NCHRP

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COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

REPORT 531

Relationship of Air Voids, Lift Thickness, and Permeability in Hot Mix Asphalt Pavements

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Relationship of Air Voids, Lift Thickness, and Permeability in Hot Mix Asphalt Pavements

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Materials and Construction

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Edward T. Harrigan
Senior Program Officer
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This report presents recommended guidelines for hot mix asphalt pavement construction to achieve satisfactory levels of in-place air voids and permeability. These guidelines were developed from the findings of a research project that examined the relationship of air voids content to permeability and hot mix asphalt lift thickness. The report will be of particular interest to materials and construction engineers in state highway agencies, as well as to materials supplier and paving contractor personnel responsible for the production and placement of hot mix asphalt.

For satisfactory performance, hot mix asphalt (HMA) pavements must be constructed with adequate field density and impermeability to moisture. During the transition to the use of the Superpave mix design method since 1994, several states reported problems with greater than expected permeability associated with the use of coarse-graded mixes. In addition, there has been ongoing debate over the in-place air voids content and layer thickness needed to ensure an impermeable pavement. Some state highway agencies have addressed these issues by increasing their field density requirements, lift thickness requirements, or both, when coarse-graded mixes are used. Such changes, however, entail increased expense. So other states have elected (1) to reduce the nominal maximum aggregate size of given lifts (e.g., use of a 19.0-mm in place of a 25.0-mm mix) or (2) to eliminate pavement layers (such as a binder layer) and increase the thickness of the remaining layers to keep the total pavement thickness at typically used levels. However, many agencies are reluctant to adopt any such change without the support of specific research results that justify the increased cost or provide evidence of satisfactory long-term performance.

Under NCHRP Project 9-27, “Relationships of HMA In-Place Air Voids, Lift Thickness, and Permeability,” the National Center for Asphalt Technology (NCAT) at Auburn University was assigned the tasks of (1) determining the minimum ratio of layer thickness, t, to nominal maximum aggregate size, NMAS, needed to achieve desirable pavement density levels, and thus impermeable pavements; (2) evaluating the permeability characteristics of different thicknesses of compacted HMA; and (3) assessing factors affecting the relationship between in-place air voids, permeability, and lift thickness. To accomplish these tasks, the research team (1) conducted a critical review of the literature on the relationship of HMA lift thicknesses to in-place air voids, the relationship of in-place air voids to permeability, and their effects on pavement performance; (2) evaluated current state DOT guidelines and requirements for minimum lift thickness and minimum in-place density; and (3) designed and carried out coordinated laboratory and field experiments to establish relationships among air voids, lift thickness, and permeability from which to develop practical field compaction guidelines.

The NCAT project team found that the HMA pavement density that can be obtained under normal rolling conditions is clearly related to the ratio t/NMAS of the

HMA. For improved compactibility, the agency recommended that t/NMAS be at least 3 for fine-graded mixes and at least 4 for coarse-graded mixes. The data for SMA mixes indicate that the ratio should also be at least 4. Ratios less than these suggested values can be used but a greater than normal compactive effort will generally be required in these situations to obtain the desired in-place density.

The results of an experiment to evaluate the effect of mix temperature on the relationship between pavement density and t/NMAS found that the more rapid cooling of the HMA is a key reason for low density in thinner sections (lower t/NMAS). Hence, for thin HMA layers NCAT emphasized the importance of paving rollers staying very close to the paving machine so that rolling can be accomplished prior to excessive cooling.

The project team further identified the in-place air voids content as the most significant factor impacting permeability of HMA mixtures, followed by coarse aggregate ratio and VMA. As the coarse aggregate ratio increases, permeability increases, but it decreases as VMA increases at constant air voids content. The variability of permeability between various mixtures is very high; some mixtures are permeable in the range of 8 to 10 percent air voids while others are not. However, to ensure that permeability is not a problem NCAT recommends an in-place air voids content between 6 and 7 percent or lower. This appears to be true for a wide range of mixtures regardless of NMAS and aggregate gradation.

The project final report presents detailed descriptions of the coordinated laboratory (Task 3) and field (Task 5) experiments; a discussion of the research results from both experiments; and the project findings, conclusions, and recommendations in five volumes:

- Volume I: Task 3—Parts 1 and 2;
- Volume II: Task 3—Part 3;
- Volume III: Task 5;
- Volume IV: Appendices for Volumes I, II, and III; and
- Volume V: Executive Summary.

This report includes Volume V only; Volumes I through IV will be available online at http://www4.trb.org/trb/onlinepubs.nsf/web/nchrp_web_documents as NCHRP Web Document 68.

The recommended guidelines from Project 9-27 have been referred to the TRB Mixtures and Aggregate Expert Task Group for its review and possible recommendation to the AASHTO Highway Subcommittees on Materials and Construction for revision of appropriate specifications and recommended practices.

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CHAPTER 1

INTRODUCTION AND PROBLEM STATEMENT

Proper compaction of hot mix asphalt (HMA) mixtures is vital to ensure that a stable and durable pavement is built. For dense-graded mixes, numerous studies have shown that initial in-place air voids should not be below approximately 3 percent nor above approximately 8 percent (*1*). Lower percentages of in-place air voids can result in rutting and shoving, while higher percentages allow water and air to penetrate into the pavement, leading to an increased potential for water damage, oxidation, raveling, and cracking. Low in-place air voids are generally the result of a mix problem while high in-place voids are generally caused by inadequate compaction.

Many researchers have shown that increases in in-place air void contents have meant increases in pavement permeability. Zube (*2*) showed in the 1960s that dense-graded pavements become excessively permeable when in-place air voids exceed 8 percent. Brown et al. (*3*) later confirmed this value during the 1980s. However, due to problems associated with coarse-graded mixes (those with a gradation passing below the maximum density line), the size and interconnectivity of air voids have been shown to greatly influence permeability. A study conducted by the Florida Department of Transportation (FDOT) (*4*) indicated that coarse-graded Superpave mixes can sometimes be excessively permeable to water even when in-place air voids are less than 8 percent.

Permeability is also a major concern in stone matrix asphalt (SMA) mixes that utilize a gap-graded coarse gradation. Data have shown that SMA mixes tend to become permeable when air voids are above approximately 6 percent.

Numerous factors can potentially affect the permeability of HMA pavements. In a study by Ford and McWilliams (*5*), it was suggested that particle size distribution, particle shape, and density (air voids or percent compaction) 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. Research by Mallick et al. (*7*) has also shown that the nominal maximum aggregate size (NMAS) and lift thickness for a given NMAS affect permeability.

Work by FDOT 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 could lead to better pavement density and hence lower permeability.

Thus permeability, lift thickness, and air voids are all interrelated. Permeability has been shown to be related to pavement density (in-place air voids). Increased lift thickness has been shown to allow desirable density levels to be more easily achieved. Westerman (*9*), Choubane et al. (*4*), and Musselman et al. (*8*) have suggested that a thickness to NMAS ratio (t/NMAS) of 4.0 is preferred. Most guidance recommends that a minimum t/NMAS of 3.0 be used (*10*). However, due to the potential problems of achieving the desired density, it is believed that this ratio should be further evaluated based on NMAS, gradation, and mix type (Superpave and SMA).

CHAPTER 2

OBJECTIVE

The objectives of NCHRP 9-27 were to (1) determine the minimum t/NMAS needed for desirable impermeable pavement density levels to be achievable, (2) evaluate the permeability characteristics of compacted samples at different thicknesses, and (3) evaluate factors affecting the relationship among in-place air voids, permeability, and lift thickness.

CHAPTER 3

RESEARCH APPROACH

The laboratory evaluation of the relationship between thickness, density, and permeability was divided into two parts. Part 1 evaluated the relationship of lift thickness, air voids, and permeability in a controlled, statistically designed experiment. This part looked at varying the lift thickness in the gyratory compactor and determining density; the experimental variables included three aggregates, four gradations, three nominal aggregate sizes for Superpave mixes, and three nominal aggregate sizes for SMA mixes. The aggregate properties are shown in Table 1. Only one asphalt binder was used for this study, a PG 64-22. After the mix designs were performed for these mixes, they were compacted in the Superpave gyratory compactor (100 gyrations) to heights of 2.0, 3.0, and 4.0 times the t/NMAS. The effect of t/NMAS on density was then determined. The plan was to select the t/NMAS that gave optimum density; but, as will be shown later, the results from the Superpave gyratory compactor data did not provide a conclusive answer; hence, additional work was needed to better establish the appropriate ratio.

It was then decided to look at many of the same mixes with a vibratory compactor, to establish whether the vibratory compactor would better simulate field compaction and would provide more conclusive results The experimental variables included two aggregates, three gradations, two nominal aggregate sizes for Superpave, and three nominal aggregate sizes for SMA. These mixtures, which had already been designed in the first part, were compacted at three thicknesses using three compactive efforts with the vibratory compactor. The density results were determined, and again the results did not identify a definitive minimum ratio. It was then decided that additional work was needed if an acceptable answer was to be obtained.

The third attempt at the effect of t/NMAS on compaction was to look at a field study during the rebuilding of the National Center for Asphalt Technology (NCAT) test track. During this work, the layer thicknesses were varied and compacted under similar conditions. Seven mixes from the track were constructed on a paved surface adjacent to the track to look at the effect of layer thickness on density. A general description of these seven mixtures is provided in Table 2. For this part of the study, seven mixes were compacted at layer thicknesses varying from two to five times the t/NMAS. For some of these seven mixes, one side was compacted with a vibratory roller and the other sided was compacted with vibratory and rubber tire rollers. The test data were evaluated, as shown later, and provided reasonable results.

Another part of the study for Part 1 looked at the effect of lift thickness on permeability. The air voids were controlled at 7 percent and the thickness varied. The permeability results were then determined. These variables were evaluated: two aggregate types, three gradations, two Superpave NMAS, three SMA NMAS, and three t/NMAS.

Part 2 of Task 3 looked at the permeability of cores obtained from the NCHRP 9-9 project. This project contained 40 sections with varying aggregate types, NMASs, thicknesses, and design gyrations. The results were evaluated to determine the effect of gradation, NMAS, thickness, and design gyration on permeability. It was assumed that this information would help to determine the in-place air voids at which permeability would become a problem. Both field and lab permeability were measured.

TABLE 1 Physical properties of aggregate

Property		Test Method	Aggregate Type		
			Granite	Limestone	Crushed Gravel
Coarse Aggregate					
Bulk Specific Gravity		AASHTO T-85	2.654	2.725	2.585
Apparent Specific Gravity		AASHTO T-85	2.704	2.758	2.642
Absorption (%)		AASHTO T-85	0.7	0.4	0.9
Flat and Elongated (%), 3:1, 5:1	19.0 mm	ASTM D4791	14, 0	10, 0	4, 0
	12.5 mm		16, 0	6, 0	16, 2
	9.0 mm		9, 1	16, 3	19, 2
Los Angeles Abrasion (%)		AASHTO T-96	37	35	31
Coarse Aggregate Angularity (%)		AASHTO TP56-99	42.9	43.0	44.0
Percent Crushed (%)		ASTM D5821	100	100	80
Fine Aggregate					
Bulk Specific Gravity		AASHTO T-84	2.678	2.689	2.610
Apparent Specific Gravity		AASHTO T-84	2.700	2.752	2.645
Absorption (%)		AASHTO T-84	0.3	0.9	0.5
Fine Aggregate Angularity (%)		AASHTO T-33 (Method A)	49.4	45.7	48.8
Sand Equivalency (%)		AASHTO T-176	92	93	94

TABLE 2 Mix information for field density study

Section	NMAS	Gradation	Asphalt Type	Aggregate Type
1	9.5 mm	Fine-Graded Superpave	Unmodified	Granite and Limestone
2	9.5 mm	Coarse-Graded Superpave	Unmodified	Limestone
3	9.5 mm	SMA	Modified	Granite
4	12.5 mm	SMA	Modified	Limestone
5	19.0 mm	Fine-Graded Superpave	Unmodified	Granite and Limestone
6	19.0 mm	Coarse-Graded Superpave	Unmodified	Granite
7	19.0 mm	Coarse-Graded Superpave	Modified	Limestone

CHAPTER **4**

TEST RESULTS AND ANALYSIS

4.1 PART 1—MIX DESIGNS FOR SPECIMENS TO STUDY THE EFFECT OF t/NMAS ON DENSITY

Of the 36 mix designs, 27 were Superpave-designed mixes and 9 were SMA mixes. The Superpave mixes were classified according to three gradations: above the restricted zone (ARZ), through the restricted zone (TRZ), and below the restricted zone (BRZ). The optimum asphalt content, the effective asphalt content (P_{be}), voids in mineral aggregate (VMA), voids filled with asphalt (VFA), percent theoretical maximum density at $N_{initial}$ (% G_{mm} at N_{ini}), and ratio of dust to effective asphalt content ($P_{0.075}/P_{be}$) for the Superpave mixes are summarized in Table 3. Data for SMA mixes are shown in Table 4. The mix design information for both mix types is presented in Appendix A. Optimum asphalt binder content was chosen to provide 4 percent air voids at the design number of gyrations. However, for the 19-mm NMAS limestone SMA mix, 4 percent air voids could be achieved with 5.7 percent asphalt content, which did not meet the minimum asphalt content requirement in accordance with the "Standard Practice for Designing SMA," AASHTO PP44-01. Therefore, the minimum asphalt content of 6.0 percent was chosen, which resulted in 3.7 percent air voids at the design number of gyrations. Some designs did not meet the requirements of VMA, VFA, % G_{mm} at N_{ini}, and/or dust/P_{be}. Efforts were made to redesign the respective mixes by changing the gradation until the requirements were met or closely approximated. This is important in that the mixes used in this project were intended to duplicate mixes utilized in the field. No modification was made for the TRZ mixes that did not meet the requirements, as little could be done to modify these gradations and still pass through the restricted zone.

4.2 EVALUATION OF EFFECT OF t/NMAS ON DENSITY USING GYRATORY COMPACTOR

Before the evaluation was done, two methods of measuring density, or bulk specific gravity, were compared: the AASHTO T166 (SSD) and the vacuum sealing (ASTM D6752-02a) methods. All samples were measured using both methods. Figures 1 through 4 present these measurements for the three gradations of Superpave mixes and the SMA mixes.

As shown in Figure 1, the air voids for ARZ mixes as measured by the two methods are approximately equal at low air voids and deviate by approximately 0.5 percent at the highest air void level. This figure indicates that for ARZ mixes, the two methods provide similar results. For the TRZ, BRZ, and SMA mixes, Figures 2 through 4 suggest that the bulk specific gravity measurements derived from the two methods moved farther apart as density decreased. The results also indicate that, as the gradation became coarser, the difference in the test results for the two test methods increased. This finding agrees with the research by Cooley et al. (*11*).

The apparent reasons for the different results according to the two test methods is loss of water during density measurement when using the T-166 method and the effect of surface texture. The loss of water when blotting in the T-166 method causes a test error resulting in higher measured density. The surface texture can result in the vacuum seal device measuring a lower density than the actual density. Because the vacuum seal device is more accurate in measuring the density of porous samples, it was used to determine density for this research project.

The main objective of this part of the study was to determine the minimum t/NMAS. To achieve this objective, relationships of average air voids for the three aggregate types versus t/NMAS with respect to NMAS and gradation were evaluated; the results are illustrated in Figures 5 through 10. Originally it was intended to determine the t/NMAS at which the air voids began to level out and to pick that t/NMAS level as the minimum level recommended to achieve optimum compaction. However much of the data in Figures 5 through 10 indicate that the air voids continue to drop with increasing t/NMAS past typical t/NMAS values. These data therefore did not provide reasonable guidance for selecting a minimum t/NMAS. Hence an air void content of 7.0 percent was selected as the criteria to determine the minimum t/NMAS. This level of air voids was selected because compaction of most pavements in the field is targeted at 92.0 to 94.0 percent of theoretical maximum density. Because of the uncertainty in the relationship of average air voids to t/NMAS, as indicated by the data, it was determined to compact some laboratory samples with a vibratory compactor and also to compact some mixes in the field during reconstruction of the NCAT test track. These two efforts, which are discussed later in the report, should provide sufficient information to make reasonable conclusions concerning desired t/NMAS levels.

One potential problem with the Superpave gyratory compactor is that it applies a constant strain to the mix during compaction and the force required varies as necessary to provide the desired strain. This is not the approach that is observed in

TABLE 3 Summary of mix design results for Superpave mixes

Aggregate	NMAS, mm	Gradation	Optimum Asphalt, %	P_{be}, %	VMA %	VFA %	% G_{mm} at N_{ini}	$P_{0.075}/P_{be}$
Granite	9.5	ARZ	6.7	6.2	18.4	76	89.0	0.8
	9.5	BRZ	5.3	4.9	15.7	73	86.7	1.0
	9.5	TRZ	5.4	5.0	15.6	75	88.9	1.0
	19.0	ARZ	4.7	4.3	14.1	72	89.5*	1.2
	19.0	BRZ	4.4	3.9	13.3	68	86.0	1.0
	19.0	TRZ	4.0	3.6	12.5*	68	88.8	1.4*
	37.5	ARZ	4.2	4.0	13.7	69	89.8*	0.8
	37.5	BRZ	3.3	3.0	11.3	64	86.8	1.0
	37.5	TRZ	3.6	3.3	12.0	65	88.1	0.9
Gravel	9.5	ARZ	6.7	6.5	18.3	78*	88.4	0.8
	9.5	BRZ	6.2	5.6	16.7	75	86.5	0.8
	9.5	TRZ	6.0	5.4	16.3	75	87.7	0.9
	19.0	ARZ	4.9	4.4	14.0	72	88.5	1.1
	19.0	BRZ	4.5	3.9	12.9*	69	86.3	1.3*
	19.0	TRZ	4.4	3.8	12.8*	69	88.0	1.3*
	37.5	ARZ	4.4	3.9	13.0	70	89.7*	0.8
	37.5	BRZ	3.6	3.2	11.7	63	85.5	1.0
	37.5	TRZ	3.9	3.5	12.0	66	85.6	0.9
Limestone	9.5	ARZ	6.0	5.7	17.4	76	87.8	0.7
	9.5	BRZ	5.0	4.6	15.3	72*	85.5	0.9
	9.5	TRZ	4.4	4.2	14.4	70*	86	1.2
	19.0	ARZ	4.1	3.5	12.6*	66	88.3	1.4*
	19.0	BRZ	4.7	4.4	14.3	71	85.5	0.7
	19.0	TRZ	3.3	2.8	11.0*	62*	85.7	1.8*
	37.5	ARZ	3.2	3.1	11.8	64	88.8	1.0
	37.5	BRZ	2.7	2.6	10.6*	60*	86.0	1.2
	37.5	TRZ	2.8	2.6	10.6*	61*	87.7	1.1

* Did not meet Superpave Design Requirements

the field where the stress is constant and the strain varies. Hence, the Superpave gyratory compactor likely does not provide a reasonable answer because the compaction provided by this device is different from the field. The big problem with using this concept to establish a minimum t/NMAS is that the voids continue to increase significantly as the t/NMAS increases, making it impossible to select an optimum value.

The optimum t/NMASs established using the Superpave gyratory compactor vary from less than 2.5 up to approximately 8. This wide range of numbers did not allow specific criteria to be established. Hence, additional testing was performed using the laboratory vibratory compactor and field test section.

4.3 EVALUATION OF EFFECT OF t/NMAS ON DENSITY USING VIBRATORY COMPACTOR

After obtaining the results for the Superpave gyratory compactor, it was concluded that more tests needed to be conducted to better simulate compaction in the field. The air voids determined from the vacuum seal device were utilized in the analysis. To further evaluate the relationship between density and lift thickness, a similar study was conducted, but on a smaller scale, using the vibratory compactor as the compaction mode. This was not part of the original proposed work, but it was believed that the vibratory compactor might provide compaction that has more typical of in-place compaction.

