EVALUATION OF HOT MIX ASPHALT (HMA) LIFT THICKNESS

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16. Abstract:

   The range of lift thicknesses allowed by the Mississippi Department of Transportation has worked well for many years. However, because of the current availability of gravels of sufficient size to crush, modification to the allowed lift thicknesses amy be warranted. Therefore, the objective of this project was to evaluate the influence of lift thickness on the ability to achieve a desirable density with a reasonable compactive effort.

   The research approach under taken to achieve the project objective was to conduct a detailed field study. A total of ten field projects were utilized in this study. At each of the field projects, the field compaction process was monitored and field date obtained. Data obtained from the field projects included four different mat temperature measurements over time, mat density after each pass of the roller suing a nuclear gauge, and final density and thickness obtained form cores. Cores cut from the roadway were also brought back to the laboratory for permeability testing.

   Based upon analyses conducted on the data, several conclusions were drawn. The thickness of the placed layer does affect the amount of time that an HMA layer will remain at compaction temperatures. Thicker lifts will maintain temperature longer. Lift thickness did have an affect on the final in-place density. As lift thickness increased, final in-place density also increased. No impact related to lift thickness was found for density gradients within field compacted layers. Finally, there did not appear to be an influence of thickness on the permeability of HMA layers. Based upon these conclusions, new allowable lift thickness limits were recommended.

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CHAPTER 1 - INTRODUCTION

1.1   Introduction and Problem Statement

Proper compaction of hot mix asphalt (HMA) mixture is vital to ensuring that a stable and durable pavement is constructed. For typical dense-graded HMA mixes, numerous studies have shown that initial in-place air voids should not be below approximately 3 percent or above approximately 8 percent. Low in-place air voids can result in rutting and/or shoving, while high in-place air voids allow water and air to penetrate into the pavement leading to an increased potential for water damage, oxidation, raveling, and/or cracking.

There are many, many factors that can affect the compaction of HMA. Mix characteristics such as gradation, nominal maximum aggregate size (NMAS), asphalt binder stiffness, etc. can all affect the ability to achieve adequate in-place density. Environmental factors such as ambient temperature, base temperature, wind speed, solar energy (daytime/nighttime paving), etc. can also significantly affect the ability to achieve the desired density. Finally, construction related characteristics will also affect the ability to achieve a desirable pavement density. One important factor is the temperature of the mix when it arrives at the project site. Mix that arrives at the project site that is below the desired compaction temperature can make it difficult to achieve adequate density with a reasonable compactive effort. The number, type, and passes of rollers can also greatly affect the achieved density. Another factor that affects the ability to achieve an adequate density is lift thickness. Work by the Florida Department of Transportation (DOT) has shown that lift thickness does affect the ability to achieve density ([1]). Similar results have been found in Wisconsin ([2]). Work during National Cooperative Highway Research Program Project 9-27 confirmed these conclusions ([3]).

Relatively thick lifts of HMA provide several benefits with respect to compactability. Relatively thicker lifts will maintain a desirable compaction temperature longer than thinner lifts as more volume of HMA is placed o the roadway. Thicker lifts also provide more room for aggregate particles to orient themselves under the compactive effort leading to easier densification. In other words, the increased thickness allows the aggregate particles to slide past each other which makes it easier to achieve density with a reasonable compactive effort.

Though all of the above factors affect the ability to achieve the desired pavement density, the subject of this project is lift thickness. Table 1 provides MDOT's current lift thickness requirements for a single lift of HMA. As shown in the table, the allowable lift thickness for a layer is based upon NMAS. Minimum lift thicknesses are generally 2.5 to 3 times the NMAS while the maximum lift thickness is generally 4 times the NMAS.

Table 1: MDOT Allowable Lift Thickness (4)

Mixture (NMAS)	Single Lift Laying Thickness, Inches	
	Minimum	Maximum
25mm	3	4
19mm	2 ¼	3
12.5mm	1 ½	2
9.5mm	1	1 ½
4.75mm	½	3/4

The range of allowable lift thicknesses shown in Table 1 have worked well in Mississippi for many years. However, because of the current availability of gravels in Mississippi, modification to Table 1 may be warranted. Most current gravel sources are producing particle sizes that are in the range of 1 ½ to 2 inches. Once crushed to provide the desired particle angularity, most of the particles are less than ½ inch in diameter. This means that the most rut resistant mixes (mixes containing the most angular aggregates) have a small NMAS. As NMAS decreases, the quality of HMA, therefore, increases.

Under the requirements of Table 1, the typically highest quality HMA mix used in Mississippi, a 9.5mm NMAS, can not be used for a 2 inch mill and fill project. Likewise, a high quality 12.5mm NMAS can not be utilized for a 2 ½ or 3 inch upper binder layer. As such, the requirements in Table 1 may be restricting the use of high quality HMA on certain projects because of layer thickness even through these mixes will perform well. Therefore, research was needed to evaluate the appropriate lift thickness for HMA mixes used in Mississippi.

1.2   Objective

The objective of this project was to evaluate the influence of lift thickness on the ability to achieve desirable in-place density levels with a reasonable compactive effort. If appropriate, recommendations were to be made for new lift thickness requirements.

CHAPTER 2 – RESEARCH APPROACH

2.1   Research Approach

The research approach undertaken to accomplish the project objective involved a detailed field study. A total of ten field projects were utilized in this study. Five of the projects were designed to have a 9.5mm NMAS and the remaining five 12.5mm NMAS. Projects were selected based upon lift thickness. Projects having lift thicknesses that were both within and outside MDOT's lift thickness requirements were identified and included in the study.

For each of the ten projects, the field compaction process was monitored because density was deemed as the performance property related to lift thickness. This included documenting roller types, pavement temperature and the pavement density between roller passes. For each project, plant mix was sampled from a truck. This truck was then followed to the project site and a test location selected representing the sampled HMA. At this location, pavement temperature was monitored over time by two methods. The first method entailed obtaining the surface temperature of the mix using an infrared temperature gun. Secondly, thermo-couples were inserted into the test layer at the bottom, middle and top of the layer. Temperature was monitored at the location from the time that the mix passed through the paver until the final pass by the finish roller.

Pavement density was monitored during construction using a nuclear gauge at each location. Immediately after the paver passed over the selected test location, an initial density was obtained. Subsequently, pavement density was obtained after each pass of a roller. Similar to the temperature measurements, the time from being placed to the roller pass was also measured.

After the finish roller made its final pass over the test location, a core was cut from the test location. The core was brought back to the laboratory and the density determined. Plant mix was utilized to determine the theoretical maximum specific gravity such that the percent theoretical maximum density could be determine for each core. After determining the density of the core, laboratory permeability was determined using a falling head, flexible wall permeameter. Because one concern with thicker lifts is a layer not being uniformly compacted throughout its depth, each core was also cut into two or three layers. Three layers per core was the target; however, some cores were too thin to cut safely into three layers. The density of each layer was determined.

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CHAPTER 3 – MIXTURE AND PROJECT INFORMATION

3.1   Mixture and Project Information

A total of ten pavements were tested for this project. Table 2 presents the average properties for the HMA at each of the ten test locations. Based upon the production data, five of the projects had an NMAS of 9.5mm while five had an NMAS of 12.5mm. Project 8 was designed as a 12.5mm NMAS mix; however the average gradation during production resulted in a 9.5mm NMAS. Table 3 provides information for each of the test locations.

Table 2: Properties of HMA for the Ten Field Projects

Project	1	2	3	4	5	6	7	8	9	10
N_{des}	85	85	85	50	50	85	50	50	85	85
Pb, %	5.5	5.4	5.6	5.5	5.5	5.5	5.2	5.5	5.3	5.3
VTM, %	4.9	5.7	4.7	3.7	3.7	4.8	3.	3.5	3.6	4.2
VMA, %	14.5	14.8	15.4	14.8	14.5	15.1	714.1	14.9	14.8	15.4
VEA, %	9.6	9.1	10.7	11.1	10.8	10.3	10.4	11.4	11.2	11.2
Gmm	2.451	2.469	2.449	2.361	2.369	2.457	2.446	2.401	2.412	2.413
Act.t, mm	67.3	50.0	36.5	40.9	47.4	41.9	47.0	42.5	32.2	47.8
% Passing										
25.0mm	100	100	100	100	100	100	100	100	100	100
19.0mm	99.8	100	100	100	100	100	100	100	100	100
12.5mm	97.8	97.7	98.7	95.2	94.1	100	95.2	100	100	100
9.5mm	84.1	88.0	96.3	86.2	80.9	97.1	84.7	90.7	91.6	92.8
4.75mm	44.5	48.3	59.5	61.5	56.7	58.1	44.2	61.7	55.5	55.3
2.36mm	28.3	28.3	35.1	44.2	38.6	33.9	18.9	41.9	32.3	31.7
1.18mm	20.3	20.0	23.7	---	---	22.8	---	---	---	---
0.6mm	15.1	14.3	16.6	23.2	18.5	15.9	17.4	24.0	15.9	15.4
0.3mm	11.0	9.9	11.1	12.2	12.2	10.4	10.2	12.4	9.4	9.3
0.15mm	7.6	6.3	---	---	---	---	---	---	---	---
0.075mm	5.7	5.1	5.1	4.9	5.4	4.2	5.1	4.9	5.5	5.5

Table 3: Test Location Information

	Project 1							Project 2	Project 3		Project 4		Project 5		
	Location							Location	Location		Location		Location		
	1	2	3	4	5	6	7	1	1	2	1	2	1	2	3
t, in	2.905	2.458	3.010	2.445	2.710	2.750	2.272	1.989	1.497	1.374	1.82	1.40	1.8	1.7	2.1
t, mm	73.8	62.4	76.5	62.1	68.8	69.9	57.7	50.5	38.0	34.9	46.2	35.6	45.7	43.2	53.3
NMAS	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	9.5	9.5	12.5	12.5	12.5	12.5	12.5
t/NMAS	5.90	4.99	6.12	4.97	5.50	5.59	4.62	4.04	4.00	3.67	3.70	2.85	3.66	3.46	4.26
%G_{mm}	94.6	93.9	93.8	93.7	92.2	93.1	89.9	94.2	95.3	90.9	94.6	95.0	94.0	93.7	93.8
K, 10^{-5} cm/sec	I	I	I	I	I	I	476	14	I	100	I	I	12.3	40.3	35.5
T_i, °F	282	270	289	284	261	254	253	262	253	253	245	278	261	280	284
Ambient, °F	75	68	67	81	N/A	N/A	N/A	84	N/A	84	76	76	82	84	N/A
Base, °F	77	72	73	86	81	N/A	88	91	N/A	96	77	98	107	112	130
Wind, mph	0-5	0-5	0-5	0-5	10-15	10-20	Calm	Calm	Calm	Calm	5-10	5-10	0-5	0-5	0-5
Conditions	Clear	Clear	Clear	Partly Cloudy	Partly Cloudy	Partly Cloudy	Partly Cloudy	Partly Cloudy	Clear	Clear	Partly Sunny	Partly Sunny	Sunny	Sunny	Sunny
Day/Night	Night	Night	Night	Night	Night	Night	Night	Night	Night	Night	Day	Day	Day	Day	Day

