strong. Project 20 had the lowest design gyration level (65 gyrations) compared to the other projects.

Observation of Figure 7 suggests that the 19.0 mm NMAS mixes are more permeable than the 9.5 and 12.5 mm NMAS mixes at similar in-place air void contents. At an air void content of 6 percent, the 19.0 mm regression line yields a field permeability value of 178×10^{-5} cm/sec. At a similar air void content, the 9.5 and 12.5 mm NMAS mixes had permeability values of 36 and 29×10^{-5} cm/sec, respectively.

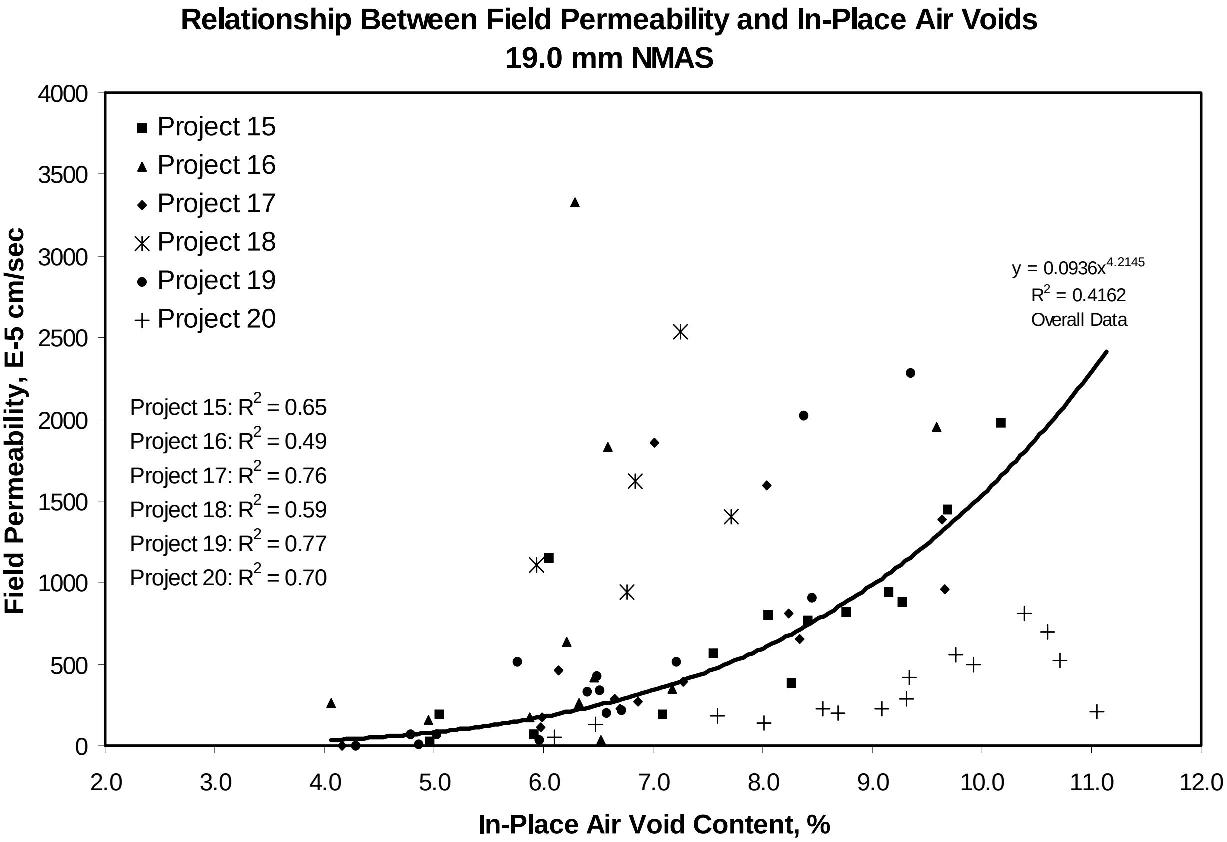

Figure 7. Relationship Between Permeability and Density ~ 19.0 mm NMAS Mixes

At in-place air void contents below approximately 4 to 5 percent, the permeability values are low. Above 5 percent, the field permeability began to increase sharply with small increases in in-place air void content.

A critical density (as related to permeability) for 19.0 mm NMAS mixes of 5.5 percent has been suggested by Cooley et al. (*19*). Data in Figure 7 seems to also suggest that when in-place air voids are above 5.5 to 6 percent, pavements become excessively permeable.

The relationship between in-place air voids and field permeability for 25.0 mm NMAS mixes is illustrated in Figure 8. The R^2 value for the overall data set is 0.50, which is reasonable. Data for Figure 8 includes three different mixes that came from two different states. Two different operators were used in the testing.

Compared to the other three NMAS, the 25.0 mm mixes are more permeable at similar air void contents. At 6 percent in-place air voids, the regression line yields a field permeability value of 581×10^{-5} cm/sec. This permeability value is much higher than those of the other NMAS.

The lowest in-place air void content measured for the three projects was approximately 4 percent. Above 4 percent, permeability values increased significantly with small changes in density. Cooley et al. (*19*) suggested that 25.0 mm coarse-graded Superpave mixes become permeable at 4.4 percent in-place air voids. Data in Figure 8 also appears to suggest that 25.0 mm NMAS mixes are excessively permeable above 4 to 5 percent voids.

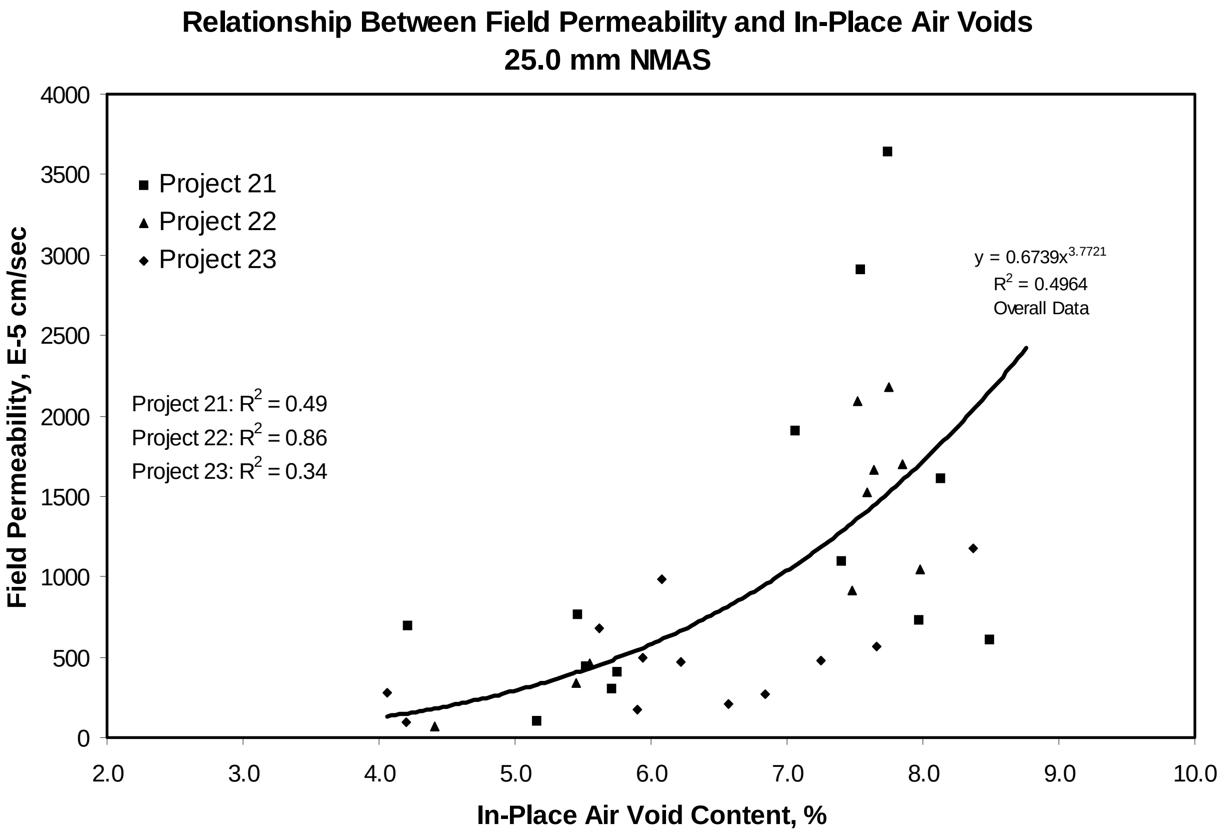

Figure 8. Relationship Between Permeability and Density ~ 25.0 mm NMAS Mixes

Based upon the previous discussions and Figures 5 through 8, it is obvious that pavement in-place density significantly affects the permeability characteristics of coarse-graded HMA pavements. At low in-place air voids, permeability is typically low. As density decreases (in-place air voids increase) permeability increases. At some point within this relationship, small changes in density lead to large increases in permeability. This defines the point where excessive permeability begins. It is evident that larger NMASs require higher density values to ensure impermeability.