TABLE 4 Summary of mix design results for SMA mixes

Aggregate	NMAS, mm	Optimum Asphalt, %	P_{be}, %	VMA, %	VFA, %	VCA_{mix},[a] %	VCA_{drc},[b] %
Granite	9.5	7.2	6.6	18.7	78	30.9	41.9
	12.5	6.6	6.4	18.8	77	30.3	42.7
	19.0	6.4	5.9	17.6	77	29.6	42.0
Gravel	9.5	7.3	6.5	18.6	77	30.4	41.8
	12.5	6.8	6.1	17.7	77	31.1	42.1
	19.0	6.7	6.2	17.8	76	29.3	42.0
Limestone	9.5	6.2	5.8	17.4	76	30.7	38.4
	12.5	7.4	7.0	19.6	80	31.1	38.9
	19.0	6.0	5.6	16.8[c]	77	29.8	40.3

[a] VCA = Voids in Compacted Aggregate
[b] drc = dry-rodded compacted
[c] Did not meet SMA Design Requirements

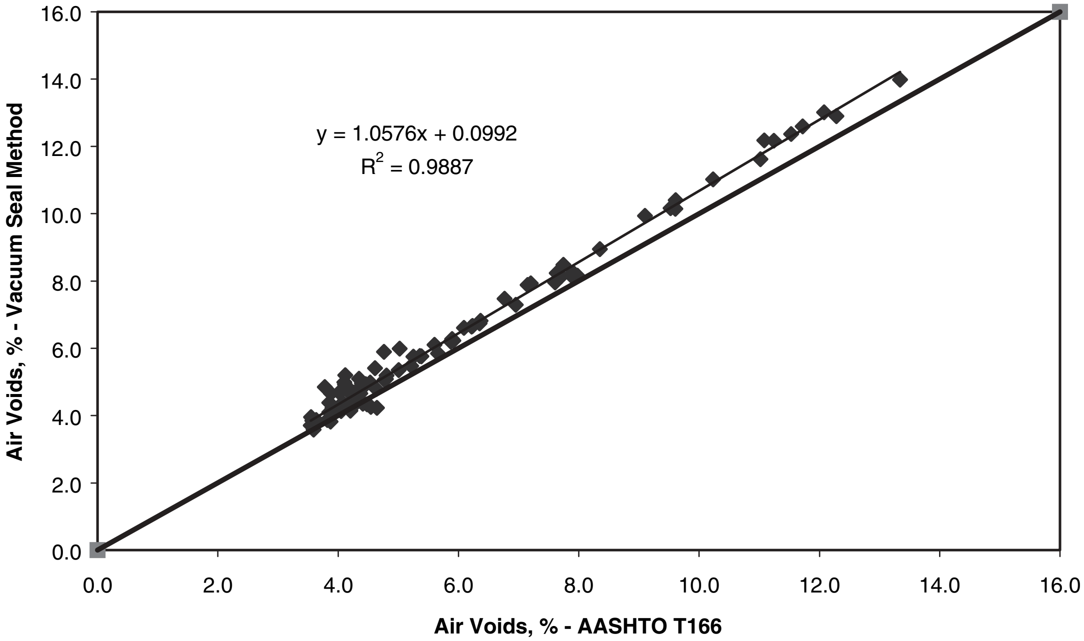

Figure 1. Relationship between air voids for ARZ mixes.

The vibratory compactor used compacted beam samples for the wheel-tracking device.

Of the 36 mix designs analyzed for Part 1, 14 mixes were selected for further study. Two types of aggregates, granite and limestone were used. For Superpave designed mixes, two gradations were utilized (ARZ and BRZ) along with two NMASs (9.5 mm and 19.0 mm). The 37.5-mm NMAS mix was excluded from the study because the maximum thickness of the vibratory specimen that could be obtained was 75.0 mm, which would only be 2.0 t/NMAS. For the SMA mixes, three NMASs were selected (9.5 mm, 12.5 mm, and 19 mm). The t/NMAS ratios utilized were 2.0, 3.0, and 4.0. The compactive effort for each t/NMAS was varied over a range including 30 sec, 60 sec, and 90 sec of compaction. The range of compactive efforts was selected for two reasons: (1) there is no standard compactive effort for the vibratory compactor and

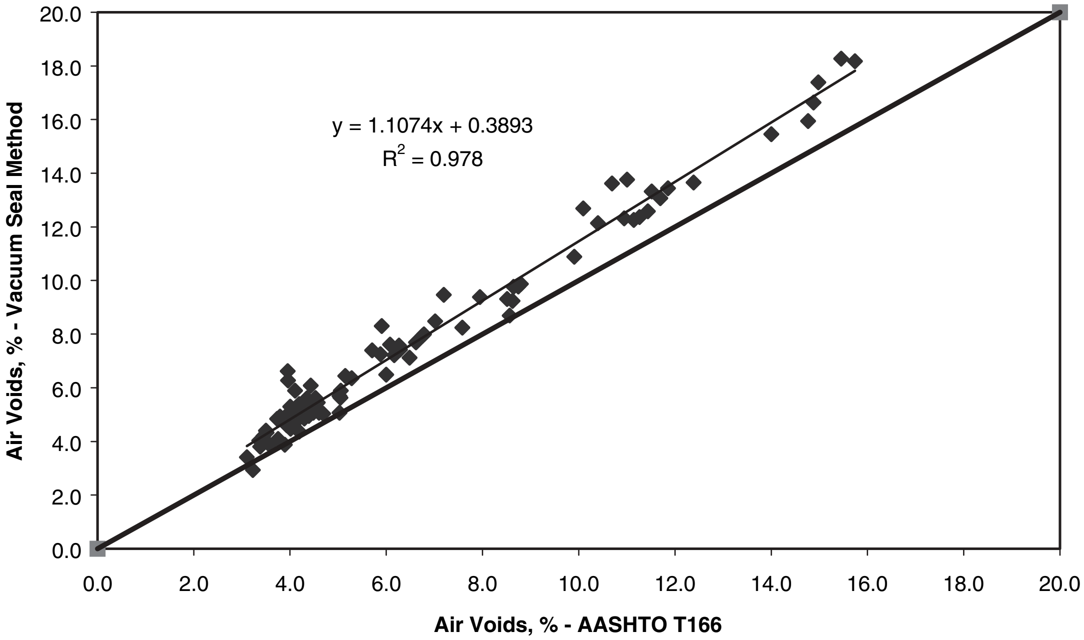

Figure 2. Relationship between air voids for TRZ mixes.

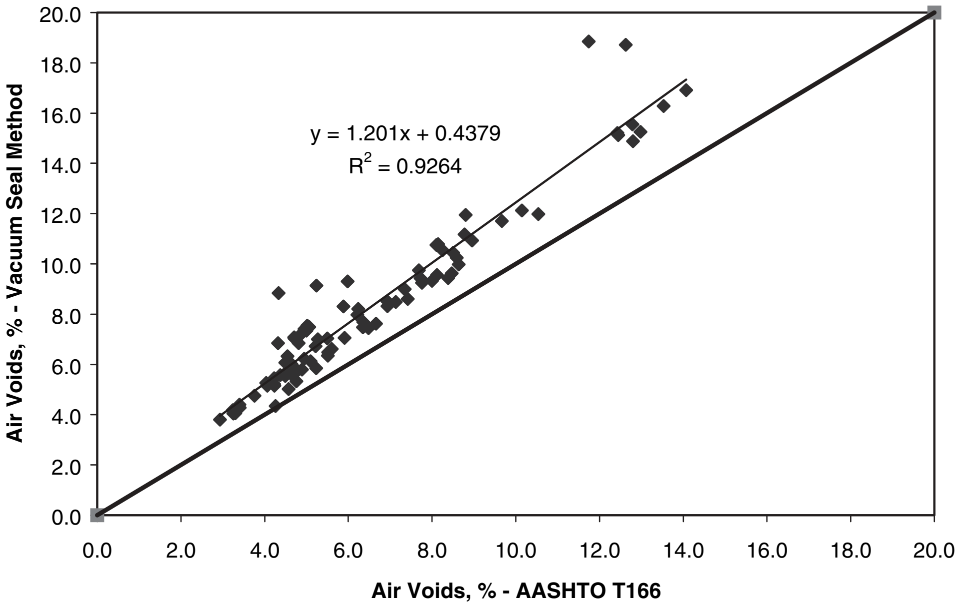

Figure 3. Relationship between air voids for BRZ Mixes.

(2) the effects of compactive effort on density at different thicknesses could be evaluated. After compaction, the bulk specific gravity was measured and the data were analyzed to provide recommendations concerning the minimum t/NMAS.

To determine the minimum t/NMAS, relationships between average air voids for the two types of aggregates and t/NMAS were plotted for each NMAS, compaction time, and gradation, as shown in Figures 11 through 17. In many cases there was very little difference between the densities for the different t/NMAS values. However, in a few cases there was a difference. Also, in many cases the best t/NMAS was 2.0, which is significantly lower than that observed on field projects. Typically, it was assumed that coarse graded mixes would have a desired t/NMAS greater than fine-graded mixes. The results did not always follow that trend. It was judged that some fieldwork was necessary to validate the results with the Superpave gyratory compactor and with the vibratory compactor.

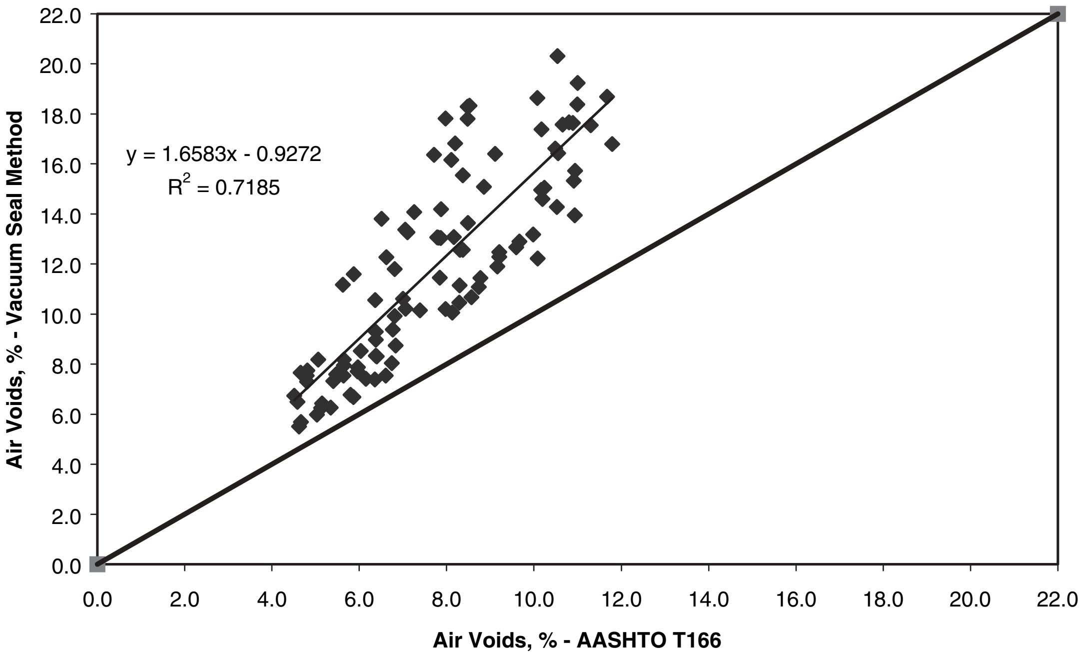

Figure 4. Relationship between air voids for SMA mixes.

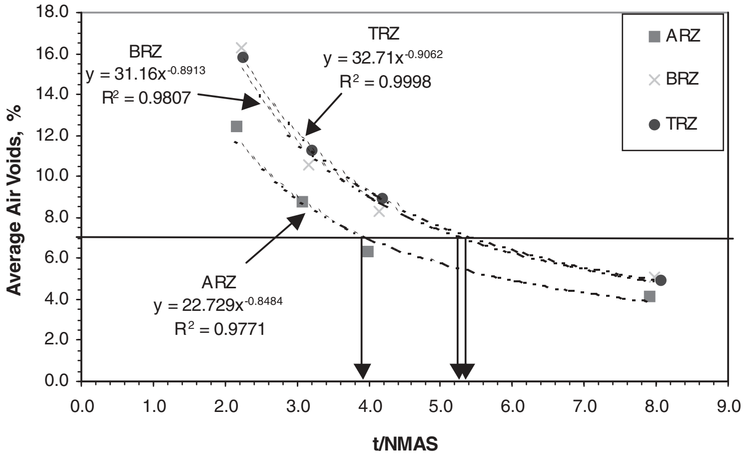

Figure 5. Relationships between air voids and t/NMAS for 9.5-mm Superpave mixes.

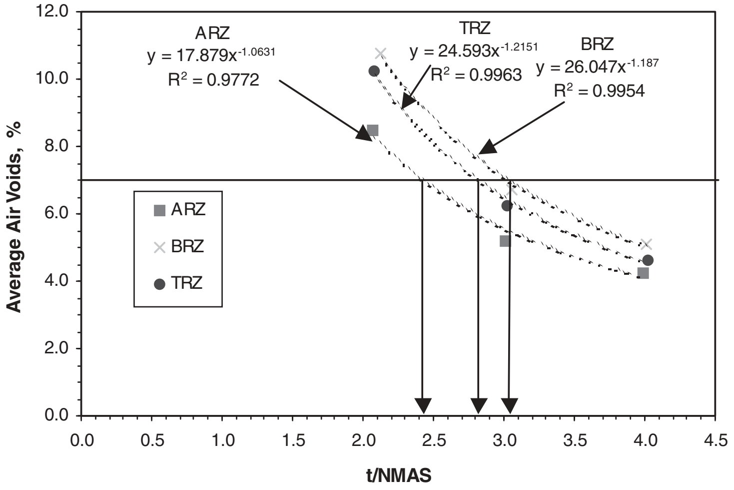

Figure 6. Relationships between air voids and t/NMAS for 19.0-mm Superpave mixes.

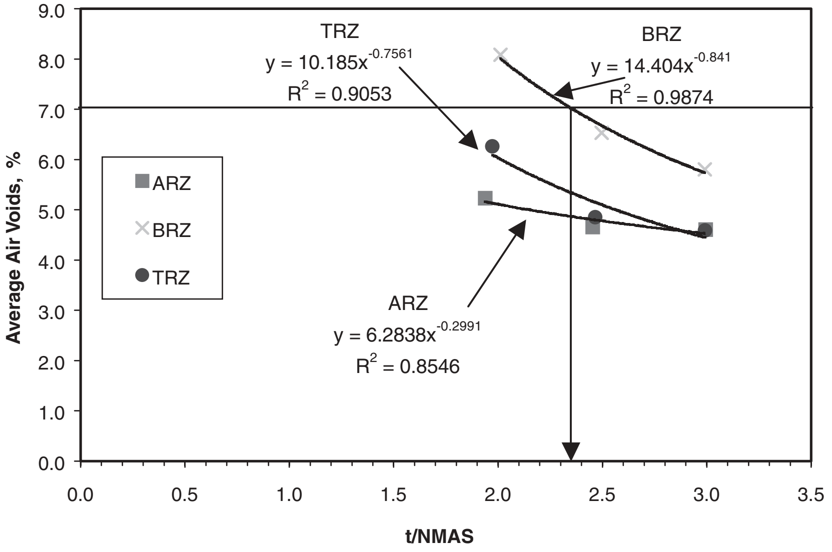

Figure 7. Relationships between air voids and t/NMAS for 37.5-mm Superpave mixes.

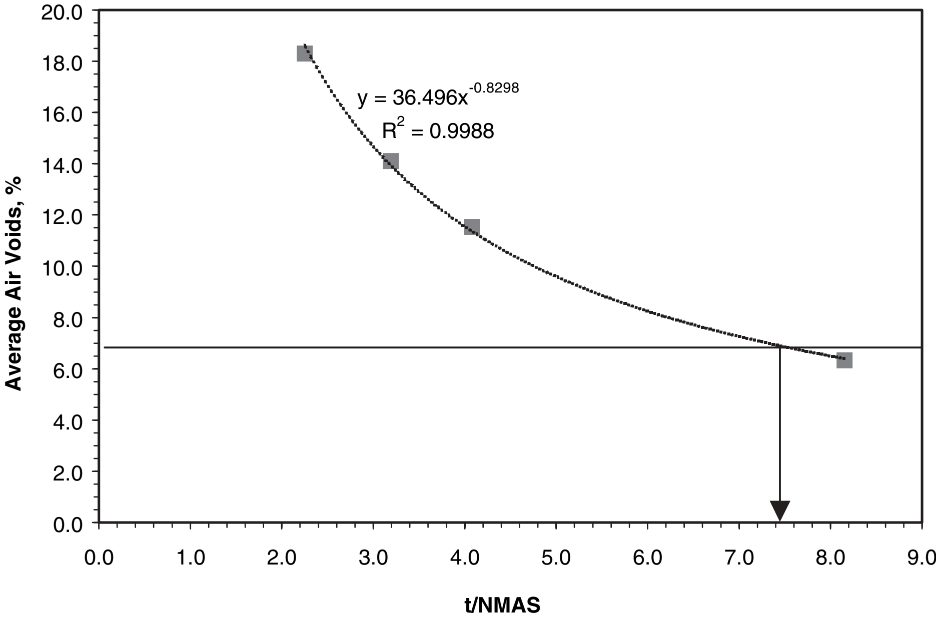

Figure 8. Relationships between air voids and t/NMAS for 9.5-mm SMA mixes.

4.4 EVALUATION OF EFFECT OF t/NMAS ON DENSITY FROM FIELD STUDY

The field test sections consisted of 7 mixes that were to be placed on the test track. These mixes had to be verified before placing on the track; hence, these mixes could be placed and tested without significant costs. Some of the mixes did not meet volumetrics and other requirements, but they were judged sufficient for this part of the study because determining the desired thickness range was a relative value based on t/NMAS.

4.4.1 Section 1

Section 1 was constructed on July 18, 2003, and consisted of a 2.0 to 5.0 t/NMAS overlay of an existing HMA layer. This construction was performed adjacent to the NCAT Test Track. The mix was a 9.5-mm NMAS fine-graded mixture. The length of the section was about 40 m, and the width was about 3.5 m. On some of the sections the placement began on the thick side and in some cases the placement began on the thin side. This technique was used so that there would be no bias due to the placement of the HMA. On this sec-

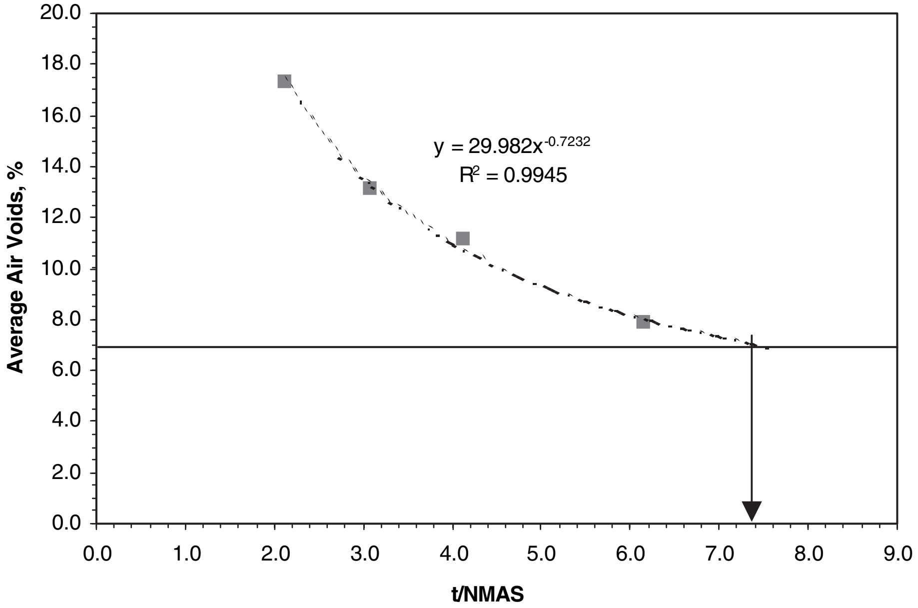

Figure 9. Relationships between air voids and t/NMAS for 12.5-mm SMA mixes.

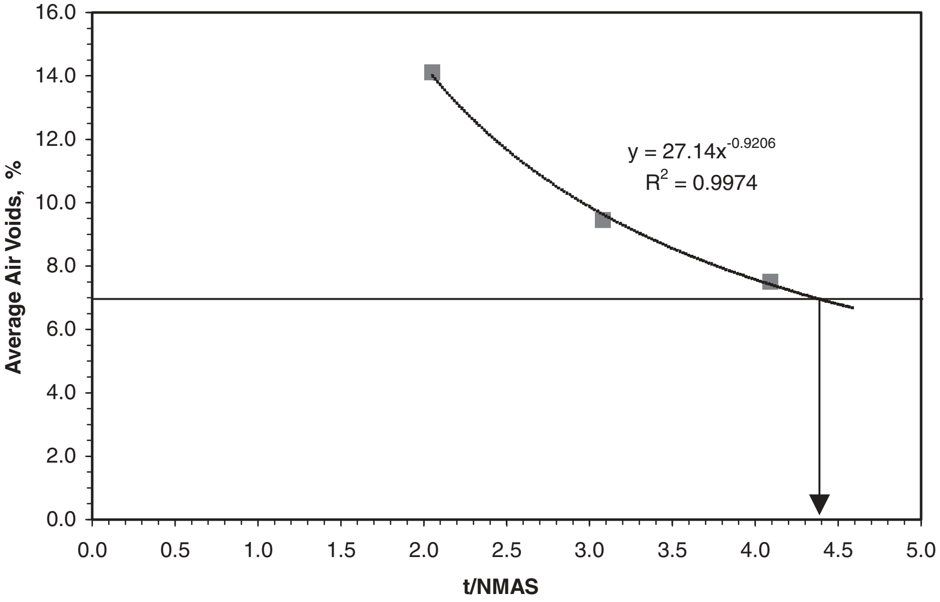

Figure 10. Relationships between air voids and t/NMAS for 19.0-mm SMA mixes.

tion the paving began with the thicker portion of the section and the thickness was slowly decreased as the paver moved down the test lane. The desired mat thickness was achieved by gradually adjusting the screed depth crank of the paver during the paving operation. The weather conditions during the paving were 84°F, overcast, with calm wind. The existing surface temperature prior to overlay was also 84°F.