I – Impermeable

N/A – Not Available

Table 3 Continued: Test Location Information

	Project 6		Project 7				Project 8				Project 9			Project 10
	Location		Location				Location				Location			Location
	1	2	1	2	3	4	1	2	3	4	1	2	3	1
t, in	1.561	1.739	1.8	1.9	1.8	1.9	1.7	1.8	1.6	1.6	1.45	1.13	1.22	1.88
t, mm	39.6	44.2	45.7	48.3	45.7	48.3	43.2	45.7	40.6	40.6	36.8	28.7	31.0	47.8
NMAS	9.5	9.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	9.5	9.5	9.5	9.5
t/NMAS	4.17	4.65	3.66	4.02	3.66	4.02	3.45	3.66	3.25	3.25	3.87	3.02	3.26	5.03
%G_{mm}	92.9	93.4	92.3	93.1	91.9	93.0	96.1	94.5	95.1	94.1	93.8	86.9	88.3	92.5
K, 10^{-5} cm/sec	6	39	170	18	120	9	I	I	I	I	12	894	944	116
T_i, °F	275	267	275	310	274	285	278	280	274	267	305	287	277	302
Ambient, °F	86	84	N/A	84	86	88	80	82	84	88	81	83	81	79
Base, °F	97	95	88	83	93	115	88	89	94	106	99	95	92	89
Wind, mph	0-5	Calm	0-5	0-5	0-5	0-5	Calm	Calm	Calm	Calm	0-5	0-5	0-5	0-5
Conditions	Clear	Clear	Sunny	Sunny	Sunny	Sunny	Sunny	Sunny	Sunny	Sunny	Clear	Clear	Clear	Clear
Day/Night	Night	Night	Day	Day	Day	Day	Day	Day	Day	Day	Night	Night	Night	Night

I – Impermeable

N/A – Not Available

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CHAPTER 4 – TEST RESULTS AND ANALYSES

As described in the research approach, the experimental design was developed to evaluate the influence of lift thickness on three different properties: temperature, density and permeability. The following sections discuss the test results and analyses conducted for each of these properties.

4.1 Temperature

Temperature measurements were obtained over time at four locations during construction at each of the field test locations. Generally, measurements were obtained intermittingly from the time the HMA exited the paver until the finish roller completed compaction. The surface temperature was measured utilizing an infrared temperature gun. Temperatures within the lift were measured using three thermo-couples, placed into the lift directly below the surface, at the mid-point of the lift, and just above the bottom of the lift.

Temperature measurements were obtained for each of the projects. However, each of the projects had different conditions. For example, some projects were constructed at night while others were constructed during the day. Mix temperatures out of the paver varied from test location to test location. Any time that research is conducted in the field, these types of variabilities are expected. Therefore, the analysis technique selected to evaluate the effect of lift thickness on temperature was regression analysis.

The first step in analyzing the data was to normalize the data. Table 4 presents a typical subset of temperature data. Temperature values at a time equal to zero represent temperatures immediately after the mixture had been placed by the paver. Subsequent temperature measurements were obtained for each roller pass. Normalization of the temperature data for each measurement (surface, top of lift, mid-point or bottom of lift) involved subtracting the temperature at a given time from the initial temperature. This resulted in a measure of temperature loss over time. Normalization was needed because the initial temperature of the mixture at each test location was different. Normalized temperatures are also shown in Table 4.

Table 4: Typical Temperature Data for a Test Location

Time (min.)	Raw values				Normalized Values			
	Surface, °F	Top, °F	Mid, °F	Bottom, °F	Surface, °F	Top, °F	Mid, °F	Bottom, °F
0.00	284	293	294	273	0	0	0	0
4.75	237	288	296	271	47	5	-2	2
5.50	233	274	291	268	51	19	3	5
7.00	201	271	288	258	83	22	6	15
8.25	213	262	284	250	71	31	10	23
10.00	215	277	280	240	69	16	14	33
10.75	212	260	279	237	72	33	15	36
12.80	199	260	281	230	85	33	13	43
12.75	200	274	273	227	84	19	21	46
14.25	185	275	267	222	99	18	27	51
14.50	184	243	261	220	100	50	33	53
19.00	192	229	242	206	92	64	52	67
19.50	192	213	246	204	92	80	48	69
20.00	187	219	237	202	97	74	57	71
20.75	188	218	234	200	96	75	60	73
21.25	187	216	232	198	97	77	62	75
22.00	188	215	230	196	96	78	64	77
22.50	188	225	232	195	96	68	62	78
23.50	182	210	224	193	102	83	70	80
37.25	159	171	180	167	125	122	114	106

After normalizing all data, the normalized data was regressed versus the time data. The selected model for these regressions was the Morgan-Mercer-Flodin (MMF) model, which is a sigmoidal function having the form shown in Equation 1. This model was selected because it consistently provided low standard errors of the estimate and high correlation coefficients. Figure 1 illustrates the results of the regression analysis for the surface data in Table 4 using the MMF model.

Equation 1

Where;

y = predicted temperature loss, °F
x = time, seconds
a, b, c, d = regression coefficients
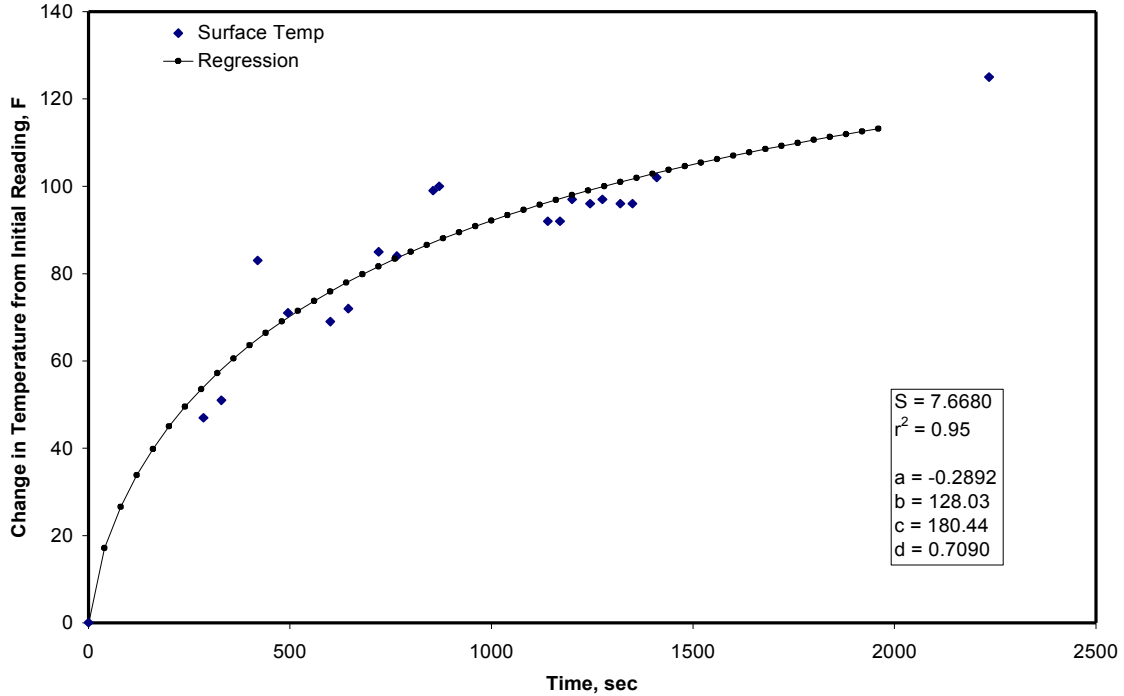
Figure 1: Typical Regression Results for Temperature Data

After conducting all regressions (for each test location), the data was divided into two subsets which were the 12.5mm NMAS data and 9.5mm NMAS data. For each subset, the data was grouped by thickness. Thickness was normalized by using the ratio of thickness to NMAS (t/NMAS). Different categories were developed for each NMAS to evaluate the effect of thickness on temperature loss. Each category of thickness was a range of t/NMAS. The following categories were developed: t/NMAS < 3.0; 3.0<t/NMAS <3.5; 3.5< t/NMAS<4.0; 4.0< t/NMAS<4.5; 4.5< t/NMAS<5.0; and t/NMAS>5.0. Within each thickness category, the regression coefficients were used to obtain an average relationship between temperature measurement, location and NMAS, resulting in a total of eight relationships. These relationships are depicted in Figures 2 through 9.

Figure 2 presents the relationship between surface temperatures (infrared gun) and time for the 9.5mm mixes. In order to compare the various mixes, an initial mix temperature of 280°F was assumed and the temperature loss regressions utilized. Based upon Figure 2, lifts having a t/NMAS between 3.0 and 3.5 lost the most temperature while lifts having a t/NMAS between 4.5 and 5.0 maintained temperature longer. This is as expected in that thicker lifts mean more volume of HMA on the pavement. More volume should maintain temperature better.