Effect of NMAS on Field Permeability

The data illustrated in Figures 5 through 8 suggested that the NMAS of a mixture significantly affects permeability characteristics. Figure 9 illustrates the effect of NMAS on field permeability based on the regression equations developed in Figures 5 through 8. Similar to Cooley et al. (19), Figure 9 suggests that the permeability characteristics of 9.5 and 12.5 mm NMAS are similar. This was not unexpected as the percent passing the 2.36 mm (No. 8) sieve is not very different for these mixes. For the thirteen 9.5 or 12.5 mm NMAS mixes (excluding the one 9.5 mm SMA mix), the percent passing the 2.36 mm (No. 8) sieve ranged from 28 to 44.

At a given air void content, the 19.0 mm NMAS mixes show significantly higher permeability values than the 9.5 and 12.5 mm NMAS mixes. Also, the 25.0 mm NMAS mixes have about three times higher permeability value than the 19.0 mm NMAS mixes at the same air void content.

Figure 9, based on the best-fit line for all projects at each NMAS, clearly shows that NMAS significantly affects the permeability characteristics of a pavement.

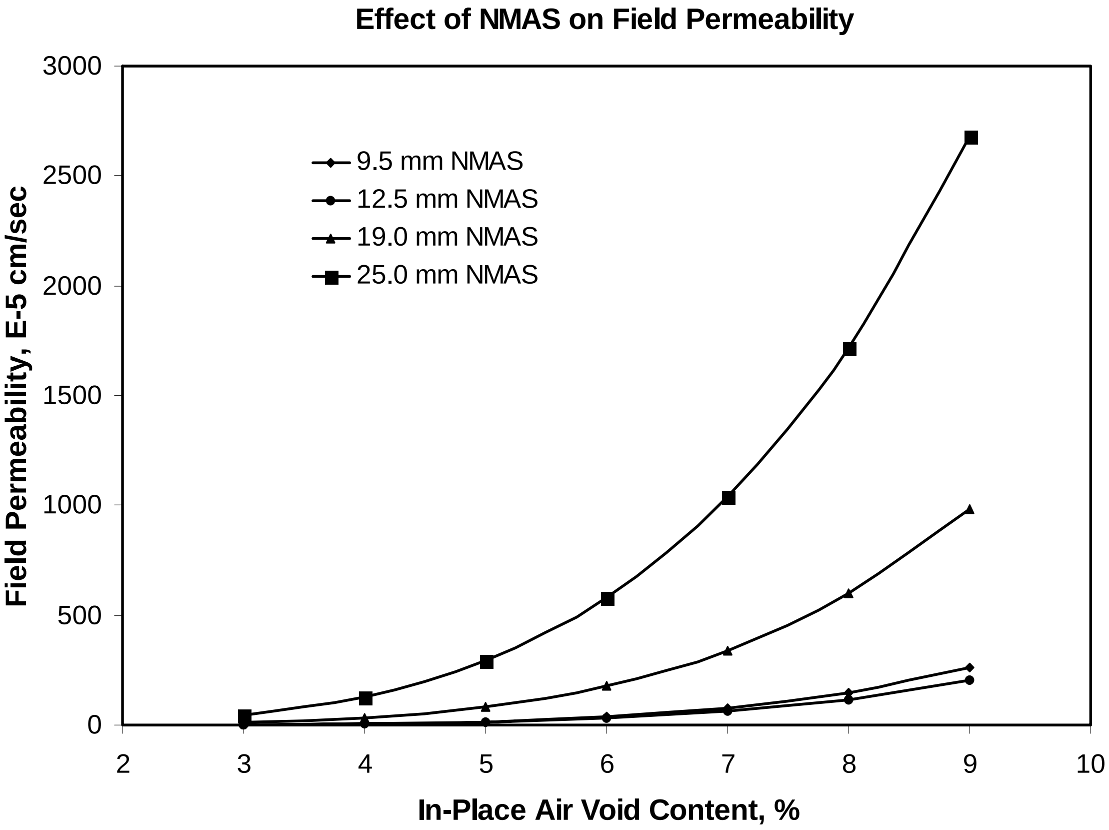

Figure 9. Effect of NMAS on Permeability

Comparison of Lab and Field Permeability Measurements

Laboratory permeability tests were conducted on cores cut from 16 of the 23 projects. Using the laboratory permeability data, a comparison was made between the lab and field permeability test methods. The comparison is illustrated in Figure 10 (irrespective of NMAS).

Figure 10 illustrates the lab permeability results from cores taken at the location at which field permeability tests were conducted versus the field results. The R^2 value for this relationship was strong at 0.71. The relationship between field and laboratory permeability results is interesting. At permeability values less than about 500×10^{-5} cm/sec, there is an almost one-to-one correlation (regression falls near line of equality). Above permeability values of 500×10^{-5} cm/sec, the laboratory test method provided higher permeability values. This was not as expected. It was anticipated that the field results would always provide higher permeability values since water can flow from the field device in any direction, while laboratory device restricts water flow to one direction. Therefore, one would expect higher permeability values using the field test method.

A possible explanation for the deviation from what was expected is provided. Based on Figures 5 through 8, permeability values of 500×10^{-5} cm/sec were associated with high in-place air void contents (ranging from a high of about 10 percent for the 9.5 and 12.5 mm NMAS mixes to a low of about 6 percent for the 25 mm NMAS mixes). At permeability values above 500×10^{-5} cm/sec, HMA mixes have a high percentage of interconnected air voids. In the field, an interconnected air void may or may not be of a length that it allows water to flow. Within the laboratory permeability device, a single large interconnected air void that extends through the length of the sample can lead to high laboratory permeability values.

Because the relationship is basically one-to-one at low permeability values, it can be surmised that the two methods of measuring permeability provide somewhat similar results. However, at high air void contents (which leads to a high probability of large interconnected air voids), laboratory permeability results would be higher.