The roller utilized in this section was an 11-ton steel roller HYPAC C778B with a 78-in. wide drum that could operate in vibratory or static mode. The rubber tire roller available did not meet desired requirements for weight and tire pressure, and thus the data generated for the rubber tire roller compacted mixture were omitted from the analysis for this section. The breakdown rolling was performed with one pass in the static mode on the mat at a temperature of about 300°F. This was followed by three passes in the vibratory mode at low amplitude and high frequency (3800 vibrations per minute [vpm]) and one pass in the static mode. It was determined that this compaction effort reached the peak density; hence, additional rolling was not performed.

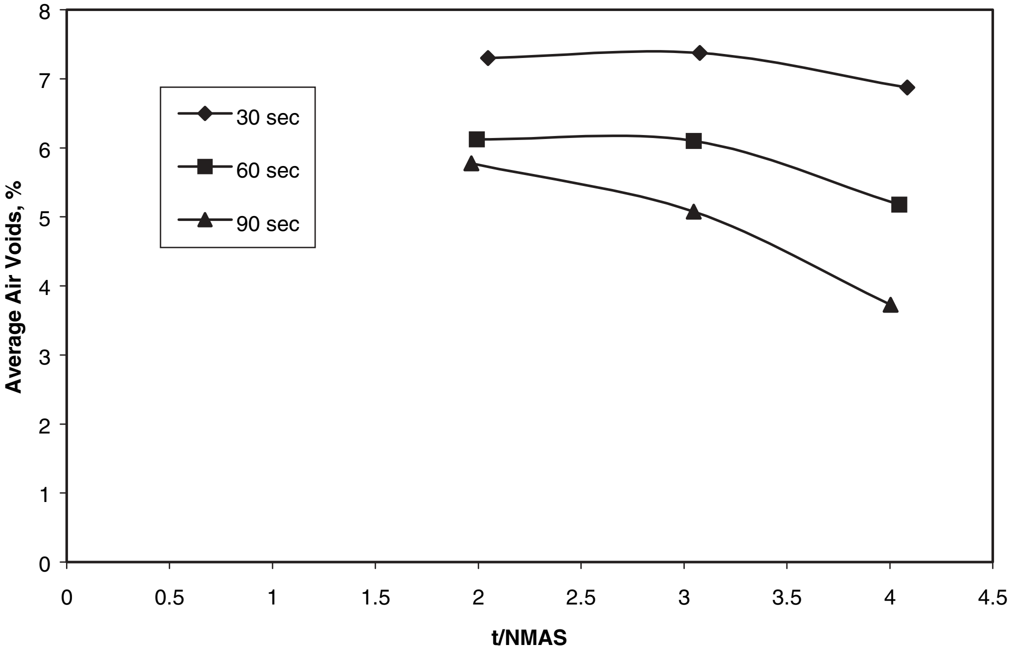

Figure 11. Relationships between air voids and t/NMAS for 9.5-mm ARZ mixes.

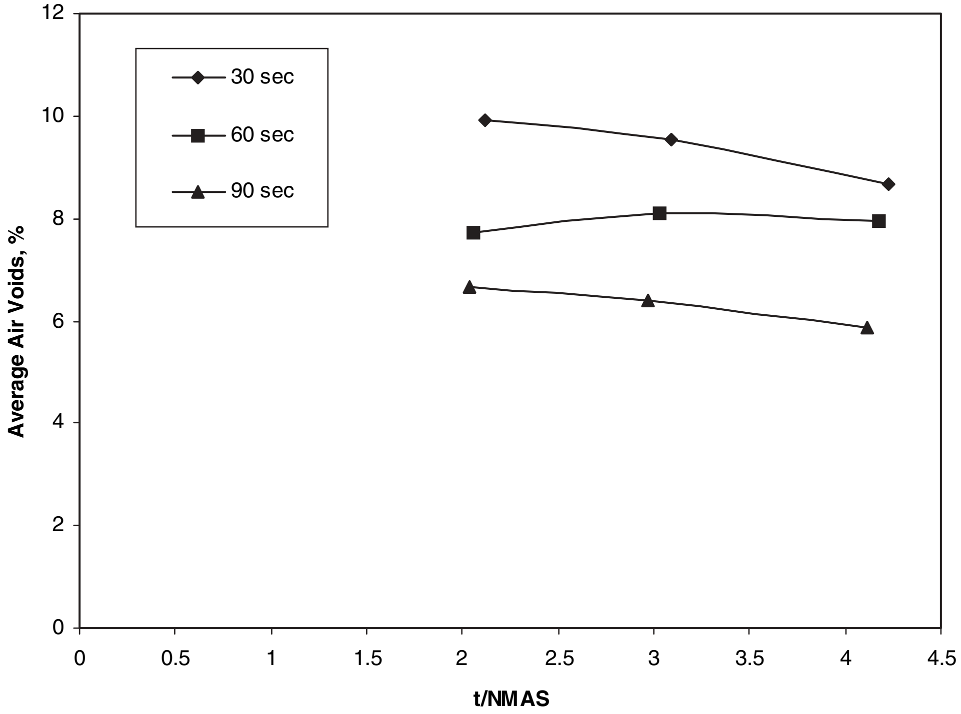

Figure 12. Relationships between air voids and t/NMAS for 9.5-mm BRZ mixes.

A total of 16 cores were obtained from this section and the test results of the cores are presented in Figure 18. The results include the thickness of cores, t/NMAS, and the air voids determined from the vacuum seal device.

A review of the data indicated that a polynomial function provided the best fit line. The best-fit line indicates that the air voids decreased as the t/NMAS increased to a point where additional thickness resulted in increased air voids. The recommended thickness range was selected as the point(s) where the air voids increased by 0.5 percent (less than 0.5 percent were considered insignificant). This number is somewhat arbitrary, but it is realistic. Therefore, as shown in Figure 18, the recommended t/NMAS range for 9.5-mm fine-graded mix was 3.4 to 5.8. This does not mean that satisfactory compaction cannot be obtained outside of these limits, but it does indicate that more compactive effort would be needed. So this recommended range should only be used as a guide and should not be a rigid requirement. The effect of t/NMAS on

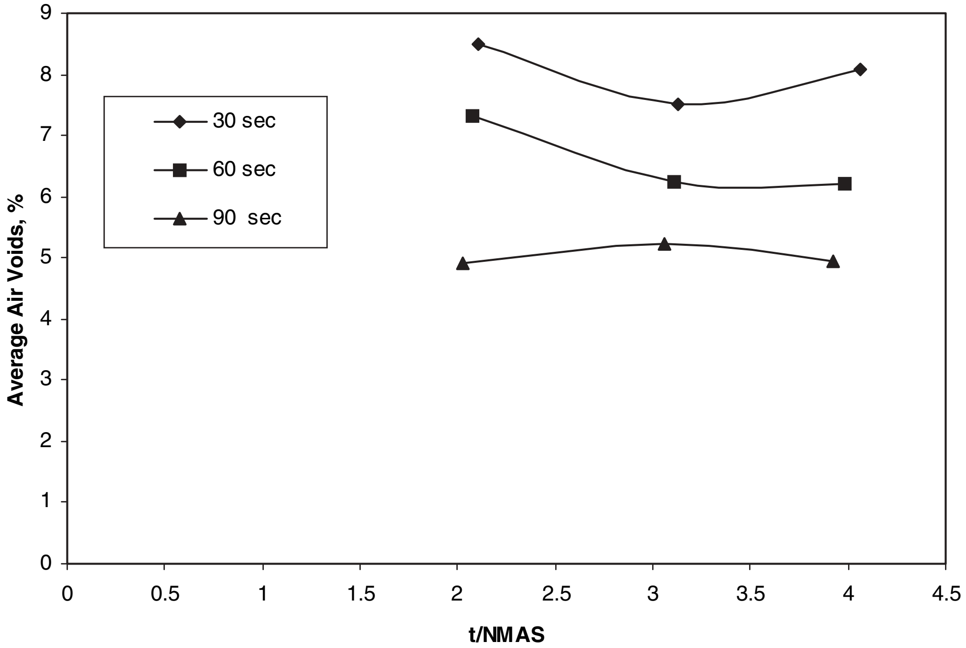

Figure 13. Relationships between air voids and t/NMAS for 19.0-mm ARZ mixes.

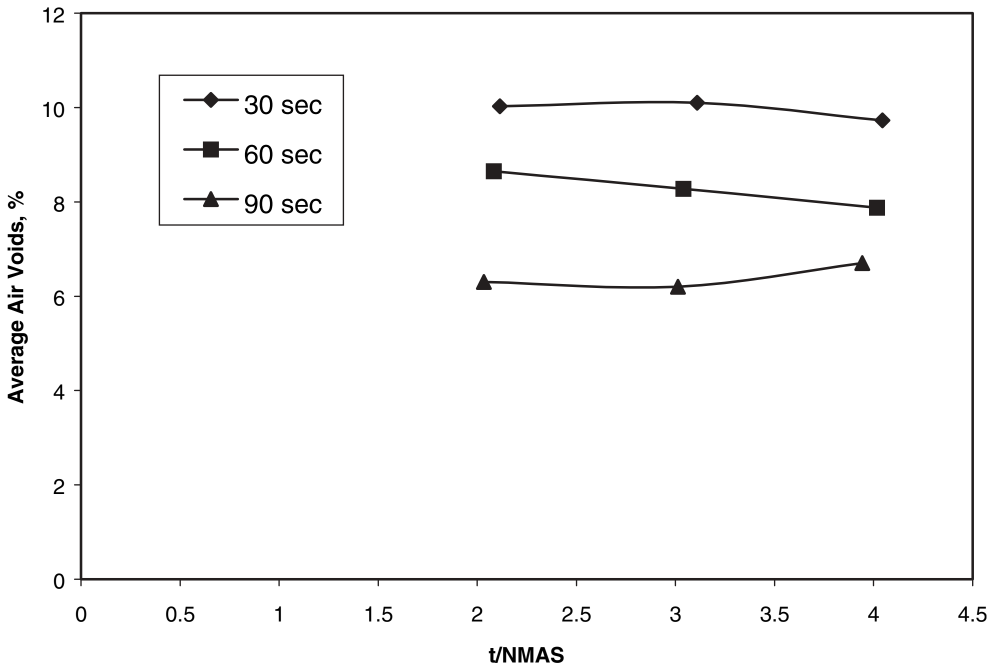

Figure 14. Relationships between air voids and t/NMAS for 19.0-mm BRZ mixes.

the measured density was determined from Figure 18. Data in the figure indicate that the lowest air voids (7.0 percent air voids) occurred at t/NMA 4.4. Table 5 shows the air voids at various t/NMAs as related to this minimum.

4.4.2 Section 2

Section 2 was constructed on August 7, 2003, and the t/NMAS for this overlay ranged from 2.0 to 5.0. The mixture was a 9.5-mm NMAS coarse-graded mixture. The length of the section was about 40 m, and the width was about 3.5 m. The paving started from the thick portion of the mat and progressed toward the thinner portion. The weather conditions during the paving were 82°F, overcast, with calm wind. The existing surface temperature was 96°F.

The roller utilized in this section was an 11-ton steel drum roller HYPAC C778B with a 78-in. wide drum that could operate in vibratory or static mode. The rubber tire roller was a 15-ton HYPAC C560B with a tire pressure of 90 psi. For the side of the mat utilizing only the steel drum roller, the initial rolling was performed with four passes in the vibratory mode at low amplitude and high frequency (3800 vpm) at a mix tem-

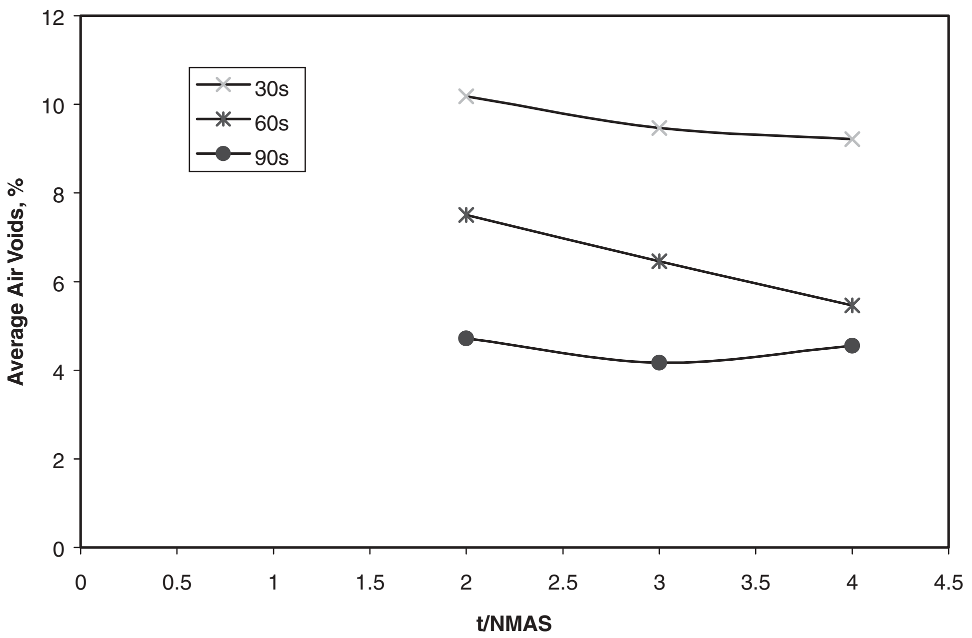

Figure 15. Relationships between air voids and t/NMAS for 9.5-mm SMA mixes.

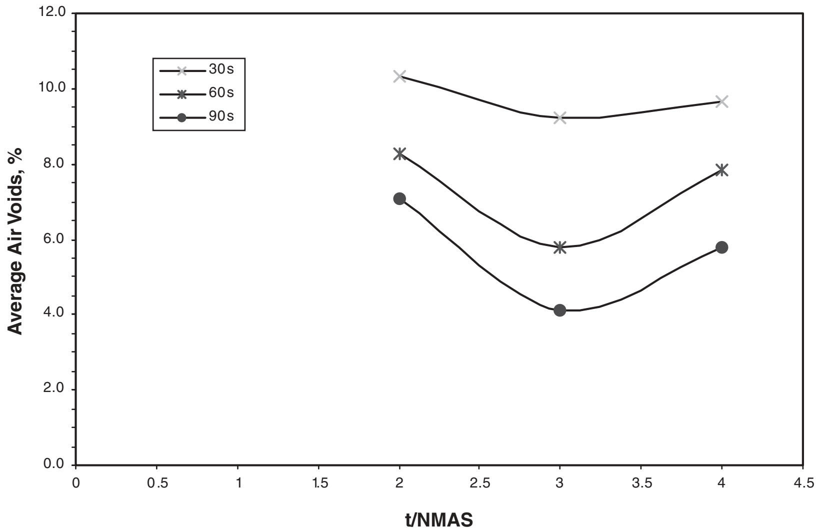

Figure 16. Relationships between air voids and t/NMAS for 12.5-mm SMA mixes.

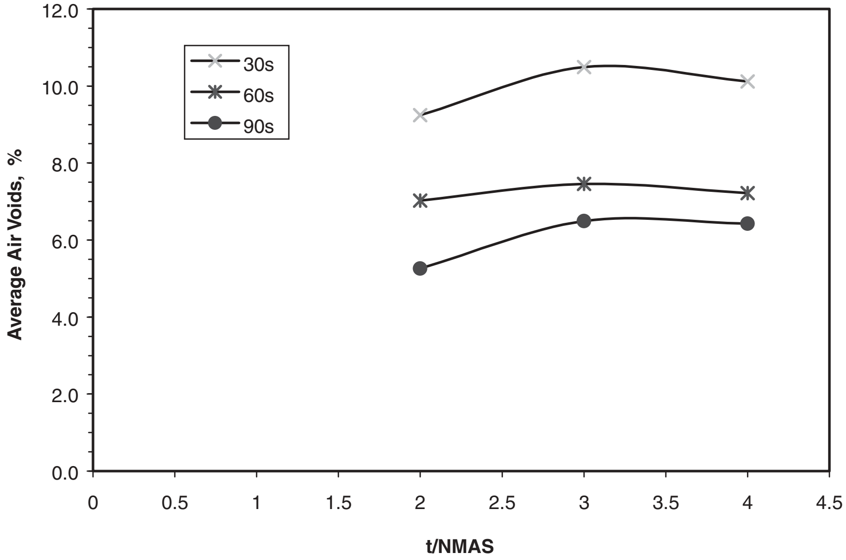

Figure 17. Relationships between air voids and t/NMAS for 19.0-mm SMA mixes.

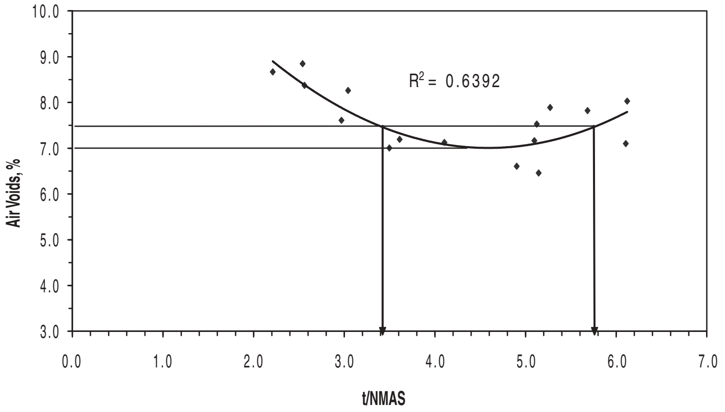

Figure 18. Relationships of air voids and t/NMAS for 9.5-mm fine-graded mix.

TABLE 5 Relationship of air voids and t/NMAS for 9.5-mm fine-graded HMA compacted with steel roller

t/NMA	Percentage points above lowest
4.4 (lowest air voids, 7.0 %)	0.0
2	2.5
3	1.0
4	0.1
5	0.1

perature of about 300°F. This was followed with four passes in the static mode. For the side of the mat that used a rubber tire roller as an intermediate roller, the breakdown rolling was performed with four passes in the vibratory mode operated at low amplitude and high frequency (3800 vpm). This was followed with five passes of the rubber tire roller and one pass of the steel roller in the static mode.

A total of 15 cores were obtained from the side that utilized only a steel drum roller and 16 cores from the side that used the rubber tire roller. The relationship of air voids measured from the vacuum seal device and t/NMAS was evaluated for each rolling pattern. The results are illustrated in Figure 19.

A review of the data indicated that a polynomial function provided the best fit. As the thickness increased, the air voids decreased until a point where additional thickness resulted in increased air voids. The plots also suggest that the side utilizing only a steel drum compactor had better compaction. To determine the desired thickness, it was decided to use air voids 0.5 percent larger (a void level less than 0.5 percent different was not considered significantly different) than the minimum air voids from the best-fit line. Therefore, as shown in Figure 19, the desired t/NMAS range for 9.5-mm coarse-graded mix was 3.5 to 5.9 for compaction with a steel wheel roller and 2.9 to 4.6 for compaction with the steel and rubber tire roller. The effect of t/NMAS on the measured density was determined from Figure 19. Data in the figure indicate that the lowest in-place air voids (10 percent air voids for the steel wheel roller only and 10.5 percent air voids for the steel and rubber tire rollers) occurred at t/NMAS of 4.7 for the steel wheel roller and 3.8 for the rubber and steel wheel roller. Table 6 shows the air voids at various t/NMAs as related to this minimum.

4.4.3 Section 3

Section 3 was constructed on July 25, 2003, and consisted of a 2.0 to 5.0 t/NMAS overlay of an existing HMA layer. The mix was a 9.5-mm NMAS SMA. The length of the section was about 40 m, and the width was about 3.5 m. The paving started from the thick portion of the mat and progressed to the thinner portion. The desired mat thickness was achieved by gradually adjusting the screed depth crank of the paver during the operation. The weather conditions during the paving were 95°F, partly cloudy, with calm wind. The existing surface temperature was 115°F.