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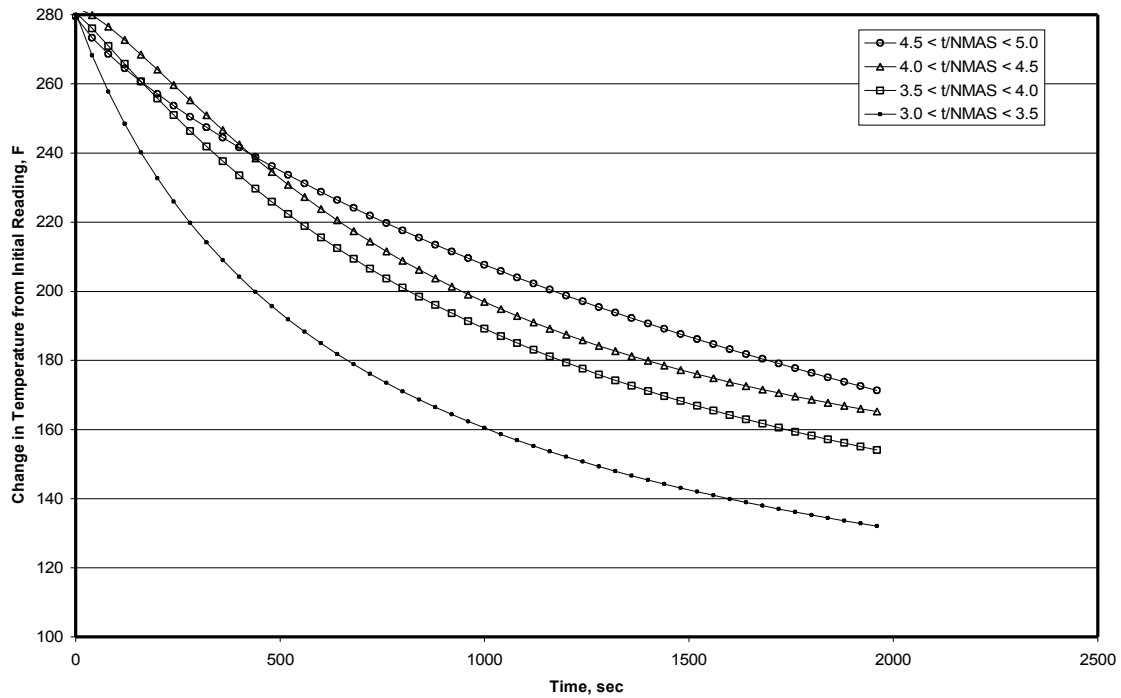
Figure 2: Average Temperature Loss Data for Surface Measurements - 9.5 mm NMAS Mixes

Figure 3 illustrates the temperature loss data for 12.5mm NMAS mixes using the infrared temperature gun at the surface. Based upon this figure, the lifts having a t/NMAS greater than 5 maintained temperature much better than the other lift thicknesses. The t/NMAS category of between 4.5 and 5.0 was next in the ability to maintain temperature followed by the less than 3.0 category. Lifts having a t/NMAS of less than 3.0 and between 3.5 and 4.0 appear to have similar temperature loss characteristics. Interestingly, the lift thickness category of between 4.0 and 4.5 had the highest temperature loss.

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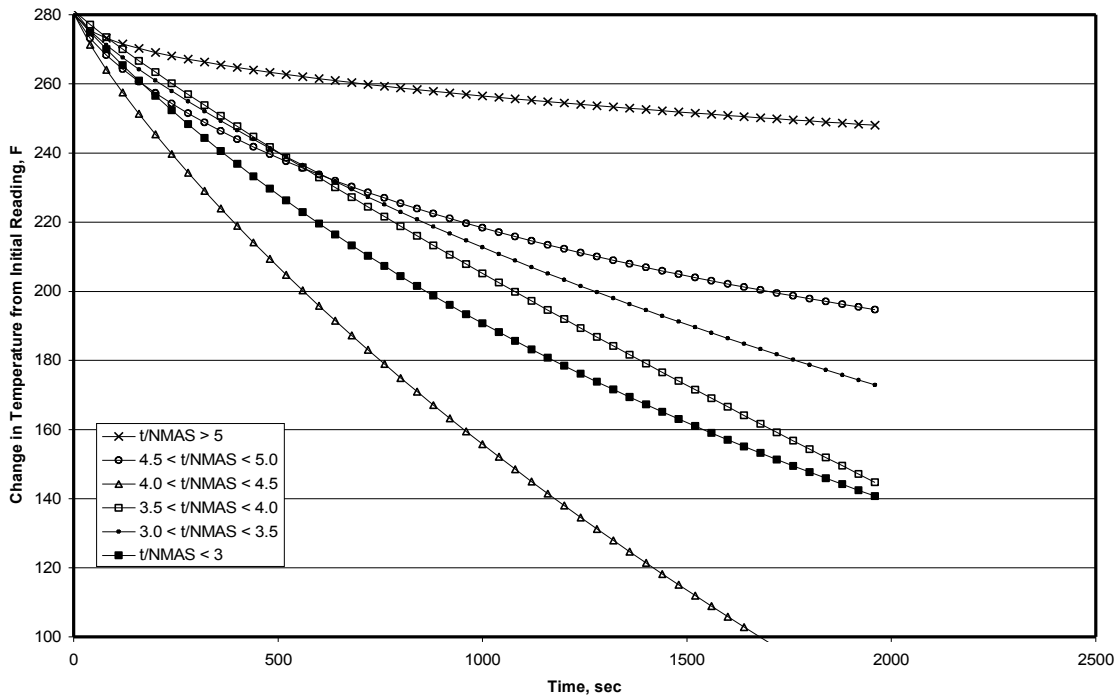
Figure 3: Average Temperature Loss Data for Surface Measurements - 12.5 NMAS Mixes

Figure 4 presents the top of lift temperature data from the thermo-couples for the 9.5mm NMAS mixes. This figure suggests that at the top of a lift, the loss of temperature over time was similar for all four t/NMAS categories. However, the two thicker categories did lose the least amount of temperature over time compared to the two thinner categories.
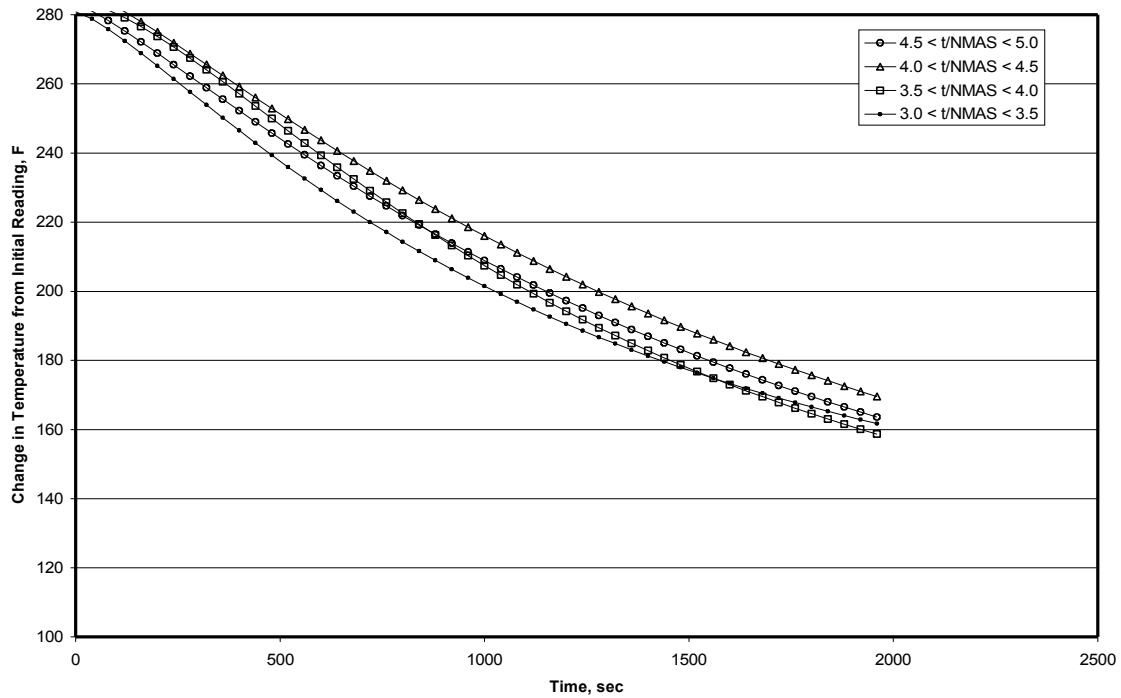
Figure 4: Average Temperature Loss Data for Top of Lift Measurements - 9.5 mm NMAS Mixes

Top of lift temperature loss for 12.5mm NMAS mixes is illustrated in Figure 5. Similar to Figure 3, one relationship, 3.0<t/NMAS <3.5, appears to be much different than the others. Lift thickness categories of 4.0 to 4.5 and 4.5 to 5.0 had similar temperature loss relationships and showed the least amount of temperature loss over time. These two relationships were followed by the less than 3.0 category. Categories of greater than 5 and between 3.5 and 4 had a somewhat similar relationship between temperature and time.

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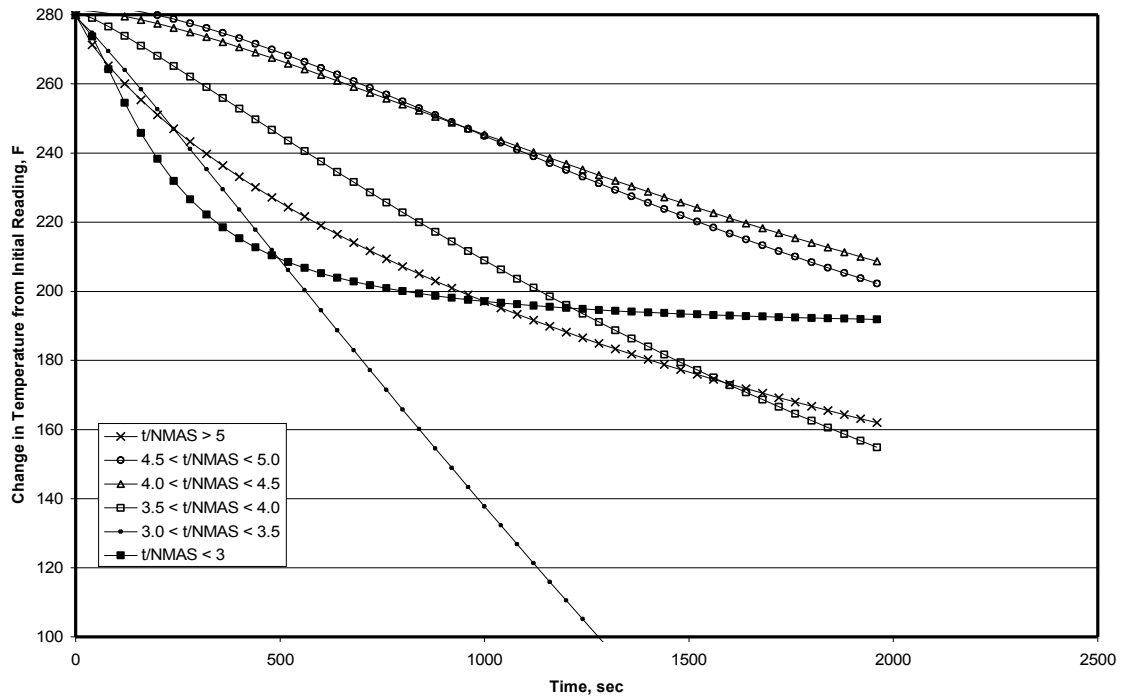
Figure 5: Average Temperature Loss Data for Top of Lift Measurements - 12.5 mm NMAS Mixes