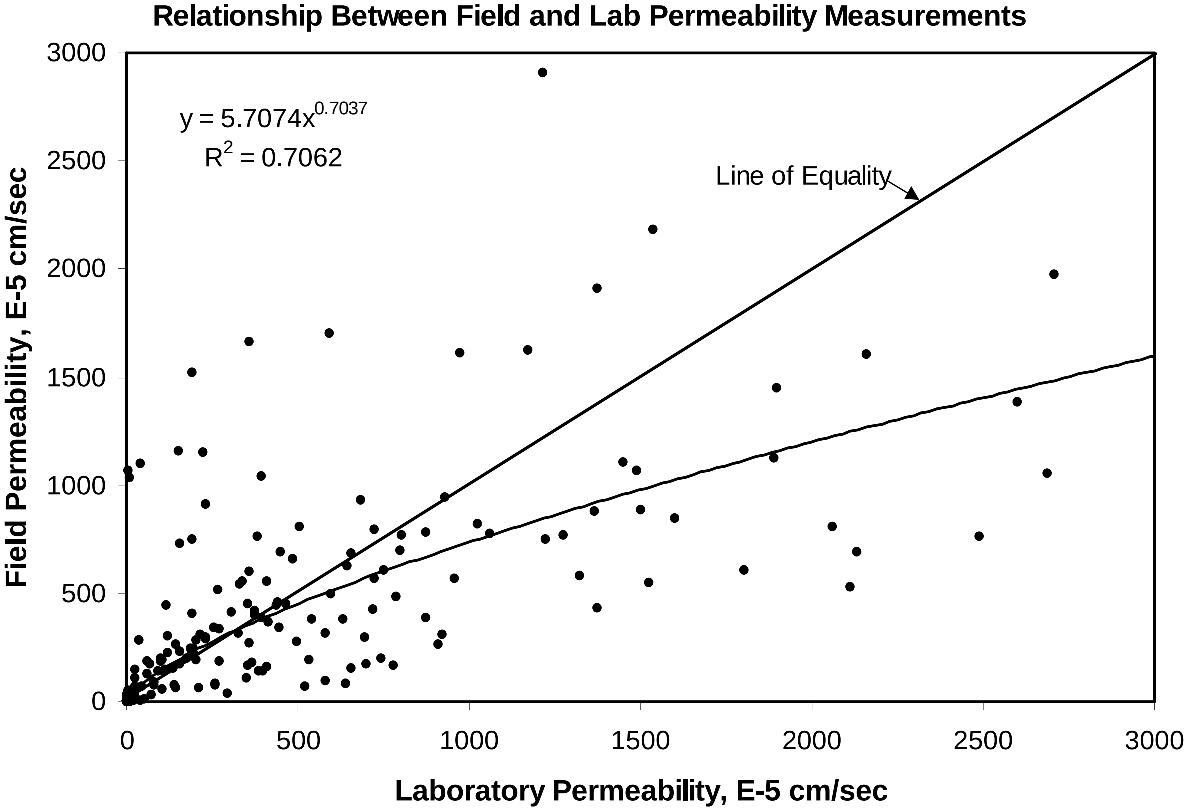

Figure 10. Relationship Between Field and Lab Permeability Measurements

Figures 11 through 13 illustrate that the relationship between lab and field permeability results versus in-place density are similar. These figures present the relationships between permeability (lab and field) and density for 9.5, 12.5, and 19.0 mm NMAS mixes, respectively, in which laboratory permeability results were obtained. All three figures illustrate that a similar relationship is observed between permeability and density. At low in-place air voids, permeability values are relatively low while at high in-place air voids permeability values are high.

Based upon this discussion on the relationship between lab and field permeability measurements, it appears that both methods provide similar results at permeability values that are not excessive. Additionally, both methods had a similar relationship with field density. Cooley et al. (19) suggested that field permeability values should be less than 150×10^{-5} cm/sec. The relationship between field and lab measurements was approximately one-to-one at permeability values less than about 500×10^{-5} cm/sec. This suggests that the field permeameter does provide reasonable results when compared to the more controlled lab test method. The field device is advantageous since it provides more rapid test results and is non-destructive.

