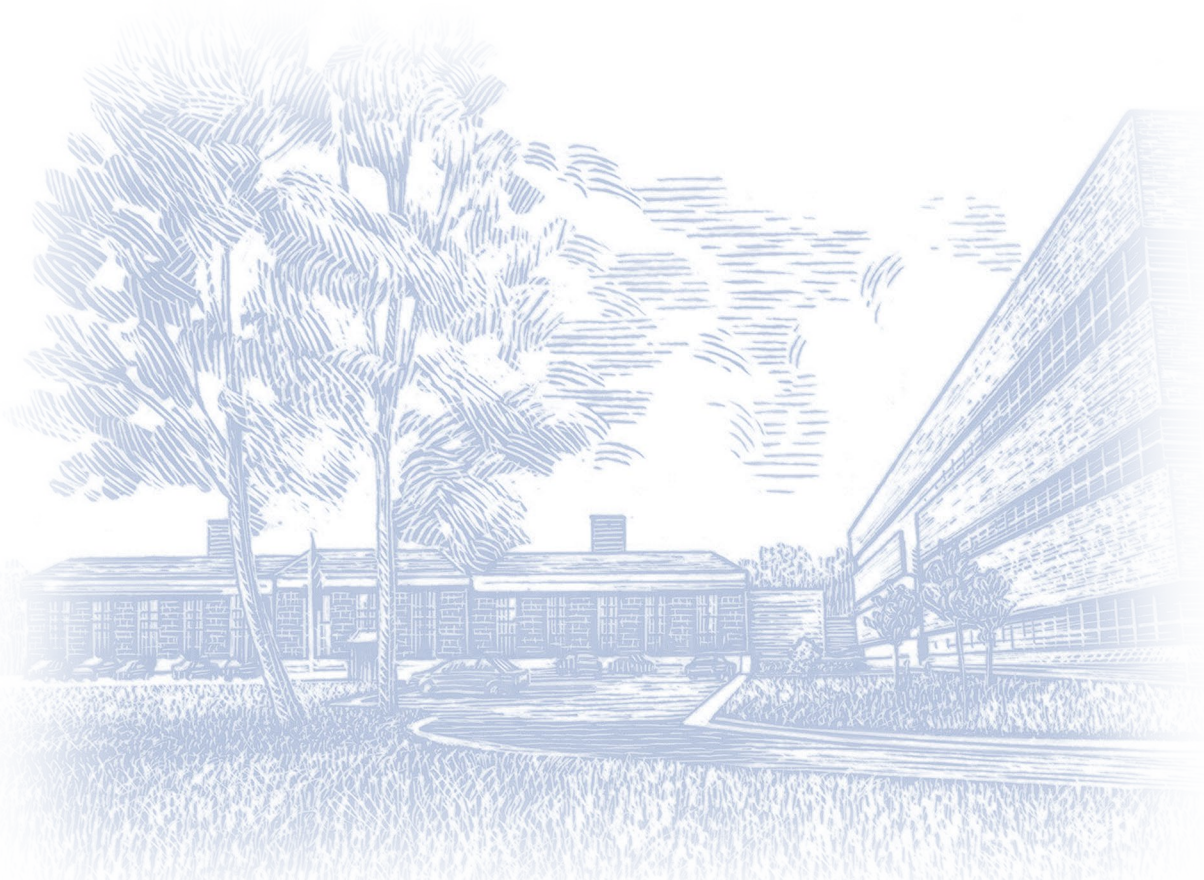


Methodology for Determining Compaction Temperatures for Modified Asphalt Binders

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Foreword

This report documents a Federal Highway Administration research study that was performed to assist asphalt mixture technologists in choosing an appropriate laboratory compaction temperature for asphalt mixture design. This temperature is important because it can affect both the optimum asphalt binder content and the mechanical properties of an asphalt mixture.

Historically, standardized procedures for determining what compaction temperature should be used in the laboratory for mixture design have not provided valid temperatures for many asphalt mixtures containing polymer-modified asphalt binders. The use of an incorrect laboratory compaction temperature as a basis for adjusting the temperature of a hot-mix asphalt plant has caused significant problems in the field. Therefore, paving contractors generally use plant temperatures recommended by the suppliers of polymer-modified asphalt binders. Standardized procedures for determining the compaction temperature to be used in the laboratory are based on the equiviscous principle, which was developed 30 to 40 years ago for unmodified asphalt binders. This principle states that the allowable compaction temperature range is the range that provides an asphalt binder viscosity from 250 to 310 mm²/s. There are methods for determining appropriate laboratory compaction temperatures for mixtures containing polymer-modified asphalt binders, but they require additional mixture tests to be performed during mixture design. A methodology like the equiviscous principle greatly reduces the amount of mixture testing that needs to be performed.

The use of polymer-modified asphalt binders is increasing and should continue to increase as more highway agencies use Superpave procedures for choosing asphalt binders. Manufacturers of polymer-modified asphalt binders are also currently developing new formulations so that their binders can be used in more applications. The development of a procedure for determining a valid compaction temperature is needed.

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Research and Development

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16. Abstract <p>The equiviscous principle, which is based on the viscosities of an asphalt binder, determines the compaction temperature to be used during asphalt mixture design. When this principle is used, theoretically, all asphalt binders should provide the same optimum asphalt binder content at a 4-percent design air-void level when all other variables, such as compaction effort and aggregate gradation, are held constant. The compaction temperature determined by this principle is also used by asphalt paving contractors as an indicator of how workable a mixture should be during construction.</p> <p>The equiviscous principle was developed using unmodified asphalt binders. For some polymer-modified asphalt binders, the equiviscous principle gives a compaction temperature that is significantly higher than what is needed. Excessively high temperatures may damage the asphalt binder, generate fumes, cause asphalt binder draindown, and may lead to a low asphalt binder content in some mixtures.</p> <p>The objective of this study was to find an asphalt binder or mastic property that can provide appropriate compaction temperatures for use during asphalt mixture design. The data collected in this study strongly suggest that there is not a single viscosity range that can be used for all asphalt binders. It is recommended that the current standardized asphalt binder viscosity range be used for unmodified asphalt binders. For polymer-modified asphalt binders, this study recommends a different viscosity range.</p>			

The allowable compaction temperature range was based on obtaining an air-void range of 3.5 to 4.5 percent after each mixture was compacted using the Superpave gyratory compactor. This tolerance provided a relatively wide allowable compaction temperature range. Mechanical properties were not measured. The allowable compaction temperature ranges for these mixtures could be narrower if they were to be based on obtaining the same mechanical properties. Mechanical properties could be more sensitive than density to differences in age-hardening that occur during short-term oven aging and compaction. Additional studies are needed to determine this.

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SI* (Modern Metric) Conversion Factors

Approximate Conversions to SI Units				
Symbol	When You Know	Multiply By	To Find	Symbol
Length				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
Area				
in²	square inches	645.2	square millimeters	mm ²
ft²	square feet	0.093	square meters	m ²
yd²	square yard	0.836	square meters	m ²
ac	acres	0.405	hectares	ha
mi²	square miles	2.59	square kilometers	km ²
Volume				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft³	cubic feet	0.028	cubic meters	m ³
yd³	cubic yards	0.765	cubic meters	m ³

NOTE: volumes greater than 1000 L shall be shown in m ³				
Mass				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
Temperature (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
Illumination				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m ²	cd/m ²
Force and Pressure or Stress				
lbf	poundforce	4.45	newtons	N
lbf/in²	poundforce per square inch	6.89	kilopascals	kPa

Approximate Conversions from SI Units				
Symbol	When You Know	Multiply By	To Find	Symbol
Length				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
Area				
mm²	square millimeters	0.0016	square inches	in ²
m²	square meters	10.764	square feet	ft ²
m²	square meters	1.195	square yards	yd ²
ha	hectares	2.47	acres	ac
km²	square kilometers	0.386	square miles	mi ²
Volume				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal

m³	cubic meters	35.314	cubic feet	ft ³
m³	cubic meters	1.307	cubic yards	yd ³
Mass				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
Temperature (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
Illumination				
lx	lux	0.0929	foot-candles	fc
cd/m²	candela/m ²	0.2919	foot-Lamberts	fl
Force and Pressure or Stress				
N	newtons	02.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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Methodology for Determining Compaction Temperatures for Modified Asphalt Binders

A. Background

The equiviscous principle, which is based on the viscosities of an asphalt binder, determines the compaction temperature to be used during asphalt mixture design. The compaction temperature is the temperature where the kinematic viscosity of an asphalt binder is 280 ± 30 mm²/s. When this principle is used, theoretically, all asphalt binders should provide the same optimum asphalt binder content at a 4-percent design air-void level when all other variables, such as compaction effort and aggregate gradation, are held constant. Unaged asphalt binders are used to determine the compaction temperature. Therefore, the methodology assumes that each asphalt binder will age harden approximately the same prior to compaction.