Figure 6 depicts the temperature-time relationships for 9.5mm NMAS mixes utilizing the temperatures obtained mid-depth. Based upon the relationships, the t/NMAS category of between 4.5 and 5.0 showed the lowest temperature loss followed by the category of between 3.0 and 3.5. The category of between 4.0 and 4.5 showed the most temperature loss.
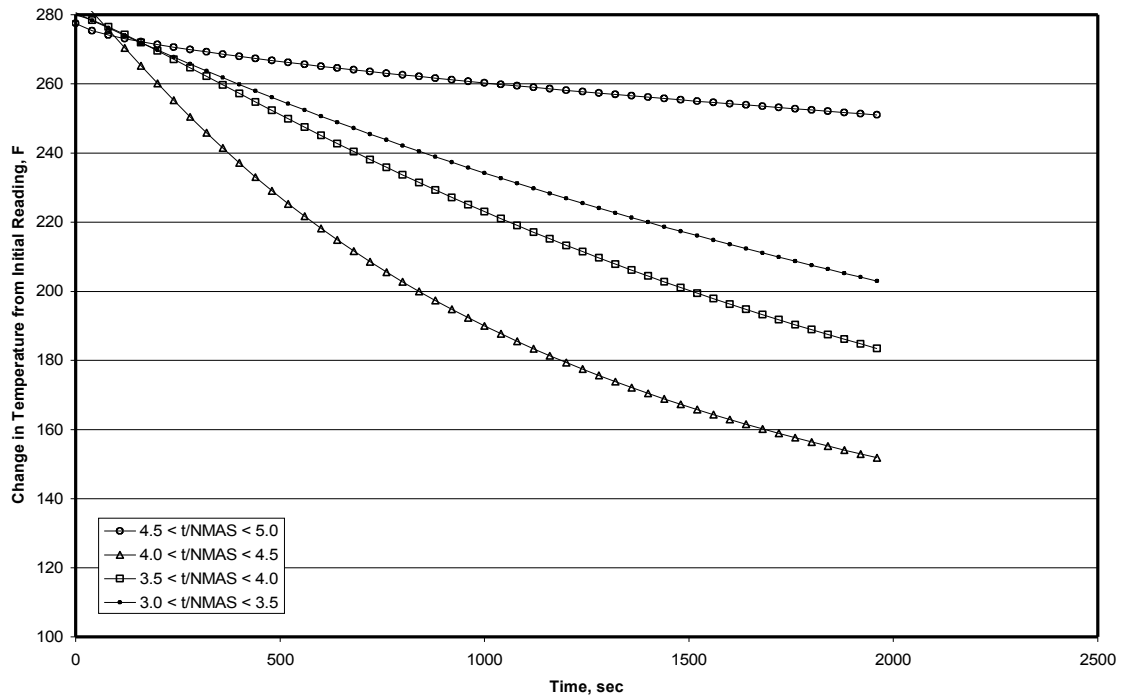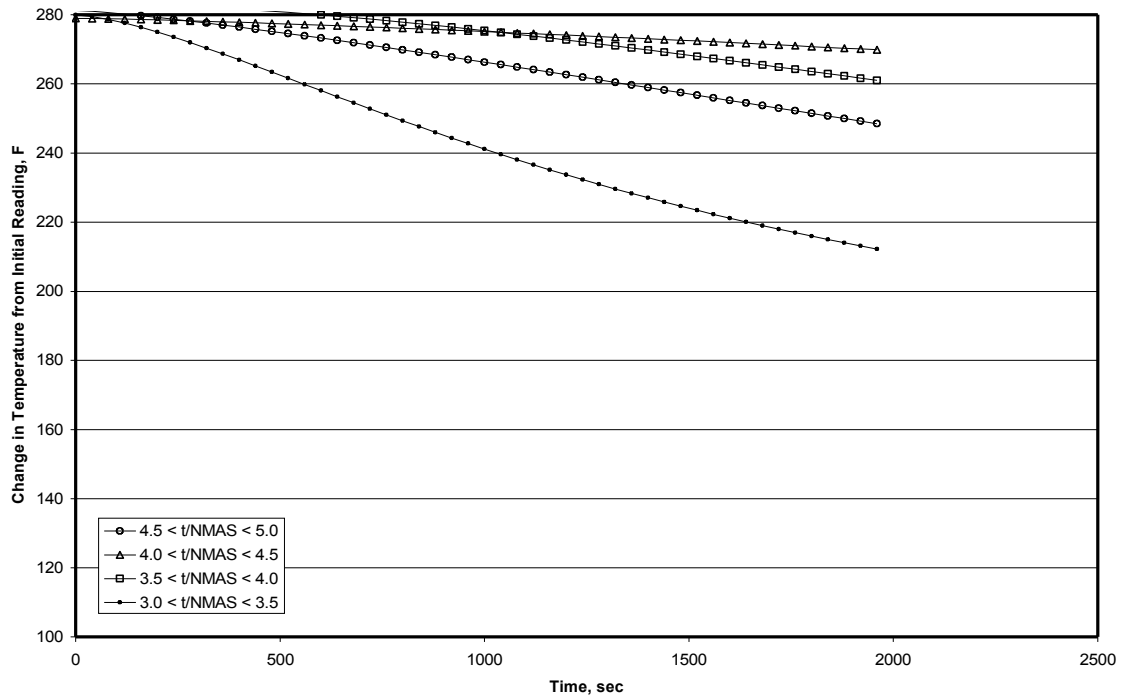
Figure 6: Average Temperature Loss Data for Mid-Layer Measurements - 9.5 mm NMAS Mixes

Mid-depth temperature measurements for the 12.5mm mixes are illustrated in Figure 7. Again, one of the relationships is much different in that the t/NMAS category of between 3.5 and 4 showed a significant amount of temperature loss in a very short time. The relationship for the 4.0 and 4.5 category also appears to be an outlier in that it showed very little temperature loss.

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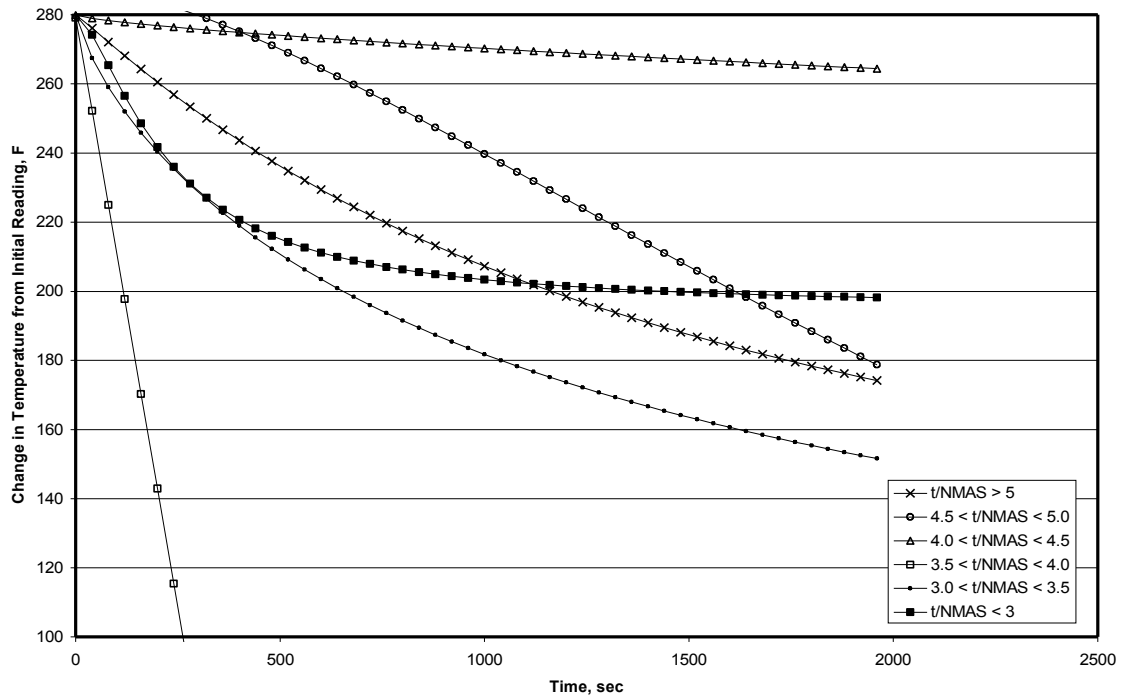
Figure 7: Average Temperature Loss Data for Mid-Layer Measurements - 12.5 mm NMAS Mixes

Figure 8 illustrates the temperature relationships for the 9.5mm NMAS mixes using the bottom of lift temperature measurements. The initial observation about Figure 8 is that there was much less loss of temperature at the bottom of the lift compared to the other temperature locations. The only relationship that appears different is the t/NMAS category of between 3.0 and 3.5. This relationship showed more temperature loss than the others.

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Figure 8: Average Temperature Loss Data for Bottom-Layer Measurements - 9.5 mm NMAS Mixes

The final temperature-time relationships are shown in Figure 9. Interestingly, the thinnest lift category showed the least amount of temperature loss over time. The t/NMAS category showing the most temperature loss was the 3.0<t/NMAS <3.5 category.