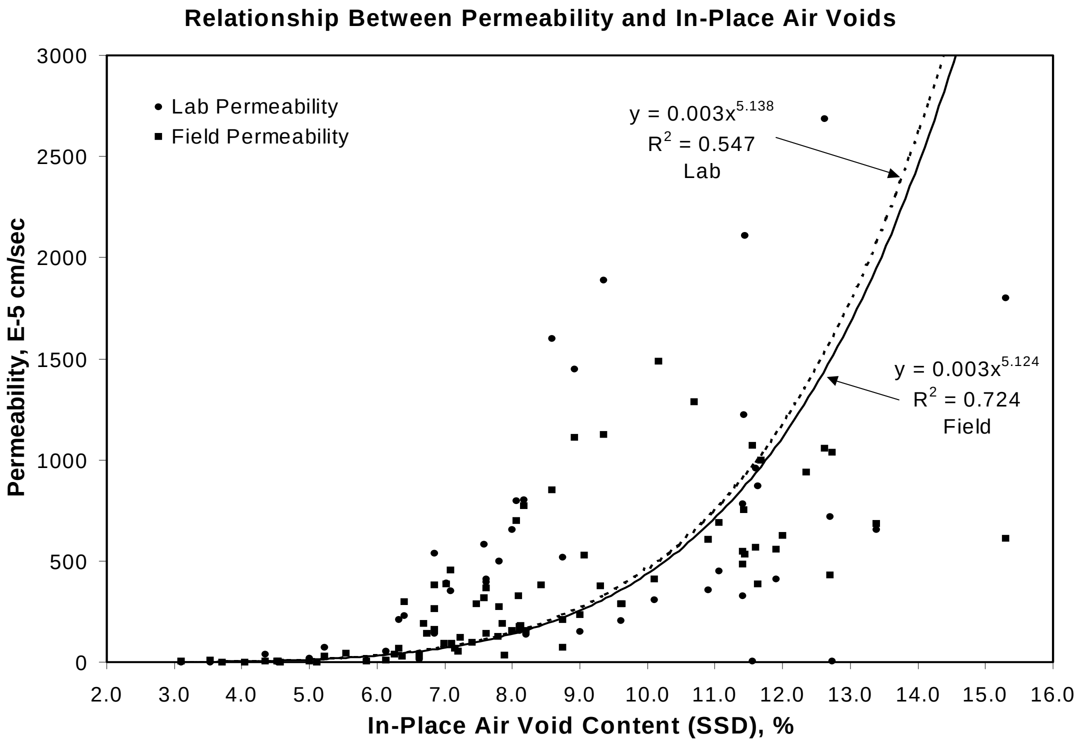

Figure 11. Pavement Density vs. Permeability ~ 9.5 mm Mixes

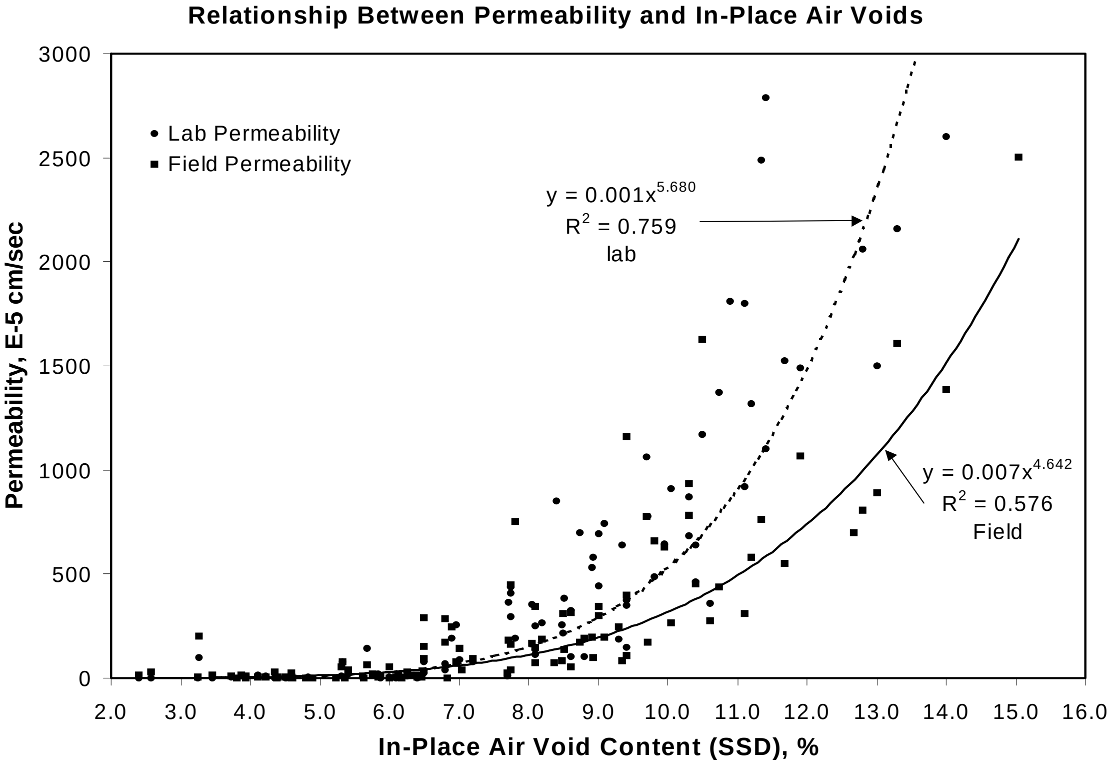

Figure 12. Pavement Density vs. Permeability ~ 12.5 mm Mixes

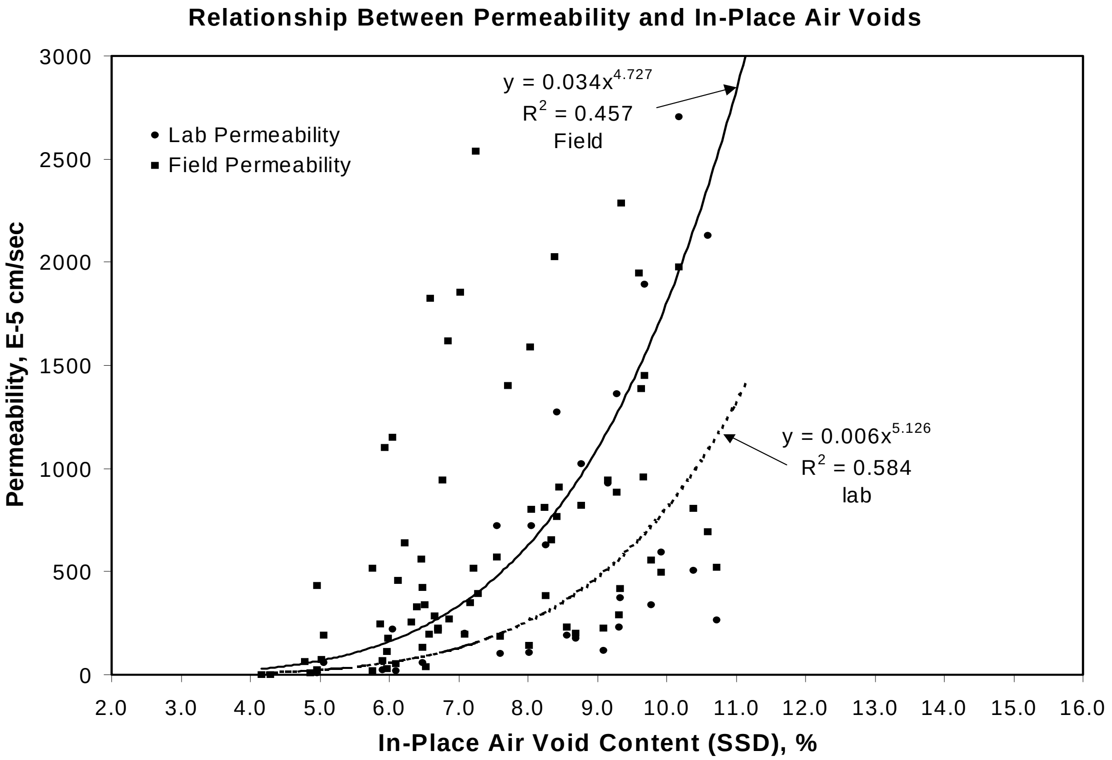

Figure 13. Pavement Density vs. Permeability ~ 19.0 mm Mixes

Relationship Between Density, Lift Thickness and Permeability

As stated previously, density, lift thickness, and permeability are all interrelated. To evaluate the interrelatedness of these three factors, a stepwise multiple linear regression was conducted. A multiple linear regression is a tool that is used for relating two or more independent variables (e.g., density, thickness, NMAS, etc.) to a dependent variable (permeability). A stepwise procedure was selected because it evaluates all of the independent variables and systematically selects the variables that provide the best relationship and significance with the dependent variable.

For this analysis, the natural log of field permeability was the dependant factor while in-place air voids, natural log of in-place air voids, NMAS, pavement thickness (as defined by cores), and the pavement thickness-to-NMAS ratio were included as independent variables. As shown previously, the relationship between permeability and density is not linear. Therefore, the natural log of permeability and air voids were also included within the stepwise regression.

Multiple linear regressions (MLR) were conducted for both the field and laboratory permeability results using all of the data except projects 2 and 5. Project 2 was eliminated due to poor control during construction. Project 5 was the SMA project.

For both MLR procedures (field and lab permeability results), density (in-place air voids), NMAS, and thickness were identified as significantly affecting permeability. Figure 14 illustrates the results of the MLR for the field permeability data. Independent variables identified by the MLR were in-place air void content, NMAS, and the pavement thickness-to-NMAS ratio. The correlation for the MLR results was good ($R^2 = 0.66$). This R^2 value indicates that 66 percent of the variability in field permeability results can be attributed to in-place air voids, NMAS, and thickness-to-NMAS ratio.

Because the relationship between permeability and density was previously illustrated, the regression lines on Figure 14 only show the effect of thickness-to-NMAS ratio (t/NMAS) on permeability. For each of the regression lines illustrated in Figure 14, a single in-place air void content is shown and is based upon the critical values for a given NMAS suggested by Cooley et al. (*19*).

As expected, Figure 14 shows that as the thickness of the pavement (t/NMAS) increases, permeability decreases. Also, based upon the regression equation presented on the figure, as in-place air voids decrease the permeability decreases. Figure 14 indicates NMAS affects measured permeability. However, as shown previously in Figures 5 and 6, 9.5 and 12.5 mm NMAS mixes have similar permeability characteristics at the same void level. The NMAS factor in the regression equation provided in Figure 14 creates a difference between the two that does not match field experience.

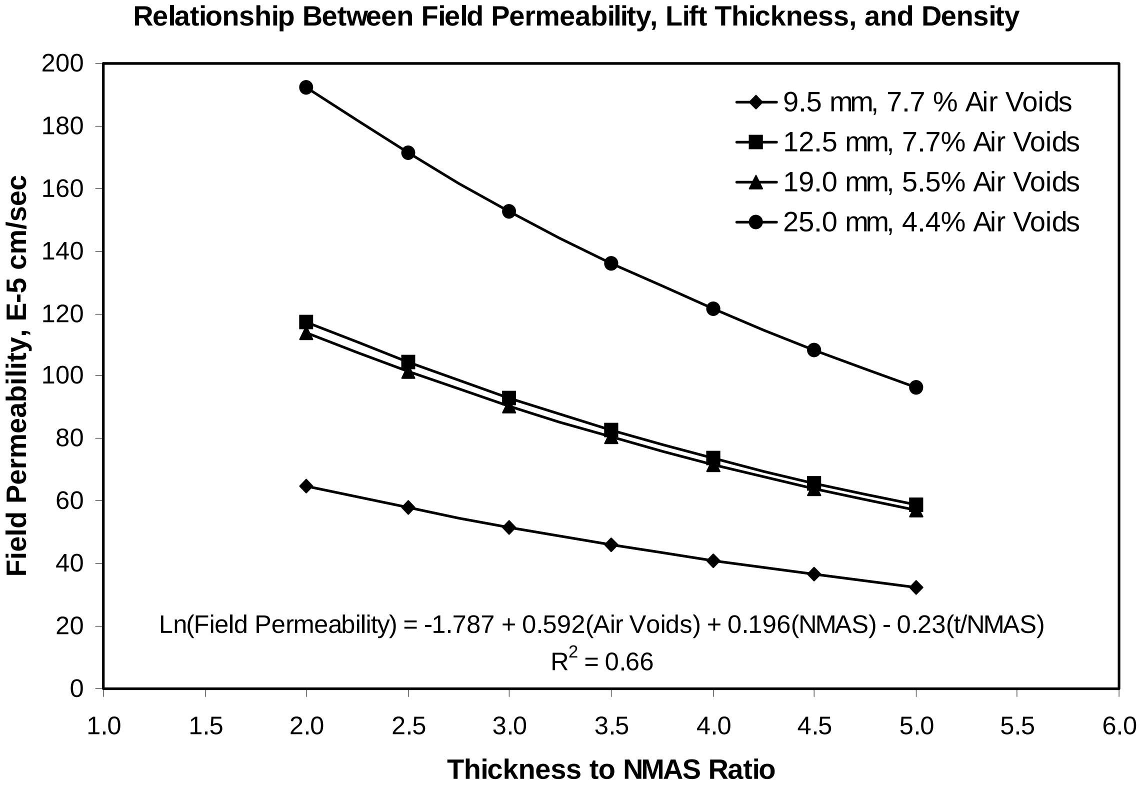

Figure 14. Results of MLR for Field Permeability Data

Results of the MLR for the lab permeability data are illustrated in Figure 15. Figure 15 is based on 8 of the 10 projects for which lab permeability was available. Two projects, 2 and 5 were eliminated from the data set as discussed previously. Independent variables identified as being significant in this MLR were the natural log of in-place air voids, NMAS, and pavement thickness. A reasonable R^2 value of 0.51 was obtained.