The equiviscous principle was developed using unmodified asphalt binders. For some polymer-modified asphalt binders, the equiviscous principle gives a compaction temperature that is significantly higher than what is needed. Excessively high temperatures may damage the asphalt binder, generate fumes, cause asphalt binder draindown, and may lead to a low asphalt binder content in some mixtures.

The compaction temperature determined by the equiviscous principle is also used by the paving contractor as an indicator of how workable a mixture should be during construction relative to the workability of other asphalt binders. As the compaction temperature increases, the mixture may be more difficult to compact unless the mixing and compaction temperatures used in the field are increased. The paving contractor may also need to adjust the rolling pattern. Currently, the temperatures determined by the equiviscous principle for some polymer-modified asphalt binders are excessively high and should not be used to select temperatures for field use.

The compaction temperatures for mixtures containing polymer-modified asphalt binders that do not obey the equiviscous principle are usually based on past experience. An alternative method is to use the asphalt binder content provided by an unmodified asphalt binder. However, this method does not give the measure of workability needed by the asphalt paving contractor, especially for asphalt binders that the contractor has not used to a significant degree. A mixture containing a polymer-modified asphalt binder can also be compacted at several temperatures to find the temperature that gives the same asphalt binder content as an unmodified asphalt binder. However, a methodology like the equiviscous principle eliminates the need for these trial tests.

The compaction temperature used in the laboratory is also important because when volumetric design procedures are developed, including the procedure used by Superpave, the methodology used to determine the compaction temperature becomes an integral part of the procedure. Volumetric design procedures are developed to provide an optimum asphalt binder content based on field performance. If it is assumed that a particular volumetric design procedure does provide the optimum asphalt binder content, then arbitrarily changing the compaction temperature may lead to an asphalt binder content that is not the optimum content.

B. Objective

The objective of this study was to find an asphalt binder or mastic property that can provide the compaction temperatures needed for asphalt mixture design.

C. Scope

The Superpave gyratory compactor was used to compact a mixture with an unmodified asphalt binder at various temperatures to obtain the range in temperature that did not affect the volumetric properties of the mixture at N-design. Polymer-modified asphalt binders were then substituted for the unmodified asphalt binder. The volume of binder was kept constant. The temperature range that gave the same volumetric properties as the unmodified asphalt binder was found for each modified binder. The rheological properties of the asphalt binders and mastics used in the mixtures were then measured to determine what property provides temperatures that meet the temperature ranges given by the compaction process. The methodology was then repeated using two other aggregates.

D. Experimental Design

1. Aggregates

Three aggregates were used. Two aggregates were variations of an aggregate blend used extensively in a previous Federal Highway Administration (FHWA) study and in two National Cooperative Highway Research Program (NCHRP) studies.⁽¹⁻³⁾ The properties of the aggregates are given in table 1. The blending percentages used in the three referenced studies were 61-percent No. 68 diabase, 30-percent No. 10 diabase, 8-percent natural sand, and 1-percent hydrated lime. This blend met the requirements for a Virginia Department of Transportation (VDOT) SM-3 surface mixture gradation.⁽⁴⁾

The current equiviscous principle, which is based on asphalt binder viscosity, gives a single ranking for all asphalt binders. This ranking is independent of other variables, such as aggregate gradation and asphalt binder content. These variables affect the workability of a mixture, but it is assumed that the ranking given by the equiviscous principle remains valid for all mixtures. It is possible that some aggregate characteristic might interact with a polymer-modified asphalt binder so that the ranking is not always constant. If this occurs, then the equiviscous principle based on asphalt binder viscosity cannot be used. Perhaps, a principle based on the viscosities of mastics should be used. What aggregate property, if any, causes an interaction is not known.

Table 1. Aggregate properties for mixtures containing diabase.

Aggregate Gradations, Percent Passing:						
Sieve Size (mm)	No. 68 Diabase	No. 10 Diabase	Natural Sand	Hydrated Lime	Using 0% Hydrated Lime	Using 1.25% Hydrated Lime
25.0	100.0				100.0	100.0
19.0	97.9				98.6	98.6
12.5	60.7				74.9	75.1
9.5	37.7	100.0	100.0		61.9	62.3
4.75	9.2	99.2	95.8		43.7	44.4

	2.36	2.2	75.6	88.2		30.5	31.3
	1.18	1.7	52.5	74.8		23.0	24.0
	0.600	1.4	37.8	46.0		16.1	17.2
	0.300	1.3	27.9	14.1		10.5	11.7
	0.150	1.1	19.6	4.8		7.0	8.2
	0.075	0.9	12.5	2.9	100.0	4.6	5.9
Specific Gravities (SG) and Percent Water Absorption:							
Bulk Dry SG	2.943	2.914	2.565			2.900	2.886
Bulk SSD SG	2.962	2.945	2.601			2.924	2.910
Apparent SG	2.999	3.007	2.659	2.262		2.971	2.956
% Absorption	0.6	1.1	1.4			0.82	0.81
Flat & Elongated Particles at a 3-to-1 Length-to-Thickness Ratio, % by Mass:							
	21	NA	NA				
Flat & Elongated Particles at a 5-to-1 Length-to-Thickness Ratio, % by Mass:							
	2	NA	NA				
Los Angeles Abrasion, % Loss by Mass:							
	14	NA	NA				
Fine Aggregate Angularity:							
	NA	49	45				

NA = not applicable

Based on the results from asphalt binder and mastic tests performed during a previous FHWA study, varying the composition of the minus 75-m aggregate may lead to an interaction.⁽¹⁾ Dynamic shear rheometer tests performed on five asphalt binders gave the following ranking from most to least susceptible to rutting at 58°C: AC-5, AC-10, AC-20, Novophalt, and Styrelf. (The last binder is also called Stylink.) These asphalt binders had Superpave performance grades (PGs) of 58-34, 58-28, 64-22, 76-22, and 82-22, respectively. Pavement rutting tests provided the following ranking: AC-5, AC-10, AC-20, Styrelf, and Novophalt. Mastics consisting of the asphalt binders with the minus 75-m fractions of the aggregates shown in table 1 were also tested by the dynamic shear rheometer at 58°C. Tests using the minus 75-m fraction without hydrated lime were inconclusive. The first set of tests gave the same ranking as the asphalt binders. However, when the tests were repeated, Novophalt and Styrelf switched places, and the ranking agreed with the pavement rutting tests: AC-5, AC-10, AC-20, Styrelf, and Novophalt. Tests on mastics that included the hydrated lime clearly gave the correct ranking, even though the dust-to-binder ratio by volume was constant for all mastics.

Based on these findings, it was decided to vary the composition of the mastic. Note, though, that the above interaction was found at 58°C, which is well below the temperature needed for compaction. The first aggregate type contained no hydrated lime, while the second aggregate type contained 1.25-percent hydrated lime. Details on how the 1.25-percent level was chosen are given in section F of this report. In this report, these two aggregate types, or blends, are referred to as the diabase aggregate with and without hydrated lime.

The third aggregate type consisted of 100-percent limestone aggregate. This aggregate was designated "RC" by the Strategic Highway Research Program. The properties of the aggregate are given in table 2.

2. Asphalt Binders

The initial polymer-modified asphalt binders used in this study were the Novophalt (PG 76-22) and Styrelf (PG 82-22) asphalt binders used in the previous FHWA study.⁽¹⁾ The unmodified PG 58-28 and PG 64-22 asphalt binders were chosen to be the control binders. The Superpave properties of these binders are given in table 3. Additional properties are given in table 4. Other polymer-modified asphalt binders were to be included in the study after the tests on these asphalt binders were completed.

3. Number of Mixing and Compaction Temperatures

It was expected that a minimum of four compaction temperatures would be needed to obtain a range in temperature that does not affect the volumetric properties of a mixture at N-design. The experimental design using four temperatures and three asphalt binders is given in table 5. A full factorial using two replicates required 24 specimens per asphalt binder.