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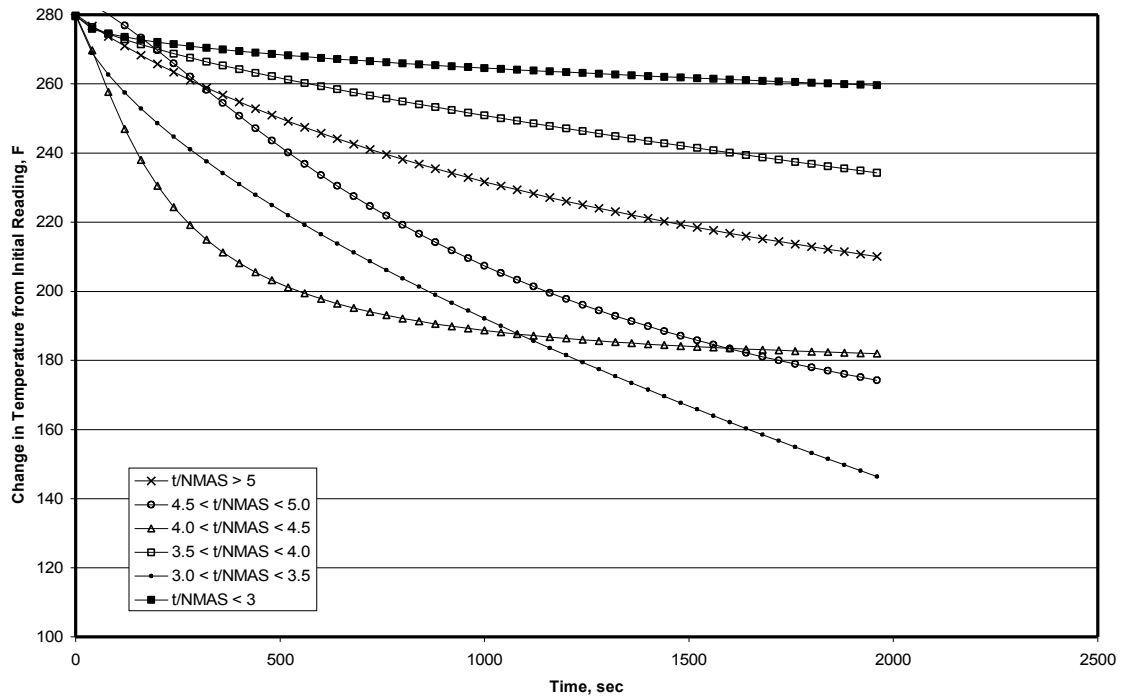
Figure 9: Average Temperature Loss Data for Bottom-Layer Measurements - 12.5 mm NMAS Mixes

Table 5 summarizes the analyses conducted utilizing the time and temperature data. This table shows the rank of each t/NMAS category with respect to temperature loss after 200 seconds. The rankings are divided by NMAS. Based upon the individual rankings, an average ranking was developed in order to evaluate the data as a whole. For the 9.5mm mixes, the rankings indicated that thicker lifts maintained temperature better. This is shown as the decreasing average ranking as the t/NMAS increases. For the 12.5mm mixes, the thinnest lift ranked highest signifying that it lost the least amount of temperature over time. It should be stated; however, that only a single test location had a t/NMAS of less than 3.0. Therefore, this observation could be an anomaly. Based upon the other 12.5mm rankings, lifts having a t/NMAS above 4.0 ranked similarly. Each successive thinner category ranked lower. Based upon the analyses conducted in this section, thicker lifts do maintain temperature better than thinner lifts. Therefore, more time would be available to compact thicker lifts to a desirable density.

Table 5: Rankings for Temperature-Time Relationships by Location

NMAS	Temperature Location	t/NMAS Category					
		<3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0	>5.0
9.5mm	Surface	---	4	3	2	1	---
	Top	---	3	4	1	2	---
	Middle	---	2	3	4	1	---
	Bottom	---	4	2	1	3	---
	Average	**---**	**3.25**	**3.0**	**2.0**	**1.5**	**---**
12.5mm	Surface	5	3	4	6	2	1
	Top	3	6	5	1	2	4
	Middle	2	5	6	1	3	4
	Bottom	1	6	2	4	5	3
	Average	**2.75**	**5.0**	**4.25**	**3.0**	**3.0**	**3.0**

4.2   Density

As stated previously, the final pavement density was determined for each of the test sections using cores obtained from the pavement. The final pavement density values were needed to evaluate the effects of different properties on the final density values. As shown in Tables 2 and 3, a significant amount of data was collected at each test location, including mix design, production, and field data. Mix design data included all typical properties of a designed HMA, such as NMAS, gradation, volumetrics, etc. Production data included information like NMAS, gradation and volumetrics. Information from the field included temperature measurements, thickness, weather conditions, etc.

As alluded to in the analysis of the temperature data, a formalized experimental design was not utilized as conditions in the field generally make formalized designs difficult. Therefore, a regression analysis was again utilized. For this analysis, all of the data was utilized to conduct a multiple linear regression. The final in-place pavement density was designated as the dependent variable and the remaining laboratory, production and field data were designated the independent variables. This regression analysis was not conducted to develop an equation to predict the final density; rather, it was conducted to determined what factors affected the final density.

Results of the multiple linear regression yielded Equation 2. Variables identified within the regression technique included the accumulated compaction pressure, percent passing the No. 200 sieve, initial temperature of the pavement layer at mid-depth, thickness-to-NMAS ratio, air void content of the laboratory compacted specimens during production, and the deviation of the produced gradation from the primary control sieve. An analysis of variance conducted for the regression indicated that the equation was significant (p-value = 0.000) at a 95 percent level of confidence. The coefficient of determination (R^2) was reasonably high at 0.58. Brief descriptions of the variables contained with Equation 2 are provided below.

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Equation 2

where:

        FinDens = final density of pavement layer, % Rice gravity
        ACP = accumulated compaction pressure, psi
        P200 = percent passing No. 200 sieve of produced mix
        InitTempM = initial temperature of pavement layer at mid-depth, F
        t/NMAS = thickness-to-NMAS ratio
        VTMProd = air voids in laboratory compacted specimens during production, %
        IPCS = percent above (+) or below (-) the primary control sieve

The accumulated compaction pressure (ACP) has been described by Leiva and West (5). This property is utilized to quantify the total compactive effort used during the compaction of an HMA layer. Simply, it is the summation of the pressure applied to the pavement surface during each pass of a roller, as shown in Equation 3.

Equation 3

where:

        r = roller type
   p = pass number
        CP = compaction pressure

As stated in the Research Approach, HMA was sampled at the plant and the sampled truck followed to the project site. The sampled mix was used to determine various properties, including gradation of the produced mix and volumetric properties. The percent passing the No. 200 sieve (P200) and the deviation of the gradation from the maximum density line on the primary control sieve (±PCS) were both obtained from the gradation data. The maximum density line and primary control sieve were utilized as defined in the National Asphalt Pavement Association Information Series 128 (6). For the ± PCS data, positive numbers were used for gradations passing above (finer) the PCS and negative numbers were used for gradations passing below (coarser) the PCS. The air voids of the produced HMA (VTMProd) represent the laboratory air void contents of the plant produced samples compacted to their respective design compactive effort.

At each of the test locations, temperature was measured over time at four locations (surface, top of lift, mid-point of lift and bottom of lift). The variable identified within the regression analysis and shown in Equation 2 is the initial (immediately behind paver) temperature of the HMA at the mid-point of the lift (InitTempM)

The final variable identified as important during the regression analysis was the thickness-to-NMAS ratio (t/NMAS). This ratio was calculated for each test location by dividing the thickness of the layer (determined from cores) and dividing by the NMAS of the produced mix. Units for both of these properties were millimeters.

In order to evaluate Equation 3, a sensitivity analysis was conducted. For this sensitivity analysis, values for a selected variable were changed while keeping all other variables constant in order to evaluate the effect of the selected variable on the final pavement density. The other variables were held at their average value. The first variable selected was the ACP. The effect of ACP on the final density is illustrated in Figure 10. As shown in this figure, the final pavement density increased as the ACP increased. Intuitively, the observation makes sense. As ACP increases, more compactive effort is applied to the pavement resulting in higher densities.

ACP = Changing
P200 = 5.2%
IniTempMid = 259 F
t/NMAS = 4.4
VTMProd = 4.2
± PCS = -9.1
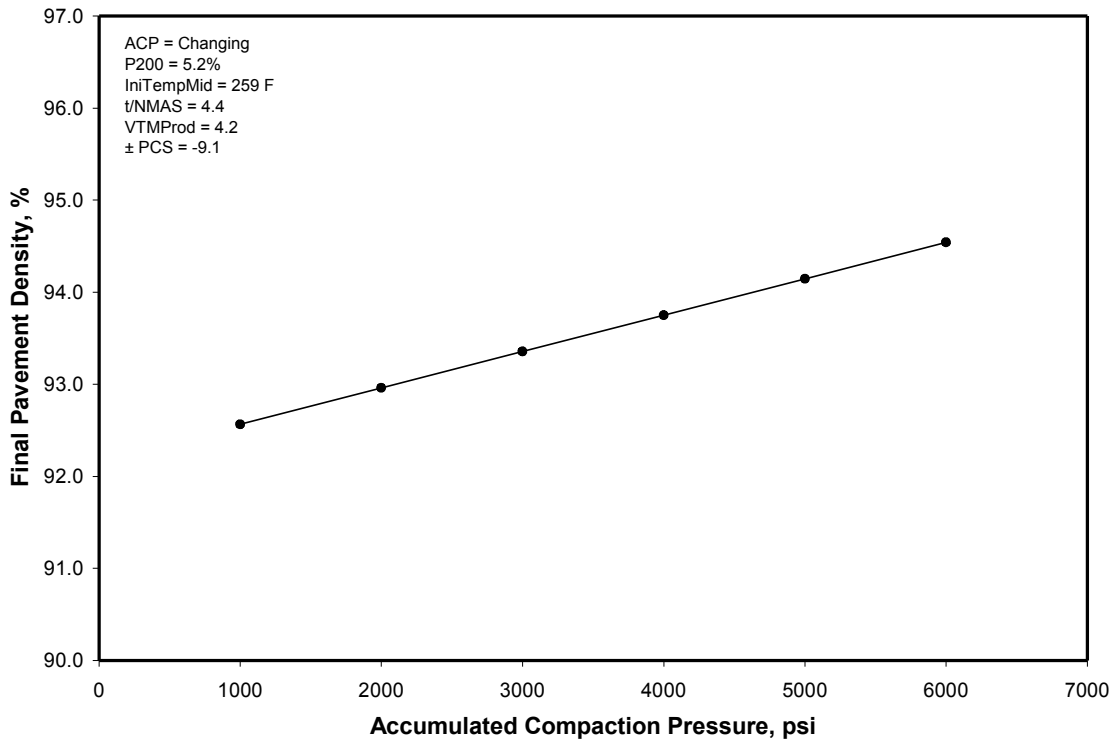
Figure 10: Effect of Accumulated Compaction Pressure on Final Pavement Density

