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DETERMINATION OF MAXIMUM IN-PLACE AIR VOID FOR IMPERMEABLE HOT MIX ASPHALT PAVEMENTS

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Abstract: Obtaining adequate density is a major requirement in the construction of hot mix asphalt (HMA) pavements. Density is very much related to the air voids. As air voids increase, the density decreases. This study determined the maximum in-place air void for impermeable HMA pavements. A total of 497 core samples were obtained from 57 different ongoing HMA construction projects immediately after rolling. Nine different mix types utilised in this study were fine dense-graded 9.5 mm, 12.5 mm, 19.0 mm and 25.0 mm nominal maximum aggregate size (NMAS) mixes, coarse dense-graded 9.5 mm, 12.5 mm and 19.0 mm NMAS mixes, and Stone Matrix Asphalt (SMA) 9.5 mm and 25.0 mm NMAS mixes. Bulk specific gravity of each core sample was determined using both American Association of State Highways and Transportation Officials (AASHTO) T 166 and vacuum sealing methods, and permeability was determined using American Society for Testing and Materials (ASTM) PS129-01. This study found that in-place air void content was the most significant factor affecting permeability. The in-place air voids for dense-graded HMA pavements should not exceed 7%.

Keywords: *Permeability; Hot Mix Asphalt Pavement; Air voids; Gradations.*

Abstrak: Kepadatan yang mencukupi merupakan satu kriteria penting dalam pembinaan turapan asfalt turapan panas (HMA). Kepadatan berkait rapat dengan lompang udara. Jika lompang udara meningkat maka kepadatan akan berkurangan. Kajian ini menentukan lompang udara maksimum HMA di tapak supaya ketertelapan tidak berlaku dalam turapan. Sebanyak 497 sampel tebukan dianalisis daripada 57 projek pembinaan HMA sebaik sahaja selesai proses pemadatan. Sembilan jenis campuran HMA yang berbeza digunakan iaitu gred halus padat 9.5 mm, 12,5 mm, 19.0 mm dan 25.0 mm saiz niminal maksimum agregat (NMAS), gred kasar padat 9.5 mm, 12.5 mm dan 19.0 mm NMAS dan asfalt matriks batu (SMA) 9.5 mm dan 25.0 mm NMAS. Graviti tentu pukal setiap sample tebukan ditentukan menggunakan kaedah AASHTO T 166 dan salut vakum manakala ujian ketertelapan pula ditentukan menggunakan ASTM PS129-01. Keputusan kajian menunjukkan kandungan lompang udara di tapak merupakan faktor utama yang mempengaruhi ketertelapan. Lompang udara di tapak bagi campuran padat HMA mestilah tidak melebihi 7%.

Katakunci: *Ketertelapan; Turapan Asfalt Campuran Panas; Lompang Udara; Pengredan.*

1.0 Introduction

Good compaction and correct mix design of HMA mixtures are two important parameters influencing the stability and durability of a pavement. For dense-graded mixes, initial in-place air voids should be within the range of 3 to 8% percent (US Army Corp, 2000). Low in-place air voids generally result from a mix problem which can lead to rutting and shoving. High in-place air voids are generally caused by inadequate compaction which permits the entrance of water and air into the permeable pavement causing an increased potential for water damage, oxidation, raveling, and cracking (Kumar and Goetz, 1977a). Kumar and Goetz (1977b) have noted that the permeability of HMA provides a better indication for long-term durability of a pavement than air voids alone. Gotolski et al. (1972) and Maupin (2000) have suggested the use of permeability as a mix design criteria for HMA mixes.

The increase in traffic loading has led the asphalt mix designer to select coarser mixes as they could provide better stability. However, many asphalt technologists have discovered that some stretches of highways showed signs of permeability. Permeability is also a major concern in stone matrix asphalt (SMA) mixes since they utilise a gap-graded coarse gradation. A survey by Brown et al. (1999) suggested that coarse dense-graded mixes seem to be more permeable than conventional dense-graded mixes at similar air void contents. Work by Westermann (1998) and Choubane et al. (1998) using a laboratory permeability device showed that coarse-graded Superpave mixes became excessively permeable when in-place air void contents exceeded 6%. A survey by Choubane et al. (1998) revealed that the problems encountered with coarse-graded Superpave mixes are associated with the size and interconnectivity of air voids instead of the total volume of air voids. A lack of fine material has resulted in more air voids in the mixes and increased the potential for interconnected voids.