The mixing temperature was held constant for a given asphalt binder. It was not varied with the compaction temperature. The mixing temperature is normally around 10°C higher than the compaction temperature. Thus, the mixing temperatures used in this study may be too high or too low compared to standard practice. This was done so that for a given asphalt binder, changes in the volume of absorbed asphalt binder would be a function of the compaction temperature alone. This eliminated the potentially confounding effect that a variable mixing temperature might have on the volume of absorbed asphalt binder. Even though the mixing temperature was fixed, it was hypothesized that changes in the mixing temperature would have no effect on asphalt binder absorption because the mixing time of 90 s was relatively short compared to the 2 h of short-term oven-aging (STOA), which was done at the compaction temperature. Also, the water absorption for the two diabase blends was low, being 0.8 percent by mixture mass. The water absorption for the limestone aggregate was slightly higher at 1.45 percent. Mixtures were compacted using a realistic mixing temperature when the test data indicated that this was necessary.

E. Equiviscous Temperatures

The kinematic viscosities of an asphalt binder and the equiviscous principle are used to determine mixing and compaction temperatures. The equiviscous mixing temperature is the temperature where the kinematic viscosity of the unaged asphalt binder is $170 \pm 20 \text{ mm}^2/\text{s}$.⁽⁵⁾ The equiviscous compaction temperature is the temperature where the kinematic viscosity of the unaged asphalt binder is $280 \pm 30 \text{ mm}^2/\text{s}$.⁽⁵⁾ Prior to Superpave, the equiviscous temperatures were determined using capillary viscometers. The kinematic viscosity of an asphalt binder was measured at 135°C, and the absolute viscosity was measured at 60°C. The absolute viscosity was converted to kinematic viscosity. Capillary viscosity tests were performed in this study at 60 and 135°C in accordance with American Association of State Highway and Transportation Officials (AASHTO) test methods T 201 and T 202.⁽⁶⁾ The viscosities determined by these tests are given in table 4. Superpave uses a Brookfield viscometer, AASHTO test method TP4, and American Society for Testing and Materials (ASTM) test method D 4402 to measure the

viscosities of asphalt binders.^(5,7) A minimum of five temperatures were used in this study to determine the relationship between viscosity and temperature. The data are given in table 6.

Mixing and compaction temperatures for the asphalt binders are shown in table 7. Two methods were used to calculate the temperatures from the capillary viscosities: (1) log-log kinematic viscosity vs. temperature, and (2) log-log kinematic viscosity vs. log temperature in degrees Kelvin. The first method is generally used by the hot-mix industry, while the second method is the standardized method. Table 7 shows that the Brookfield viscometer gave the highest mixing and compaction temperatures for Novophalt and Styrelf, followed by the capillary tests where "log temperature" was used. All of the temperatures for Novophalt and Styrelf are high. Mixing temperatures for these two binders rarely exceed 180°C, because higher temperatures may lead to blue smoke. VDOT specified a maximum hot-mix plant temperature of 177°C.⁽⁴⁾

Table 2. Aggregate properties for mixtures containing limestone.

Aggregate Gradations, Percent Passing:		
Sieve Size (mm)	100% Limestone	
19.0	100.0	
12.5	97.0	
9.5	87.5	
4.75	58.4	Bulk Dry Specific Gravity: 2.625
2.36	36.3	Bulk SSD Specific Gravity: 2.663
1.18	18.3	Apparent Specific Gravity: 2.729
0.600	12.4	Water Absorption: 1.45
0.300	9.1	
0.150	7.0	
0.075	6.0	
Flat & Elongated Particles at a 5-to-1 Length-to-Thickness Ratio, % by Mass:		8
Los Angeles Abrasion, % Loss by Mass:		39
Fine Aggregate Angularity:		46

Table 3. Superpave asphalt binder properties.

Pre-Superpave Designation:	AC-10	AC-20	Novophalt	Styrelf
Superpave PG:	58-28	64-22	76-22	82-22
Original Binder Temperature at $G^*/\sin\delta$ of 1.00 kPa and 10 rad/s, °C	61.9	67.9	77.3	87.2
RTFO Residue Temperature at $G^*/\sin\delta$ of 2.20 kPa and 10 rad/s, °C	65.0	70.2	76.6	88.0
RTFO/PAV Residue Temperature at $G^*/\sin\delta$ of 5000 kPa and 10 rad/s, °C	14.7	16.7	20.0	17.7
Temperature at Creep Stiffness (S) of 300 MPa and 60 s, °C	-22.1	-19.8	-19.7	-20.9
Temperature at an m-Value of 0.30 and 60 s, °C	-20.3	-17.1	-13.6	-17.4

RTFO = Rolling Thin-Film Oven

PAV = Pressure Aging Vessel

Table 4. Other properties of the asphalt binders.

	AC-10	AC-20	Novophalt	Styrelf
Binder Property	58-28	64-22	76-22	82-22
Penetration, 25°C, 0.1 mm	113	73	54	47
Absolute Viscosity, 60°C, dPa·s	1 195	2 644	13 814	60 308
Kinematic Viscosity, 60°C, mm ² /s	119 900	265 900	1 389 200	6 076 600
Kinematic Viscosity, 135°C, mm ² /s	322	476	2 184	2 484
Specific Gravity, 25/25°C	1.024	1.022	1.022	1.020
Solubility in Trichloroethylene, %	100.00	100.00	95.92	100.00
Flash Point, COC, °C	304	304	326	312

Table 5. Experimental design.

Aggregate Blend	Asphalt Binder		
	PG 58-28 (AC-10)	PG 76-22 (Novophalt)	PG 82-22 (Styrelf)
Diabase With No Lime	T ₁ T ₂ T ₃ T ₄	T ₁ T ₂ T ₃ T ₄	T ₁ T ₂ T ₃ T ₄
Diabase With Lime	T ₁ T ₂ T ₃ T ₄	T ₁ T ₂ T ₃ T ₄	T ₁ T ₂ T ₃ T ₄
Limestone	T ₁ T ₂ T ₃ T ₄	T ₁ T ₂ T ₃ T ₄	T ₁ T ₂ T ₃ T ₄

T_x = compaction temperature

Table 6. Brookfield viscosity (mm²/s) vs. test temperature.

Temperature °C	PG 58-28 (AC-10)	PG 64-22 (AC-20)	PG 76-22 (Novophalt)	PG 82-22 (Styrelf)
115	935	1630	11300	6090
125	535	856	7570	3880
135	325	503	4270	1870
142		332		
148		253		
150	170		2020	940
163	105		695	582
180	60		366	345
200	33		179	137
220			110	

Table 7. Equiviscous mixing and compaction temperatures (°C).

	AASHTO T 201 and T 202, Capillary Viscometers			
	Log-Log Viscosity vs. Temperature		Log-Log Viscosity vs. Log Temperature	
Asphalt Binder	Mixing Temperature at 170 mm²/s	Compaction Temperature at 280 mm²/s	Mixing Temperature at 170 mm²/s	Compaction Temperature at 280 mm²/s
PG 58-28 AC-10	147	138	149	138
PG 64-22 AC-20	154	145	157	146
PG 76-22 Novophalt	185	173	193	180
PG 82-22 Styrelf	181	171	188	176

	AASHTO TP4-97, Brookfield Viscometer		Current Practice	
Asphalt Binder	Mixing Temperature at 170 mm²/s	Compaction Temperature at 280 mm²/s	Mixing Temperature at 170 mm²/s	Compaction Temperature at 280 mm²/s
PG 58-28 AC-10	151	139	145	137
PG 64-22 AC-20	155	146	148	142
PG 76-22 Novophalt	204	188	166	159
PG 82-22 Styrelf	196	187	163	157

	AASHTO TP4-97, Brookfield Viscometer	
Asphalt Mastic	Mixing Temperature	Compaction Temperature
PG 58-28 AC-10	145	134
PG 64-22 AC-20	148	142
PG 76-22 Novophalt	180	174

Table 7 includes the temperatures used in the previous FHWA study and by VDOT under the heading "Current Practice."⁽¹⁾ These temperatures did not produce smoke in the laboratory or at the hot-mix plant. It was decided to use these temperatures as the starting temperatures. It was thought that temperatures 20°C above and below the starting temperature would lead to different air-void levels. This provided the first three compaction temperatures to be evaluated.

The temperatures determined by the equiviscous principle can be excessively high for polymer-modified asphalt binders. Therefore, mastics were also tested to determine if they could provide usable temperatures. The optimum mixing temperatures for the mastics were determined first. Table 7 shows that the optimum mixing temperatures for the Novophalt and Styrelf mastics were 180 and 175°C. The methodology used to determine these temperatures is documented elsewhere.⁽⁶⁾ The mixing temperature ranges for the mastics containing the two unmodified asphalt binders were relatively wide. Therefore, the mixing temperatures for the unfilled asphalt binders under "Current Practice" were used.