Figure 11 illustrates the effect of the P200 on the final density. As shown in the figure, the P200 within the HMA did not have as significant of an impact on the final density as the ACP. The trend of the line is very slightly upward indicating that as P200 increases, the final density also increases.
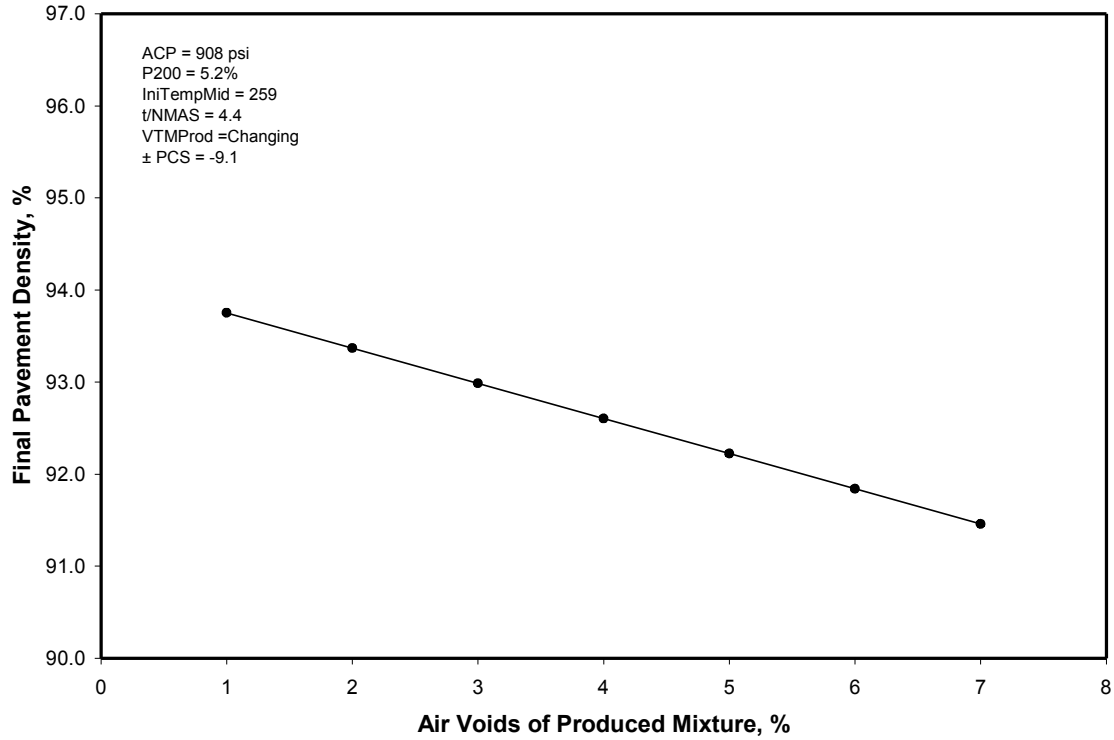
27
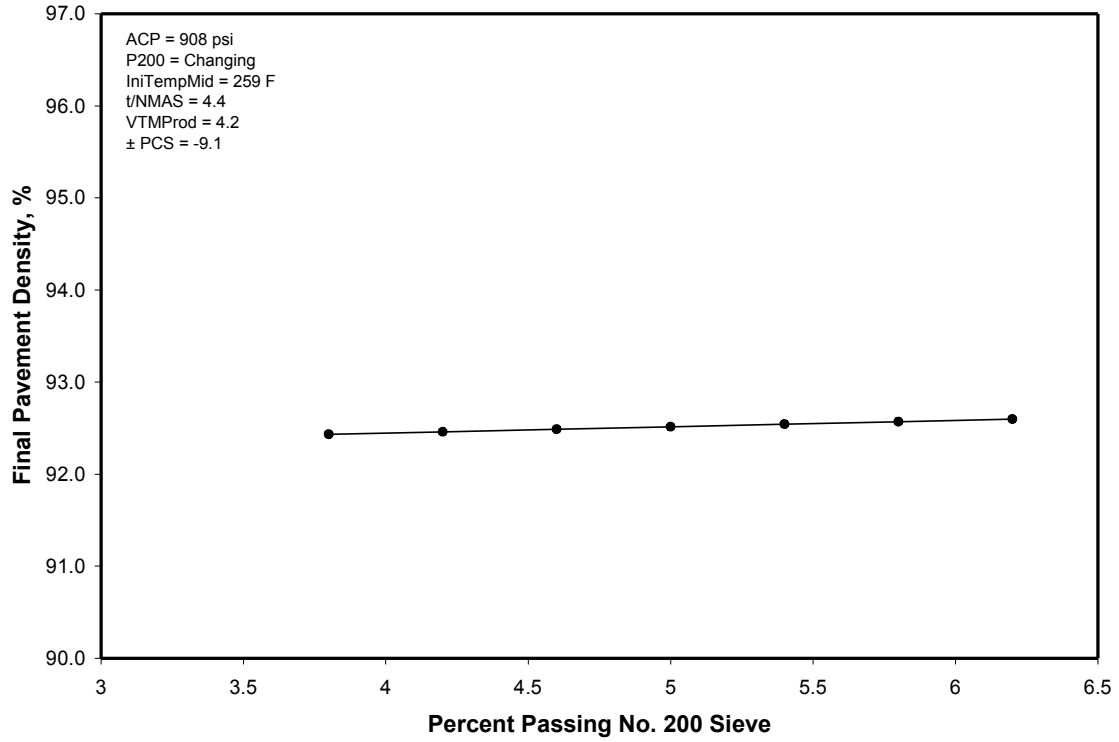
Figure 11: Effect of Percent Passing No. 200 Sieve on Final Pavement Density

       The effect of the InitTempM on final density is illustrated in Figure 12. As would be expected, increases in temperature resulted in higher densities.
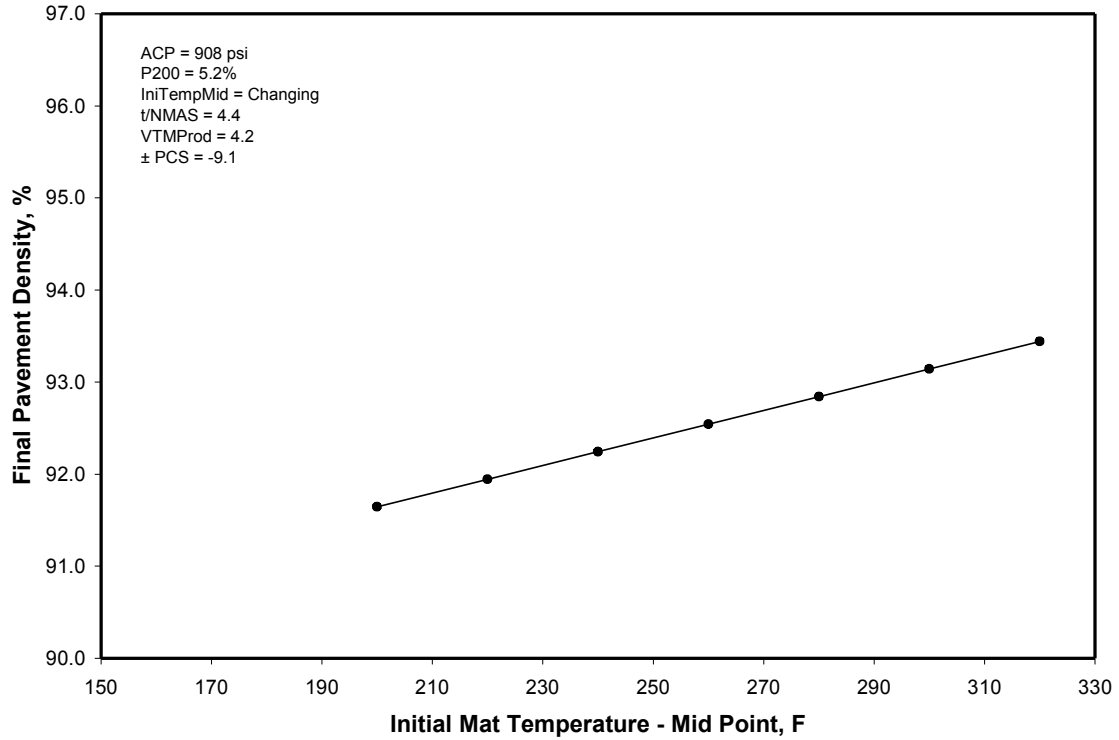
Figure 12: Effect of Initial Mat Temperature at Mid-Depth on Final Pavement Density

Figure 13 depicts the influence of the laboratory air voids in the produced HMA on the resulting final pavement density. Again, the trend of the relationship makes sense in that as the air voids decrease, the final density increases. A decrease in laboratory air voids generally results from an increase in asphalt binder content. Increased asphalt binder within the HMA would generally result in increased density, for a constant compactive effort.