Although many studies have investigated the permeability characteristics of HMA mixes, the results are quite inconsistent. This could be due to differences in the devices used, the testing environments, and the size of the experiment model conducted. Hence, there is a need for a detailed study to identify factors influencing the permeability of HMA mixes using a standard test method. The objectives of this study are to identify factors affecting permeability and to determine the maximum in-place air voids for impermeable pavements.

2.0 Methodology

A total of 57 on-going HMA construction projects in the South Eastern region of the USA, were visited by the researchers from the National Center for Asphalt Technology (NCAT), Auburn University, Alabama, USA. Of the 57 projects visited, 20 of them were from National Cooperative Highway Research Program (NCHRP) 9-27 under the research title “Relationships of Air voids, Lift Thickness and Permeability”. The other 37 were from NCHRP 9-9(1) which cater for a study entitled “Verification of Gyration Levels in the N_{des} Table”. Nine different combinations of gradation shape and nominal maximum aggregate size (NMAS) were studied: fine-graded 9.5 mm, 12.5 mm, 19.0

mm and 25.0 mm NMAS mixes, coarse-graded 9.5 mm, 12.5 mm and 19.0, and stone mastic asphalt (SMA) 9.5 mm and 25.0 mm NMAS mixes. In this paper, projects were identified as fine-graded or coarse-graded according to the definition given by the National Asphalt Pavement Association (NAPA) as shown in Table 1.

Table 1: Definition of fine and coarse-graded mixes (NAPA, 2001)

Mixture NMAS	Coarse-Graded	Fine-Graded
37.5 mm (1 ½”)	<35 % Passing 4.75 mm Sieve	>35 % Passing 4.75 mm Sieve
25.0 mm (1”)	<40 % Passing 4.75 mm Sieve	>40 % Passing 4.75 mm Sieve
19.0 mm (3/4”)	<35 % Passing 2.36 mm Sieve	>35 % Passing 2.36 mm Sieve
12.5 mm (1/2”)	<40 % Passing 2.36 mm Sieve	>40 % Passing 2.36 mm Sieve
9.5 mm (3/8”)	<45 % Passing 2.36 mm Sieve	>45 % Passing 2.36 mm Sieve
4.75 mm (No. 4 Sieve)	N/A (No standard Superpave gradation)	

At each project, cores were obtained from the roadway after construction but before traffic so that the actual lift thickness and in-place air voids could be determined. Cores brought back to the laboratory from field projects were sawed and tested for bulk specific gravity (both using AASHTO T 166-93-saturated surface dry (SSD) and the vacuum sealing method), thickness, and permeability. Permeability tests were conducted on each core in accordance to ASTM PS 129-01 by means of falling head approach. Each core was vacuum-saturated for five minutes prior to testing. Water from a graduated standpipe was allowed to flow through the saturated sample and the time to reach a known change in head was recorded. Saturated condition of the samples was considered adequate when four consecutive time interval measurements did not differ by more than 10% of the mean. In this method, Darcy’s Law was applied to determine the permeability of the sample as shown in the following equation.

$$k = \frac{aL}{At} \ln \frac{h_1}{h_2} \tag{1}$$

where k is coefficient of permeability (cm/s), a is area of standpipe (cm^2), A is soil sample area (cm^2), L is soil sample length (cm), and t is time for standpipe head to decrease from h_1 to h_2.

Plant-produced mix was also sampled at each project in order to determine the theoretical maximum density (TMD) and the project gradation. The TMD test was performed according to AASHTO T209-94. Besides air voids and thickness to NMAS ratio, other factors influencing the permeability such as gradation, NMAS, and voids in mineral aggregate (VMA) were also investigated. Statistical analysis was performed to determine the effects of these factors on permeability which was measured in laboratory.

3.0 Results

3.1 Test Results

A total of 497 cores were obtained from the 57 projects. Of the 57 projects, 17 utilized 9.5 mm NMAS mixes, 29 used 12.5 mm NMAS mixes, 9 used 19.0 mm NMAS mixes, and 2 used 25.0 mm NMAS.