The roller utilized in this section was an 11-ton steel drum roller HYPAC C778B with a 78-in. wide drum that could operate in vibratory or static mode. The rubber tire roller was a 15-ton HYPAC C560B with a tire pressure of 90 psi. For the side of the mat utilizing only the steel drum roller, the initial rolling was performed with one pass in the static mode followed by five passes in the vibratory mode operated in low amplitude and high frequency (3800 vpm) on the mat having a mix temperature of about 320°F. This was followed with two passes in the static mode for the finish rolling. For the side of the mat that used a rubber tire roller as an intermediate roller, the breakdown rolling was performed with one pass in the static mode and four passes in the vibratory mode operated in low amplitude and high frequency (3800 vpm). This

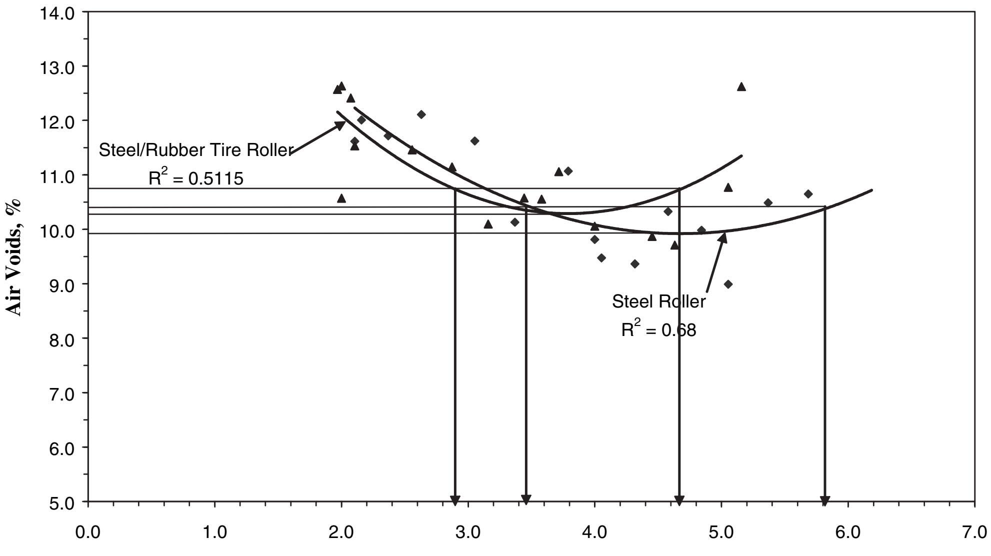

Figure 19. Relationships of air voids and t/NMAS for 9.5-mm coarse-graded mix.

TABLE 6 Relationship of air voids and t/NMAS for 9.5-mm coarse-graded HMA compacted with steel roller and with steel and rubber tire rollers

Steel roller		Steel and rubber tire rollers	
t/NMA	Percentage points above lowest	t/NMA	Percentage points above lowest
4.7 (lowest air voids, 10.0 %)	0.0	3.8 (lowest air voids, 10.5 %)	0.0
2	2.5	2	2.0
3	1.0	3	0.5
4	0.5	4	0.0
5	0.0	5	1.0

was followed with eight passes of the rubber tire roller and two passes of the steel wheel roller in the static mode.

A total of 12 cores were obtained from the side that utilized only the steel drum roller and another 12 cores from the side that used the rubber tire roller. To determine the range of recommended t/NMAS for this mix, the relationship of air voids from the vacuum seal device and t/NMAS was evaluated for each rolling pattern. The results are illustrated in Figure 20.

The best-fit lines indicate that the air voids decreased as the thickness increased to a point where additional thickness resulted in increased air voids. The plots also suggest that the side utilizing only the steel drum compactor had higher density. Rubber tire rollers are not used on SMA mixtures and these data confirm that there is no need to use the rubber tire roller. As shown in Figure 20, the recommended range for t/NMAS for the 9.5-mm SMA mix is 3.8 to 5.3 for the compaction with a steel wheel roller and 2.6 to 5.1 for compaction with a steel and rubber tire roller. The effect of t/NMAS on the measured density was determined from Figure 20. Data in the figure indicate that the lowest in-place air voids (8.5 percent air voids for the steel wheel roller only and 10.3 percent air voids for the steel and rubber tire rollers) occurred at t/NMAS of 4.5 for the steel wheel roller and 3.8 for the rubber and steel wheel roller. Table 7 shows the air voids at various t/NMAs as related to this minimum.

4.4.4 Section 4

Section 4 was constructed on August 12, 2003, and consisted of a 2.0 to 5.0 t/NMAS overlay of an existing HMA layer. The mix was a 12.5-mm NMAS SMA. The length of the section was about 40 m, and the width was about 3.5 m. The paving started from the thinner portion and proceeded toward the thicker portion of the mat. The weather conditions during the paving were 80°F, overcast, with calm wind. The existing surface temperature was 85°F.

The roller utilized in this section was an 11-ton steel drum roller HYPAC C778B with a 78-in. wide drum that could operate in vibratory and static modes. The rubber tire roller was a 15-ton HYPAC C560B with a tire pressure of 90 psi. For the side of the mat utilizing only the steel drum roller, the initial rolling was performed with four passes in the vibratory mode operated at low amplitude and high frequency (3800 vpm). The mat temperature was approximately 320°F. This was followed with three passes in the static mode including finish rolling. For the side of the mat that used a rubber tire roller as an intermediate roller, the initial rolling was performed with four passes in the vibratory mode operated at low amplitude and high frequency (3800 vpm). This was followed with four passes of the rubber tire roller and one pass of the steel roller in the static mode.

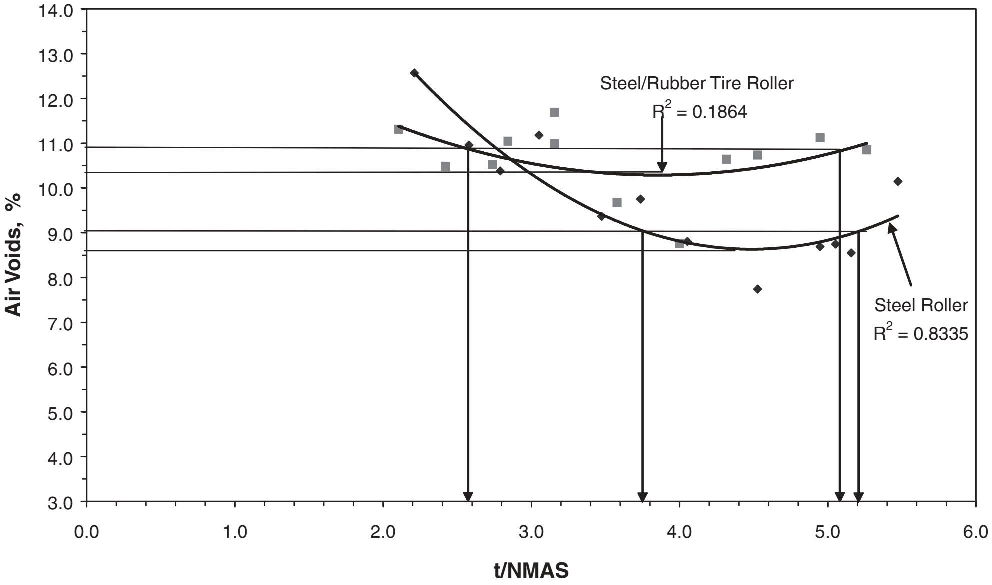

Figure 20. Relationships of air voids and t/NMAS for 9.5-mm SMA mix.

TABLE 7 Relationship of air voids and t/NMAS for 9.5-mm SMA mix compacted with steel roller and with steel and rubber tire rollers

Steel roller		Steel and rubber tire rollers	
t/NMA	Percentage points above lowest	t/NMA	Percentage points above lowest
4.5 (lowest air voids, 8.5 %)	0.0	3.8 (lowest air voids, 10.3 %)	0.0
2	5.5	2	1.2
3	2.0	3	0.2
4	0.2	4	0.0
5	0.2	5	0.5

A total of 21 cores were obtained from the side that utilized only a steel drum roller and 21 cores from the side that used the rubber tire roller. To determine the recommended t/NMASs for this mix, the relationship of air voids from the vacuum seal device and t/NMAS was evaluated for each rolling pattern. The results are illustrated in Figure 21.

The best-fit lines indicate that the air voids decreased as the thickness increased to a point where additional thickness resulted in increased air voids. The plots also suggest that the side utilizing only the steel drum compactor had higher density. As shown in Figure 21, the suggested minimum t/NMAS for 12.5-mm SMA mix is 3.8 for compaction with steel wheel roller and 4.6 for compaction with steel and rubber tire rollers. For these mixes, the density increased as the t/NMAS increased even at the thicker portions. Also the curve did not fit the data as well as desired, so the data points were actually used to select the suggested t/NMAS number. Note in the plots that the data points continue downward with increasing t/NMAS to a point and then the air voids remain relatively constant as the t/NMAS increased.

The effect of t/NMAS on the measured density was determined from Figure 21. Data in the figure indicate that the lowest in-place air voids (4.7 percent air voids for the steel wheel roller only and 7.5 percent air voids for the steel and rubber tire rollers) occurred at t/NMAS of 4.5 for the steel wheel roller and 4.8 for the rubber and steel wheel rollers. Table 8 shows the air voids at various t/NMAs as related to this minimum.

4.4.5 Section 5

Section 5 was constructed on July 16, 2003, and consisted of a 2.0 to 5.0 t/NMAS overlay of an existing HMA. The mix consisted of a 19.0-mm NMAS fine-graded HMA. The length of the section was about 40 m, and the width was about 3.5 m. The paving started on the thin end of the section and proceeded to the thicker portion. The desired mat thickness was achieved by gradually adjusting the screed depth crank of the paver during the operation. The weather conditions during the paving were 90°F, clear, with calm wind. The existing surface temperature was 96°F.

The roller utilized in this section was an 11-ton steel roller HYPAC C778B with a 78-in. wide drum that operated in vibratory and static modes. The rubber tire roller used did not meet the tire pressure requirements and the results were omitted from the analysis for this section. The breakdown rolling was performed with four passes in the vibratory mode operated in low amplitude and high frequency (3800 vpm). The

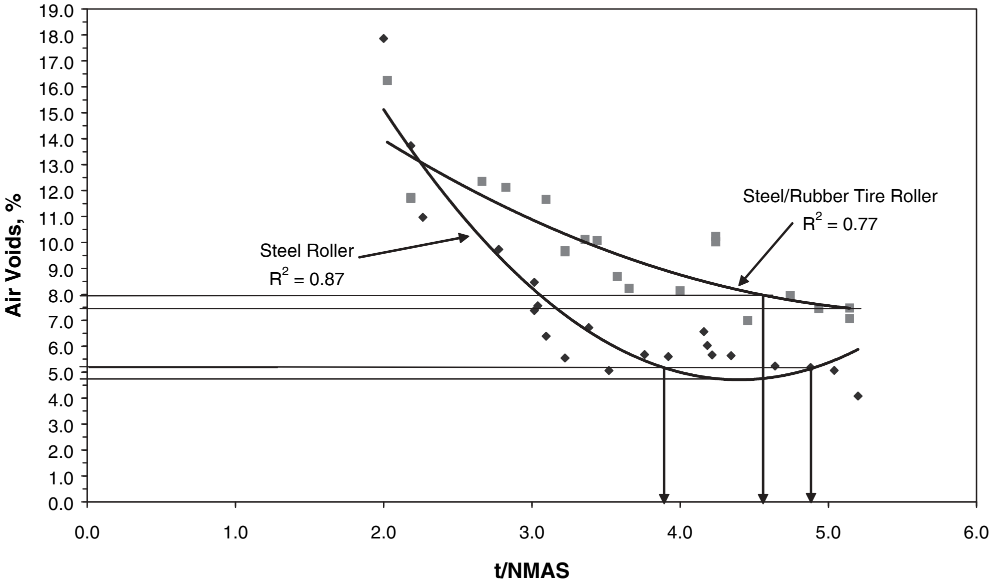

Figure 21. Relationships of air voids and t/NMAS for 12.5-mm SMA Mix.

TABLE 8 Relationship of air voids and t/NMAS for 12.5-mm SMA mix compacted with steel roller and with steel and rubber tire rollers

Steel roller		Steel and rubber tire rollers	
t/NMA	Percentage points above lowest	t/NMA	Percentage points above lowest
4.5 (lowest air voids, 4.7 %)	0.0	4.8 (lowest air voids, 7.5 %)	0.0
2	11.3	2	6.5
3	3.3	3	3.5
4	0.3	4	0.5
5	0.5	5	0.0

mat temperature was approximately 300°F. Three passes in the static mode and one pass for finish rolling followed this initial rolling.

A total of 20 cores were obtained from this section. To determine the minimum t/NMAS for this mix, the relationship between air voids (from the vacuum seal device) and thickness was evaluated. The results are illustrated in Figure 22.

The best-fit line indicated that the air voids decreased as the thickness increased to a point where additional thickness resulted in increased air voids. As shown in Figure 22, the recommended t/NMAS range for the 19.0-mm fine-graded mix was 3.1 to 4.6. The effect of t/NMAS on the measured density was determined from the figure. Data in the figure indicate that the lowest in-place air voids (6.2 percent air voids) occurred at t/NMAS of 3.8. Table 9 shows the air voids at various t/NMAs as related to this minimum.

4.4.6 Section 6

Section 6 was constructed on August 6, 2003, and consisted of a range of 2.0 to 5.0 t/NMAS overlay of an existing HMA. The mix was a 19.0-mm NMAS coarse-graded HMA. The length of the section was about 40 m, and the width was about 3.5 m. The paving started from the thinner portion of the mat and proceeded to the thicker portion. The weather conditions during the paving were 79°F, cloudy, with calm wind. The existing surface temperature was 84°F.

The roller utilized in this section was an 11-ton steel drum roller HYPAC C778B with a 78-in. wide drum that could operate in vibratory and static mode. The rubber tire roller was a 15-ton HYPAC C560B with a tire pressure of 90 psi. For the side of the mat utilizing only the steel drum roller, the initial rolling was performed with four passes in the vibratory mode operated at low amplitude and high frequency (3800 vpm). The mat temperature was approximately 300°F. This initial rolling was followed with six passes in the static mode. For the side of the mat that used a rubber tire roller as the intermediate roller, the initial rolling was performed with four passes in the vibratory mode operated in low amplitude and high frequency (3800 vpm). This initial rolling was followed with four passes of the rubber tire roller and two passes with a steel wheel roller in the static mode.

A total of 22 cores were obtained from the side that utilized only a steel drum roller and 16 cores from the side that used the rubber tire roller. To determine the minimum t/NMAS for this mix, the relationship between air voids from vacuum seal

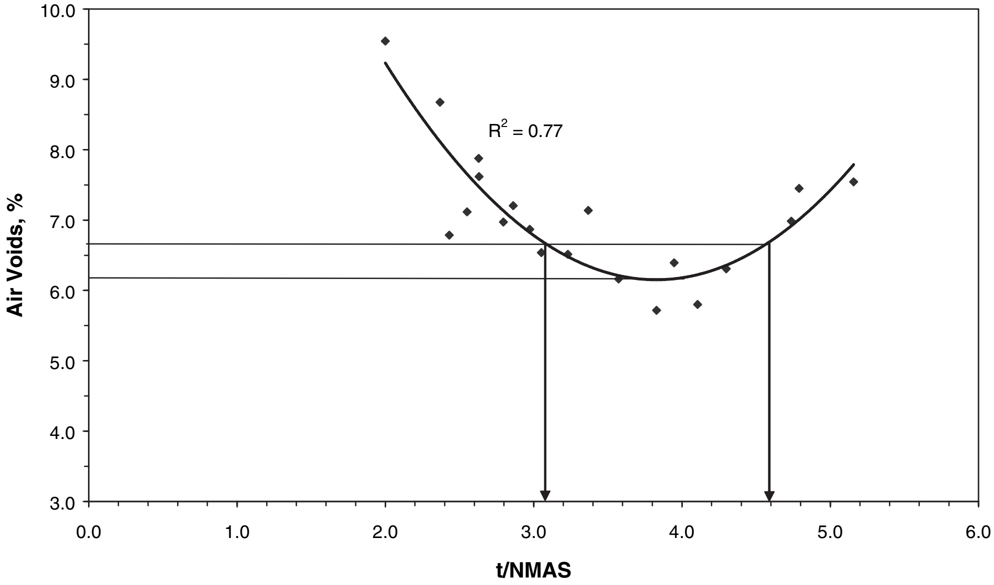

Figure 22. Relationships of air voids and t/NMAS for 19.0-mm fine-graded mix.

TABLE 9 Relationship of air voids and t/NMAS for 19.0-mm fine-graded mix compacted with steel roller

t/NMA	Percentage points above lowest
3.8 (lowest air voids, 6.2 %)	0.0
2	3.1
3	0.6
4	0.0
5	1.3

Table 10 Relationship of air voids and t/NMAS for 19.0-mm coarse-graded mix compacted with steel and rubber tire roller*

t/NMA	Percentage points above lowest
4.5 (lowest air voids, 5.7 %)	0.0
2	1.8
3	0.6
4	0.1
5	0.1

*The steel wheel roller alone was not used because it produced too much scatter in the data

device and thickness was evaluated for each rolling pattern. The results are illustrated in Figure 23. The best-fit lines indicate that the air voids decreased as the thickness increased to a point where additional thickness resulted in increased air voids. The plots also suggest that the side utilizing the rubber tire roller had higher density. As shown in Figure 23, the recommended minimum thickness for 19.0-mm coarse-graded mix was 3.0 for compaction with the steel and rubber tire rollers. There is too much scatter in the data to make a good selection of a recommended value for compaction with a steel wheel roller.

The effect of t/NMAS on the measured density was determined from Figure 23. Data in the figure indicate that the lowest in-place air voids (5.7 percent for the steel and rubber tire roller, the steel wheel roller alone was not used because it produced too much scatter in the data) occurred at t/NMAS of 4.5. Table 10 shows the air voids at various t/NMAs as related to this minimum.

4.4.7 Section 7

Section 7 was constructed on August 14, 2003, and consisted of a range of 2.0 to 5.0 t/NMAS overlay of an existing HMA. The mix consisted of a 19.0-mm NMAS coarse-graded HMA and utilized a modified asphalt. The length of the section was about 40 m, and the width was about 3.5 m. The paving started from the thicker portion of the mat and proceeded to the thinner portion. The weather conditions during the paving were 90°F, clear, with calm wind. The existing surface temperature was 120°F.

The roller utilized in this section was an 11-ton steel drum roller HYPAC C778B with a 78-in. wide drum that could operate in the vibratory and static modes. The rubber tire roller was a 15-ton HYPAC C560B with a tire pressure of 90 psi. For the side of the mat utilizing only the steel drum roller, the initial rolling was performed with four passes in the vibratory mode operated in low amplitude and high frequency (3800 vpm). The mat temperature was about 330°F. This was followed with another five passes in the vibratory mode operated at low amplitude and high frequency (3800 vpm). There was one additional pass with the steel wheel roller in the static mode to finish the mat. For the side of the mat that used a rubber tire roller as an intermediate roller, the initial rolling was performed with two passes in the vibratory mode operated at low amplitude and high frequency (3800 vpm). This was followed with ten passes with

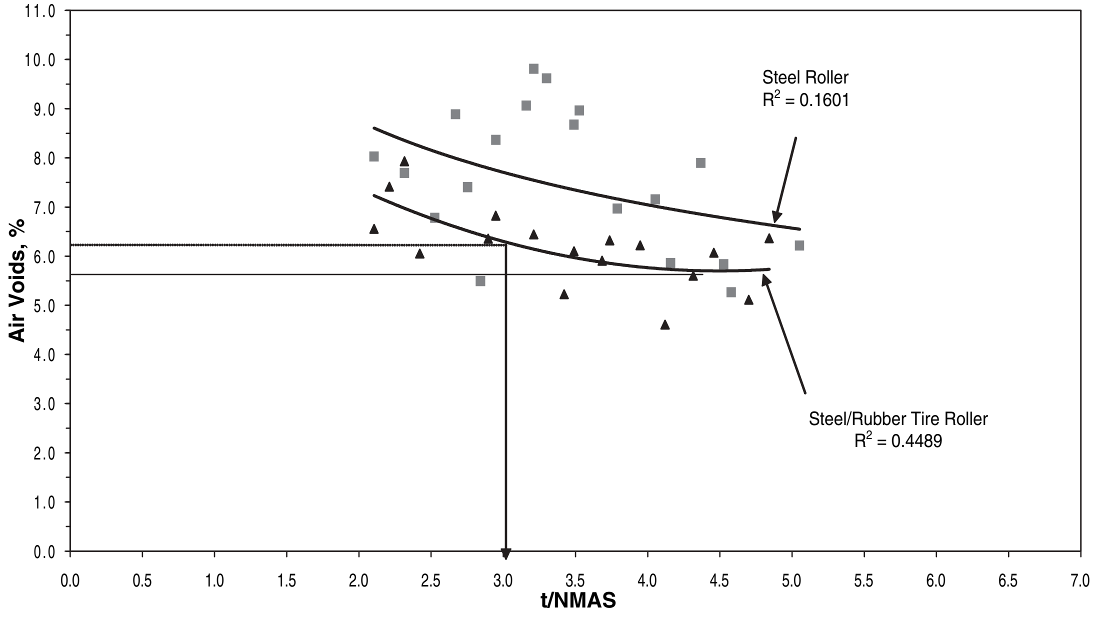

Figure 23. Relationships of air voids and t/NMAS for 19.0-mm coarse-graded mix.

the rubber tire roller and two passes of the steel wheel roller in the static mode.