The chart shows the following annotations:

ACP = 908 psi
P200 = 5.2%
IniTempMid = 259
t/NMAS = 4.4
VTMProd =Changing
± PCS = -9.1

X-axis: Air Voids of Produced Mixture, %
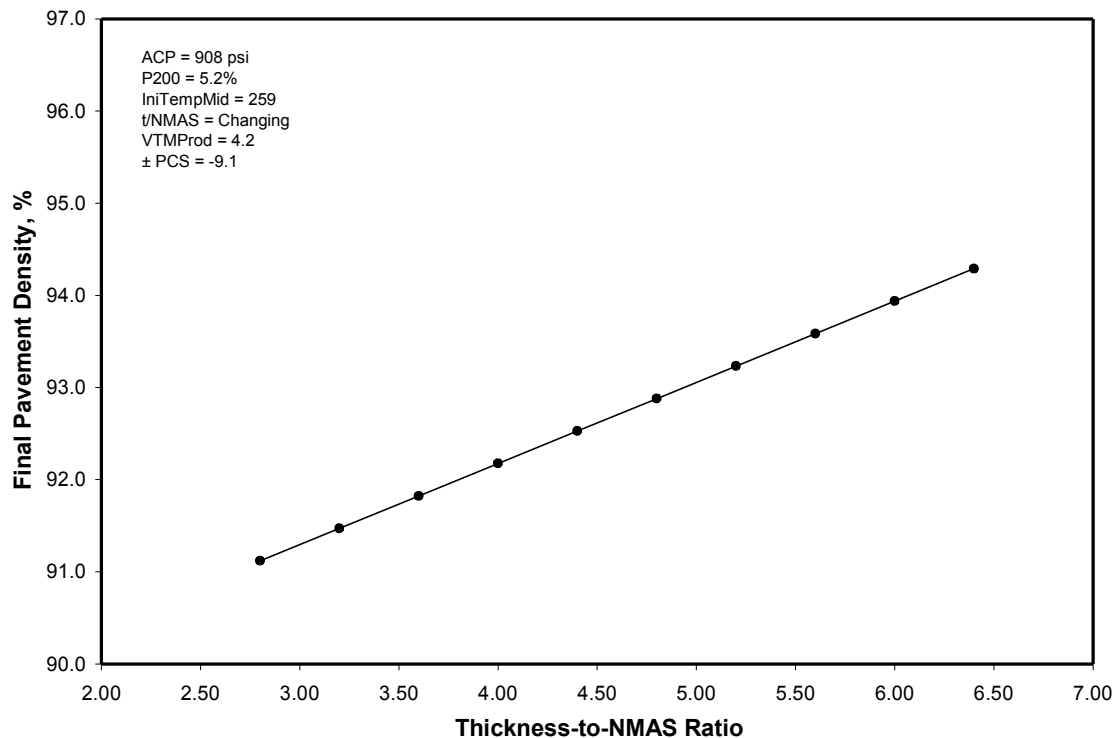Y-axis: Final Pavement Density, %

Figure 13: Effect of Air Voids in Produced Mix on Final Pavement Density

The influence of gradation shape on the final density is illustrated on Figure 14. This figure suggests that it is more difficult to achieve compaction for coarser gradations than for finer gradations. As the gradation fell farther below the maximum density line at the PCS, the final pavement density decreased. Based upon the slope of the relationship, compared to Figures 10 through 13, gradation has an important influence on the ability to achieve density.

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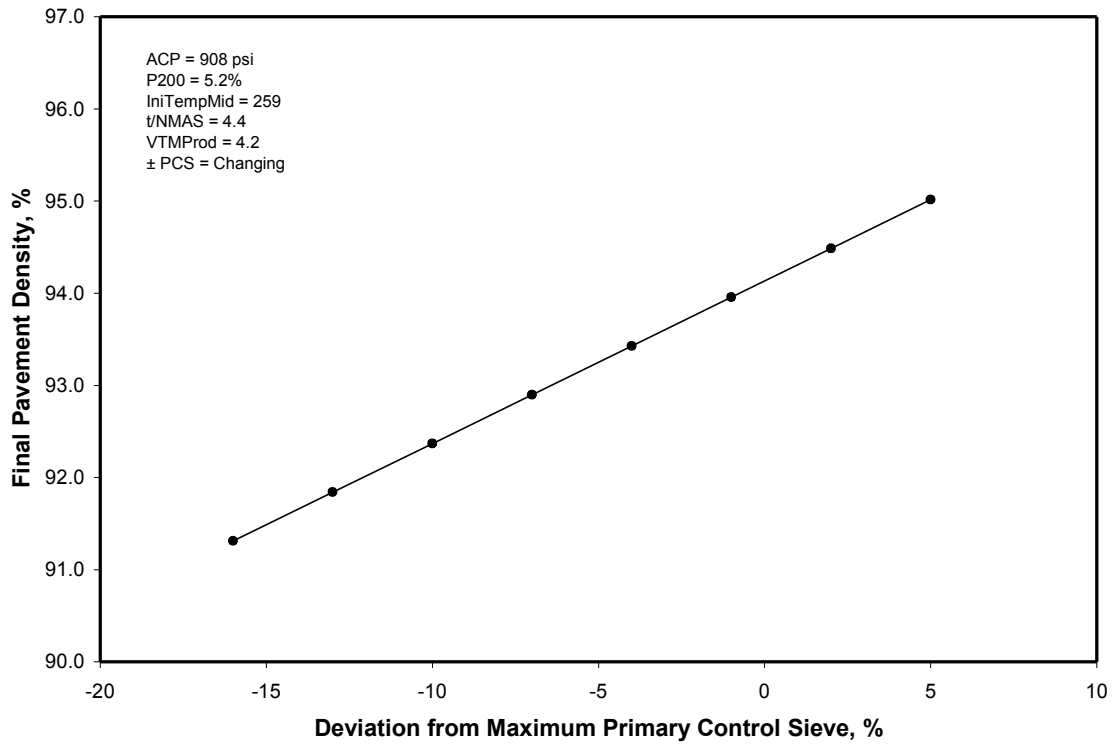
Figure 14: Effect of Deviation from Primary Control Sieve on Final Pavement Density

The sensitivity analysis for the last variable, and most important to this project, is presented in Figure 15. This figure depicts the effect of the t/NMAS on the final pavement density. Based upon this figure, increased t/NMAS ratios result in higher final densities.

The chart shows data points with the following annotations in the upper left:

```
ACP = 908 psi
P200 = 5.2%
IniTempMid = 259
t/NMAS = Changing
VTMProd = 4.2
± PCS = -9.1
```

X-axis: Thickness-to-NMAS Ratio (2.00 to 7.00)
Y-axis: Final Pavement Density, % (90.0 to 97.0)

Figure 15: Effect of t/NMAS Ratio on Final Pavement Density

Based upon the sensitivity analysis, several variables were identified that enhance the ability to achieve the desired density level in the field. Of most importance to this project, Figure 15 showed that increased t/NMAS ratios resulted in higher pavement densities than did lower t/NMAS ratios.

Recall, another concern with thicker lifts of HMA was that thicker layers may not result in uniform compaction within the layer. As such, the cores obtained from each test location were cut into either two or three layers and the density of each layer determined (and expressed as air void contents). Cores from six projects were of a thickness that they were cut into two layers (Projects 4, 5, 7, 8, 9 and 10). Cores from three projects could be cut into three layers (Project 1, 3 and 6).

In order to determine if there was a difference between the density among the various layers, a one way Analysis of Variance (ANOVA) was conducted on the two subsets of data (one ANOVA for data with two layers and one ANOVA for the data with three layers). When conducting the ANOVA, air void content was designated the dependent variable and layer location the independent. For the data subset containing two layers, results from the ANOVA indicated that the air void contents of the top and bottom portions of the core were similar (F-statistic = 0.78 and p-value = 0.384) at a 95 percent level of confidence. However, even though not significantly different, there is a

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trend that the bottom portion of the core had lower in-place air voids (higher density) as shown in Figure 16. Figure 16 presents all the air void contents for the top and bottom layers for each of the cores obtained. Top layers are always signified by black bars while bottom layers are signified by white bars. Also contained on this figure above the bars are the t/NMAS representing each core. The results trend toward higher density (lower air voids) at the bottom of the layer; however, this trend is true no matter the t/NMAS.
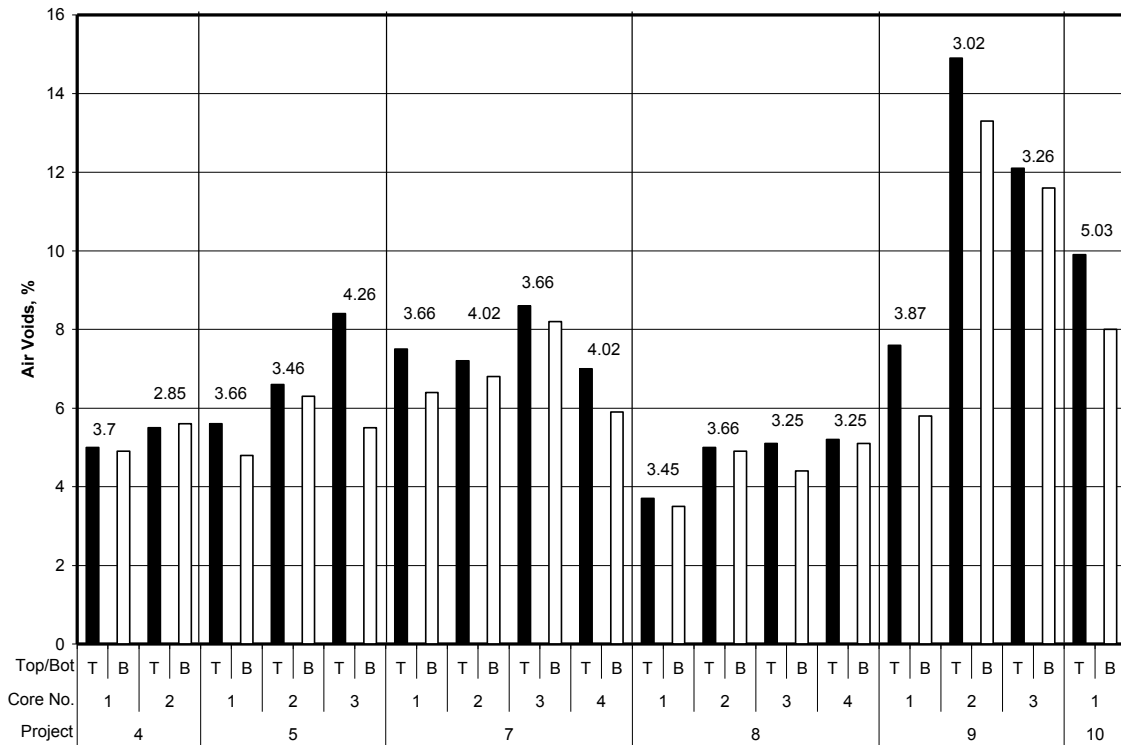
Figure 16: Air Void Contents for Top and Bottom Layers of Field Cores