Table 2: Average air voids, water absorption and permeability for field projects

Project No.	NMAS (mm)	Gradation	Average Thickness (mm)	Average Voids SSD (%)	Average Voids Vac. Seal (%)	Average Water Abs. (%)	Average VMA Vac. Seal (%)	Average Lab. Perm. (10^{-5} cm/sec)
1	9.5	Coarse	34.3	8.1	8.1	0.4	18.9	74
2	9.5	Coarse	40.5	9.5	11.8	1.2	NA	468
3	9.5	Coarse	44.5	9.1	10.7	1.0	19.9	214
4	9.5	Coarse	45.7	8.3	9.9	0.9	18.8	242
5	9.5	Coarse	31.2	16.3	17.0	1.7	27.0	2198
6	9.5	Coarse	33.9	8.4	8.6	0.4	18.5	108
7	9.5	Coarse	34.9	7.6	8.1	0.3	NA	130
8	9.5	Coarse	44.1	9.9	11.1	1.5	20.8	606
9	9.5	Coarse	22.3	9.7	10.4	0.7	20.0	339
10	9.5	Coarse	32.8	9.0	11.1	2.6	17.7	575
11	9.5	SMA	26.8	10.2	13.7	3.0	22.0	1893
12	9.5	Fine	40.5	7.1	7.3	0.2	18.8	6
13	9.5	Fine	32.4	10.4	11.3	0.4	NA	385
14	9.5	Fine	48.7	8.3	8.7	0.9	15.8	59
15	9.5	Fine	41.0	9.4	9.9	1.6	14.2	118
16	9.5	Fine	40.6	5.6	5.9	0.7	14.6	7
17	9.5	Fine	41.5	8.6	9.0	0.3	13.5	493
18	12.5	Coarse	39.9	11.6	13.1	1.7	24.4	453
19	12.5	Coarse	42.4	12.5	16.9	2.4	24.8	5656
20	12.5	Coarse	38.0	10.6	12.3	0.8	22.3	420
21	12.5	Coarse	33.7	10.4	11.7	0.6	21.1	279
22	12.5	Coarse	53.5	8.1	9.3	2.2	18.5	346
23	12.5	Coarse	51.0	11.3	12.5	3.3	19.0	2379
24	12.5	Coarse	52.8	8.8	9.9	1.2	19.9	238
25	12.5	Coarse	56.8	9.6	10.8	1.1	21.7	361
26	12.5	Coarse	50.6	6.9	7.7	0.2	17.7	39
27	12.5	Coarse	47.6	6.3	7.0	0.7	16.9	92
28	12.5	Coarse	44.1	5.3	5.8	0.2	NA	2
29	12.5	Coarse	51.1	7.3	9.1	0.4	NA	260
30	12.5	Coarse	78.8	8.6	9.3	1.3	20.0	59
31	12.5	Coarse	48.4	6.5	8.1	0.3	18.1	30
32	12.5	Coarse	50.3	5.6	5.6	0.7	10.9	42
33	12.5	Coarse	43.8	8.0	9.7	2.2	15.6	337
34	12.5	Coarse	44.5	8.7	9.1	1.0	14.3	1027

NA – Not Available

Table 2: (Cont'd.)

Project No.	NMAS	Gradation	Average Height (mm)	Average Voids SSD (%)	Avergae Voids Vac. Seal (%)	Average Water Abs. (%)	Average VMA Vac. Seal (%)	Average Lab. Perm. (10^{-5} cm/sec)
35	12.5	Fine	53.3	5.3	6.2	0.2	17.5	9
36	12.5	Fine	44.3	8.6	9.0	0.8	19.3	133
37	12.5	Fine	45.8	10.3	10.4	0.3	19.6	86
38	12.5	Fine	39.8	8.1	8.3	0.3	25.3	19
39	12.5	Fine	51.2	9.2	10.3	0.5	NA	124
40	12.5	Fine	55.2	7.9	8.2	0.4	NA	78
41	12.5	Fine	34.8	9.6	10.4	0.8	20.2	318
42	12.5	Fine	38.7	8.5	8.5	0.4	17.9	144
43	12.5	Fine	36.3	7.7	7.7	0.2	17.7	43
44	12.5	Fine	68.6	6.1	6.6	0.4	12.5	33
45	12.5	Fine	43.3	10.2	10.2	0.7	16.6	786
46	12.5	Fine	34.5	8.7	10.4	1.0	16.0	619
47	19	Coarse	64.9	5.9	7.0	0.5	13.0	6
48	19	Coarse	58.9	9.5	10.2	1.0	13.4	107
49	19	Coarse	96.4	5.6	6.6	0.3	11.9	65
50	19	Coarse	70.9	6.4	7.9	1.3	11.1	390
51	19	Coarse	38.0	7.2	8.2	1.5	14.2	241
52	19	Coarse	50.4	11.5	13.6	4.0	19.2	1075
53	19	Fine	33.0	8.4	8.4	0.4	17.8	12
54	19	Fine	49.6	6.6	6.5	0.2	15.9	38
55	19	Fine	48.7	7.0	7.0	0.1	16.8	12
56	25	SMA	42.6	5.6	6.9	1.1	14.5	225
57	25	Fine	70.0	9.3	10.2	1.5	16.2	300