Figure 15 shows that similar to the MLR results for field permeability, as lift thickness increases the permeability decreases.

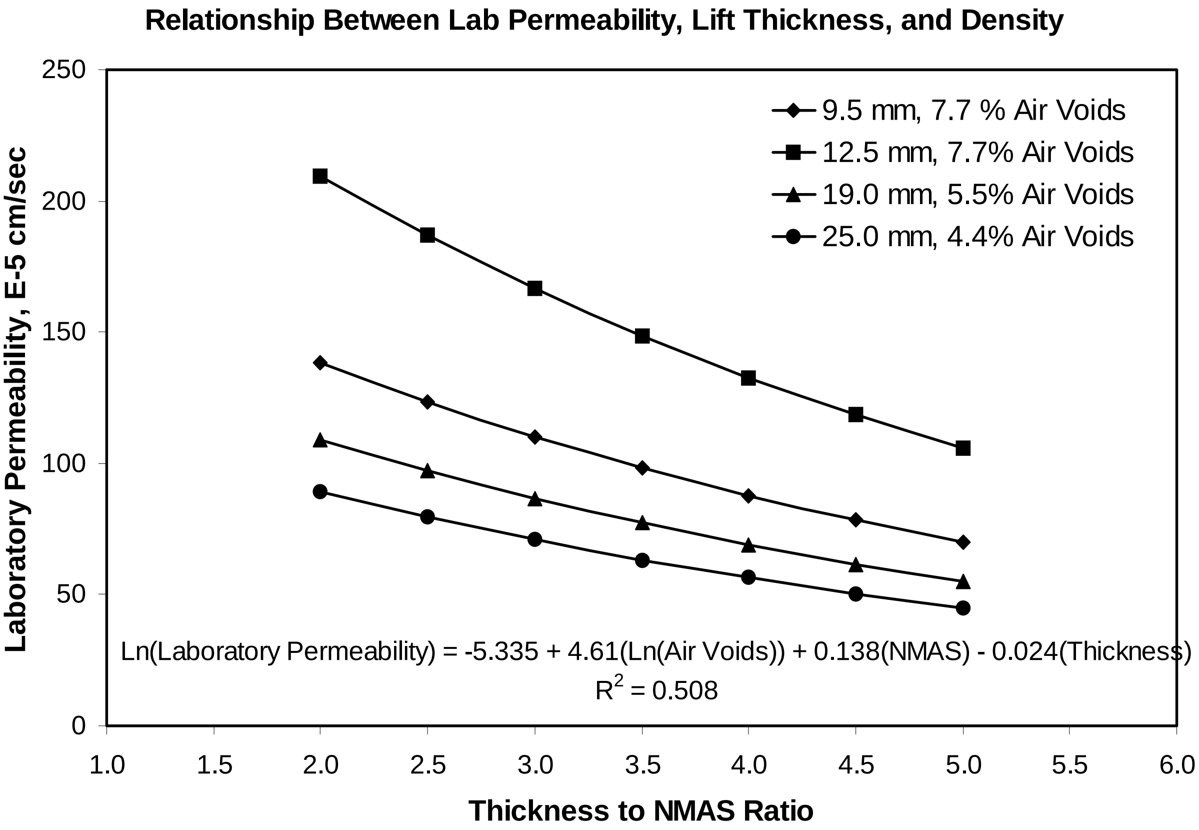

Figure 15. Results of MLR for Lab Permeability Data

Laboratory Prediction of Field Permeability

As agencies begin to include permeability specifications, mix designers need tools they can use during the mix design process to evaluate the permeability characteristics of a given aggregate structure. This could be a difficult task. The primary problem is that laboratory and field compacted samples have different air void distributions (23). Because of the differences in air void distribution (or density gradients), similar interconnected void structures is unlikely. This could then lead to different relationships between permeability and density with lab and field compacted mixes. Two techniques were evaluated in this study: laboratory permeability measurements on samples compacted using the Superpave gyratory compactor and water absorption determined with AASHTO T 166 or the Corelok device. The goal of each technique was to determine whether relationships existed and then use those relationships (if they exist) to identify a parameter(s) that would indicate potential field permeability problems during the design phase.

Relationship Between the Permeability of Field Cores and Gyratory Compacted Samples

Data comparing the laboratory permeability of field cores and field mix (representative of the cores) compacted using the Superpave gyratory compactor (SGC) was available for six projects representing three NMAS. Since the 50 mm tall, SGC samples could not be produced at the exact same air void levels as the field cores, the relationship between air voids and lab permeability is shown for each of the three NMAS. The 9.5 mm mix, Project 6, is shown in Figure 16.

Based on Figure 16 and the Project 6 data, there is a difference of greater than three percent air voids where the mix becomes impermeable. In both cases there is a strong relationship between sample air voids and permeability. However, the trends between permeability and density are different for the two sample types. Field results show higher permeability at a given air void content. However, the lab results do begin to show increases in permeability above 8 percent which is close to the critical value of 7.7 percent suggested by Cooley et al. (19).

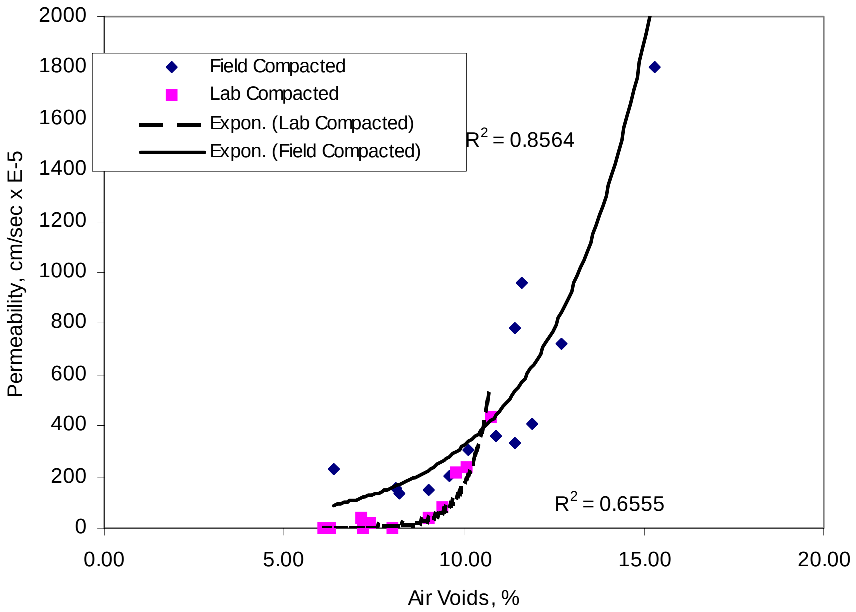

Figure 16. Density versus Permeability of 9.5 mm NMAS Field Cores and SGC Samples

Figure 17 shows the relationship between permeability and density for three 12.5 mm NMAS projects (12, 13 and 14). For the three 12.5 mm NMAS projects, the field cores and SGC samples predict that the mix will become excessively permeable at about the same air void level (8 percent). The relationship diverges slightly at higher air void levels above the permeability level of interest. The correlation between density and laboratory permeability is good for the field cores and fair to poor for the SGC samples.

The 19.0 mm NMAS mix, Project 20, is shown in Figure 18. The relationship between density and laboratory permeability is good for both the field cores and the SGC samples. The air void level at which the mix becomes impermeable differs by less than 0.5 percent. This indicates that SGC samples could be used to predict field permeability for the 19.0 mm NMAS.

With the exception of the 9.5 mm NMAS samples, this limited data set indicates that SGC samples have the potential to be used to estimate the necessary field compaction level required to produce an impermeable mix. Knowing the specified field compaction level, a mix designer could evaluate whether a given aggregate structure would tend to produce an impermeable mix by comparing 50 mm laboratory prepared samples to specified field density levels and measuring the laboratory permeability. This process would likely add another day to the mix design process but could be completed concurrently with moisture susceptibility testing.