The ANOVA conducted on the data set containing three layers per core indicated significant differences in air void contents between the three layers at a level of confidence of 95 percent (F-statistic = 4.59 and p-value = 0.019). The individual air void contents for each layer of each core are illustrated in Figure 17. Because of the significant differences indicated by the ANOVA, a Duncan's Multiple Range Test (DMRT) was conducted to determine which layers were different. Results of the DMRT are presented in Table 6. Based upon these rankings, the air void content of the middle layer and top layer were significantly different; however, the comparisons between the middle and bottom and the bottom and top indicated that the air void contents were similar. Results in Figure 17 illustrate the DMRT results. In general, the air void content of the core's top layer is the highest followed by the bottom layer. The middle layer is in most cases the highest density layer (lowest air voids). Similar to Figure 16, the t/NMAS ratios for each core are also provided on Figure 17. Based upon these t/NMAS ratios and

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the individual core layer density data, there does not appear to be a relationship between t/NMAS and the difference in air void contents within the layers.
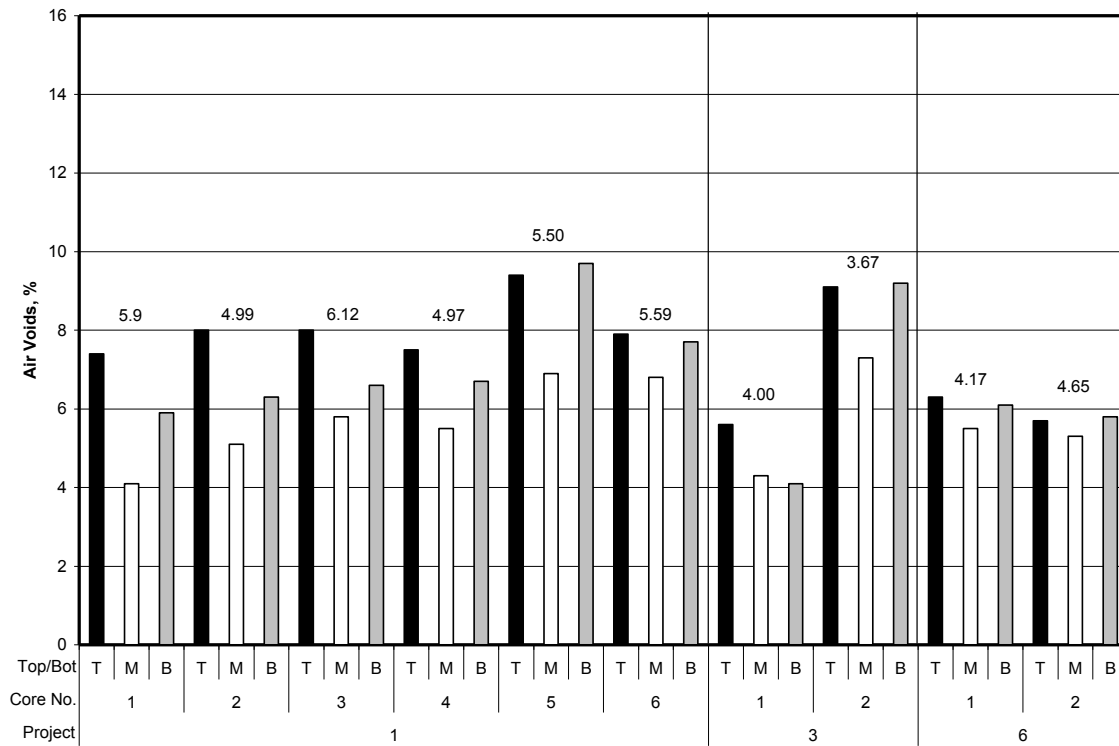
Figure 17: Air Void Contents of Top, Middle, and Bottom of Field Cores

**Table 6: Results of DMRT of Air Void Contents in Cores Cut into Three Layers**

Layer	Average Air Void Content, %	DMRT Ranking *
Middle	5.66	A
Bottom	6.81	AB
Top	7.49	B

* Means with different letters are significantly different.

4.3   Permeability

Each of the cores obtained from the projects were brought back to the laboratory and tested to determine permeability. Results from permeability testing and the core thicknesses were utilized to determine if the thicknesses of the layers affected the permeability characteristics of the pavement. To accomplish this, the data was again divided into categories, similar to the temperature data. Four categories based upon t/NMAS ratio were developed including : <3.5, 3.5< t/NMAS<4.0, 4.0<t/NMAS<4.5 and >4.5. For each of these categories, the in-place air void content was plotted versus the

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permeability results and a best fit line developed. These relationships are shown in Figure 18.
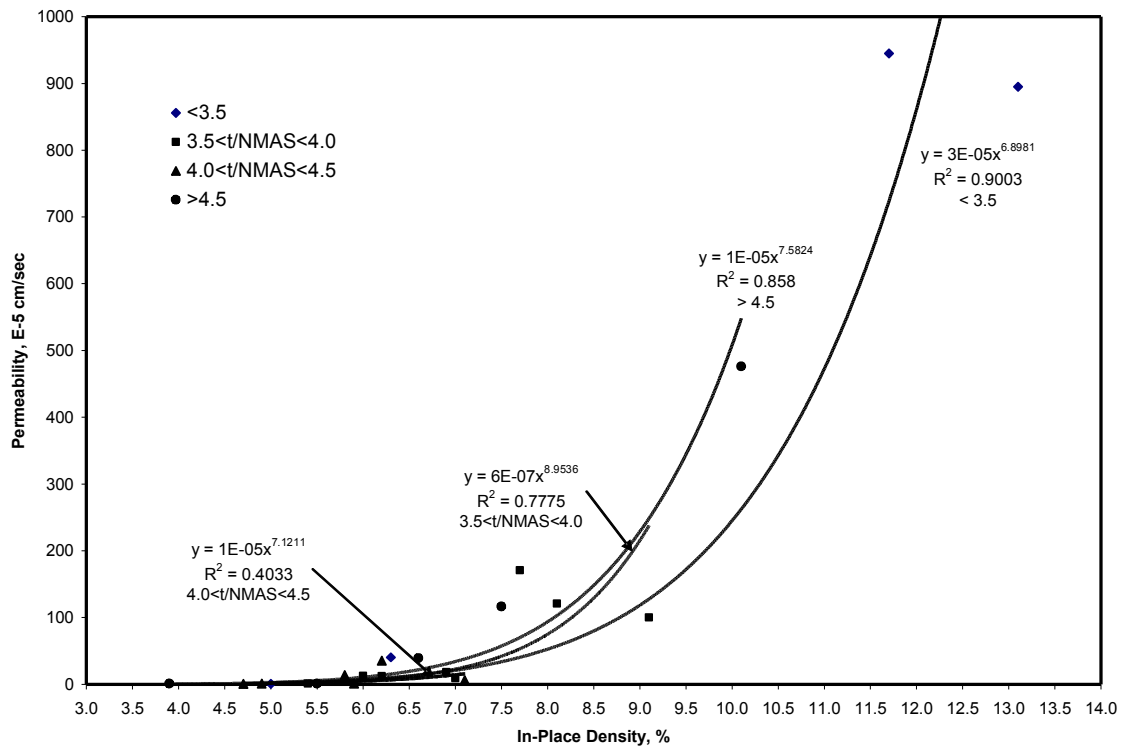
Figure 18: Relationship Between Permeability and Air Voids for Different t/NMAS Categories

Figure 18 shows that the relationship between the in-place air void contents and permeability were similar for three of the four categories. The only relationships that appears to be different is the category containing t/NMAS ratios less than 3.5. Interestingly, this thinnest category suggests that these layers result in less permeability at in-place air void contents above approximately 8 percent. It should be pointed out, however, that this category had the fewest data points. Therefore, this trend may or may not be significant.

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CHAPTER 5 – CONCLUSIONS AND RECOMMENDATIONS

5.1   Conclusions and Recommendations

The objective of this study was to evaluate the influence of lift thickness on the ability to achieve desirable in-place density levels with a reasonable compactive effort. To accomplish this objective, a field study was conducted in which ongoing field projects were visited and testing conducted. Three properties were considered important for evaluating lift thickness: temperature, density and permeability. Based upon the data accumulated in this study, the following were concluded:

- The thickness of the layer does affect the amount of time that an HMA layer will remain at compaction temperature. Thicker layers were shown to generally maintain temperature for a longer period of time than thinner layers.
- Factors found related to the level of final in-place density were the accumulative compaction pressure, percent passing the No. 200 sieve, initial temperature of the mat at the mid-point of the layer, laboratory air void content of field produced HMA, the deviation from the maximum density line at the primary control sieve, and the thickness-to-NMAS ratio.
- As the accumulative compaction pressure increased, final in-place density increased.
- As the percent passing the No. 200 sieve increased, the final in-place density increased.
- As the initial temperature of the mat at the mid-point of the layer increased, the final in-place density increased.
- As the laboratory air void content of the field produced mix decreased, the final in-place density increased.
- As the gradation became coarser, it became more difficult to compact HMA.
- As the thickness-to-NMAS ratio increased, the final in-place density increased.
- No impact related to thickness-to-NMAS ratio was found for density gradients within field compacted HMA layers.
- There did not appear to be an influence of thickness-to-NMAS ratio on the permeability of HMA layers.

Based upon these conclusions, it is recommended that MDOT adopt new requirements for allowable lift thicknesses for constructed HMA layers. This recommendation is based upon the increased density achieved with thicker layers, the increased time that thicker layers will maintain a desirable compaction temperature, the lack of influence of thickness-to-NMAS ratio on density gradients and the lack of influence of thickness-to-NMAS ratio on permeability. Because of these reasons, Table 7 provides the new recommended allowable lift thicknesses.

Table 7: Recommended MDOT Allowable Lift Thicknesses

Mixture (NMAS)	Single Lift Laying Thickness, Inches	
	Minimum	Maximum
25mm	3	4
19mm	2.5	3.5
12.5mm	1.5	3
9.5mm	1	2
4.75mm	0.5	1.25

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