NA-Not Available

The average thickness of the cores ranged from 22.3 to 96.4 mm, the average air voids (vacuum sealing method) from 5.6 to 17.0%, the average VMA from 10.9 to 27.0% and the average lab permeability from 2 to 5656 x 10^{-5} cm/sec (Table 2). The mixes consisted of fine-graded, coarse-graded and SMA gradation. For all mix types, there was a difference between the air voids measured by SSD and vacuum sealing methods. The variations become more significant for samples having higher air void contents that involve coarse–graded and SMA mixes. These results agree with Cooley et al. (2002) suggesting that the coarse-graded mixes had higher potential errors during the SSD measurements which lead to a higher measured density than the actual density. This could be the reason why the coarse dense-graded mix is more permeable than fine-graded mix at a given air void content. Cooley et al. (2002) also noted that vacuum sealing method was more accurate for measuring the bulk specific gravity. Hence, it was decided to use the air voids values determined from vacuum sealing method throughout the analysis.

3.2 Statistical Analysis

In order to determine the significance of in-place air voids impacting permeability and to investigate other factors affecting permeability, a multiple linear regression (MLR) was performed using a statistical software, MINITAB. A "best subset regression" was used to evaluate all independent variables and select the variables that provide the most significant relationship with the dependent variable (permeability). The best subsets regression procedure allows the user to input numerous factors that have the potential to impact the dependent parameter. For this analysis, the natural log of permeability was selected as the response, while natural log of in-place air voids, NMAS, sample thickness, natural log of voids in mineral aggregates (VMA), and coarse aggregate ratio were included as the predictors. As obtained by Mallick et al., (2001), the relationship between permeability and air voids is not linear. Hence, the natural log of air voids and permeability were used in the best subsets regression. The coarse aggregate ratio was defined as the percent retained on a sieve, three sizes lower than the NMAS, divided by the percent passing that particular sieve. Therefore, for NMAS of 19.0 mm, 12.5 mm, and 9.5 mm the associated sieve sizes were 4.75 mm, 2.36 mm, and 1.18 mm, respectively. The coarse aggregate ratio indicated whether a gradation was coarse or fine-graded.

Of the 497 core samples, only 436 had the VMA values available. Thus, the MLR was performed based on results of the 436 core samples and the best subsets regression analysis is presented in Table 3. C_p statistic and R^2 values were used to determine the best-fit model. Theory suggests that the best-fitting model should have C_p statistic about the same value with the number of variables. Based on the C_p and R^2 values, the best model that could predict permeability was a combination of the natural log of air voids, the natural log of VMA, coarse aggregate ratio, and thickness. The four identified factors were then regressed against the natural log of permeability and the following regression equation was obtained.

$$\ln(k) = -2.67 + 6.55\ln(\text{Void}) + 0.252(\text{C}Aratio) - 2.5\ln(VMA) - 0.0146(\text{Thickness}) \quad (2)$$

where ln (k) is natural log of permeability, ln (Void) is natural log of air voids, *CAratio* is coarse aggregate ratio, and ln(*VMA*) is natural log of voids in mineral aggregate.

There was a fairly good correlation for the above equation with an R^2 of 0.64. This R^2 value indicates that 64 percent of the variability in the lab permeability results are attributed to in-place air voids, coarse aggregate ratio, VMA and thickness. The positive constant for air voids in the equation indicates that permeability increased as the air voids increased.

Table 3: Best Subsets Regression on factors affecting permeability

No.of Variable	R-Sq	R-Sq(adj)	C_p	NMAS	Thickness	Ln (Void)	CAratio	Ln (VMA)
1	60.9	60.8	41.7			X		
1	24.4	24.2	483.8					X
2	62.3	62.1	27.2			X		X
2	61.7	61.5	34.2			X	X	
3	63.6	63.4	12.9			X	X	X
3	63.5	63.2	14.3		X	X		X
4	**64.4**	**64.1**	**5.1**		**X**	**X**	**X**	**X**
4	63.6	63.3	14.8	X		X	X	X
5	64.5	64.1	6	X	X	X	X	X

The coarse aggregate ratio also has a positive constant which suggests that permeability increased as the coarse aggregate ratio increased. The coarser are the gradations, the larger are the individual air voids leading to higher potential for interconnected air voids.