A total of 23 cores were obtained from the side that utilized only the steel drum roller and 26 cores from the side that used the rubber tire roller. To determine the minimum t/NMAS for this mix, the relationship of air voids from the vacuum seal device and t/NMAS was evaluated for each rolling pattern. The results are illustrated in Figure 24.

The best-fit lines indicate that the air voids decreased as the thickness increased to a point where additional thickness resulted in increased air voids. The plots also suggested that the side utilizing only the steel drum compactor had higher density. As shown in Figure 24, the minimum t/NMAS range for 19.0-mm coarse-graded with modified asphalt mix was 3.4 to 4.8. The effect of t/NMAS on the measured density was determined from Figure 24. Data in the figure indicate that the lowest in-place air voids (5.6 percent air voids for the steel wheel roller only and 7.4 percent air voids for the steel and rubber tire rollers) occurred at t/NMAS of 4.2 for the steel wheel roller and 5.3 for the rubber and steel wheel roller. Table 11 shows the air voids at various t/NMAs as related to this minimum.

4.4.8 Summary

In summary, the data for the seven sections appear to be reasonable and to match past experience. A summary of the results compared to the t/NMAS for lowest voids is provided in Table 12. These results indicate that the t/NMAS should be somewhere between 3 and 5 for best results. Based on the limited data, a t/NMAS of 3 is probably reasonable for fine-graded mixes, because there is less than 1 percentage point change in density when the t/NMAS is reduced from optimum to 3.0. The t/NMAS should be set at 4.0 for coarse-graded mixes due to the significant increase in voids when reducing the t/NMAS from optimum down to 3.0.

4.5 EVALUATION OF THE EFFECT OF TEMPERATURE ON THE RELATIONSHIP BETWEEN DENSITY AND t/NMAS

Three locations were selected for temperature measurements for each section in the field experiment; one near the beginning of the section, one near the middle, and one near the end of the section. To determine the effect of mix temperature on the density, the temperature at 20 minutes after placement of the mix at each location was selected because this provides a reasonable compaction time. Because the mixes in this study used two different types of asphalt binder, PG 67-22 and PG 76-22, the temperatures at 20 minutes were normalized by subtracting the high temperature grade of the asphalt type from the temperatures at 20 minutes. Table 13 presents the t/NMAS, the average temperature readings at 20 minutes, the asphalt high temperature grade, and the difference between mix temperature and high temperature grade. The differences in temperature were plotted against the t/NMAS together with the core densities for each section, as shown in Figures 25 through 31.

The relationship between density and t/NMAS for all sections is shown in Figure 32. The best-fit line has an R^2 of 0.26 and indicates that the density increased as the thickness increased to a point where additional thickness resulted in a decrease in density. The effect of the layer thickness and cooling time on mix temperature is provided in Figure 33. The data were obtained from the thermocouples installed in the pavement. This plot indicates that, during hot weather,

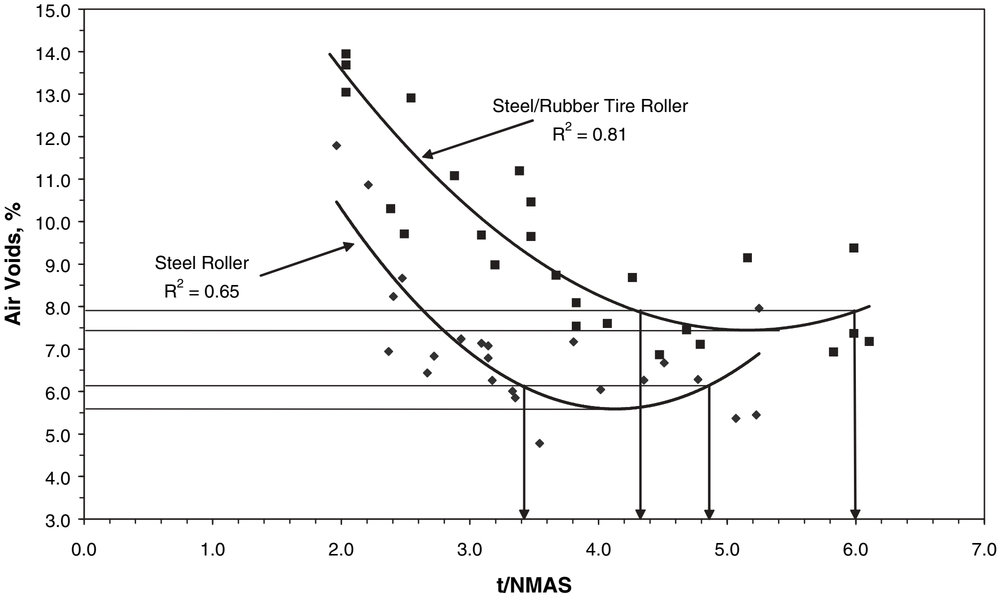

Figure 24. Relationships of air voids and t/NMAS for 19.0-mm coarse-graded mix with modified asphalt.

TABLE 11 Relationship of air voids and t/NMAS for 19.0-mm coarse-graded mix with modified asphalt compacted with steel roller and with steel and rubber tire rollers

Steel roller		Steel and rubber tire rollers	
t/NMA	Percentage points above lowest	t/NMA	Percentage points above lowest
4.2 (lowest air voids, 5.6 %)	0.0	5.3 (lowest air voids, 7.4 %)	0.0
2	4.9	2	6.1
3	1.3	3	3.4
4	0.0	4	0.8
5	0.8	5	0.0

compaction time for a layer thickness of 1.5 in. is approximately twice that for a 1-in. layer. This clearly shows that one of the problems in obtaining density is layer thickness regardless of the t/NMAS. If the amount of compaction time is reduced by 50 percent, it may be very difficult to compact the mixture to an adequate density. To place the same amount of compactive effort on an HMA mixture prior to cooling to some defined temperature will take twice as many rollers at a 1-in. thickness as that required for a 1.5-in. surface. It is likely to be significantly more difficult to compact a 1-in. layer than to compact a 1.5-in. layer simply because of the cooling rate.

TABLE 12 Effect of t/NMAS on compactibility of HMA

Description of Mix	Increase in Air Voids for t/NMAS=2	Increase in Air Voids for t/NMAS=3	Increase in Air Voids for t/NMAS=4	Increase in Air Voids for t/NMAS=5
Section 1-9.5mm Fine Graded—Steel Roller	2.5%	1.0%	0.1%	0.1%
Section 2-9.5mm Coarse Graded-Steel Roller	2.5%	1.0%	0.5%	0.0%
Section 2-9.5mm Coarse Graded-Steel and Rubber Roller	2.0%	0.5%	0.0%	1.0%
Section 3-9.5mm SMA(mod AC) Steel Roller	5.5%	2.0%	0.2%	0.2%
Section 3-9.5mm SMA(Mod AC) Steel & Rubber Roller	1.2%	0.2%	0.0%	0.5%
Section 4-12.5mm SMA (mod AC) Steel Roller	11.3%	3.3%	0.3%	0.5%
Section 4-12.5mm SMA (mod AC) Steel & Rubber Roller	6.5%	3.5%	0.5%	0.0%
Section 5-19mm Fine Graded Steel Roller	3.1%	0.6%	0.0%	1.3%
Section 6-19mm Coarse Graded Steel and Rubber Roller	1.8%	0.6%	0.1%	0.1%
Section 7-19mm Coarse Graded (mod AC) Steel Roller	4.9%	1.3%	0.0%	0.8%
Section 7-19mm Coarse Graded (mod AC) Steel & Rubber Roller	6.1%	3.4%	0.8%	0.0%

TABLE 13 t/NMAS, temperature in °C at 20 min., asphalt high temperature grade, and difference in temperature

Section/Mix		Temp. at 20 min., °C	Asphalt Grade, PG	Difference
1	2.5	60	67	-7
9.5mmFG	3.6	82	67	15
	5.1	95	67	28
2	2.1	64	67	-3
9.5mmCG	2.4	72	67	5
	5.1	105	67	38
3	2.2	65	76	-11
9.5mmSMA	3.7	100	76	24
	5.2	112	76	36
4	2.2	72	76	-4
12.5mmSMA	3.1	118	76	42
	3.8	120	76	44
5	2.6	124	67	57
19mmFG	3.0	122	67	55
	5.2	130	67	63
6	2.1	82	67	15
19mmCG	3.2	120	67	53
	5.1	118	67	51
7	2.7	86	76	10
19mmCG	3.8	120	76	44
	5.2	142	76	66

4.6 EVALUATION OF EFFECT OF t/NMAS ON PERMEABILITY USING GYRATORY COMPACTOR

Specimens were compacted to 7.0 ± 1.0 percent air void content at t/NMAS of 2.0, 3.0, and 4.0. For most mixes, specimens could not achieve the target air voids even when the gyrations were increased up to 300 gyrations. This shows the difficulty of compacting mixes at thinner lifts in the gyratory mold. Permeability testing was only performed on specimens that met the desired air voids. The results were very limited, but, did show that generally the coarser mixes (larger maximum aggregate size or higher percentage of coarse aggregate) had higher permeabilities.

4.7 EVALUATION OF EFFECT OF t/NMAS ON PERMEABILITY USING VIBRATORY COMPACTOR

All specimens compacted at t/NMAS of 2.0, 3.0, and 4.0 did achieve the target air void content, which was 7 ± 1.0 percent. Figure 34 shows the relationship between average permeability for the two aggregate types and t/NMAS. In general, the permeability decreased as t/NMAS increased. Most of the mixes had permeability values fewer than 50×10^{-5} cm/sec. However, at t/NMAS equal to 2.0, the 9.5-mm and 12.5-mm NMAS SMA mixes had average permeability values of 173×10^{-5} cm/sec and 196×10^{-5} cm/sec, respectively. These values for the SMA exceed the recommended maximum permeability value of 125×10^{-5} cm/sec. It appears from these data that a specification requirement of 7 percent air voids would be acceptable for all of the mixes if the t/NMAS is 3 or greater. The likely reason that the thinner samples have high permeability is that the voids are more likely to be interconnected all the way through the samples when the samples are thinner. Hence when mixes are placed thin, in this case

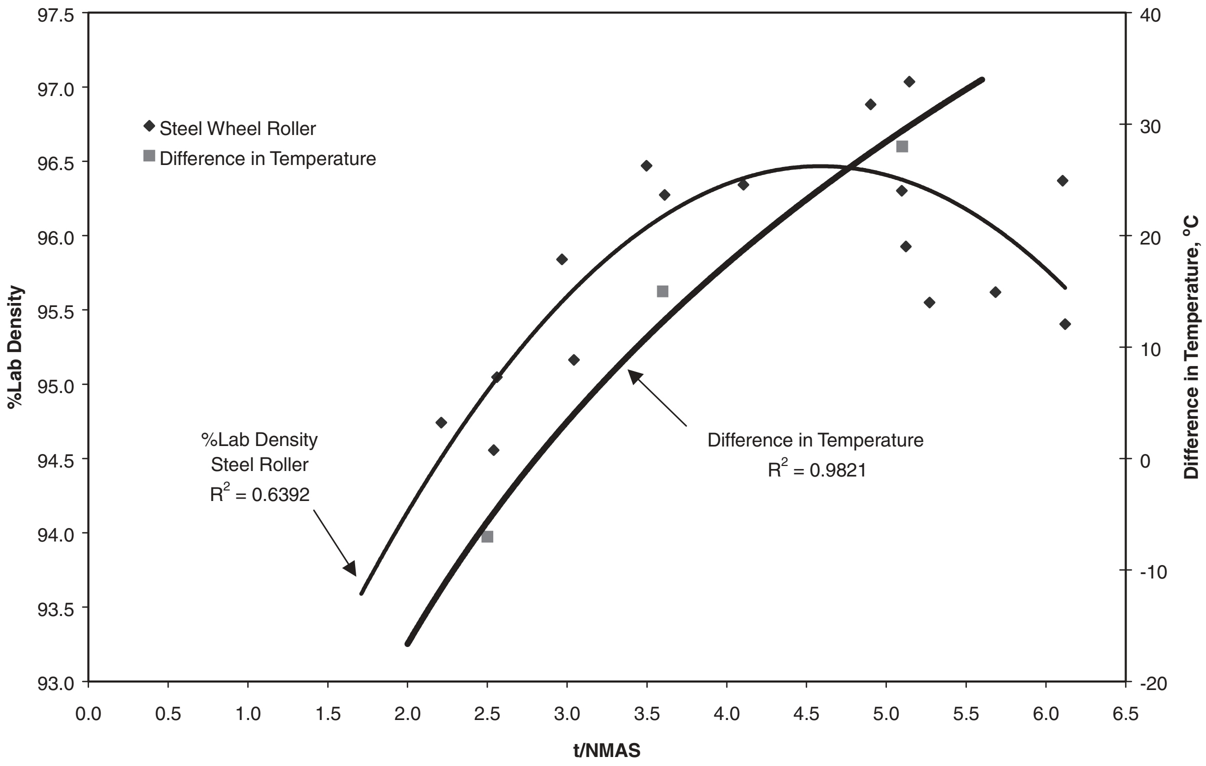

Figure 25. Relationships between density, t/NMAS, and temperature for Section 1.

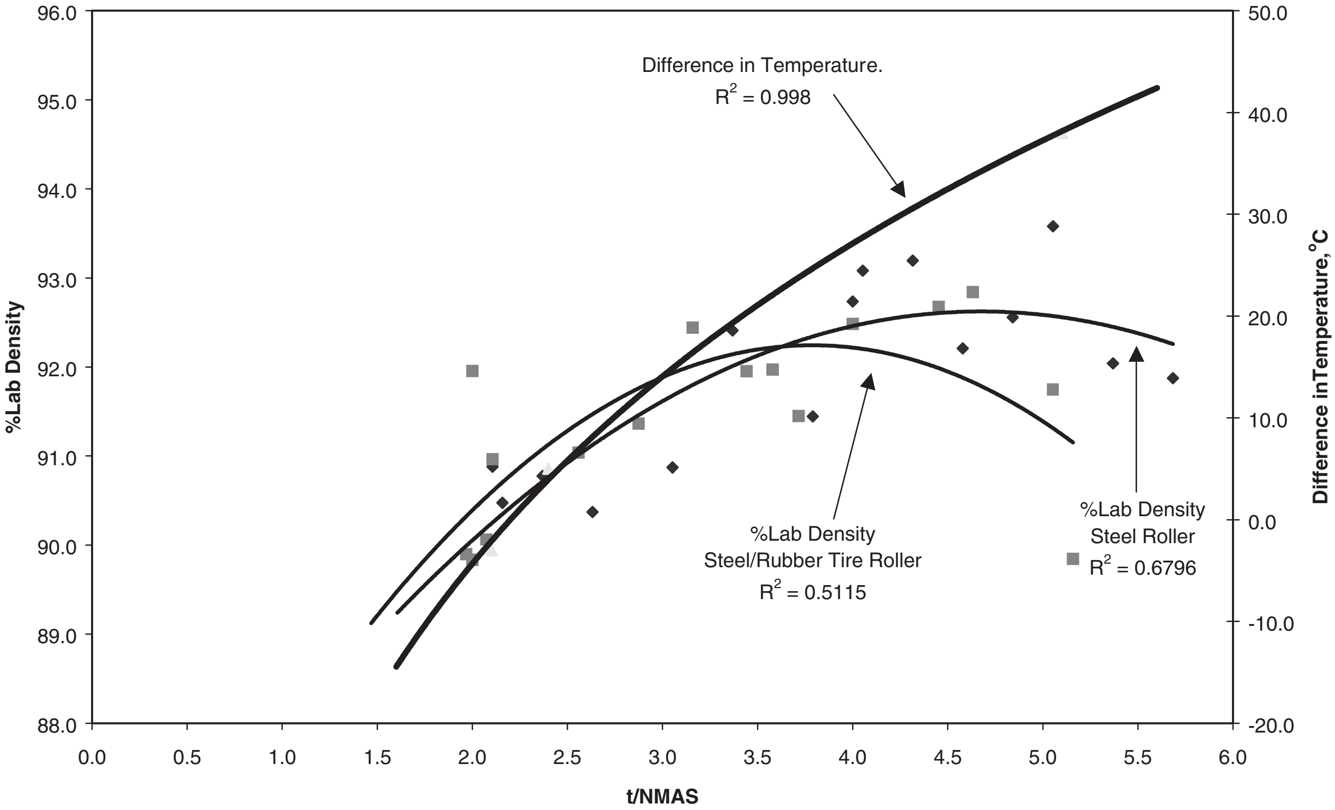

Figure 26. Relationships between density, t/NMAS, and temperature for Section 2.

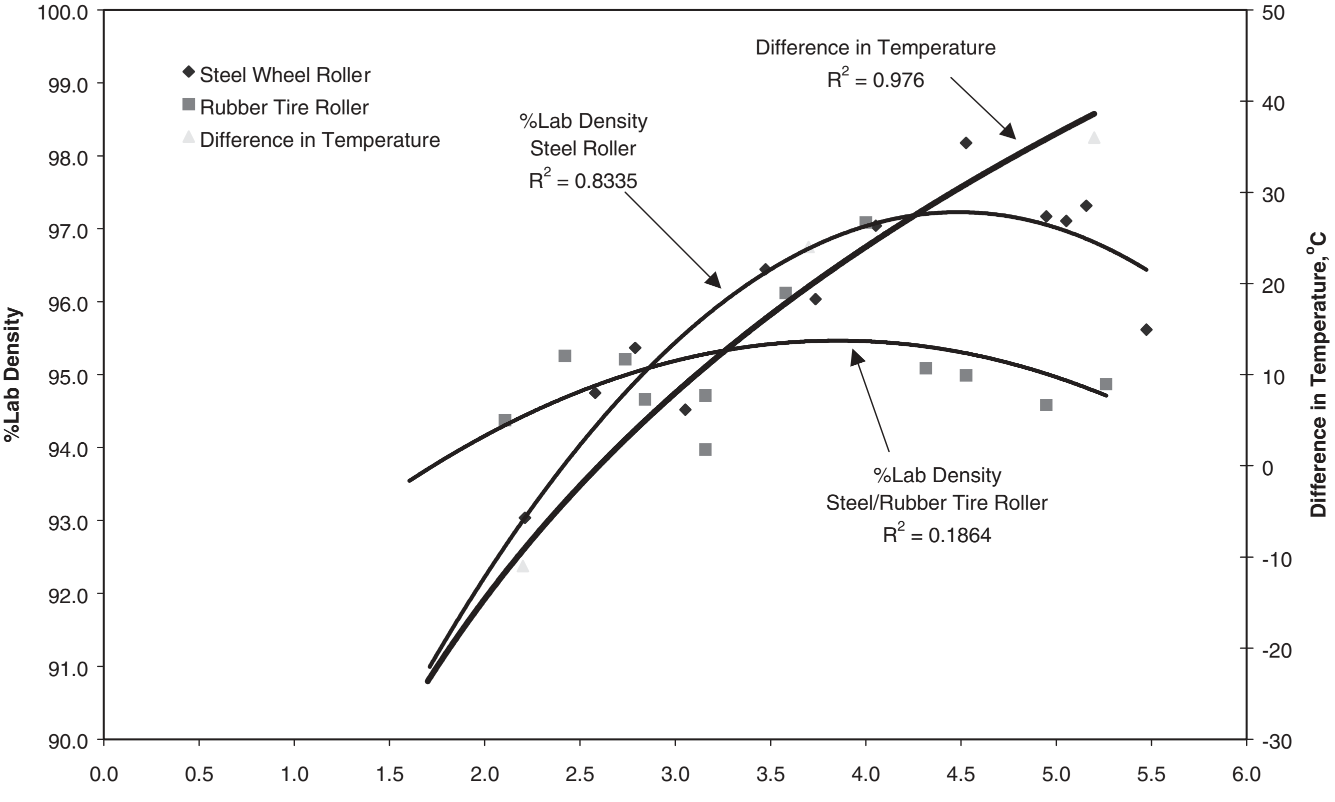

Figure 27. Relationships between density, t/NMAS, and temperature for Section 3.