The compaction temperatures for the mastics were determined using the PG 64-22 mastic as the control. The compaction temperature for this mastic was assigned to be 142°C, which was the compaction temperature for the PG 64-22 asphalt binder under "Current Practice." The kinematic viscosity of this mastic was 1500 mm²/s at 142°C. The compaction temperatures for the other mastics were the temperatures that also provided a kinematic viscosity of 1500 mm²/s. These temperatures are included in table 7. The temperatures provided by the Novophalt and Styrelf mastics, like the Novophalt and Styrelf unfilled binders, were high compared to current practice.

Originally, the PG 64-22 asphalt binder and mastic were to be the primary control materials. However, after the mastic tests using this binder were completed, the supply of this asphalt binder dwindled because it had to be used in two important NCHRP studies.⁽²⁻³⁾ The PG 58-28 asphalt binder and mastic were then designated to be the control materials. Based on the mastic test data, this change would have no significant effect on the mastic compaction temperatures given in table 7.

F. Asphalt Mixture Design

1. Selection of N-Design

There were three options for choosing an N-design for the mixtures. The first option was to use an N-design of 100 or 125 gyratory revolutions, which are used to design mixtures for relatively high traffic levels. One hundred revolutions are used for 10 to 30 million equivalent single-axle loads (ESALs) and 125 revolutions are used for more than 30 million ESALs. The advantage of using one of these N-designs is that most polymer-modified asphalt binders will probably be used in pavements subjected to more than 10 million ESALs.

The second option was to use an N-design of 75 revolutions, which is used for medium traffic levels of 0.3 to 3 million ESALs. The potential advantage of using 75 revolutions is that the higher asphalt binder content that generally occurs with the use of 75 revolutions, compared to 100 and 125 revolutions, may give a narrower compaction temperature range. Density may be more sensitive to changes in compaction temperature as the optimum binder content increases. If so, the temperature range for 75 revolutions should be applicable to 100 and 125 revolutions. An N-design of 50 revolutions was eliminated because 50 revolutions is only used to design asphalt mixtures for low-volume roads. A third option was to use two levels of N-design.

The second option using 75 revolutions was chosen for the two mixtures with diabase aggregate. The applicability of the measured temperature range to N-designs of 100 and 125 revolutions was to be investigated using a partial factorial experimental design if necessary. For the mixture with limestone

aggregate, 100 revolutions was chosen because the asphalt binder drained from the mixture during STOA using the optimum asphalt binder content for 75 revolutions. The limestone mixture still appeared to be rich in asphalt binder at 100 revolutions, but there was little to no draindown.

2. Optimum Asphalt Binder Content

The optimum asphalt binder content was chosen for each mixture using: (a) the AC-10 (PG 58-28) control asphalt binder; (b) mixing and compaction temperatures of 145 and 137°C, respectively; (c) 2 h of STOA at the compaction temperature of 137°C; (d) N-designs of 75 or 100 revolutions; (e) a 4-percent air-void level; and (f) two replicate specimens per mixture. The asphalt binder content by volume varied from aggregate to aggregate, but it was held constant for a given aggregate.

Table 8 shows selected properties of the mixtures with the diabase aggregate and various percentages of hydrated lime. The dust-to-binder ratio was allowed to vary with the hydrated lime content so that the mastics would be significantly different in terms of composition. The percentage of hydrated lime to be used in the second mixture was 1.25 percent. This was the highest amount of hydrated lime that could be used based on the Superpave specifications. Hydrated lime contents above 1.25 percent would lead to mixtures with voids in the mineral aggregates (VMAs) below the specified minimum allowable level of 13.0 percent, and a dust-to-binder ratio greater than 1.6. Table 8 shows that the optimum asphalt binder contents for the mixtures with 0- and 1.25-percent hydrated lime were 4.6 and 4.1 percent by mass of the mixture.

Note that the VMA decreased by 1.6 percent with the addition of 2.0-percent hydrated lime by total aggregate mass (14.0 vs. 12.4). This quantity of hydrated lime would decrease the volume of asphalt binder by approximately 1.4 percent if it is assumed that the addition of the hydrated lime does not change the total volume of the compacted asphalt mixture. The VMA would drop from 14.0 to 12.6 percent. Therefore, a large portion of the decrease in the VMA with increasing hydrated lime content could be due to the substitution of hydrated lime for asphalt binder.

Table 9 shows selected properties of the mixture with the limestone aggregate. All properties met the Superpave specification. The effective asphalt binder contents of the mixtures with the limestone aggregate and the diabase aggregate with no hydrated lime were close at 10.2 and 10.5 percent by total volume, respectively, although the mixture with limestone appeared to be much richer in asphalt binder content.

G. Analysis of the Data

The response variable used to determine the compaction temperature range was the air voids at N-design. The temperature that provided the design air-void level of 4.0 percent with an allowable error of ± 0.5 percent was found for each asphalt binder. Therefore, the acceptable air-void range was 3.5 to 4.5 percent. This range means that up to approximately 0.2-percent asphalt binder by mixture mass would have to be added or removed to obtain a 4.0-percent air-void level. Thus, the total allowable deviation in asphalt binder content was ± 0.2 percent by mixture mass. Although the current equiviscous principle should be valid for the PG 58-28 unmodified asphalt binder, various compaction temperatures were used with this binder so that its allowable temperature range could be compared to the ranges for the other asphalt binders.

For each aggregate, the asphalt binders and mastics were ranked according to their average compaction temperature. Each aggregate should provide the same ranking; otherwise, some type of interaction between the materials has occurred. If an interaction is found, then the compaction temperature cannot be determined using the asphalt binder or mastic property that was measured.

The experimental design assumes that all asphalt binders will provide the same effective (non-absorbed) asphalt binder content for a given aggregate at a 4.0-percent air-void level. If the effective asphalt binder contents are not the same, differences in the compaction temperature ranges for the asphalt binders for a given aggregate may partially be related to the differences in the effective asphalt binder contents. If this is found to be true, the asphalt binder contents may have to be adjusted on a trial-and-error basis so that the effective asphalt binder content is constant.

H. Potential Limitations of This Study

- It was assumed in this study that the optimum asphalt binder content for a given aggregate type and gradation should not vary with the type or grade of asphalt binder. However, a methodology for determining the compaction temperature is still needed if it is found through pavement performance studies that the optimum asphalt binder content should vary with the type of asphalt binder.

Table 8. Mixture properties at a 4.0-percent air-void level for the diabase aggregate.

Mixture Property	Percent Hydrated Lime						Spec
	0.0	0.5	1.0	1.25	1.5	2.0	
Asphalt Binder Content							
Total Asphalt Binder Content, Percent by Mixture Mass	4.6	4.4	4.3	4.1	4.0	3.8	
Effective Asphalt Binder Content, Percent by Mixture Mass	3.9	3.8	3.6	3.6	3.4	3.2	
Asphalt Binder Absorption, Percent by Mixture Mass	0.7	0.6	0.7	0.6	0.6	0.6	
Effective Asphalt Binder Content, Percent by Total Volume	10.1	9.7	9.3	9.1	8.7	8.4	
Voids Analyses							
Maximum Specific Gravity of the Mixture	2.719	2.720	2.728	2.724	2.729	2.738	
Effective Specific Gravity of the Aggregate	2.955	2.945	2.948	2.932	2.933	2.932	
Total Air Voids, Percent by Volume	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Voids in the Mineral Aggregate (VMA), Percent by Total Volume	14.1	13.7	13.3	13.1	12.7	12.4	13.0
Voids Filled With Asphalt (VFA), Percent by Total Volume	72	71	70	69	69	68	65-78
Dust Content							
Dust Content, Percent Finer Than 75µm by Aggregate Mass	4.6	5.1	5.6	5.9	6.1	6.6	
Dust-to-Binder Ratios							
Dust by Aggregate Mass to Total Binder Content by Mixture Mass	1.0	1.2	1.3	1.4	1.5	1.7	
Dust by Aggregate Mass to Effective Binder Content by Mixture Mass	1.2	1.3	1.6	1.6	1.8	2.1	0.6-1.6

Dust by Mixture Mass to Effective Binder Content by Mixture Mass	1.1	1.3	1.5	1.6	1.7	2.0	
Dust by Volume to Effective Binder Content by Volume	0.38	0.46	0.54	0.58	0.63	0.74	

Table 9. Mixture properties at a 4.0-percent air-void level for the limestone aggregate.

Mixture Property	Value	Superpave Specification
Asphalt Binder Content		
Total Asphalt Binder Content, Percent by Mixture Mass	5.7	
Effective Asphalt Binder Content, Percent by Mixture Mass	4.4	
Asphalt Binder Absorption, Percent by Mixture Mass	1.3	
Effective Asphalt Binder Content, Percent by Total Volume	10.5	
Voids Analyses		
Maximum Specific Gravity of the Mixture	2.480	
Effective Specific Gravity of the Aggregate	2.724	
Total Air Voids, Percent by Volume	4.0	4.0
Voids in the Mineral Aggregate (VMA), Percent by Total Volume	14.5	14.0
Voids Filled With Asphalt (VFA), Percent by Total Volume	72	65-78
Dust Content		
Dust Content, Percent Finer Than 75 μ m by Aggregate Mass	6.0	
Dust-to-Binder Ratios		
Dust by Aggregate Mass to Total Binder Content by Mixture Mass	1.1	
Dust by Aggregate Mass to Effective Binder Content by Mixture Mass	1.4	0.6-1.6
Dust by Mixture Mass to Effective Binder Content by Mixture Mass	1.3	
Dust by Volume to Effective Binder Content by Volume	0.49	

- Workability during laboratory compaction may not be the same as workability during field compaction for all mixtures. The required compaction temperature may vary with the type of compaction. This study only addresses compaction using the Superpave gyratory compactor, even though laboratory workability vs. field workability is an important issue.

- This study did not address possible differences in the mechanical properties of laboratory-produced specimens and specimens cut from pavements when the two types of specimens have the same volumetric properties and aggregate gradation. This is an important issue, but it was beyond the scope of the study.
- If the compaction temperature must be based on a mastic property and cannot be based on an asphalt binder property, then a procedure will be needed showing how to fabricate a mastic for testing prior to hot-mix plant production. Hot-mix plant production often changes the gradation and surface area of the minus 75- μm material.

I. Results for the Mixtures With Diabase Aggregate and No Hydrated Lime

1. PG 58-28 Unmodified Asphalt Binder

Table 10 shows the data for the PG 58-28 unmodified asphalt binder. The mixing temperature was fixed at 145°C. When the compaction temperature was 157°C, a small amount of smoke was produced during STOA. Therefore, additional specimens were fabricated using a mixing temperature of 165°C and a compaction temperature of 157°C. The mixing temperature should be approximately 165°C when the compaction temperature is 157°C. A large amount of smoke was produced during mixing; therefore, these temperatures cannot be used. Recommended compaction temperatures are from 127 to 147°C.

Table 11 shows that the air voids of the two specimens compacted at 117°C had a difference of 0.9 percent (4.1 vs. 5.0 percent). This is a large difference based on the air voids at the other compaction temperatures. A reason for this was not evident.

2. Novophalt (PG 76-22) Polymer-Modified Asphalt Binder

Table 12 shows the data for Novophalt (PG 76-22). The mixing temperature was fixed at 166°C. When the compaction temperature was 179°C, a large amount of smoke was produced during STOA. Therefore, this compaction temperature cannot be used. Recommended compaction temperatures are from 119 to 159°C, although the data did not provide a firm minimum temperature. Table 12 shows that all of the average air voids were greater than 4.0 percent and the allowable air-void range of 3.5 to 4.5 percent could not be applied to the data. This means that additional asphalt binder would be added during mixture design to obtain a 4.0-percent air-void level. Perhaps the type or grade of asphalt binder would have less effect on the ultimate density if an N-design of 100 or 125 were to be used.

Table 11 shows that the air voids using mixing and compaction temperatures of 166 and 139°C were 1.0 percent apart (5.6 vs. 4.6 percent). These tests were repeated using new materials. Tables 11 and 12 show that the average air-void level for the repeat tests was 4.3 percent, compared to 5.0 percent for the original test. A reason for this was not evident.

Table 12 also shows that the average mixing and compaction temperatures of 180 and 174°C for the mastic could not be used because these temperatures led to a large amount of smoke. There was no smoke or evidence of polymer degradation when preparing the mastics and testing them for viscosity.

3. Styrelf (PG 82-22) Polymer-Modified Asphalt Binder

Table 13 shows the data for Styrelf (PG 82-22). The mixing temperature was fixed at 163°C. When the compaction temperature was 177°C, a small amount of smoke was produced during STOA. Therefore, additional specimens were fabricated using a mixing temperature of 184°C and a compaction temperature of 177°C. The mixing temperature should be approximately 184°C when the compaction temperature is 177°C. A large amount of smoke was produced during mixing; therefore, these

temperatures cannot be used. Recommended compaction temperatures are from 147 to 167°C. Table 13 shows that all of the average air-void levels were greater than 4.0 percent. Even so, the allowable air-void range of 3.5 to 4.5 percent was applied to the data.

The average mixing and compaction temperatures for the mastic were 175 and 166°C. The average air-void level of 5.1 percent shown at the bottom of table 13 was significantly greater than the average air-void levels of 4.3 and 4.2 percent using compaction temperatures of 157 and 177°C. Therefore, the compaction tests using 175 and 166°C were repeated using new samples. The new tests provided an average air-void level of 4.3 percent. A reason for the change in the average air-void level was not evident.

Table 11 shows that the air voids for the two specimens using mixing and compaction temperatures of 184 and 177°C, respectively, were 1.2 percent apart (3.8 vs. 5.0 percent). This is a large difference based on the air voids for the other compaction temperatures.

4. Effective Asphalt Binder Contents

Tables 10, 12, and 13 show that the effective asphalt binder contents for the mixtures did not vary significantly with compaction temperature or with the type or grade of asphalt binder.

5. Recompacted Specimens

Table 11 gives the air voids for the mixtures where the compacted specimens were heated, broken apart, and recompact. The air voids always decreased upon recompact. Table 14 shows that the compaction process degraded the aggregate slightly. The coarse aggregate used in this mixture had a low L.A. Abrasion of 14. These data indicate that if the air-void level for a specimen is relatively high, the specimen should not be recompact. New materials must be mixed and compacted.

J. Results for the Mixture With Diabase Aggregate and 1.25-Percent Hydrated Lime

1. Effect of Gyratory Compactor

The data using the diabase aggregate with no hydrated lime indicated that the gyratory compaction process was not always precise. The difference in air voids between the two replicate specimens was sometimes greater than 0.7 percent, even though the effective asphalt binder content did not vary significantly from specimen to specimen or from temperature to temperature.

Three factors may increase the variability in air voids: (a) the amount of age hardening due to the STOA procedure is not always consistent, (b) the process of placing the loose mixture into the gyratory compactor mold is not always consistent, and (c) the gyratory compactor does not consistently apply the same angle. A combination of these factors is also possible. The first reason alone is probably not the answer because the measured allowable compaction temperature ranges were relatively wide. Temperature affects the stiffness of the asphalt binder as does aging.

When the mixture with the PG 58-28 unmodified asphalt binder, diabase aggregate, and 1.25-percent hydrated lime was compacted, the air voids of the replicate specimens varied significantly. The mixture was then compacted using a second gyratory compactor to determine if it could provide more repeatable data. The data are given in table 15. The original gyratory compactor is #1. The data show that neither compactor provided more consistent air voids; therefore, it was decided not to change the compactor. Based on the variability shown in table 15, the number of replicate specimens was increased from two to four. The dry mixing time was also increased. The data for the second pair of specimens using the

original compactor are given under "Gyratory Compactor #1 (Repeat)." The new data were more consistent. Increasing the dry mixing time may have allowed more uniform dispersion of the hydrated lime.

Table 10. Effect of compaction temperature on the mixture with PG 58-28, diabase aggregate, and no hydrated lime.

Temperature, °C (Current Practice)		Measured Air Voids, Percent	Measured Effective Asphalt Binder Content, Percent by Volume	Additional Asphalt Binder Content Needed To Obtain 4-Percent Air Voids ^a		Amount of Smoke Produced (Blank = No Smoke)	
Mixing (145)	Compaction (137)			Percent by Volume	Percent by Mixture Mass	During Mixing	During STOA
165	157	4.2	10.0	0.2	0.1	High	Low
145	157	4.0	10.0	0.0	0.0		Low
145	137	4.0	10.0	0.0	0.0		
145	117	4.6	10.0	0.6	0.3		
145	107	4.6	10.0	0.6	0.3		

^aAssumes that the additional asphalt binder will not change the amount of asphalt binder absorption or workability during compaction.

Table 11. Air voids for the mixtures with diabase aggregate and no hydrated lime.

Temperature, °C		Air Voids, Percent		Air Voids After Recompaction, Percent	
Mixing	Compaction	Replicate 1	Replicate 2	Replicate 1	Replicate 2
PG 58-28					
165	157	4.3	4.2		
145	157	4.0	4.1		
145	137	4.0	4.0		
145	117	4.1^a	5.0^a	3.9	4.1
145	107	4.5	4.8		
Novophalt (PG 76-22)					
166	179	5.2	4.6	4.5	3.9
166	159	4.4	4.8	3.6	3.8
166	139	5.6^a	4.6^a	3.9	3.7
166	139 (repeat)	4.4	4.1		
166	119	5.2	4.7		
Styrelf (PG 82-22)					
184	177	3.8^a	5.0^a	3.6	4.1
163	177	4.2	4.1		
163	157	4.6	3.9		

163	137	4.7	4.6		
163	117	5.4	5.7		
175	166	5.2	5.0	3.9	3.8
175	166 (repeat)	4.1	4.5		

^aThe difference in air voids is large. A difference of 0.7-percent air voids means that the 67- and 95-percent confidence limits for the average asphalt binder content by mass at a 4-percent air-void level will be ± 0.25 and ± 0.5 percent, respectively, using two replicate specimens.

Table 12. Effect of compaction temperature on the mixture with Novophalt (PG 76-22), diabase aggregate, and no hydrated lime.

Temperature, °C (Current Practice)		Measured Air Voids, Percent	Measured Effective Asphalt Binder Content, Percent by Volume	Additional Asphalt Binder Content Needed To Obtain 4- Percent Air Voids ^a		Amount of Smoke Produced (Blank = No Smoke)	
Mixing (166)	Compaction (159)			Percent by Volume	Percent by Mixture Mass	During Mixing	During STOA
166	179	4.9	9.9	0.9	0.4		High
166	159	4.6	10.0	0.6	0.3		
166	139	5.0	9.9	1.0	0.5		
166	139 (repeat)	4.3	10.0	0.3	0.1		
166	119	4.9	9.9	0.9	0.4		
Using the Average Mixing and Compaction Temperatures From Tests on the Mastic							
180	174	Not compacted because the amount of smoke was very high.				High	High

^aAssumes that the additional asphalt binder will not change the amount of asphalt binder absorption or workability during compaction.

Table 13. Effect of compaction temperature on the mixture with Styrelf (PG 82-22), diabase aggregate, and no hydrated lime.

Temperature, °C (Current Practice)		Measured Air Voids, Percent	Measured Effective Asphalt Binder Content, Percent by Volume	Additional Asphalt Binder Content Needed To Obtain 4-Percent Air Voids ^a		Amount of Smoke Produced (Blank = No Smoke)	
Mixing (163)	Compaction (157)			Percent by Volume	Percent by Mixture Mass	During Mixing	During STOA
184	177	4.3	10.0	0.3	0.1	High	Low
163	177	4.2	10.0	0.2	0.1		Low
163	157	4.3	10.0	0.3	0.1		
163	137	4.6	10.0	0.6	0.3		
163	117	5.5	9.9	1.5	0.7		
Using the Average Mixing and Compaction Temperatures From Tests on the Mastic							
175	166	5.1	10.0	1.1	0.5	Low	
175	166 (repeat)	4.3	10.0	0.3	0.1	Low	

^aAssumes that the additional asphalt binder will not change the amount of asphalt binder absorption or workability during compaction.

Table 14. Aggregate gradations before compaction, after compaction, and after recompaction.

Sieve Size (mm)	Original Gradation	PG 82-22 Styrelf		PG 76-22 Novophalt	
	for Both Asphalt Binders	Gradation After Compaction	Gradation After Recompaction	Gradation After Compaction	Gradation After Recompaction
25.0	100.0	100.0	100.0	100.0	100.0
19.0	98.6	99.0	99.1	99.1	99.0
12.5	74.9	76.0	78.0	77.1	77.4
9.5	61.9	62.7	64.4	62.9	63.9
4.75	43.7	44.9	46.5	44.9	46.0
2.36	30.5	31.8	33.8	31.9	33.4
1.18	23.0	23.8	24.3	24.1	24.4
0.600	16.1	17.1	17.6	17.7	17.8

0.300	10.5	11.5	11.8	12.0	12.0
0.150	7.0	7.9	8.2	8.1	8.0
0.075	4.7	5.3	5.6	5.2	5.0

Table 15. Effect of using two different gyratory compactors on the mixture with PG 58-28, diabase aggregate, and 1.25-percent hydrated lime.

Temperature, °C (Current Practice)		Measured Air Voids, Percent			Measured Effective Asphalt Binder Content, Percent by Volume	Amount of Smoke Produced (Blank = No Smoke)	
Mixing (145)	Compaction (137)	Replicate 1	Replicate 2	Average		During Mixing	During STOA
Gyratory Compactor #1							
145	157	4.7	3.5	4.1	9.1		Medium
145	137	4.9	2.6	3.7	9.1		
145	117	5.0	6.0	5.5	9.0		
Gyratory Compactor #2							
145	157	4.4	4.6	4.5	9.1		Medium
145	137	4.3	3.2	3.7	9.1		
145	117	4.1	5.7	4.9	9.0		
Gyratory Compactor #1 (Repeat)							
145	157	3.2	3.5	3.4	9.2		Medium
145	137	4.2	3.8	4.0	9.1		
145	117	3.7	3.7	3.7	9.1		

2. PG 58-28 Unmodified Asphalt Binder

Table 16 shows the data for the PG 58-28 unmodified asphalt binder. When the compaction temperature was 157°C, a medium amount of smoke was produced during STOA. Therefore, this temperature cannot be used. The data in the top half of the table were from the four replicate specimens. The data at temperatures of 117, 137, and 157°C each had one outlier that was then removed. The data from the remaining specimens are in the bottom half of table 16. Recommended compaction temperatures are from 107 to 147°C, although the minimum temperature may be lower than 107°C. The air voids for the four replicate specimens are given in table 17.

3. Novophalt (PG 76-22) Polymer-Modified Asphalt Binder

Table 18 shows the data for Novophalt (PG 76-22) after one outlier was removed. When the compaction temperature was 179°C, a large amount of smoke was produced during STOA. Therefore, this compaction temperature cannot be used. Recommended compaction temperatures are from 139 to 159°C. The air voids for the four replicate specimens are given in table 17.

4. Styrelf (PG 82-22) Polymer-Modified Asphalt Binder

Table 19 shows the data for Styrelf (PG 82-22). Recommended compaction temperatures are from 147 to 167°C. The maximum temperature was again based on the amount of smoke produced. The air voids for the four replicate specimens are given in table 17.

Changing the composition of the mastic by adding hydrated lime did not change the ranking for the asphalt binders based on the average compaction temperature. The average compaction temperature for Styrelf was higher than for Novophalt with and without hydrated lime. An interaction between the modified asphalt binders and the aggregate was not evident. Based on this finding, testing mastics with hydrated lime was not necessary and was not done.

K. Results for the Mixtures With Limestone Aggregate

1. PG 58-28 Unmodified Asphalt Binder

Table 20 shows the data for the PG 58-28 unmodified asphalt binder. Recommended compaction temperatures are from 107 to 147°C, although the minimum temperature may be lower than 107°C. The air voids for the four replicate specimens are given in table 21.

2. Novophalt (PG 76-22) Polymer-Modified Asphalt Binder

Table 22 shows the data for Novophalt (PG 76-22). Recommended compaction temperatures are from 119 to 159°C. The air voids for the four replicate specimens are given in table 21.

3. Styrelf (PG 82-22) Polymer-Modified Asphalt Binder

Table 23 shows the data for Styrelf (PG 82-22). Recommended compaction temperatures are from 117 to 167°C, although the minimum temperature may be lower than 117°C. The air voids for the four replicate specimens are given in table 21.

L. Discussion on Recommended Compaction Temperatures

Based on the recommended compaction temperatures given in table 24, a compaction temperature of 145°C could be used for all mixtures. Even so, a procedure for obtaining the compaction temperature range is needed because the ranges for Novophalt and Styrelf will not overlap the range for a PG 46 or PG 52 asphalt binder.

Based on the data from the two diabase mixtures with Novophalt, the inclusion of hydrated lime increased the minimum temperature from 120 to 140°C. A firm conclusion regarding this increase could not be made because the compaction results for both mixtures were highly variable at 140°C. The inclusion of hydrated lime decreased the minimum temperature from 125 to 105°C for the diabase mixtures with the PG 58-28 unmodified asphalt binder. However, if the maximum allowable air-void level for the compaction tests were to be increased from 4.5 to 4.6 percent, both mixtures would provide a minimum temperature of 105°C.

All compaction temperatures for the diabase mixtures with Novophalt and Styrelf, but without hydrated lime, provided air-void levels slightly greater than 4.0 percent. This means that the asphalt binder content would have to be increased to obtain a 4.0-percent air-void level. Four-percent air-void levels were obtained for the diabase mixtures with hydrated lime. This is an example of the complexities that polymer-modified asphalt binders can provide.

The average compaction temperatures given in table 25 show that the temperatures from the asphalt binders and the mastics were high for Novophalt and Styrelf compared to the average temperatures from the Superpave gyratory compactor. Table 26 gives the allowable temperature ranges. The temperature ranges from the viscometers were based on viscosities of 250 and 310 mm²/s, which came from the specified viscosity of 280 ±30 mm²/s. This viscosity range provided a compaction temperature range of 5.0°C. The gyratory compactor provided a significantly higher range of 20°C for all aggregate blends and asphalt binders.

Table 26 shows that the allowable temperature ranges from the capillary viscometers for Novophalt and Styrelf were closer to the ranges from the gyratory compactor than the ranges from the Brookfield viscometer. The viscosities from the Brookfield viscometer should be more accurate because the tests were performed over a range of temperatures that were closer to the temperatures from the gyratory compactor. The marginally better results from the capillary viscometers are most likely the result of errors in the viscosities measured at 60°C. It is also possible that the linear relationship used to obtain the compaction temperatures from the capillary viscosities at 60 and 135°C may not be valid for these modified asphalt binders. Furthermore, the compaction temperatures determined using the capillary viscometers were taken from the relationship between log-log viscosity and temperature, which provided lower temperatures than the relationship using log temperature.

Table 27 shows the viscosities of the asphalt binders at the minimum and maximum allowable compaction temperatures from the Superpave gyratory compactor. Even though a compaction temperature of 145°C could be used for all mixtures, the viscosities of the unmodified and modified asphalt binders at 145°C are not the same.

The Brookfield viscosity range applicable to all aggregate blends is included in table 27. The data from this viscometer were evaluated because it is used by Superpave. The viscosity ranges for the three asphalt binders do not overlap. Therefore, a single viscosity range cannot be specified. However, if the maximum allowable air-void level were to be increased from 4.5 to 4.6 percent, the minimum allowable temperature would be 105°C for all three PG 58-28 mixtures, and the allowable viscosity range would be 200 to 950 mm²/s. The viscosity range applicable to both Novophalt and Styrelf is 900 to 1250 mm²/s. Therefore, a range of 900 to 950 mm²/s is applicable to all mixtures if the maximum air-void criterion is relaxed to 4.6 percent. It is doubtful that this range would be applicable to PG 46 or PG 52 asphalt binder.

M. NCHRP Project 09-10

NCHRP Project 09-10 recently recommended mixing and compaction temperatures for modified asphalt binders.⁽⁹⁾ When the Brookfield viscosities of asphalt binders are measured using the current standardized spindle rate of 20 rpm as in this FHWA study, NCHRP Project 09-10 recommends a target viscosity range of 1300 to 1500 mm²/s. This viscosity range is slightly higher than the range of 900 to 1250 mm²/s provided by the two polymer-modified asphalt binders tested in this study. The compaction

temperature range provided by a viscosity range of 1300 to 1500 mm²/s would be 155 to 157°C for Novophalt and 141 to 144°C for Styrelf. The compaction temperature range provided by a viscosity range of 900 to 1250 mm²/s would be 145 to 160°C. Most likely, the latter temperature range is larger because only two polymer-modified asphalt binders were tested.

The compaction temperature range using a viscosity range of 1300 to 1500 mm²/s would be 95 to 100°C for the PG 58-28 unmodified asphalt binder. This range is too low. The current standardized procedure should be used to determine the allowable compaction temperature range for this asphalt binder.

N. Conclusions

- The data strongly suggest that an allowable laboratory compaction temperature range cannot be based on a single asphalt binder viscosity range determined using current standardized procedures.
- The allowable laboratory compaction temperature range for both polymer-modified asphalt binders tested in this study should be determined using a viscosity of 1100 ±200 mm²/s.
- The maximum allowable compaction temperature for a given mixture was found to be the highest temperature where the mixture did not produce smoke during STOA. The air voids at this temperature were always in the acceptable range of 4.0 ±0.5 percent. The maximum allowable compaction temperature was then decreased slightly so that smoke would not occur during mixing, which is performed at a higher temperature. The presence of smoke was determined visually; no measurements were taken.

O. Recommendations

- Use the current viscosity of 280 ±30 mm²/s to determine the allowable compaction range for unmodified PG 46, PG 52, and PG 58 asphalt binders.
- For polymer-modified asphalt binders with a PG of 64 and greater, use a viscosity level of 1100 ±200 mm²/s determined in this study, or a level of 1400 ±100 mm²/s from NCHRP Project 09-10. No recommendation can be given for modified asphalt binders with a PG of 58 or lower. These binders need to be investigated.
- Investigate the primary procedure recommended by NCHRP Project 09-10 for determining the compaction temperature.⁽⁹⁾ When the Brookfield viscosities of asphalt binders are measured using the current standardized spindle rate of 20 rpm, NCHRP Project 09-10 recommends a target viscosity range of 1300 to 1500 mm²/s. A spindle rate of 20 rpm gives a shear rate of 6.8 s⁻¹.⁽⁹⁾ However, this is an alternative method. The primary method is to use the temperature at a viscosity of 6000 mm²/s (actually 6.0 Pa-s) determined using a shear rate of 0.001 s⁻¹. The Brookfield rheometer is not capable of applying this shear rate. Therefore, the viscosity of an asphalt binder at each temperature must be determined by performing the test at various shear rates. A curve-fitting model is then used to calculate the viscosity at 0.001 s⁻¹.

P. Final Comment

The viscosity range of 1100 ±200 mm²/s (or 1400 ±100 mm²/s) may not be valid when producing specimens with different asphalt binders for mechanical testing comparisons. The compaction temperature range for each asphalt-aggregate combination used in this study was based on obtaining an air-void level of 4.0 ±0.5 percent. No mechanical properties were measured. The compaction temperature ranges for the mixtures may be smaller with less overlap if they were to be based on obtaining the same mechanical properties. Mechanical properties may be more sensitive than density to the differences in



age-hardening provided by various compaction temperatures during STOA. The temperature used during STOA is important when comparing mixtures using performance tests.

Q. References

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Table 16. Effect of compaction temperature on the mixture with PG 58-28, diabase aggregate, and 1.25-percent hydrated lime.

Temperature, °C (Current Practice)		Measured Air Voids, Percent	Measured Effective Asphalt Binder Content, Percent by Volume	Additional Asphalt Binder Content Needed To Obtain 4- Percent Air Voids ^a		Amount of Smoke Produced (Blank = No Smoke)	
Mixing (145)	Compaction (137)			Percent by Volume	Percent by Mixture Mass	During Mixing	During STOA
145	157	3.7	9.1	-0.3	-0.1		Medium
145	137	3.8	9.1	-0.2	-0.1		
145	117	4.6	9.0	0.6	0.3		
145	107	4.0	9.1	0.0	0.0		
After the Outliers Are Removed							
145	157	3.4	9.2	-0.6	-0.3		Medium
145	137	4.3	9.1	0.3	0.1		
145	117	4.1	9.1	0.1	0.0		
145	107	4.0	9.1	0.0	0.0		

^aAssumes that the additional asphalt binder will not change the amount of asphalt binder absorption or workability during compaction. A negative sign indicates that asphalt binder would have to be removed to obtain a 4.0-percent air-void level.

Table 17. Air voids for the mixtures with diabase aggregate and 1.25-percent hydrated lime.

Temperature, °C		Air Voids, Percent				
Mixing	Compaction	Rep 1	Rep 2	Rep 3	Rep 4	Average
PG 58-28						
145	157	4.7 *	3.5	3.5	3.2	3.4
145	137	4.9	2.6 *	4.2	3.8	4.3
145	117	5.0	6.0 *	3.7	3.7	4.1
145	107	3.9	4.1	4.4	3.5	4.0
Novophalt (PG 76-22)						
166	179	4.3	4.3	4.1	3.7	4.1
166	159	4.6 *	4.1	4.0	4.0	4.0
166	139	4.6	4.5	3.9	3.6	4.2
166	119	4.7	5.3	4.5	5.0	4.9
Styrelf (PG 82-22)						
163	177	3.1	3.4	4.3	4.0	3.7
163	157	3.9	3.5	3.3	4.0	3.7
163	137	4.8	4.7	4.5	4.6	4.6

163	117	5.2	5.3	4.6	5.0	5.0
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* Outlier

Table 18. Effect of compaction temperature on the mixture with Novophalt (PG 76-22), diabase aggregate, and 1.25-percent hydrated lime.

Temperature, °C (Current Practice)		Measured Air Voids, Percent	Measured Effective Asphalt Binder Content, Percent by Volume	Additional Asphalt Binder Content Needed To Obtain 4-Percent Air Voids ^a		Amount of Smoke Produced (Blank = No Smoke)	
Mixing (166)	Compaction (159)			Percent by Volume	Percent by Mixture Mass	During Mixing	During STOA
166	179	4.1	9.1	0.2	0.1		High
166	159	4.0	9.1	0.0	0.0		
166	139	4.2	9.2	0.2	0.1		
166	119	4.9	9.1	0.9	0.4		

^aAssumes that the additional asphalt binder will not change the amount of asphalt binder absorption or workability during compaction.

Table 19. Effect of compaction temperature on the mixture with Styrelf (PG 82-22), diabase aggregate, and 1.25-percent hydrated lime.

Temperature, °C (Current Practice)		Measured Air Voids, Percent	Measured Effective Asphalt Binder Content, Percent by Volume	Additional Asphalt Binder Content Needed To Obtain 4-Percent Air Voids ^a		Amount of Smoke Produced (Blank = No Smoke)	
Mixing (163)	Compaction (157)			Percent by Volume	Percent by Mixture Mass	During Mixing	During STOA
163	177	3.7	9.0	-0.3	-0.1		Low
163	157	3.7	9.0	-0.3	-0.1		
163	137	4.6	9.1	0.6	0.3		
163	117	5.0	9.1	1.0	0.5		

^aAssumes that the additional asphalt binder will not change the amount of asphalt binder absorption or workability during compaction.

Table 20. Effect of compaction temperature on the mixture with PG 58-28 and limestone aggregate.

Temperature, °C (Current Practice)		Measured Air Voids, Percent	Measured Effective Asphalt Binder Content, Percent by Volume	Additional Asphalt Binder Content Needed To Obtain 4-Percent Air Voids ^a		Amount of Smoke Produced (Blank = No Smoke)	
Mixing (145)	Compaction (137)			Percent by Volume	Percent by Mixture Mass	During Mixing	During STOA
145	157	3.5	10.5	-0.5	-0.2		Medium
145	137	4.1	10.5	0.1	0.0		
145	117	4.2	10.5	0.2	0.1		
145	107	4.2	10.5	0.2	0.1		

^aAssumes that the additional asphalt binder will not change the amount of asphalt binder absorption or workability during compaction. A negative sign indicates that asphalt binder would have to be removed to obtain a 4.0-percent air-void level.

Table 21. Air voids for the mixtures with limestone aggregate.

Temperature, °C		Air Voids, Percent				
Mixing	Compaction	Rep 1	Rep 2	Rep 3	Rep 4	Average
PG 58-28						
145	157	4.6 *	3.3	3.6	3.5	3.5
145	137	4.2	3.7	4.1	4.3	4.1
145	117	4.6	4.0	4.1	3.9	4.2
145	107	4.4	4.1	3.8	4.3	4.2
Novophalt (PG 76-22)						
166	179	3.5 *	2.6	3.0	2.7	2.8
166	159	3.8	3.4	3.5	3.2	3.5
166	139	3.9	3.9	3.3 *	4.1	4.0
166	119	4.6	4.3	4.4	4.1	4.4
Styrelf (PG 82-22)						
163	177	3.4 *	2.9	2.9	3.0	2.9
163	157	4.1 *	3.8	3.6	3.5	3.6
163	137	4.1	3.8	3.8	3.5	3.8
163	117	4.7 *	4.3	4.2	4.1	4.2

* Outlier

Table 22. Effect of compaction temperature on the mixture with Novophalt (PG 76-22) and limestone aggregate.

Temperature, °C (Current Practice)		Measured Air Voids, Percent	Measured Effective Asphalt Binder Content, Percent by Volume	Additional Asphalt Binder Content Needed To Obtain 4-Percent Air Voids ^a		Amount of Smoke Produced (Blank = No Smoke)	
Mixing (145)	Compaction (137)			Percent by Volume	Percent by Mixture Mass	During Mixing	During STOA
145	179	2.8	10.5	-1.2	-0.6		Medium
145	159	3.5	10.4	-0.5	0.2		
145	139	4.0	10.4	0.0	0.0		
145	119	4.4	10.6	0.4	0.2		

^aAssumes that the additional asphalt binder will not change the amount of asphalt binder absorption or workability during compaction. A negative sign indicates that asphalt binder would have to be removed to obtain a 4.0-percent air-void level.

Table 23. Effect of compaction temperature on the mixture with Styrelf (PG 82-22) and limestone aggregate.

Temperature, °C (Current Practice)		Measured Air Voids, Percent	Measured Effective Asphalt Binder Content, Percent by Volume	Additional Asphalt Binder Content Needed To Obtain 4-Percent Air Voids ^a		Amount of Smoke Produced (Blank = No Smoke)	
Mixing (145)	Compaction (137)			Percent by Volume	Percent by Mixture Mass	During Mixing	During STOA
145	177	2.9	10.6	-1.1	-0.5		Medium
145	157	3.6	10.6	-0.4	-0.2		
145	137	3.8	10.5	-0.2	-0.1		
145	117	4.2	10.8	0.2	0.1		

^aAssumes that the additional asphalt binder will not change the amount of asphalt binder absorption or workability during compaction. A negative sign indicates that asphalt binder would have to be removed to obtain a 4.0-percent air-void level.

Table 24. Allowable compaction temperature range from the Superpave gyratory compactor.

Aggregate Blend	Allowable Compaction Temperature Range Rounded to the Nearest 5°C		
	PG 58-28 (AC-10)	PG 76-22 (Novophalt)	PG 82-22 (Styrelf)
Diabase No Lime	125 - 145 (135 ±10)	120 - 160 (140 ±20)	145 - 165 (155 ±10)
Diabase 1.25% Lime	105 - 145 (125 ±20)	140 - 160 (150 ±10)	145 - 165 (155 ±10)
Limestone	105 - 145 (125 ±20)	120 - 160 (140 ±20)	115 - 165 (140 ±25)

Table 25. Average compaction temperature.

Aggregate Blend	Method	Average Compaction Temperature Rounded to the Nearest 5°C		
		PG 58-28 (AC-10)	PG 76-22 (Novophalt)	PG 82-22 (Styrelf)
Diabase No Lime	Gyratory	135	140	155
	Capillary Viscosity	140	175	170
	Brookfield Viscosity	140	190	185
	Mastic	135	175	165
Diabase 1.25% Lime	Gyratory	125	150	155
	Capillary Viscosity	140	175	170
	Brookfield Viscosity	140	190	185
Limestone	Gyratory	125	140	140
	Capillary Viscosity	140	175	170
	Brookfield Viscosity	140	190	185

Table 26. Allowable compaction temperature range from the Superpave gyratory compactor and the asphalt binders at viscosities of 250 and 310 mm²/s (280 ±30 mm²/s).

Aggregate	Method	Allowable Temperature Range, °C		
		PG 58-28 (AC-10)	PG 76-22 (Novophalt)	PG 82-22 (Styrelf)
Diabase No Lime	Gyratory	125 - 145	120 - 160	145 - 165
Diabase 1.25% Lime	Gyratory	105 - 145	140 - 160	145 - 165
Limestone	Gyratory	105 - 145	120 - 160	115 - 165
All Blends	Gyratory	125 - 145	140 - 160	145 - 165
	Capillary Viscosity	135 - 140	170 - 175	170 - 175
	Brookfield Viscosity	135 - 140	185 - 190	185 - 190

Table 27. Viscosity range corresponding to the compaction temperature range from the Superpave gyratory compactor.

Aggregate	Method	Asphalt Binder		
		PG 58-28 (AC-10)	PG 76-22 (Novophalt)	PG 82-22 (Styrelf)
Diabase No Lime	Gyratory, °C	125 - 145	120 - 160	145 - 165
	Capillary Viscosity, mm ² /s	550 - 200	5500 - 650	1350 - 450
	Brookfield Viscosity, mm ² /s	550 - 200	8100 - 900	1250 - 500
Diabase 1.25% Lime	Gyratory, °C	105 - 145	140 - 160	145 - 165
	Capillary Viscosity, mm ² /s	1900 - 200	1700 - 650	1350 - 450
	Brookfield Viscosity, mm ² /s	950 - 200	3500 - 900	1250 - 500
Limestone	Gyratory, °C	105 - 145	120 - 160	115 - 165
	Capillary Viscosity, mm ² /s	1900 - 200	5500 - 650	11000 - 450
	Brookfield Viscosity, mm ² /s	950 - 200	8100 - 900	4600 - 500
All Blends	Brookfield Viscosity Range Applicable to All Aggregate Blends, mm ² /s	550 - 200 (950 - 200)	3500 - 900	1250 - 500