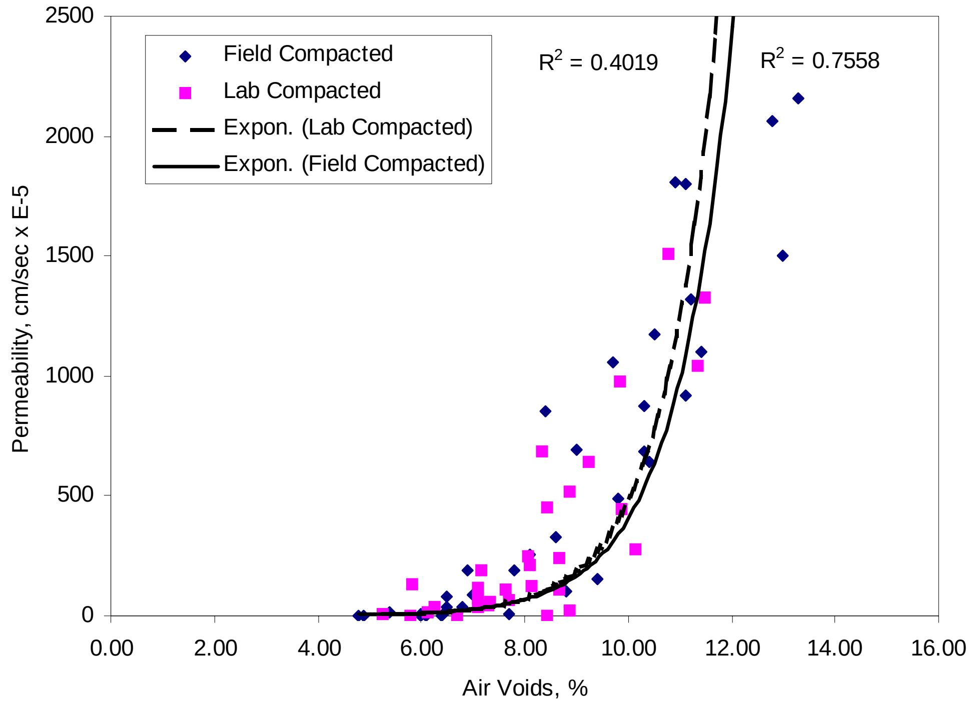

Figure 17. Density versus Permeability of 12.5 mm NMAS Field Cores and SGC Samples

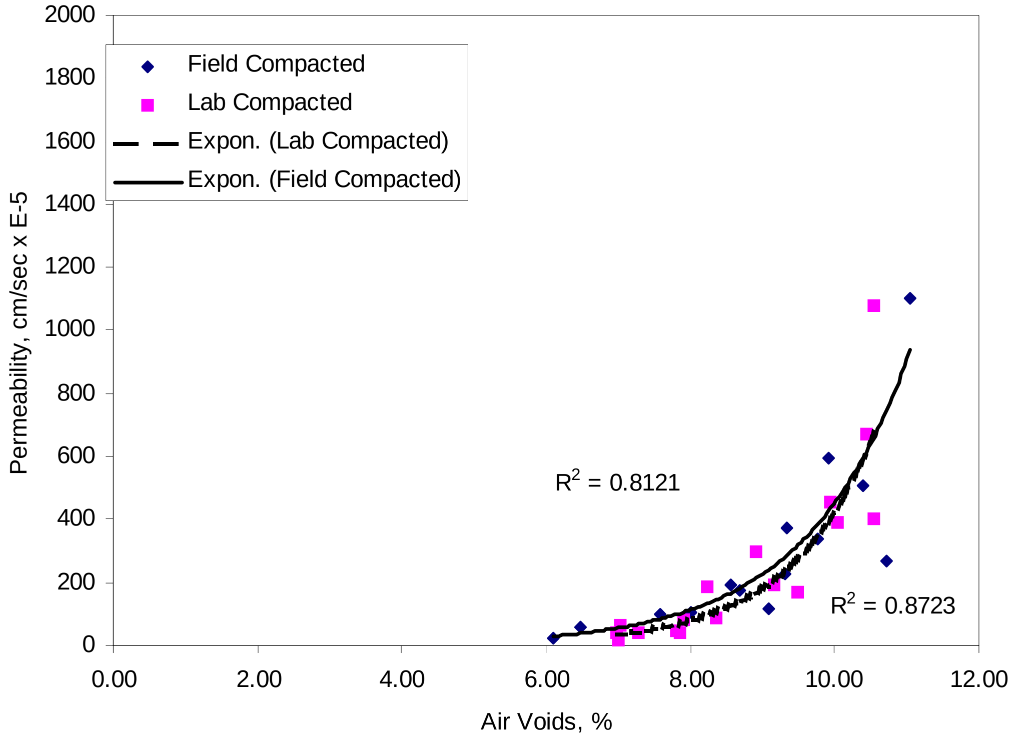

Figure 18. Density versus Permeability of 19.0 mm NMAS Field Cores and SGC Samples

Relationship Between Water Absorption and Permeability

The percentage of water permeable voids is determined in AASHTO T-166 according to Equation 1.

$$Water\ \ Absorption\ = \left(\frac{(B-A)}{B-C}\right)*100 \tag{1}$$

where:

A = core mass in air
B = core mass saturated surface dry (SSD)
C = core mass in water

The manufacturer of the Corelok proposed Equation 2 to calculate what they termed as the porosity of the sample. A better term is effective air void content.

$$Effective\ \ Air\ \ Voids\ = \left(\frac{(A-B)}{A}\right)*100 \tag{2}$$

where:

A = saturated density of sample, g/cm^3
B = sealed density of sample, g/cm^3

The Corelok manufacturer recommends that the sealed sample be opened underwater, allowing a slight vacuum to fill voids that might not otherwise become saturated. Since this technique was proposed after the majority of the testing was completed, the authors substituted the saturated density determined according to AASHTO T-166 for D_2.

It seems intuitive that the percentage of water permeable voids should be related to the available flow paths for the water and in turn to permeability. Previous research has shown that permeability is dependent on gradation as well as density. A strong relationship between water permeable voids and permeability, independent of gradation, could be used as a screening tool by a mix designer or agency. During design, it would allow the mix designer to assess the potential permeability of a given aggregate structure without conducting permeability tests. During production it could be used as a quick screening tool by the agency (if they employ a core density specification) without the additional work of laboratory permeability testing.

Corelok data and field permeability were available for 10 of the 23 projects representing three NMAS. The relationship for T-166 and Corelok water absorption versus field permeability is shown in Figure 19.

Data for AASHTO T-166 and Corelok water absorption as well as laboratory permeability were only available for six projects representing three NMAS from one state. The relationship between water absorption and laboratory permeability is shown in Figure 20.

Based upon Figures 19 and 20, there is a relationship between the percent volume of water absorbed during AASHTO T166 testing and permeability (both field and lab). It should be stated here that all cores were 150 mm in diameter. The relationship is better for the laboratory permeability data than for the field data. The flow paths for laboratory permeability are purely within the 150 mm (6 in) core and must be vertical. However, in some cases, the flow paths measured during field testing may be lateral from a single interconnected void as is sometimes seen when water appears outside the diameter of the field permeameter. Still, water absorption could be used in conjunction with in-place density as a quick field quality control screening tool to evaluate whether a pavement is excessively permeable (if cores are cut for density).