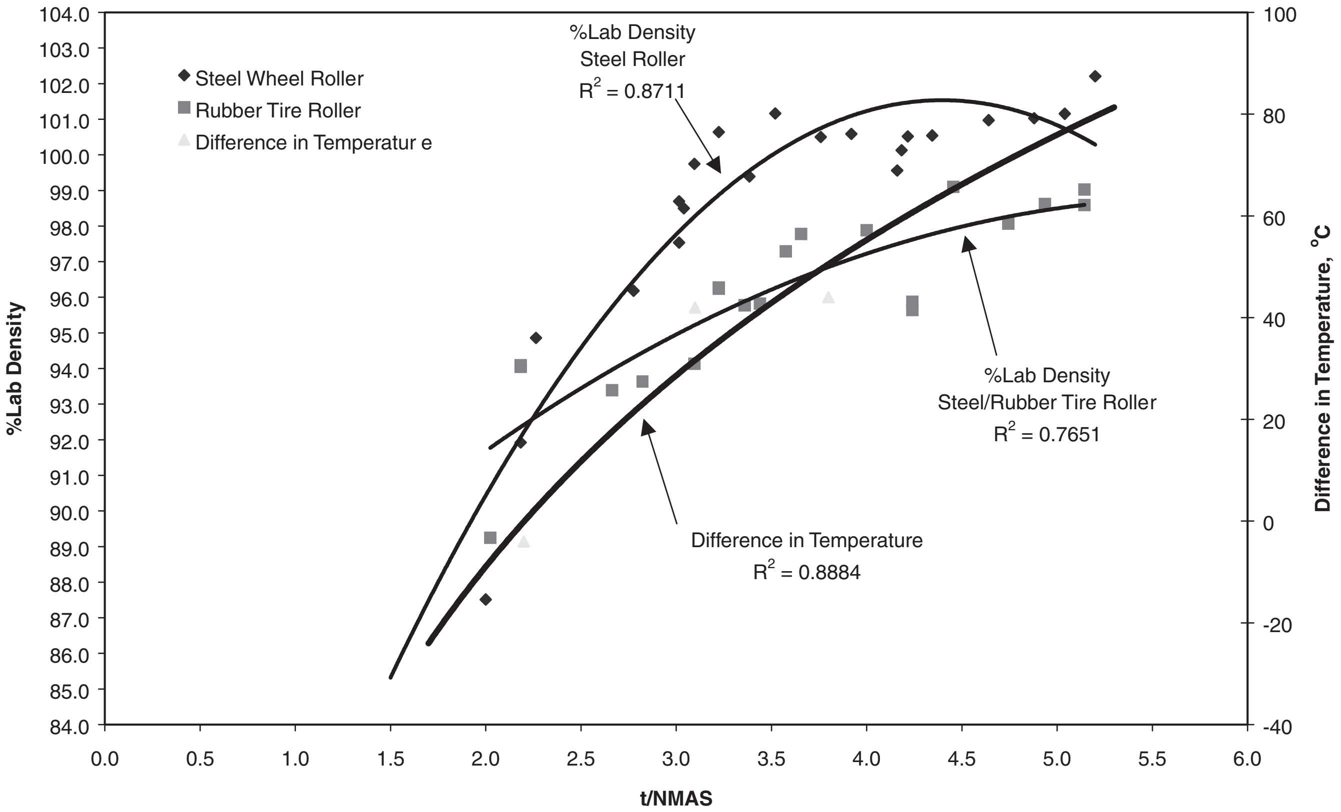

Figure 28. Relationships between density, t/NMAS, and temperature for Section 4.

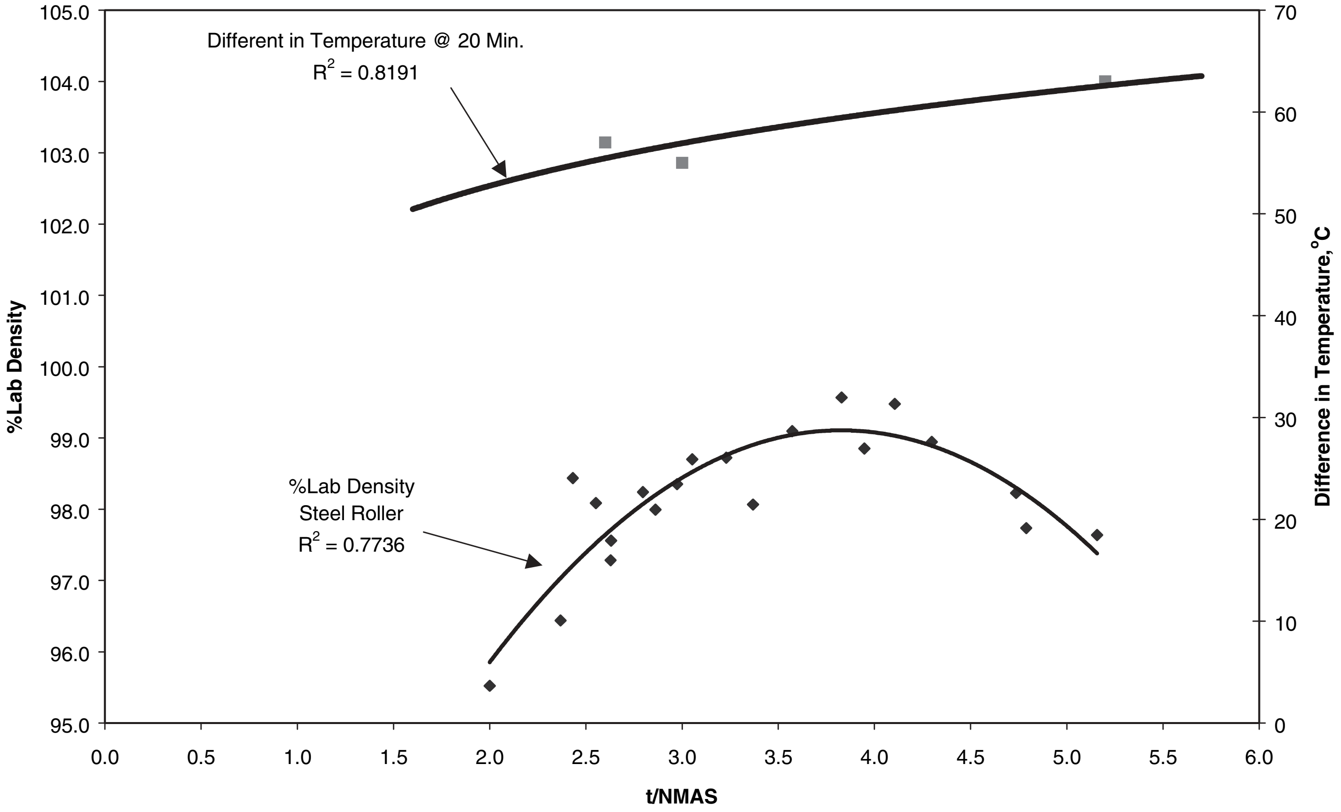

Figure 29. Relationships between density, t/NMAS, and temperature for Section 5.

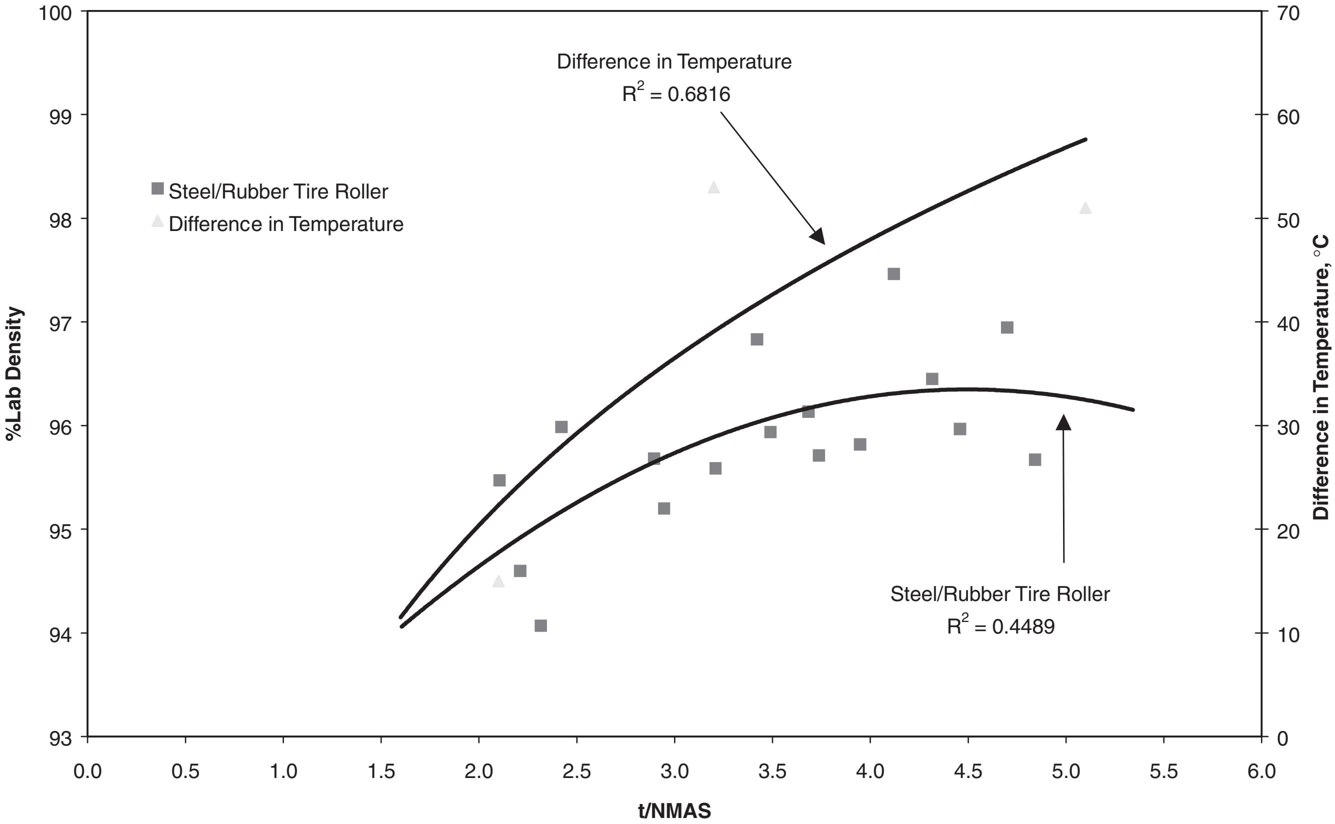

Figure 30. Relationships between density, t/NMAS, and temperature for Section 6.

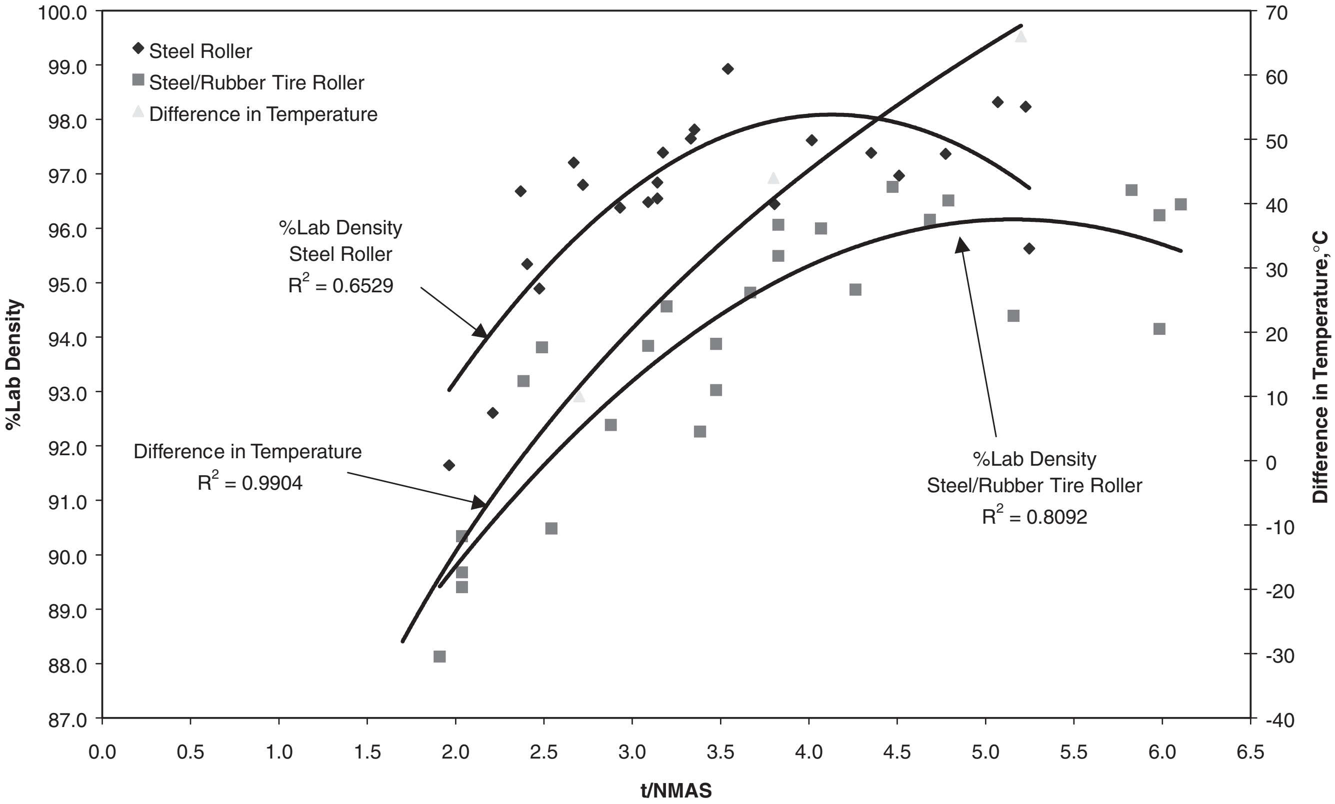

Figure 31. Relationships between density, t/NMAS, and temperature for Section 7.

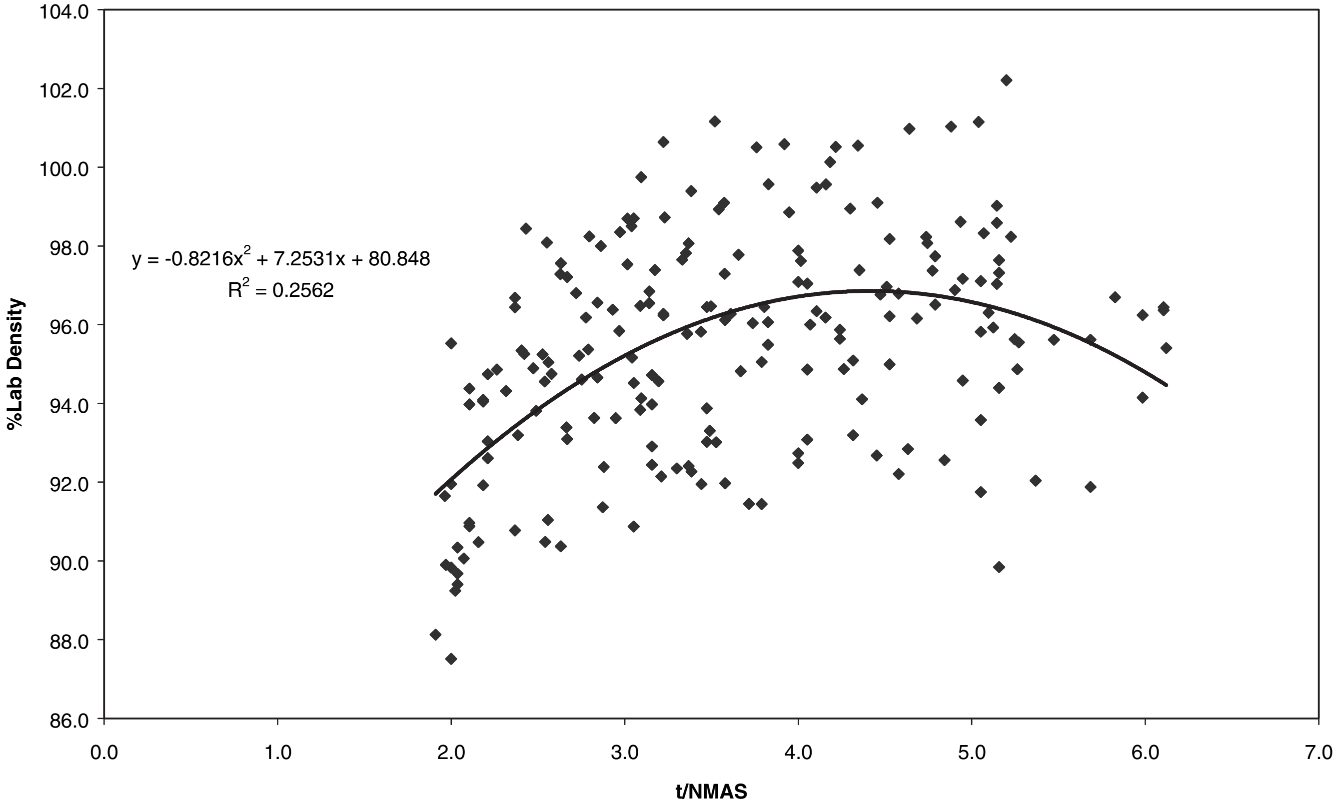

Figure 32. Relationships between density and t/NMAS for all sections.

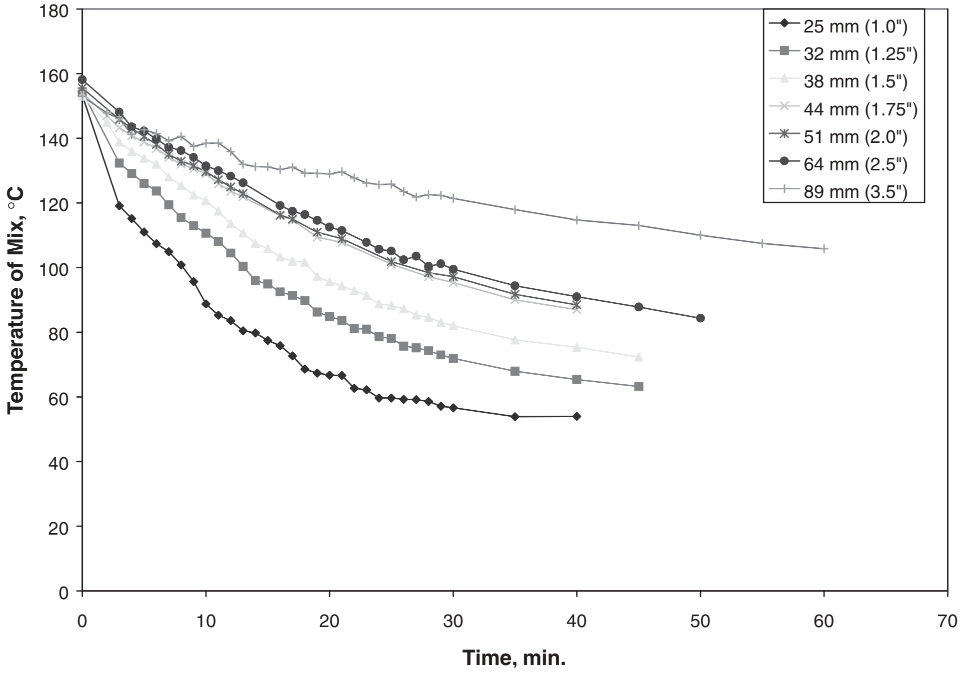

Figure 33. The effect of layer t/NMAS and cooling time on mix temperature.