The negative constant of the VMA in the equation indicates that the permeability increased as the VMA decreased. VMA is very much related to NMAS. As the NMAS increases, the total void space between large particles is smaller than that between smaller particles. Smaller VMA suggests less room for asphalt cement in a mix, which results in higher potential for interconnected air voids. Cooley et al. (2001) suggested that NMAS affected the size of air voids within an HMA. As the NMAS increases, the size of individual air voids also increase which cause higher potential for interconnected air voids. The negative constant for the thickness in the equation suggests that permeability decreased as the thickness increased. Thicker lifts tend to block void paths thus reducing the chance for voids being interconnected with an adequate length to allow water to flow. For this reason, voids in thinner pavements are much more likely to be interconnected resulting in higher permeability.

3.3 Permeability – Air Void Relationship

Since the air void content is the most important factor influencing permeability, the relationship between both variables was studied further and the results are shown in Figures 1 to 4. Figure 1 illustrates the relationship between in-place air voids and permeability for all cores of each gradation. The R^2 values for the plots are relatively high; 0.76 for SMA mixes, 0.58 for coarse-graded mixes and 0.60 for fine-graded mixes.

The best fit lines indicate that as air voids increased permeability increased. This figure suggests that at higher in-place air voids (greater than 15%), SMA mix is the most permeable followed by coarse-graded and fine-graded mix. However, a closer look is needed to determine the permeability characteristics of each gradation.

Figures 2 through 4 present the plots of lab permeability versus in-place air voids for each gradation type. The relationship between lab permeability and in-place air voids for the fine-graded mix is illustrated in Figure 2. The R^2 value for the best fit line was

0.60. The permeability begins to increase at greater rates at approximately 8.0 % air voids. At this air void content, the pavement is expected to have a permeability of 31 x 10^{-5} cm/sec. Based on the maximum permeability value of 125 x 10^{-5} cm/sec, used by Florida Department of Transportation and other researchers (e.g. Maupin, 2000; Cooley et al., 2001), the corresponding average air void content is 10.1%. However, it is important to note that this is the average air voids and samples at this air void content can still be permeable due to variability of the results.

Hence, in order to establish recommended limit for the in-place air voids, a 90% confidence interval is plotted. Using the upper 90% confidence limit as the criterion, the corresponding air void content is determined to be 6.8%.

The relationship between lab permeability and air voids for the coarse-graded mix is shown in Figure 3. The relationship was reasonable with an R^2 of 0.58. The permeability starts to increase at a greater rate at approximately 8.0 % air voids. The permeability at 8.0 % air voids for coarse-graded mix was 51 x 10^{-5} cm/sec. Based on 125 x 10^{-5} cm/sec, the corresponding average air void is 9.4%. Using the upper 90% confidence limit as the criterion, the corresponding air void content for the coarse-graded mix is determined to be 6.7% which is very close to the fine-graded mix (6.8%).

Figure 4 illustrates the relationship for SMA mixes. The relationship was relatively strong with an R^2 of 0.76. The permeability starts to increase at a greater rate at approximately 8.0% air voids. The permeability at 8.0% air voids was 40 x 10^{-5} cm/sec. Based on 125 x 10^{-5} cm/sec, the corresponding average air void is 9.6%. Using the upper 90% confidence limit as the criteria, the corresponding air void content for the coarse-graded mix is 4.7%. This value is unreasonably low as compared to typical in-place air voids of SMA of 6 to 7%. It is important to note that this value was based on data from two SMA projects and more data are needed in order to establish the critical limits.

4.0 Discussion

The selected factors identified by the best subsets regression are in-place air voids, coarse aggregate ratio, VMA and thickness. A good relationship with an R^2 of 0.64 was obtained which indicates that 64% of the variability in the lab permeability results is attributed to these four factors. However, it is important to note that air void is the most significant factor as it contributes 61% of that 64% variability. These results are also interesting because NMAS was not among the significant factors affecting permeability which is in contrast with Cooley et al. (2001) and Mallick et al. (2001). There is an inverse relationship between VMA and NMAS. As the NMAS increases, the VMA decreases. A smaller VMA suggests less room for asphalt cement in a mix, which results in higher potential for interconnected air voids. The fact that VMA is more significance in the regression analysis than NMAS and both are related, might result in NMAS not to be picked up as a significant factor. Another possible explanation is that of the 57 projects included in this study, 46 had either a 9.5 or 12.5 mm NMAS.

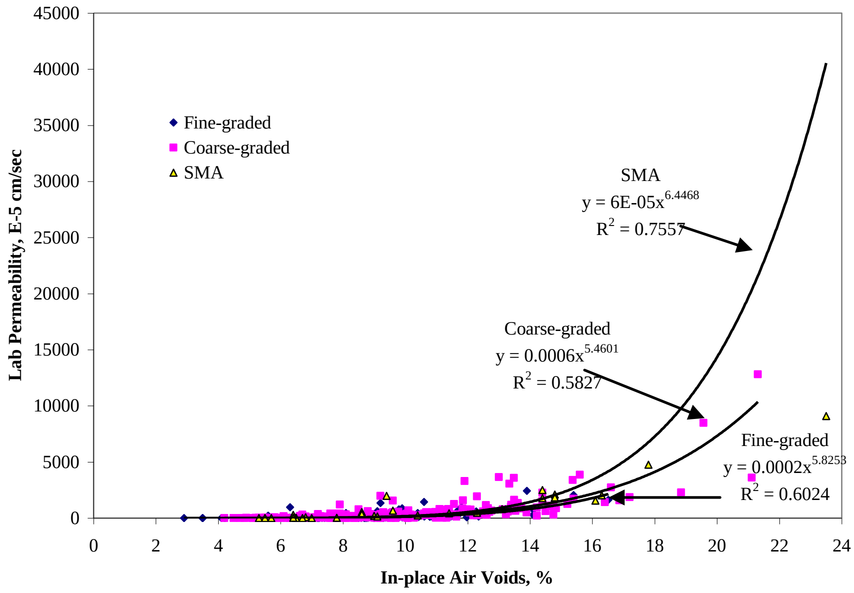

Figure 1: Plot of Laboratory Permeability versus In-place Air Voids

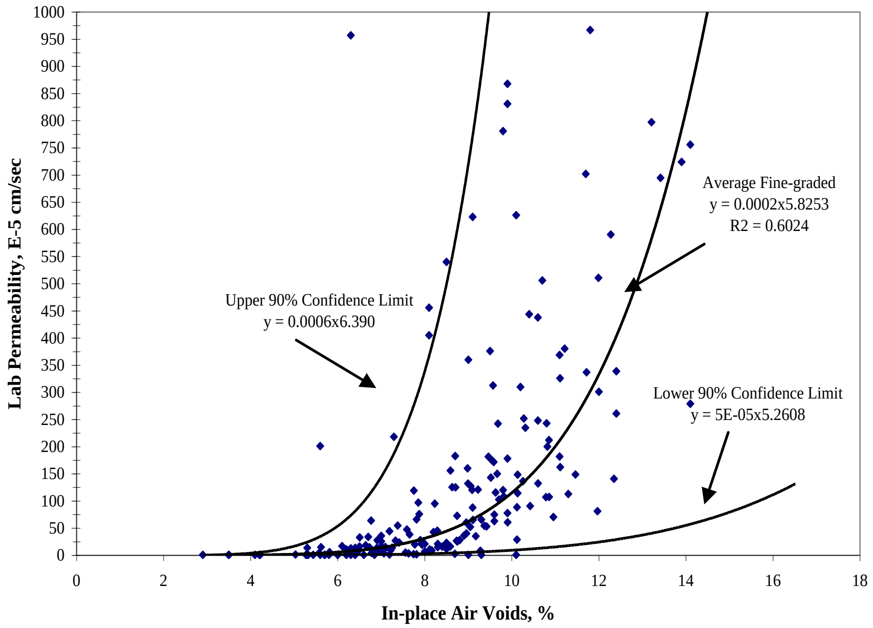

Figure 2: Plot of permeability versus in-place air voids for fine-graded mixes

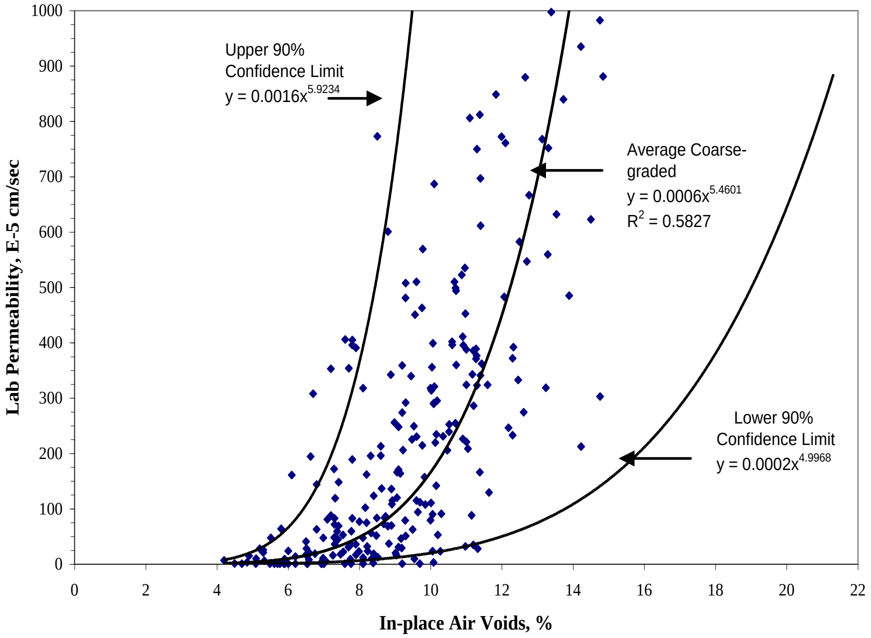

Figure 3: Plot of permeability versus in-place air voids for coarse-graded mixes.

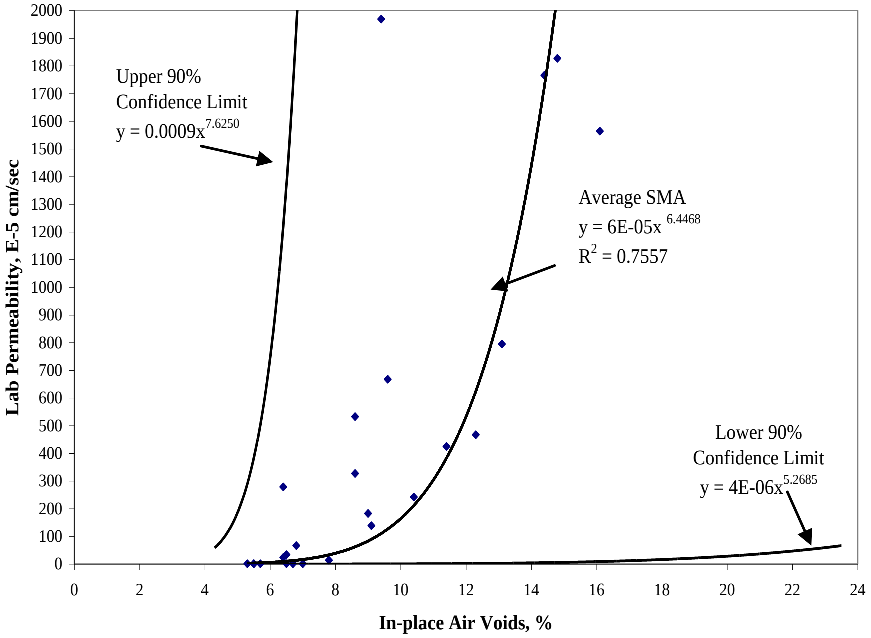

Figure 4: Plot of permeability versus in-place air voids for SMA mixes.

Therefore, there was a little variation in NMAS, which would cause it not to be significantly identified during the regression.

Based on the 497 field core samples from NCHRP 9-9 and NCHRP 9-27, relationships between permeability and in-place air voids were established. The relationships are best represented by a power function with R^2 of 0.60 for fine-graded mixes, 0.58 for coarse -graded mixes, and 0.76 for SMA mixes. The best fit lines indicated that as in-placed air voids increased, permeability increased. The permeability begins to increase at a larger rate when the air voids exceed 8.0%

One major issue that has been continuously discussed among asphalt technologists is the in-place density needed to achieve an impermeable and durable pavement. To help solve this issue, a regression equation for each gradation shape was used and the in-place air void content that corresponded to the 125 x 10^{-5} cm/sec, the maximum permeability value, was determined. The corresponding averages of air void content are 10.1% for fine-graded, 9.4% for coarse-graded and 9.6% for SMA. However, it is important to note that this is the average air voids and samples at this air void content can still be permeable due to the variability of the results. Hence, in order to establish recommended limits for the in-place air voids, a 90% confidence interval was plotted. Using the upper 90% confidence limit and maximum permeability value of 125 x 10^{-5} cm/sec as the criteria, the corresponding air void contents are 6.8% for fine-graded, 6.7% for coarse-graded and 4.7% for SMA mixes. This 4.7% air void content is very low compared to typical in-place air voids of SMA, between 6 and 7%. It is important to note that this value was based on data from two SMA projects. Hence, the 4.7% air void value was not suggested due to lack of data. For fine-graded and coarse-graded mixes, the suggested critical in-place air void of 7.0% is considered reasonable because compaction of most pavements in the field for dense-graded mixes is targeted at 92.0 to 94.0% of theoretical maximum density.

5.0 Conclusions

Based upon the above results, the following conclusions are drawn. In-place air void content was the most significant factor influencing the permeability of HMA. This is followed by the gradation, voids in mineral aggregates and the thickness of pavement. As the in-place air voids and percentage of coarse aggregate particles increase, permeability increases. On the other hand, permeability decreases as voids in mineral aggregates and thickness increase. The in-place air voids for dense graded HMA pavements should not exceed 7% to avoid permeability problem which could lead to pavement damage. More detailed studies on SMA mixes are necessary to determine the critical air voids and improve the pavement performance.

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Acronyms

HMA = Hot mix axphalt
NMAS = Nominal maximum aggregate size
AASHTO =American Association of State Highways and Transportation Officials
ASTM = American Society for Testing and Materials
SMA = Stone mastic asphalt
NCAT = National Center for Asphalt Technology
NCHRP = National Cooperative Highway Research Program
NAPA = National Asphalt Pavement Association
SSD = Saturated surface dry
TMD = Theoretical maximum density
VMA = Voids in mineral aggregate
MLR = Multiple linear regression
CAratio = Coarse aggregate ratio

References

Brown, E.R., Decker D., Mallick, R.B. and Bukowski, J. (1999) Superpave construction issues and early performance evaluations. *Journal of the Association of Asphalt Paving Technologists,* 68: 613-660.

Choubane, B. Gale, P.C. and Musselman, J.A. (1998) Investigation of water permeability of coarse graded Superpave pavements. *Journal of the of Asphalt Paving Technologists*, 67: 254-276.

Cooley, L.A. Jr., Prowell, B.D., Hainin, M.R., Buchanan, M.S., and Harrington, J. (2002) *Bulk Specific Gravity Round Robin Using the Corelok Vacuum Sealing Device*. USA: National Center for Asphalt Technology , 02-11

Cooley, L.A. Jr., Brown, E.R. and Maghsoodloo, S. (2001) Development of critical field permeability and pavement density values for coarse graded Superpave pavements. Proceedings of the 80th Annual Meeting of the Transportation Research Board. Washington, USA.

Florida Department of Transportation. (2000) *Standard Specifications for Road and Bridge Construction*. Tallahassee: Florida Department of Transportation.

Gotolski, W.H., Roberts, J.M., Smith, R.W. and Ciesielski, C.A. (1972) *Permeance as a Mix Design Criterion for Asphaltic Concrete Pavements*. Pennsylvania: Pennsylvania Department of Transportation, 68-1.

NAPA (2001) *HMA Pavement Mix Type Selection Guide Information Series 128*. National Asphalt Pavement Association.

US Army Corps (2000) *Hot-Mix Asphalt Paving Handbook*. USA: US Army Corps of Engineers.

Kumar, A. and Goetz, W.H. (1977a) Asphalt hardening as affected by film thickness, voids and permeability in asphaltic mixtures. Proceedings of the Association of Asphalt Paving Technologists, 46: 571-605.

Kumar, A. and Goetz, W.H. (1977b) Laboratory measurement of permeability of compacted asphalt mixtures. *Transportation Research Record*, 659: 37-43.

Mallick, R.B., Cooley L.A. Jr., Teto, M.R., Bradbury R.L. and Peabody, D. (2001) An evaluation of factors affecting permeability of Superpave designed pavements. Proceedings of the 80th Annual Meeting of the Transportation Research Board. Washington, USA.

Maupin, G.W. Jr. (2000) Asphalt Permeability Testing in Virginia. *Transportation Research Record*, 1723: 83-91.

Westerman, J.R. (1998) AHTD's Experience with Superpave Pavement Permeability. Proceedings of Arkansas Superpave Symposium. Arkansas, USA..