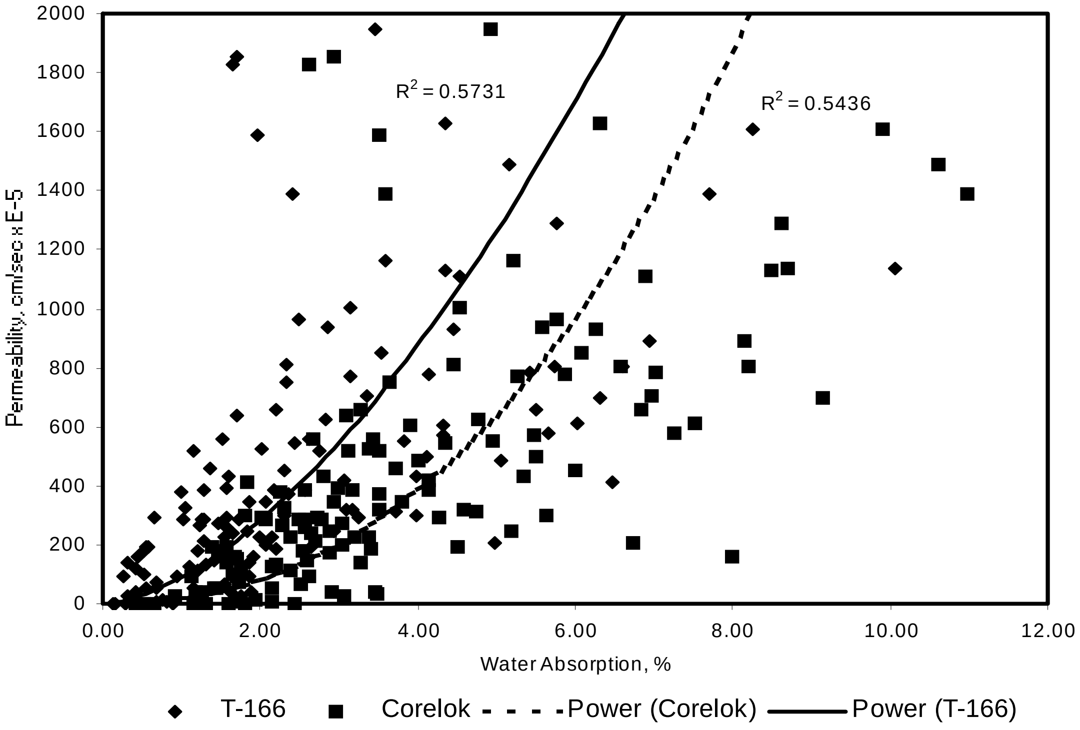

Figure 19. Water Absorption versus Field Permeability

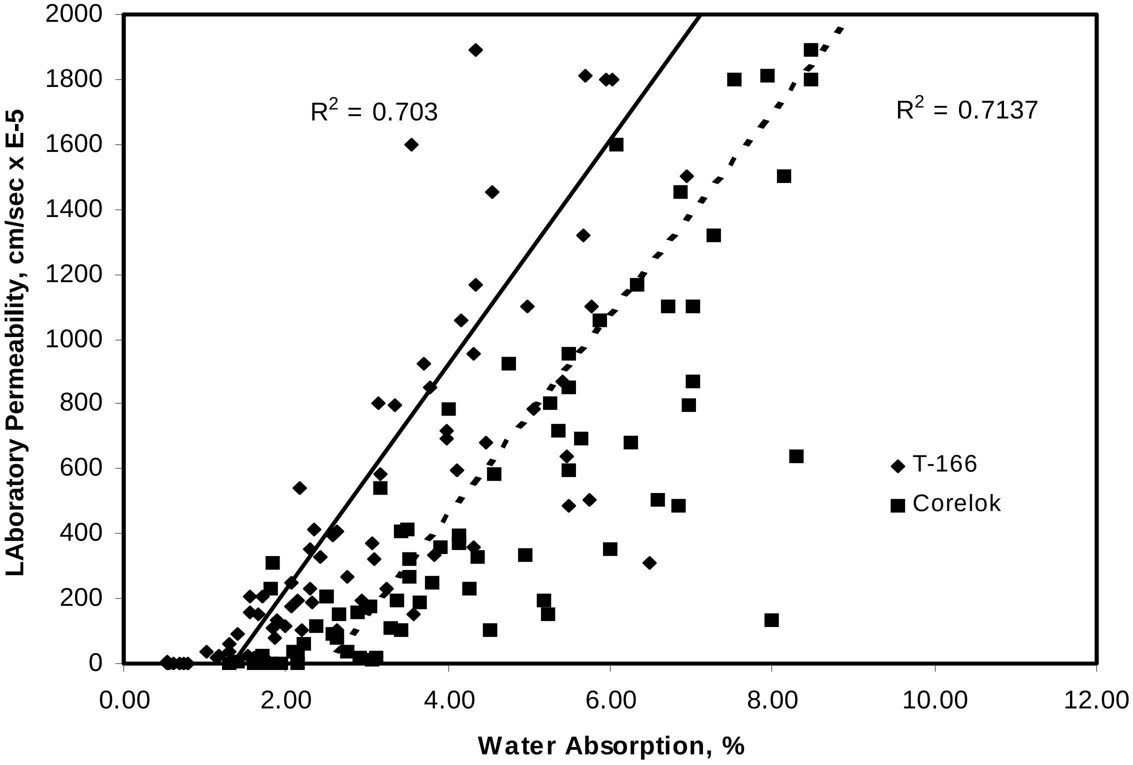

Figure 20. Water Absorption versus Laboratory Permeability

To evaluate whether a mix designer can predict the field permeability of a pavement based upon the water absorption of SGC compacted samples is a very difficult analysis. However, based upon several relationships, it can be shown that a relationship exists. The problem in the analysis is that field permeability cannot be measured on Superpave gyratory compactor (SGC) compacted samples.

The first step in the analysis was to determine whether there is a similar relationship between water absorption and air voids for SGC and field compacted samples (Figure 21). Figure 21 is based upon 6 projects representing three NMAS from one state. For Figure 21, the relationship between water absorption during AASHTO T166 testing and air voids is plotted for both SGC and field compacted samples. Based upon the relationships, the volume of absorbed water is slightly higher for field core samples than for the SGC compacted samples. This is likely due to the exposed aggregate faces created during the coring process. Still, based upon Figure 21, there is a strong relationship for water absorption versus air voids between the two sample types.

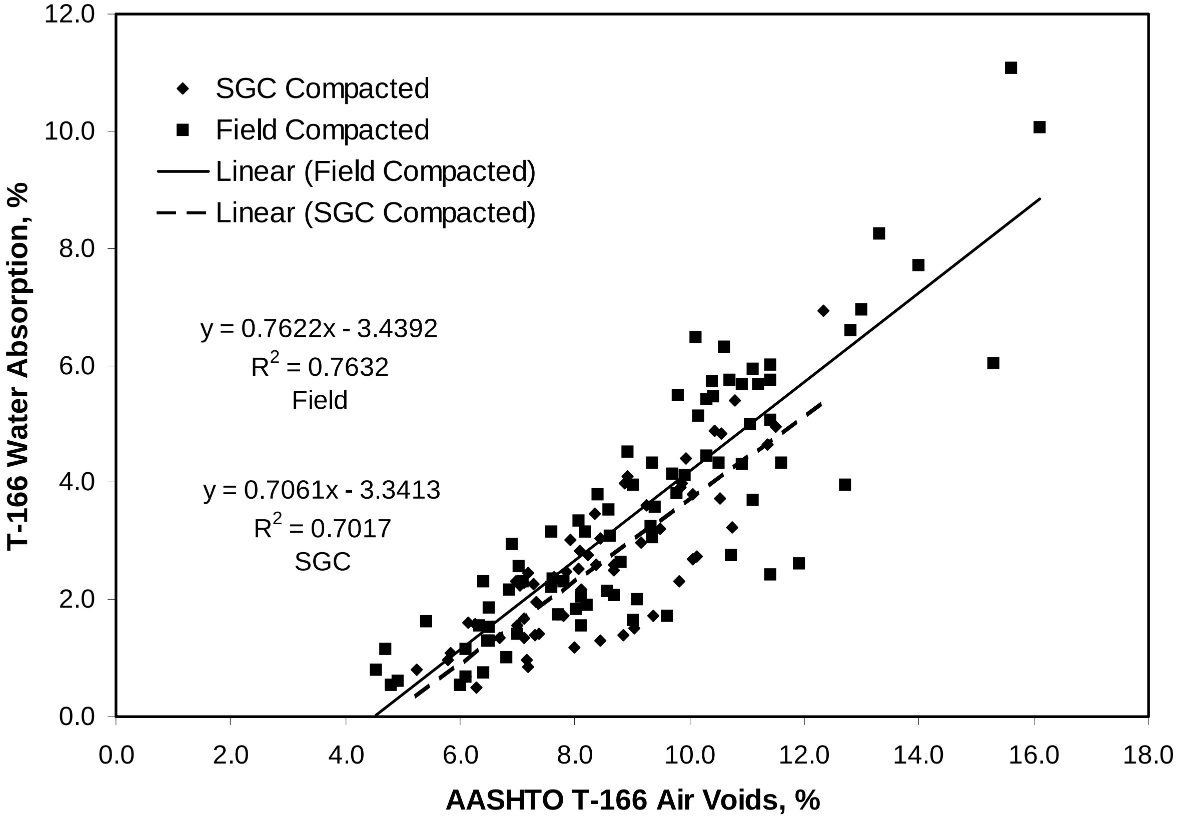

Figure 21. Relationship Between Water Absorption and Air Voids for Lab and Field Compacted Samples

Because relationships have been shown in this paper for water absorption versus density (Figure 21) for two sample types (field and lab compacted), permeability versus density (Figures 5 through 8), laboratory and field permeability, and water absorption versus permeability (Figures 19 and 20), the second step in the analysis was to plot water absorption versus permeability for the three conditions evaluated in this study: core samples-field permeability, core samples-lab permeability, and SGC samples-lab permeability. Figure 22 (based on six projects representing three NMAS from one state) shows these relationships.