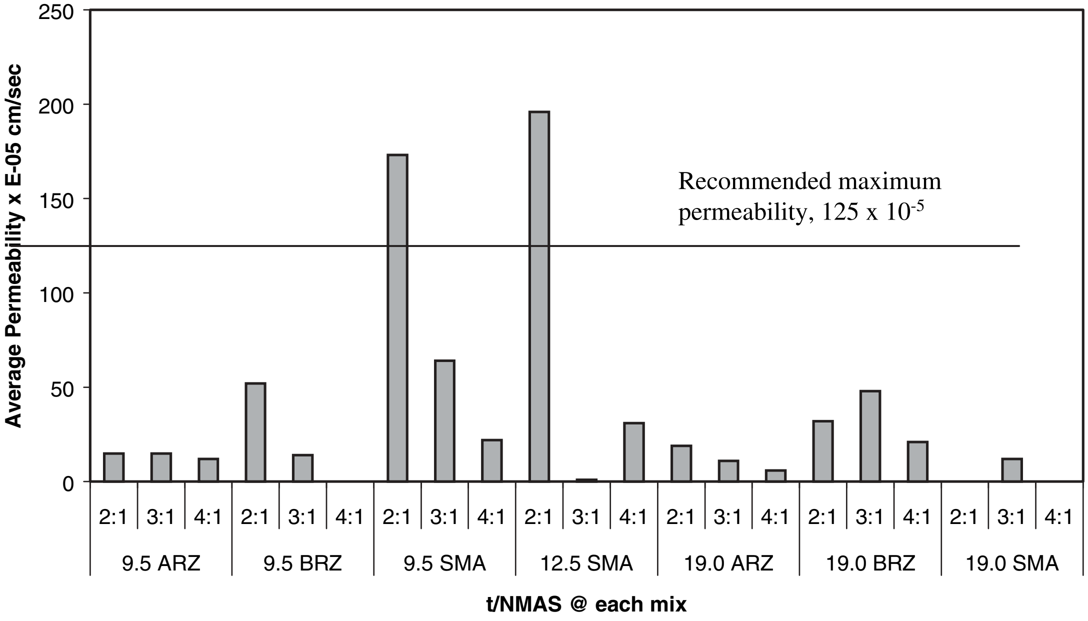

Figure 34. Relationships between permeability and t/NMAS.

less than a 3:1 t/NMAS, the air voids have to be lower to ensure that the mixes are impervious.

4.8 EVALUATION OF EFFECT OF t/NMAS ON PERMEABILITY FROM FIELD STUDY

Permeability tests were conducted on the seven HMA sections that were evaluated in the field. These tests were conducted in-place with the field permeameter and in the laboratory with the lab permeability test. Cores were taken from the in-place pavement for measurement of density and for measurement of lab permeability. The field permeability values were determined adjacent to the location where the cores were taken for density and for lab permeability. The results of these tests for the 7 sections are provided in Table 14.

In summary, the coarse-graded mixes had permeability values that exceeded the recommended value when the air voids exceeded about 8 percent. The fine graded mixes never exceeded the recommended value even up 9 to 10 percent air voids.

4.9 PART 2—EVALUATION OF RELATIONSHIP OF LABORATORY PERMEABILITY, DENSITY AND LIFT THICKNESS OF FIELD COMPACTED CORES

The average thickness, the average air void content by the vacuum seal device method, and the average laboratory permeability values were determined for each of the cores obtained from the work under NCHRP Project 9-9 (1). Figures 35 through 37 present the plots of in-place air voids versus permeability for each NMAS mix. The relationship between in-place air voids and permeability for 9.5-mm NMAS is illustrated in Figure 35. The R^2 values for both coarse-graded and fine-graded mixes were relatively high (0.70 and 0.86, respectively) and both relationships are significant (p-value = 0.000). At 8 percent air voids, the pavement is expected to have a permeability of 60×10^{-5} cm/sec for coarse-graded mix and 10×10^{-5} cm/sec for fine-graded mix. Because there are only a couple of data points for fine-graded mix above approximately 10 percent air voids, this model should not be used to predict permeability at these higher void levels. At

TABLE 14 Comparison of laboratory and field permeabilities

Section Number	Mix Type	In-Place Air Voids (percent)	Field Permeability (cm/s x 10^{-5})	Lab Permeability (cm/s x 10^{-5})
1	9.5mm FG	6.6 to 8.8	1 to 28	1 to 35
2	9.5mm CG	9.0 to 12.6	14 to 632	107 to 1070
3	9.5mm SMA	7.7 to 12.6	110 to 651	29 to 168
4	12.5mm SMA	4.1 to 17.9	3 to 1778	0.1 to 5850
5	19.0mm FG	5.7 to 9.5	38 to 161	1 to 77
6	19.0mm CG	5.3 to 9.8	10 to 1760	1 to 141
7	19.0mm CG	4.8 to 15.2	72 to 3030	0 to 1203

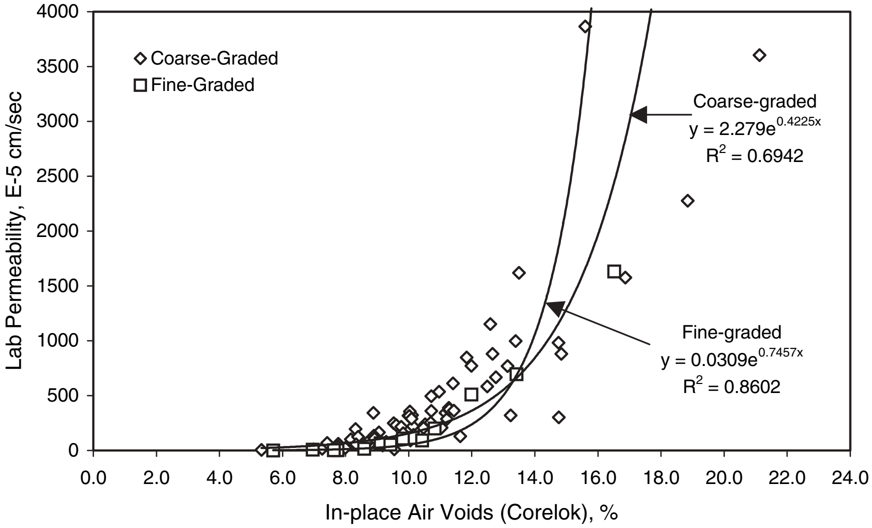

Figure 35. Plot of permeability versus in-place air voids for 9.5-mm NMAS mixes.

lower void levels the coarse-graded mixes are more permeable than fine-graded mixes.

The relationships for the coarse-graded and fine-graded 12.5-mm NMAS mixes are shown in Figure 36. For these projects there was no significant difference between fine and coarse graded mixes. The relationships between in-place air voids and permeability for both gradation types were reasonable and significant with an R^2 of 0.61 for coarse-graded mixes (p-value = 0.000) and 0.58 for fine-graded mixes (p-value = 0.000). As shown by the best-fitted lines, the permeability values for both gradation types were basically the same at a given air void content. The permeability at 8.0 percent air voids for coarse-graded and fine-graded mixes was approximately 30×10^{-5} cm/sec.

Figure 37 illustrates the relationship between in-place air voids and permeability for fine-graded 19.0-mm NMAS mixes. The R^2 value for this figure is 0.59 and the relationship is significant (p-value = 0.000). Based on the trend line, permeability is very low at air void contents less than 8 percent. At air void contents above 8 percent, the permeability begins to increase rapidly with a small increase in in-place air void content. At 8 percent air voids, the fine-graded 19.0-mm NMAS mix has a permeability value of 16×10^{-5} cm/sec.

4.10 CONTROLLED LABORATORY EXPERIMENT TO EVALUATE METHODS OF MEASURING THE BULK SPECIFIC GRAVITY OF COMPACTED HMA

4.10.1 Introduction and Problem Statement

A major concern of the HMA industry is the proper measurement of bulk specific gravity (G_{mb}) for compacted samples. This issue has become a bigger problem with the increased

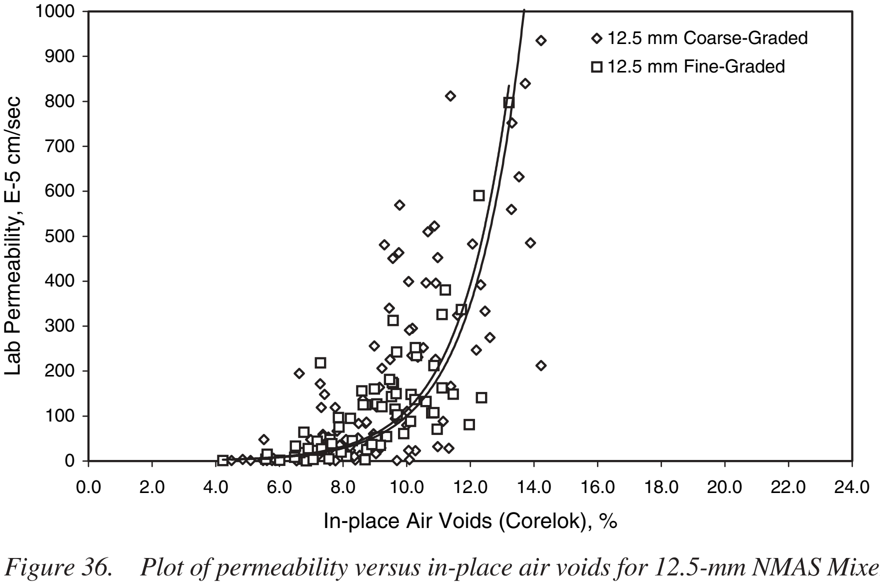

Figure 36. Plot of permeability versus in-place air voids for 12.5-mm NMAS Mixes.

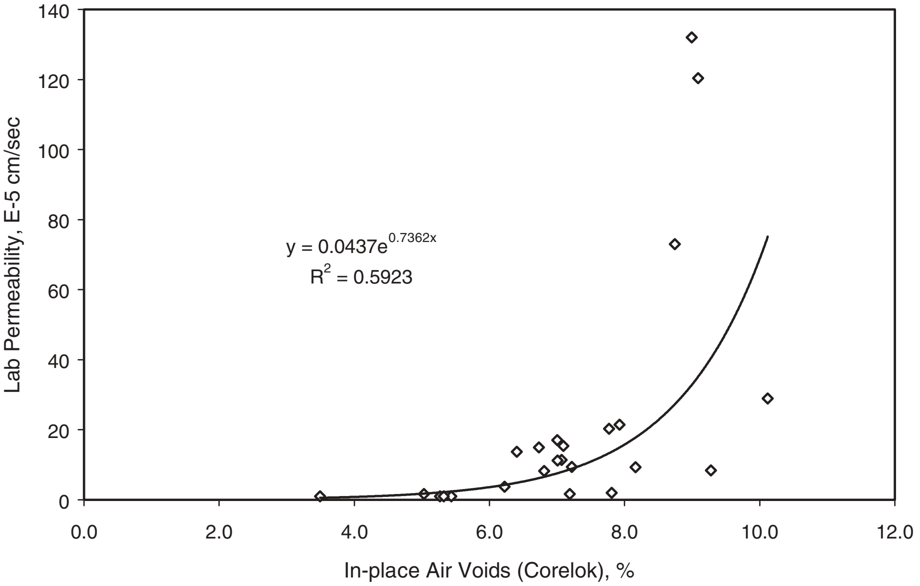

Figure 37. Plot of permeability versus in-place air voids for 9.5-mm NMAS mixes.

use of coarse gradations. Bulk specific gravity measurements are the basis for volumetric calculations used during HMA mix design, field control, and construction acceptance. During mix design, volumetric properties such as air voids, voids in mineral aggregates, voids filled with asphalt, and percent theoretical maximum density at a certain number of gyrations are used to evaluate the acceptability of mixes. All of these properties are based upon G_{mb}.

In most states, acceptance of HMA construction by the owner is typically based upon percent compaction (density based upon G_{mb} and theoretical maximum density). Whether nondestructive (e.g., nuclear gauges) or destructive (e.g., cores) tests are used as the basis of acceptance, G_{mb} measurements are equally important. When nondestructive devices are utilized, each device first has to be calibrated to the G_{mb} of cores. If the G_{mb} measurements of the cores are inaccurate in this calibration step, then the nondestructive device will provide inaccurate data. Additionally, pay factors for construction, whether reductions or bonuses, are generally based upon percent compaction. Thus, errors in G_{mb} measurements can potentially affect both the agency and producer.

For many years, the measurement of G_{mb} for compacted HMA has been accomplished by the water displacement method using saturated-surface dry (SSD) samples. This method consists of first weighing a dry sample in air, then obtaining a submerged mass after the sample has been placed in a water bath for a specified time interval. Upon removal from the water bath, the SSD mass is determined after patting the sample dry using a damp towel. Procedures for this test method are outlined in AASHTO T166 (ASTM D2726).

The SSD method has proven to be adequate for conventionally designed mixes, such as those designed according to the Marshall and Hveem methods, that generally utilized fine-graded aggregates. Historically, mixes were designed to have gradations passing close to or above the Superpave defined maximum density line (i.e., fine-graded). However, since the adoption of the Superpave mix design system and the increased use of SMA, mixes are being designed with coarser gradations than in the past.

The potential problem in measuring the G_{mb} of mixes like coarse-graded Superpave and SMA using the SSD method comes from the internal air void structure within these mix types. These types of mixes tend to have larger internal air voids than the finer conventional 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. During G_{mb} testing with the SSD method, water can quickly infiltrate into the sample through these interconnected voids. However, after 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.

Because of the potential errors noted with the saturated surface-dry test method of determining the bulk specific gravity of compacted HMA, the primary objective of this task was to compare AASHTO T166 with other methods of measuring bulk specific gravity to determine under what conditions AASHTO T166 is accurate.

The plan for this part of the study was to evaluate two separate sample types: laboratory compacted and field compacted. Laboratory compacted mixtures having various aggregate types, nominal maximum aggregate sizes, gradation shapes, and air void levels were prepared. Each of the prepared samples was tested to determine bulk specific gravity by four different test methods: water displacement, vacuum-sealing, gamma ray, and dimensional.

For the field compacted samples, cores obtained during the field validation portion of this study were subjected to the same four bulk specific gravity test methods. Because cores have a different surface texture than laboratory compacted samples, it was necessary to evaluate them also. Testing also conducted on core samples included laboratory permeability tests and effective air void content using the vacuum-sealing device.

4.10.2 Field Compacted Samples

Each of the cores obtained during the Task 5 field validation were tested to determine bulk specific gravity using the same four tests as the laboratory experiment: water displacement, vacuum sealing, gamma ray, and dimensional analysis. Because of the differences in surface texture between laboratory compacted samples (surface texture around entire sample) and field compacted samples (surface texture only on top of sample because of core bit and sawing), the experiment was also extended to core samples.

Because of the differences in resulting air voids for the four methods of measuring bulk specific gravity, a Duncan's multiple range test (DMRT) was conducted to determine which methods, if any, provided similar results. This analysis method provides a ranking comparison between the different methods. The range of sample means for a given set of data (method) can be compared to a critical valued based on the percentiles of the sampling distribution. The critical value is based on the number of means being compared (four, representing the different methods) and number of degrees of freedom at a given level of significance (0.05 for this analysis). Results of the DMRT analysis for the Superpave mixes are illustrated in Figure 38.

Statistically, results of the DMRT comparisons show that all methods produced statistically different air void contents. However, vacuum-sealing and gamma ray bulk specific gravity methods provided similar results given a difference of 0.24 percent air voids. On average, the dimensional method resulted in the highest air void contents, followed by the vacuum-sealing and gamma ray methods, respectively. Air void contents determined from AASHTO T166 resulted in the lowest air void contents. None of the alternative methods provided similar results to AASHTO T166.

The results for SMA mixtures are provided in Figure 39. As with the Superpave mixes, the vacuum-sealing and gamma ray methods resulted in similar air void contents. The dimensional method again resulted in the highest air voids and the AASHTO T166 method resulted in the lowest air voids. Analysis of both the Superpave and SMA data indicated that the four methods of measuring bulk specific gravity significantly affected resulting air voids. For both mix types, the vacuum-sealing and gamma ray methods provided similar air voids; however, the dimensional method provided significantly higher air voids and AASHTO T166 provided significantly lower air void contents.

Theoretically, the dimensional method should provide the highest measured air void content, as this method includes both the internal air voids and the surface texture of the sample. Therefore, the results in Figures 38 and 39 pass the test of reasonableness for the vacuum-sealing, gamma ray, and AASHTO T166 methods as all three provided air void content lower than the dimensional method.

Because it was assumed that the T-166 method would be accurate at low water absorption levels, it was decided to test the mixes with low absorption, less than 0.5 percent, to see which mixes provided results similar to the T-166 method. The results are provided in Figure 40. This figure shows that the vacuum-sealing and AASHTO T166 methods provided

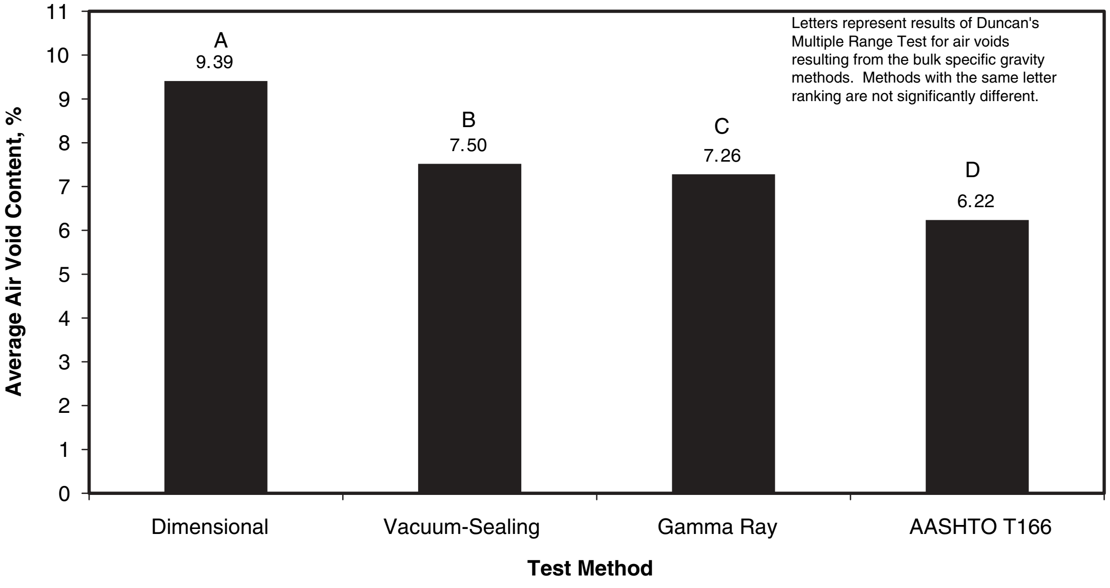

Figure 38. Average air voids and DMRT results for Superpave mixes.

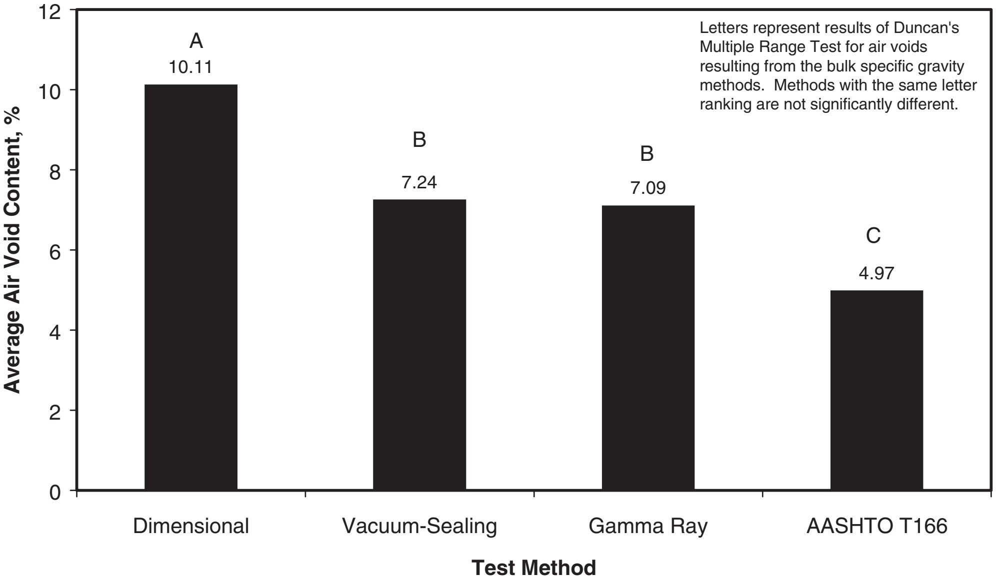

Figure 39. Average air voids and DMRT results for SMA mixes.

similar results and that both were significantly different than the dimensional and gamma ray methods. The dimensional method provided the highest air void content, as expected. The AASHTO T166 method is accurate for low water absorption mixes and at these low void levels provide similar density values to that of the vacuum seal method. These results suggest that the vacuum-sealing method provides an accurate density for low voids, which indicates that it also provides an accurate density at higher void levels because the plastic seal will clearly prevent water from being absorbed into the mixture. Figures 38 and 39 suggest that the gamma ray method does an overall adequate job of estimating bulk specific gravity; however, Figure 40 suggests that it is not as accurate as AASHTO T166 or the vacuum-sealing methods. Refinements to the gamma ray method may make this method a viable option in the future.