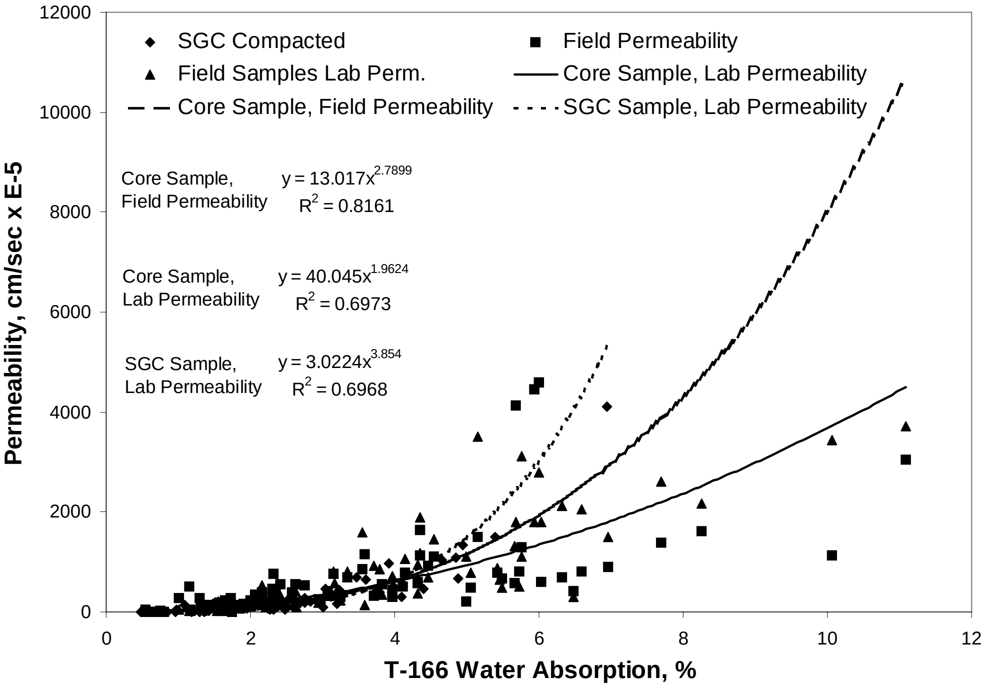

Figure 22. Relationship Between Water Absorption and Permeability for Three Conditions

Based upon Figure 22, it appears that all three conditions have somewhat similar relationships between permeability and water absorption below 4 percent water absorption. The R^2 values for the three relationships are reasonably strong as all are above 0.70. Based on this limited data set, it appears that the relationship between water absorption and permeability may be independent of NMAS. In order to better show the relationships in the zone of interest, the scale was reduced and the data points removed as shown in Figure 23.

Figure 23 illustrates the relationship between water absorption and permeability for three conditions: core samples-field permeability, core samples-laboratory permeability, and SGC samples-lab permeability. All three have a somewhat similar relationship. This infers that a mix designer could use water absorption on lab compacted samples to estimate field permeability.

The magnitude of water absorption that defines excessive permeability is different for the three conditions, but Figure 23 can be used to determine the critical value for any of the conditions. It is interesting to note that the critical water absorption values provide a permeability less than $100x10^{-5}$ cm/sec are all close to 2 percent, the upper limit allowed by AASHTO T166 to determine density by the water displacement method. Based upon Figure 23, a mix designer could produce 50 mm high SGC samples of a mix design at various expected in-place air void contents, measure the density and water absorption, and then make an educated estimate of whether a mixture has the potential for permeability problems at the field density level.

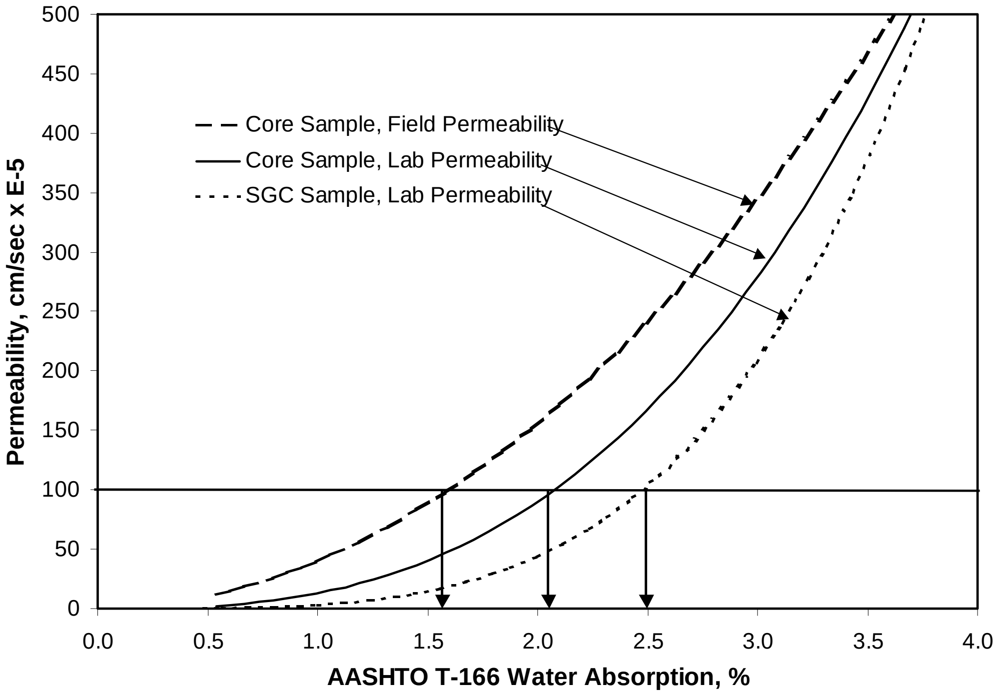

Figure 23. Reduced Scale Look At Relationship Between Water Absorption and Permeability for the Three Conditions

CONCLUSIONS

Based upon the data accumulated in this study and the analyses of the data, the following conclusions are provided:

- Permeability, whether field or lab, is related to the density of coarse-graded Superpave mixes.
- Coarse-graded Superpave mixes having nominal maximum aggregate sizes of 9.5 and 12.5 mm have similar permeability characteristics.
- The nominal maximum aggregate size of the mix affects the permeability characteristics of a pavement. Mixes having larger nominal maximum aggregate sizes have more potential for high permeability than mixes of smaller nominal maximum aggregate sizes, at the same air void level.
- At permeability values within the typically specified region for a pavement, the field and lab permeability test methods provide approximately similar results.
- There is a relationship between in-place density, lift thickness, and permeability. As density increases, permeability decreases. As lift thickness increases, permeability decreases.
- A reasonable relationship was determined between water absorption during AASHTO T-166 and water permeable voids from Corelok testing and permeability results (both field and lab). This may be used as a quick screening test to identify pavements that may be permeable.
- Some reasonable relationships were found between the permeability of lab compacted samples and laboratory permeability. These relationships suggest that a mix designer may be able to evaluate the permeability potential of a mix during mix design. Also, a mix designer may be able to compare the permeability potential of different mix designs for a given project.

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