4.10.3 Analysis of Field Compacted Samples

Included within this portion of the study were the cores obtained during the Task 5 field validation experiment. Only the vacuum-sealing and AASHTO T166 test methods were analyzed, as they were shown most accurate during the laboratory phase of this experiment. Figure 41 illustrates the relationship between air voids determined from the two methods for all field cores obtained from the 20 field projects during Task 5. This figure illustrates that when air void content is less

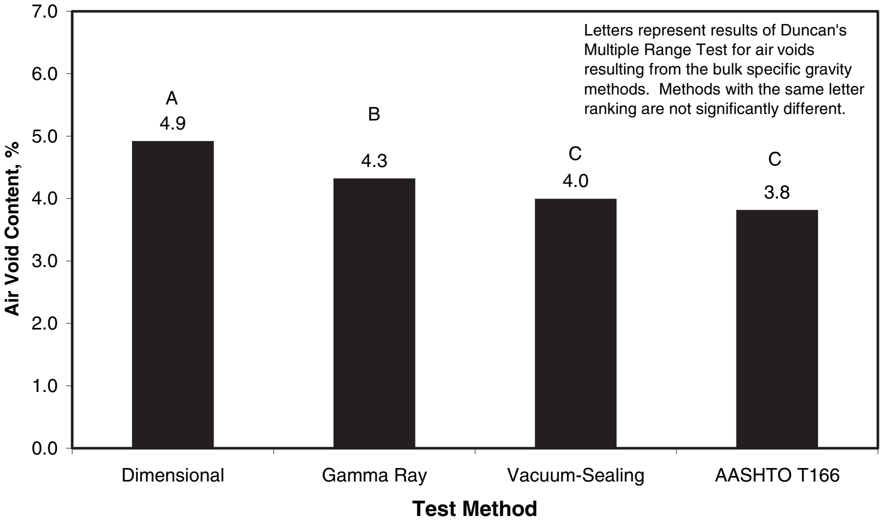

Figure 40. Comparison of test methods, mixes with low water absorption level.

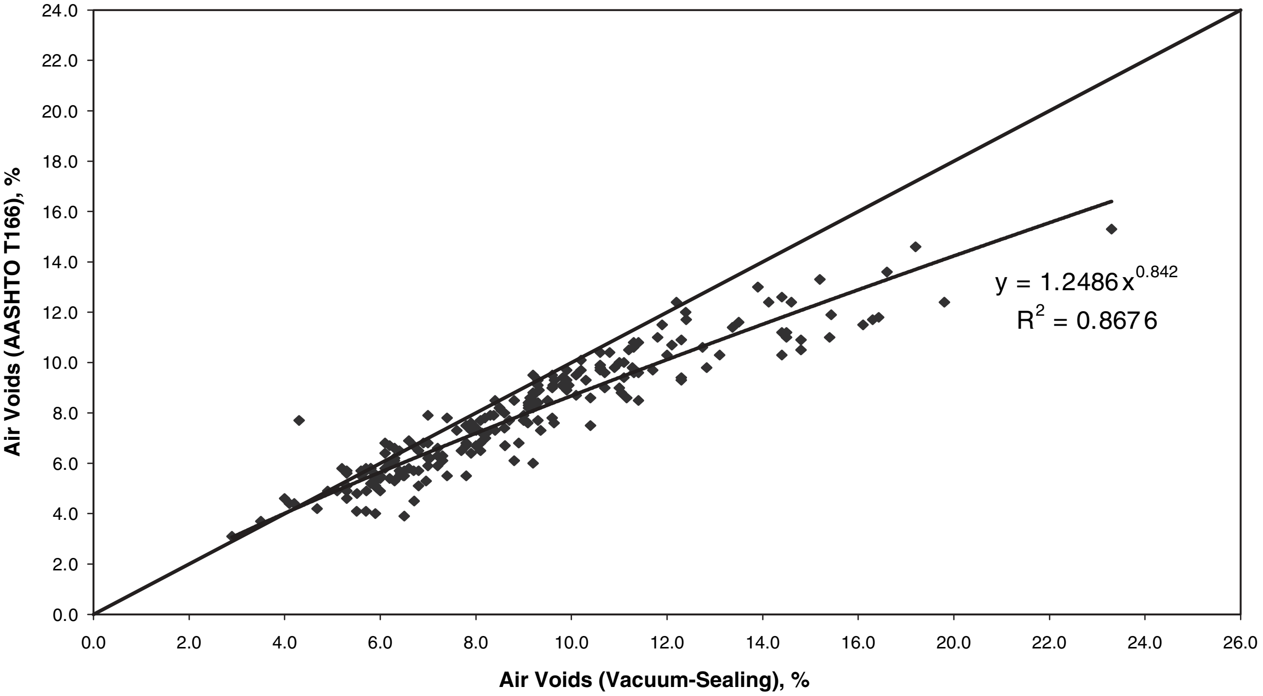

Figure 41. Comparisons between AASHTO T166 and vacuum-sealing methods, field projects.

than about 5 percent, the two methods provided approximately similar results. Above 5 percent air voids, the vacuum-sealing method resulted in higher air void contents. As air voids increased, the two methods diverged and it is believed that the reason for this divergence is the loss of water during the SSD method. Hence, at low air voids, both methods should be close to correct; however, at higher air voids the vacuum-sealing method should be more correct.

4.11 FIELD VALIDATION OF RELATIONSHIPS BETWEEN PERMEABILITY, LIFT THICKNESS, AND IN-PLACE DENSITY

The main objective of the field portion of NCHRP 9-27 (Task 5) was to provide a field validation of the relationships between permeability, lift thickness, and in-place density so the overall objectives of the study could be accomplished. In order to field verify the relationships between air voids, lift thickness, and permeability, 20 HMA construction projects were visited. Testing at these projects included tests on plant-produced mix and on the compacted pavement. Testing of the plant produced mix included compacting samples to both the design compactive effort and to a specified height. Testing on the compacted pavement included performing field permeability tests with the NCAT Field Permeameter. Selection of the 20 projects was based upon the following factors: NMAS, gradation type (fine-graded, coarse-graded, and SMA), and the lift thickness to NMAS ratio (t/NMAS). Table 15 presents the 20 projects evaluated.

Table 15 shows that both fine- and coarse-graded Superpave designed mixes were investigated for each of four NMAS, ranging from 9.5 to 25.0 mm NMAS. SMA mixes were investigated for 12.5 and 19.0 mm NMASs. The effect of lift thickness was evaluated within the 9.5, 12.5, and 19.0 mm NMASs. To determine if a general trend occurred between in-place air voids and t/NMAS, a regression was performed on the combined data. Figure 42 illustrates this general relationship. From this regression, a low R^2 of 0.09 was found. The trendline suggested that as the ratio of lift thickness to NMAS increased, in-place air voids decreased.

To determine if the relationship between in-place air voids and the t/NMAS ratio was significant, an ANOVA was conducted on the regression. For the combined data, the p-value was 0.014, which indicated that the overall relationship was significant. Then the data were separated into the three mix types. When an ANOVA was conducted on the regressions for the mix types, it was found that the relationship was not significant for any of the mix types (p-values of 0.956, 0.994, and 0.107 for fine-graded, coarse-graded, and SMA, respectively). There is a lot of scatter in the data, but, as can be seen in Figure 42, every increase of 1 in the t/NMAS results in a decrease in voids of approximately 0.6 percent. This finding involves average numbers, and it must be realized that many other factors affect the density of these field projects.

Another factor to consider for these projects is the specification requirements were approximately the same for all of these mixes. Hence, the contractor was trying to compact all mixes to a low void content. Even with the same target density the t/NMAS affected the results.

For Figure 43, a best-fit line was produced on the combined data for the 12.5-mm NMAS mixes. A low correlation was also found for this regression (0.19), but the general trend suggested that in-place air voids decreased as the lift

TABLE 15 Field project summary information

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

* Designated RA295 by the agency

thickness increased. An ANOVA conducted for the combined regression indicated that the relationship was significant (p-value = 0.001). The data were then separated into the different mix types to see if the relationship was significant for each mix type. For the fine-graded mixes, the relationship was significant (p-value = 0.000). The coarse-graded mixes did not have a significant relationship between in-place air voids and t/NMAS (p-value = 0.932). These data indicate that an increase of 1 for the t/NMAS resulted in an average decrease in air voids of 0.5 percent.

Figure 44 shows the relationship between lift thickness and in-place air voids for the combined data set for the 19.0-mm NMAS mixes, as well as for the individual mix types. For the combined data, the regression produced a low R^2 value (0.09). An ANOVA performed on the regression determined that the relationship between t/NMAS and in-place air voids for the 19.0-mm NMAS mixes was significant (p-value of 0.000). The data indicate that an increase of 1 for the t/NMAS results in an average decrease of 1.0 in the air voids.

In summary, even though there is a large amount of scatter in the data for the three NMAS mixes, the results suggest that the air voids dropped 0.5 to 1.0 percent for each increase of 1 in the t/NMAS. This shows the importance of making sure that the t/NMAS is sufficiently high.

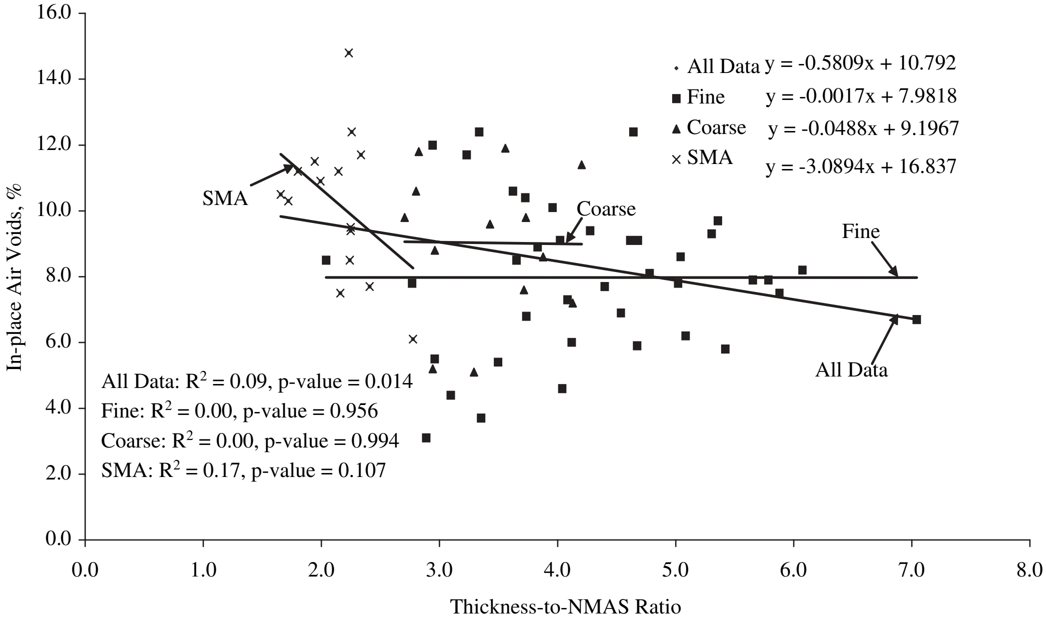

Figure 42. Relationship between t/NMAS and in-place air voids—9.5 mm, all data.

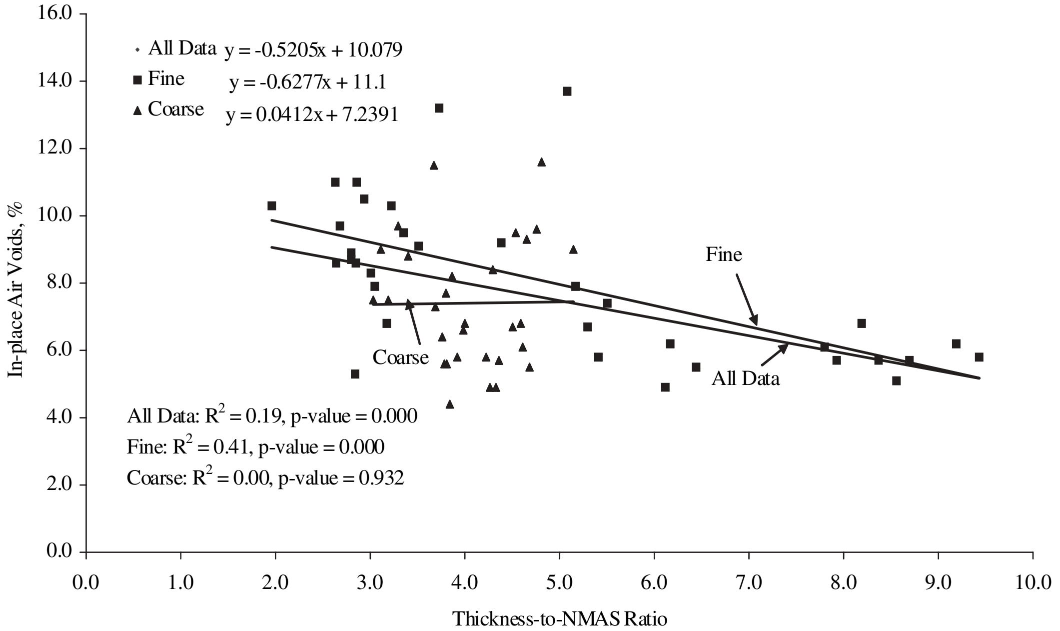

Figure 43. Relationship between t/NMAS and in-place Air Voids—12.5 mm NMAS.

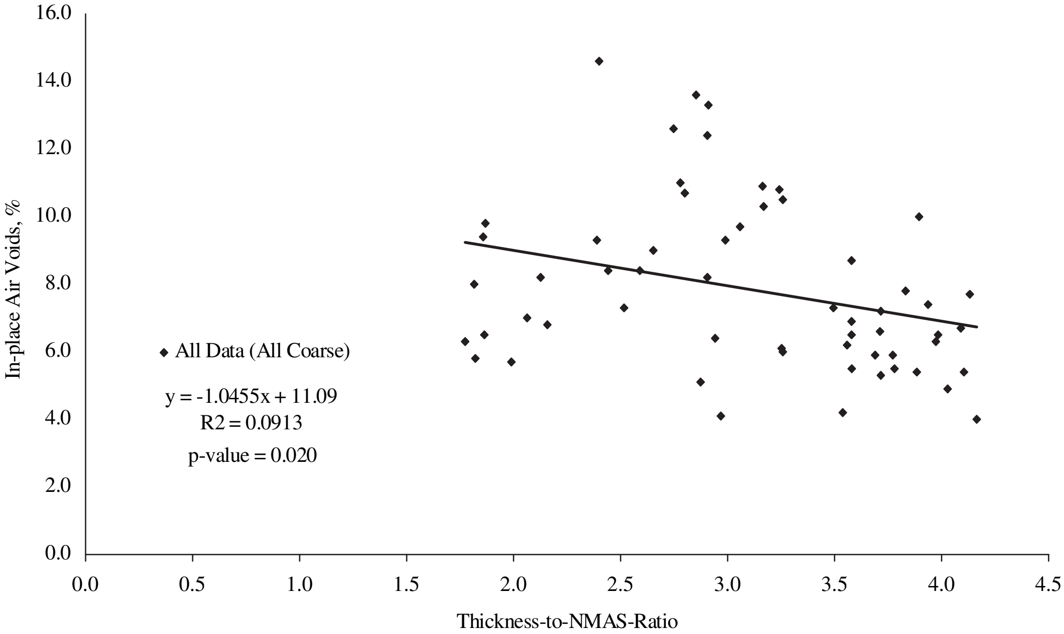

Figure 44. Relationship between t/NMAS and in-place air voids—19.0 mm NMAS.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The density that can be obtained under normal rolling conditions is clearly related to the t/NMAS. For improved compactibility, it is recommended that the t/NMAS be at least 3 for fine-graded mixes and at least 4 for coarse-graded mixes. The data for SMA indicate that the ratio should also be at least 4. Ratios less than these suggested numbers could be used, but more compactive effort would generally be required to obtain the desired density. In most cases, a t/NMAS of 5 does not result in the need for more compactive effort to obtain maximum density. However, care must be exercised when the thickness gets too large to ensure that adequate density is obtained.

The results of the evaluation of the effect of mix temperature on the relationship between density and t/NMAS indicate that one of the reasons for low density at thinner sections (lower t/NMAS) is the more rapid cooling of the mixture. Hence, for thinner layers it is even more important that rollers stay very close to the paver so that rolling can be accomplished prior to excessive cooling. For the conditions of this study, the mixes placed at the NCAT test track at 25-mm thickness cooled twice as fast as mixes placed at 37.5-mm thickness. For thicker sections (larger t/NMAS), the rate of cooling is typically not a problem.

The in-place void content is the most significant factor impacting permeability of HMA mixtures. This is followed by coarse aggregate ratio and VMA. As the values of coarse aggregate ratio increases, permeability increases. Permeability decreases as VMA increases for constant air voids.

The variability of permeability between various mixtures is very high. Some mixtures are permeable at the 8 to 10 percent void range and others do not seem to be permeable at these higher voids. However, to ensure that permeability is not a problem, the in-place air voids should be between 6 and 7 percent or lower. This appears to be true for a wide range of mixtures regardless of NMAS and grading.

When laboratory prepared samples having low levels of water absorption were evaluated, the dimensional method resulted in the highest air void contents followed by the gamma ray method. The vacuum-sealing and water displacement (AASHTO T166) methods resulted in similar air void contents when the water absorption level was low. The vacuum seal method is an acceptable method to use for low and high void levels.

At low levels of water absorption, the water displacement method is an accurate measure for bulk specific gravity. The error develops when removing the sample from water to determine the SSD weight. When water flows out of the sample, an error occurs. The allowable absorption level to use the displacement test method is specified as 2 percent in AASHTO T166, but this level of absorption can create accuracy problems, as shown in this report. It is recommended that the absorption limit for the displacement test method be reduced to 1 percent. If the vacuum-seal method is adopted on a project, the measured voids may now be somewhat higher than with the water displacement method.

The water displacement method was accurate for all water absorption levels encountered for mixes that were fine-graded (ARZ gradations). For mixes having gradations near the maximum density line (TRZ) or coarser (BRZ and SMA), the level of water absorption at which AASHTO T166 began to lose accuracy was between 0.2 and 0.4 percent.

For mix design samples and other laboratory samples that are compacted to relatively low voids, the displacement method will provide reasonably accurate answers. However, for field samples where the void levels will typically be 6 percent or higher, it is important to evaluate absorption to determine if the vacuum-seal method needs to be used.

Care must be used when using the vacuum sealing method to measure density. Many times the plastic bag develops a leak during the test, leading to an error in the result. Weighing the sample in air after measuring the submerged weight will indicate if a leak has developed. If a leak is identified, the test must be repeated until an acceptable test is achieved.

There appears to be a need for a correction factor for the vacuum-sealing and water displacement methods to provide equal measured air void contents even when the air void level is low. The correction factor for the mixtures evaluated in this report was approximately 0.2 percent air voids. A better determination of the correction factor can be made for specific dense graded mixes by compacting samples in the Superpave gyratory compactor to approximately 4 percent air voids (design air void content) and testing using the two test methods. The difference between these two tests will be the correction factor for the mix.

The in-place air voids of the 20 field projects were high. Fourteen of the 20 mixes tested had average in-place air voids above 8 percent and seven of the mixes had average air voids over 10 percent (based on test results with the vacuum-seal method). This low density on a high percentage of random projects is disturbing because this lower density will most certainly lead to significant loss in pavement life.

More emphasis must be placed on obtaining adequate density. Regardless of the method of density measurement used, some cores have to be taken and tested for calibration. The most reliable way to measure density is to take cores for density testing. If the amount of absorption during density measurement exceeds 1 percent, the T166 method will likely provide a higher measured density than the true density. The vacuum seal method is one approach to measure a density more accurately when the water absorption exceeds 1 percent.

Even though there is a lot of scatter within and between projects, most field results support the finding that higher t/NMAS ratios generally provide lower void levels. Coarse-graded mixtures generally have higher permeability values than the fine-graded mixtures for a given air void level. Air voids were clearly shown to be a key determinant of permeability. However, many times the air voids were reasonably low (5 to 7 percent) and the permeability was still high.

CHAPTER 6

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APPENDICES A THROUGH E UNPUBLISHED MATERIAL

Appendices A, B, C, D, and E as submitted by the research agency are not published herein. For a limited time, they are available for loan on request to NCHRP. Their titles are as follows:

Appendix A: Mix Design Summary Information for Part 1
Appendix B: Lift Thickness Versus Density Data Using Gyratory Compactor
Appendix C: Lift Thickness Versus Density Data Using Vibratory Compactor
Appendix D: Lift Thickness Versus Permeability Data
Appendix E: Factors Affecting Permeability Data Using Field Core Samples

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation