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research report

Design of a High-Binder-High-Modulus Asphalt Mixture

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Supplementary Notes

Abstract

Recent studies on long-life flexible pavements indicate that it may be advantageous to design and construct asphalt mixtures comprising the underlying layers in such a manner that very dense mixtures are produced. This will improve not only the fatigue characteristics but also durability through a decrease in air voids. A 19.0 mm mixture was designed and tested at asphalt contents (ACs) higher than the optimum design level. Stiffer binder and recycled asphalt pavement (RAP) were employed to help maintain stiffness in order to prevent instability.

The field voids were predicted to decrease approximately 1.0 to 1.5 percent for each 0.4 percent increase in AC, which would improve durability. Flexural stiffness peaked for an 0.5 percent increase in AC, and fatigue life trended upward but needed approximately 1.0 percent additional asphalt for a major beneficial effect. Permeability improved slightly as AC was increased. The researchers think that the Hamburg test would have been more appropriate for this study than the tensile strength ratio test, which indicated no improvement in stripping susceptibility with an increased AC, because it might simulate field conditions better.

In addition, the Mechanistic-Empirical Pavement Design Guide Software (Version 0.900) was used to evaluate trial pavement designs with several design alternatives, including varying the binder performance grade, effective binder volume, and air void content to determine the resultant changes in predicted fatigue cracking and rutting of hot-mix asphalt (HMA) layers. This theoretical pavement analysis indicated that increasing the binder content of the HMA intermediate layer beyond the design optimum and increasing the stiffness of the intermediate layer by increasing the high-temperature binder performance grade slightly decreased the predicted fatigue cracking and reduced the rutting of the HMA layers. The analysis also showed that more significant reductions in the predicted fatigue cracking could be realized by increasing the binder content of the HMA base layer slightly beyond the optimum and by reducing the in-place air void content of the HMA base layer.

It was recommended that VTRC should further investigate the effects of higher binder contents and lower air voids on the performance of base mixes. Further study of current void criteria to verify optimum pavement performance is also recommended. This project provides a stepping stone to achieve long-lasting perpetual-type flexible pavement. Designs with a high binder content offer the potential to reduce fatigue cracking 20 to 60 percent by incorporating additional asphalt binder and reducing the void content of asphalt base. The use of RAP to maintain the necessary stiffness for high binder contents should provide comparable stiffness to an increasingly expensive PG 70-22 binder for base material. Some effort is taking place in 2007 for reducing voids in base mixes with high RAP content; however, quantification of the economic benefits from that endeavor will be a future goal.

FINAL REPORT

DESIGN OF A HIGH-BINDER–HIGH-MODULUS ASPHALT MIXTURE

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(A partnership of the Virginia Department of Transportation and
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ABSTRACT

Recent studies on long-life flexible pavements indicate that it may be advantageous to design and construct asphalt mixtures comprising the underlying layers in such a manner that very dense mixtures are produced. This will improve not only the fatigue characteristics but also durability through a decrease in air voids. A 19.0 mm mixture was designed and tested at asphalt contents (ACs) higher than the optimum design level. Stiffer binder and recycled asphalt pavement (RAP) were employed to help maintain stiffness in order to prevent instability.

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INTRODUCTION

Successful use of a high-modulus (stiff) bituminous mixture has been reported by others as a means to reduce deterioration with flexible pavements and increase their service lives. Summers cites instances that are documented in the Transport Research Laboratory publications where the use of high-modulus bases has been reported.[1] Performance trends from these roads were extrapolated to predict service lives around 40 years with only an occasional replacement of the surface layer. The French have been experimenting with and designing pavements with high-modulus bases since the 1980s.[2] Both the British and French report savings as high as 25 percent because the pavement thickness was reduced when a high stiffness material was used. A high stiffness may be created by reducing binder content or using stiffer binders but the Europeans emphasize that durability is jeopardized if high binder content is not used with the high-modulus mixtures.

In recent years, a new concept has emerged in the design of flexible pavement structures. This concept is better known as *perpetual pavement design* or *long-life pavement design.* This design philosophy is supposed to result in indefinitely long-lasting pavements that do not require major reconstruction for lengthy periods (estimated at 40 to 50 years) with periodic replacement of the surface layer (approximately 20-year intervals). For traditionally designed flexible pavements, fatigue cracking is considered to be the ultimate cause of failure and it has always been considered to originate at the lower surface of the asphalt as a result of repetitive wheel loads. Long-life pavements are designed with a structure that prevents fatigue cracks at the bottom of the asphalt base layer. Top-down cracking has also been recognized recently; however, the cracking originates at the surface and extends only a short depth. The structure is considered to be perpetual and only the surface layer that is exposed directly to traffic must be replaced at lengthy intervals. Design strategies to achieve a long-life pavement are summarized in various references.[3-5]

Some documented long-life pavements have been built but not designed as such. For example, the New Jersey Turnpike Authority was honored with the first "Perpetual Pavement Award" for an asphalt pavement that has served for 50 years.[3] Other projects are now being built according to the perpetual pavement design philosophy nationally[4] and internationally.[5]

The perpetual pavement concept shown in Figure 1 consists of a flexible high-binder fatigue-resistant layer at the bottom, a high-modulus rut-resistant layer in the middle, and a high-quality surface layer that can be replaced but can endure many repetitions of traffic. The benefits of high-modulus layers in the perpetual pavement concept can be two-fold (1) the increased stiffness allows the section to be reduced or stresses to be reduced in the subgrade, and (2) possible higher binder contents increase the durability by decreasing voids. Base mixes with a high binder content may also eliminate the need for an extra fatigue-resistant layer at the bottom, as shown in Figure 1.

Not only would the high-modulus–high-binder (HMHB) mixes have the potential to be useful in new construction but their application in rehabilitation construction would also possibly be beneficial. Much of the asphalt paving is used in rehabilitation work where the upper layers are milled and replaced with an intermediate layer and a surface layer. A dense, stiff intermediate layer could allow a reduction in the thickness needed but, more important, increase durability, which would potentially result in a longer service life.

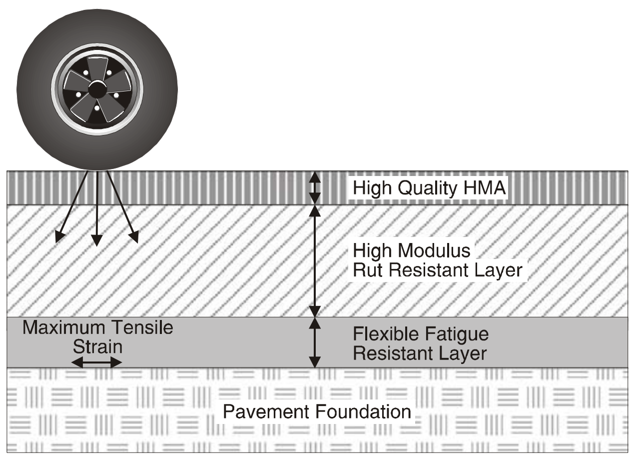

Figure 1. Perpetual Pavement Design

PURPOSE AND SCOPE

The purpose of this study was to investigate the design of an asphalt mixture having more than the normal amount of binder and high stiffness. The study was limited to a laboratory exercise and a theoretical modeling component where the results were used to indicate potential field performance.

METHODOLOGY

A 19.0 mm Superpave intermediate mixture using PG 64-22 that had been used successfully in the field was modified by various means in an attempt to achieve desirable characteristics. In order to modify the conventional mixture by adding extra asphalt to increase durability, it was necessary to use stiffer binders or incorporate recycled asphalt pavement (RAP) to maintain adequate stability. PG 70-22 and PG 76-22 binders were used, and 25 percent RAP was also tried. It was expected that high-binder mixes would possibly be less susceptible to moisture damage because there would be less chance for water to penetrate the asphalt film. The gradation, which was held constant for all mixtures, is shown in Table 1 and Figure 2. The binder properties and the recovered RAP properties are listed in Table 2. When the properties of the virgin PG 64-22 binder and recovered RAP binder were mathematically blended using 25 percent RAP in accordance with the procedure suggested in NCHRP Report 452 the resultant binder was a PG 70-22 binder.[6]

Table 1. Gradation of 19.0 mm Intermediate Mixture

Sieve Size, mm	% Passing
25.0	100
19.0	98
12.5	83
9.5	72
4.75	52
2.36	39
1.18	28
0.60	19
0.30	12
0.150	7.6
0.075	6.1

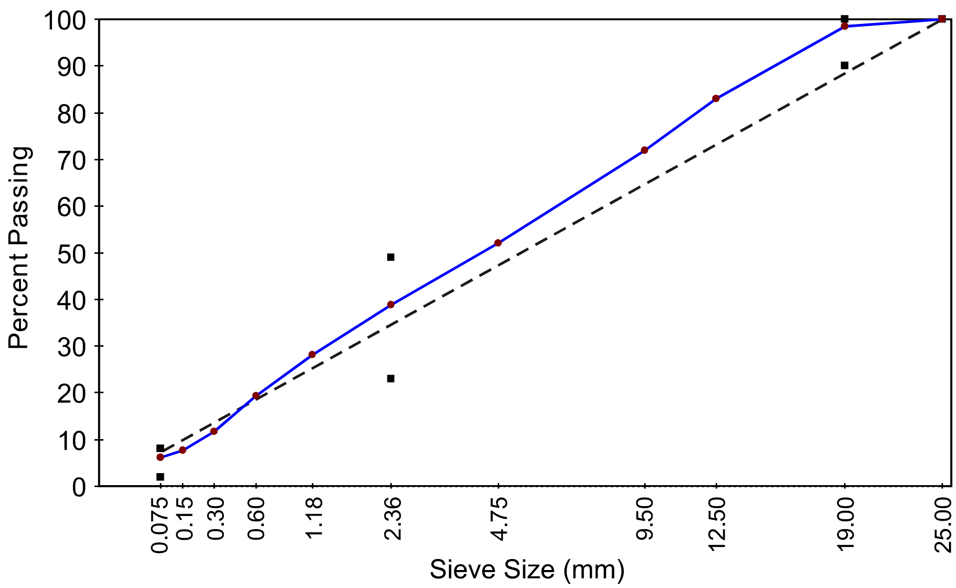

Figure 2. Gradation of 19.0 mm Mixture

Table 2. Binder and Recovered RAP properties

Aging	Property	Critical Temperature, °C			
		PG 64-22	PG 70-22	PG 76-22	RAP
Original	DSR $G^*/\sin\delta$	67	73.3	81	97.3
RTFO	DSR $G^*/\sin\delta$	68.2	73.8	80.6	101.3
PAV	DSR $G^*\sin\delta$	18.7	25.6	22.4	36.9
	BBR S-value	−17.6	−12.7	−13.7	−5.7
	BBR m-value	−19.1	−13.3	−13.3	−1.7

To characterize the performance of an HMHB mix as a part of an actual pavement, the *Mechanistic-Empirical Pavement Design Guide*[7] (MEPDG) software (Version 0.900) was used to predict the deterioration of a flexible pavement design developed for a location with high traffic volumes. A heavy-duty pavement was thought to be the most likely candidate where the HMHB concept would be implemented. The pavement analysis was performed such that the materials properties of individual layers could be modified to determine their influence on the overall pavement deterioration prediction and where the use of innovative materials and construction techniques could be optimized for best performance.

Laboratory Testing

A summary of the laboratory testing is provided in Table 3. The first step was to verify the optimum design asphalt content (AC) for all mixtures. Then, gyratory specimens were compacted to field density (7% voids total mix) to establish a field compaction effort (number of gyrations) (Figure 3). That field compaction effort (number of gyrations) was then used to determine the target void contents for the laboratory specimens containing higher ACs. Three increments of additional binder were used for each mixture.

Table 3. Summary of Testing

Mixture	% Air Voids	% Asphalt	Test	Comments
PG 64-22 Control	7	5.2	Rutting, permeability, fatigue, tensile strength	Used as control comparison
PG 70-22	Various	5.2	Gyratory	Establish field compaction effort, N, to yield 7.0% air voids
	Field voids	5.6, 6.0, 6.4	Gyratory	Compact to N revolutions to determine field air voids
	Field voids	5.2, 5.6, 6.0, 6.4	Rutting, permeability, fatigue, tensile strength	Evaluate properties
PG 76-22	Various	5.2	Gyratory	Establish field compaction effort, N, to yield 7.0% air voids
	Field voids	5.6, 6.0, 6.4	Gyratory	Compact to N revolutions to determine field air voids
	Field voids	5.2, 5.6, 6.0, 6.4	Rutting, permeability, fatigue, tensile strength	Evaluate properties
25% RAP	Various	5.4	Gyratory	Establish field compaction effort, N, to yield 7.0% air voids
	Field voids	5.8, 6.2, 6.6	Gyratory	Compact to N revolutions to determine field air voids
	Field voids	5.4, 5.8, 6.2, 6.6	Rutting, permeability, fatigue, tensile strength	Evaluate properties

Beam fatigue tests were performed in accordance with AASHTO T 321[8] on the apparatus shown in Figure 4. Three fatigue tests were performed at each AC for each mixture at an outer fiber strain level of 400 $\mu\varepsilon$. The test method defines failure as the point at which the stiffness reduces to 50 percent of the initial stiffness.

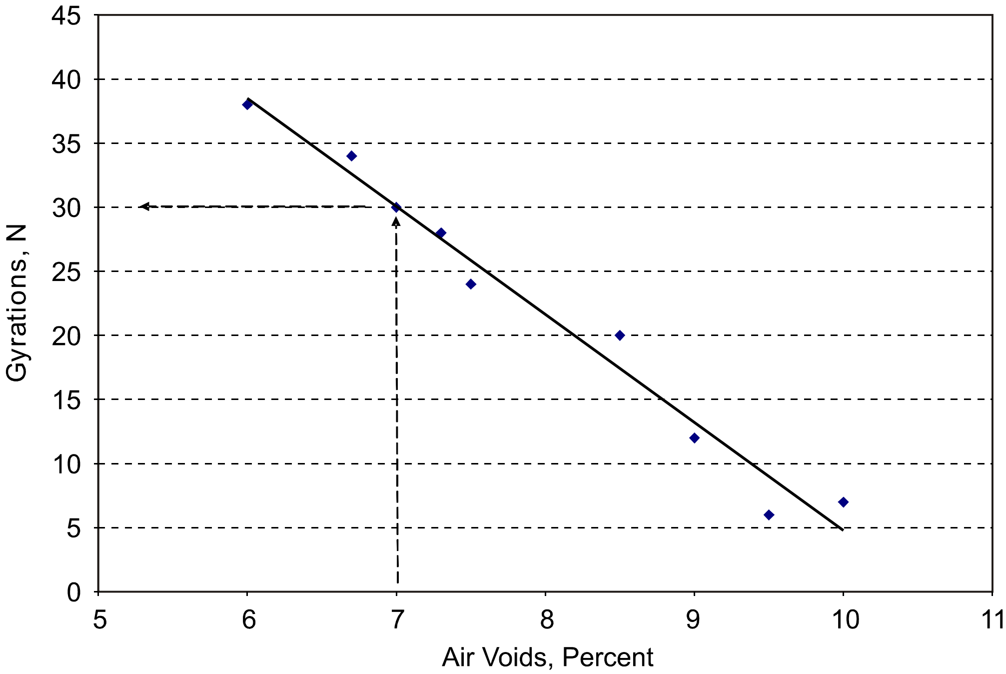

Figure 3. Example of Determining Field Compactive Effort

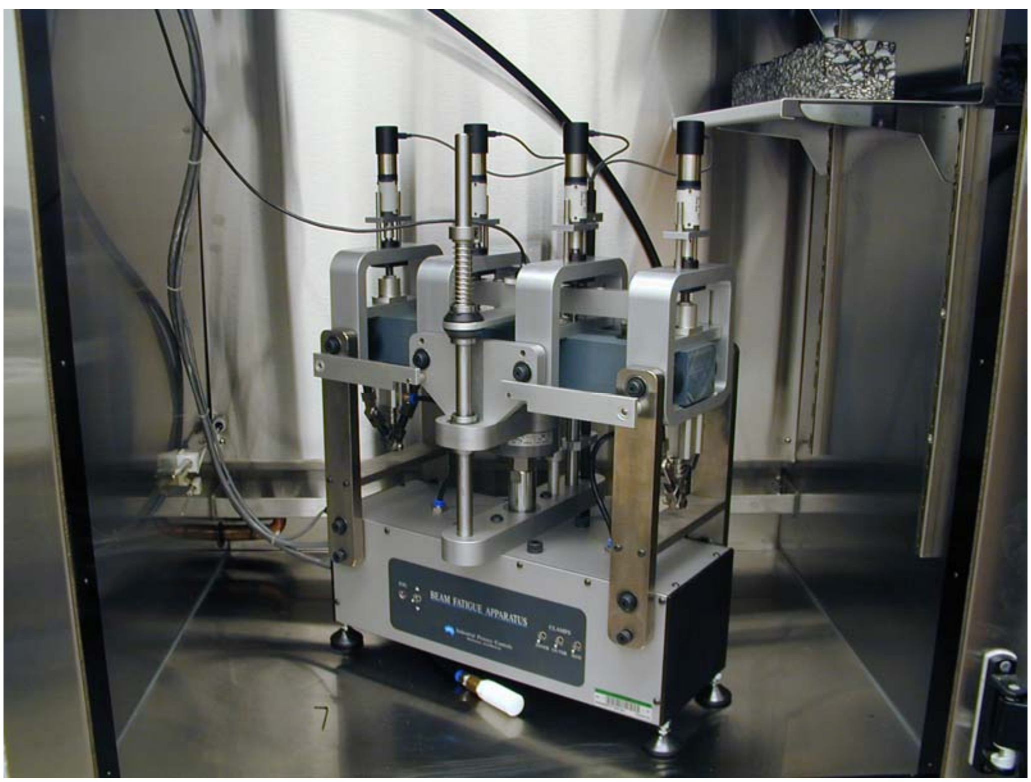

Figure 4. Fatigue Testing Device

Rut tests were performed on beams with the Asphalt Pavement Analyzer (APA) in accordance with Virginia Test Method (VTM) 110,[9] as illustrated in Figure 5. The method tests three beams simultaneously through 8,000 cycles at a load of 120 lb, a hose pressure of 120 psi, and a test temperature of 120°F.

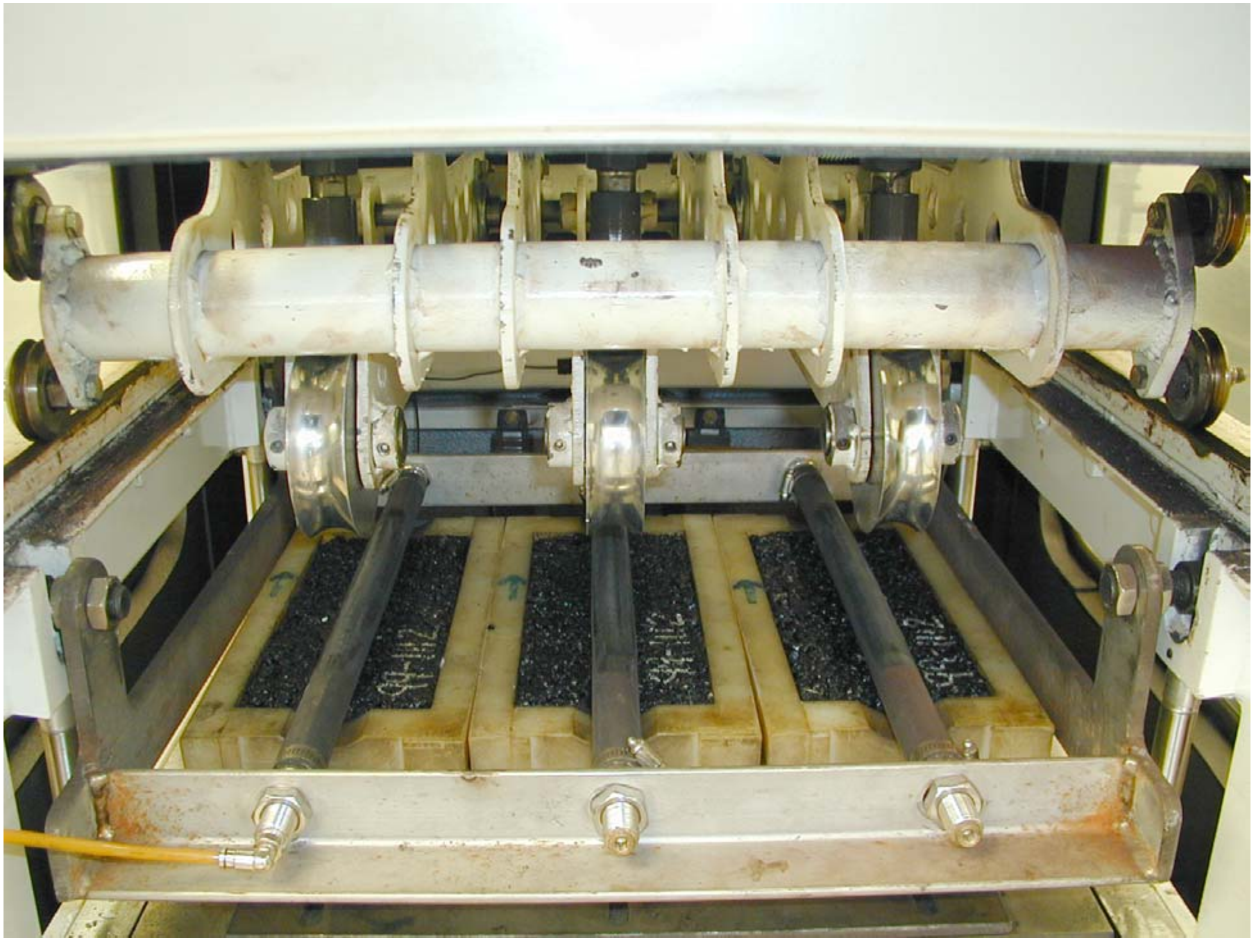

Figure 5. Asphalt Pavement Analyzer (Rut Tester)

Falling head permeability tests were performed on the laboratory specimens in accordance with VTM-120, as shown in Figure 6. At least nine specimens were made at various void contents and tested for permeability. The resultant permeability–voids regression was used to determine the permeability at the desired void content.

Tensile strength ratio (TSR) moisture susceptibility tests were performed in accordance with AASHTO T 283. Two groups of specimens were made at the same desired void content. One group was tested in indirect tension in a dry condition, and the second group was saturated to 70 to 80 percent, conditioned in a 140°F water bath, and then tested in indirect tension. The ratio of the conditioned strength to dry strength (TSR) was used to evaluate stripping susceptibility.

Theoretical Pavement Analysis

A trial flexible pavement structural design was developed for use in a high truck traffic area following the concepts of a perpetual or long-life flexible pavement design and suggestions for long lasting pavements.[4,5,10-14] The trial flexible pavement design also incorporated VDOT's criteria for designing an interstate flexible pavement using the 1993 AASHTO pavement design guide.[15] These criteria included an initial serviceability of 4.2, a terminal serviceability of 3.0, a

Figure 6. Asphalt Permeameter

95 percent reliability, a two-way annual average daily traffic (AADT) of 55,000, 34 percent trucks, and a 6.4 percent growth rate. These criteria were used to create a hypothetical 30-year design for northbound I-81 between State Route 262 and the intersection with I-64, mileposts 220 through 221.[16] The DarWin software calculated the estimated number of equivalent single axle loads (ESALs) for this section as approximately 322 million based on a subgrade resilient modulus of 8,000 psi. The required structural number (SN) was calculated to be 9.09. This heavy-duty design was thought to be the most likely type of flexible pavement where a HMHB layer might be used. The developed trial pavement design, based on the criteria, is shown in Table 4.

Two limitations of using the 1993 design guide are: (1) the stone matrix asphalt (SMA) surface layer is given the same layer coefficient as a Superpave surface mixture, and (2) the

Table 4. Trial Pavement Design

Material Type	VDOT Designation	Binder Performance Grade	Thickness, in	Layer coefficient, a_i	Thickness x layer coefficient
HMA Surface	SMA 12.5	70-22	2.0	0.44	0.88
HMA Intermediate	IM 19.0	64-22	3.0	0.44	1.32
HMA Intermediate	IM 19.0	64-22	3.0	0.44	1.32
HMA Base	BM 25.0	64-22	6.0	0.4	2.40
Aggregate Base	21-B		8.0	0.12	0.96
Subgrade			12.0	0.18	2.16
Total Structural Number (SN)					9.04

SMA surface layer with a binder performance grade (PG) 70-22 binder would have the same layer coefficient if a PG 64-22 or a PG 76-22 binder were used when previous research suggests that a difference in modulus of more than 35 percent may result.[17]

Trial pavement designs may be analyzed using multilayer elastic analysis to determine their response due to a simulated load. Two typical methods to analyze pavement designs are to evaluate the response to loading at two critical locations: at the bottom of the HMA layers and on the top of the subgrade to prevent fatigue damage and rutting damage, respectively.[18,19] Values of the maximum allowable horizontal tensile strain at the bottom of the HMA and vertical compressive strain on top of the subgrade are suggested as 70 microstrains and 200 microstrains, respectively.[17,20,21]

RESULTS

Predicted Field Voids

The compaction effort necessary to produce 7.0 percent air voids with the Superpave gyratory compactor was determined for each mixture at the optimum AC. This compaction effort was then used on gyratory specimens to predict the field void level if ACs higher than the optimum had been used in the field. Those simulated field voids were then used as targets for the void contents in the fabrication of laboratory specimens used for permeability, rutting, stripping, and fatigue tests. Figure 7 shows the results of the predicted field voids at several ACs higher than the designed optimum amount. The air void contents of the mixtures containing PG 70-22 and PG 76-22 binders decreased approximately 1 percent for each 0.4 percent increase in AC. The air void content of the mixture containing RAP decreased approximately 1.5 percent for each 0.4 percent increase in AC. Volumetrics for the mixtures at the simulated field voids are shown in Table 5. It is anticipated that the volumetric properties of mixtures in the lower layers would not change appreciably as surface mixtures do because these layers are subjected to lower stresses from traffic loads.

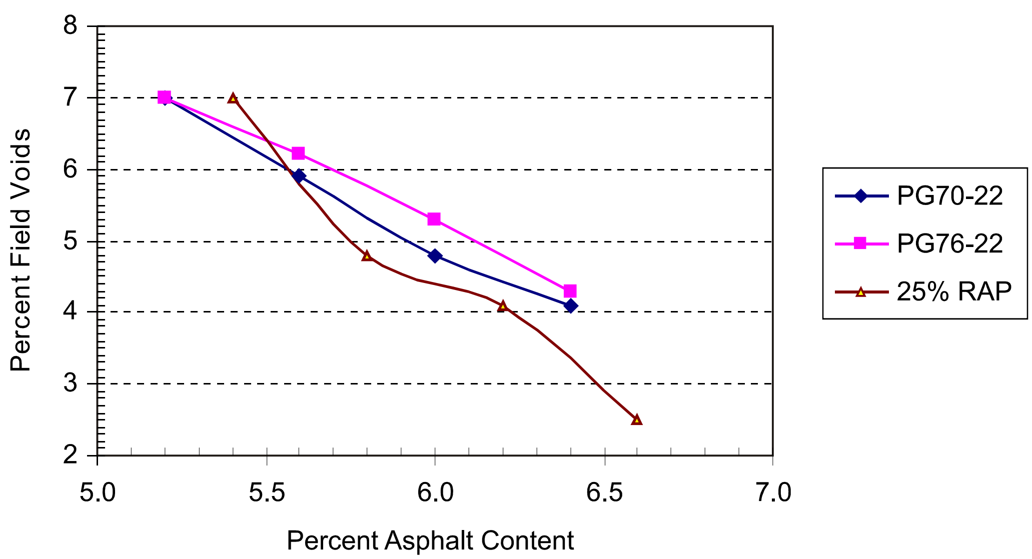

Figure 7. Predicted Field Voids With Additional Asphalt Binder

Table 5. Volumetric Properties at Simulated Field Placement

Property	PG 64-22			
% AC	5.2			
% VTM	7.0			
% VFA	59			
% VMA	17			
	PG 70-22			
% AC	5.2	5.6	6.0	6.4
% VTM	7.0	6.0	4.8	4.1
% VFA	59.1	64.7	71.8	76.0
% VMA	17.2	17.1	16.8	17.1
	PG 76-22			
% AC	5.2	5.6	6.0	6.4
% VTM	7.0	6.2	5.3	4.3
% VFA	59.2	63.9	69.2	75.0
% VMA	17.1	17.3	17.3	17.3
	25% RAP			
% AC	5.4	5.8	6.2	6.6
% VTM	6.8	4.8	4.1	2.5
% VFA	67.9	70.9	75.0	85.9
% VMA	21.0	16.4	16.5	17.8

AC = asphalt content, VTM = voids total mix, VFA = voids fine aggregate, VMA = voids in mineral aggregate

Fatigue Tests

Fatigue test results at 400 με for the mixtures containing PG 70-22, PG 76-22, and RAP are shown in Figure 8. The average fatigue life at optimum AC was approximately equal for mixtures containing PG 70-22 and RAP; however, the fatigue life at the optimum AC for the mixture containing PG 76-22 was approximately 100 percent higher. In general, fatigue life

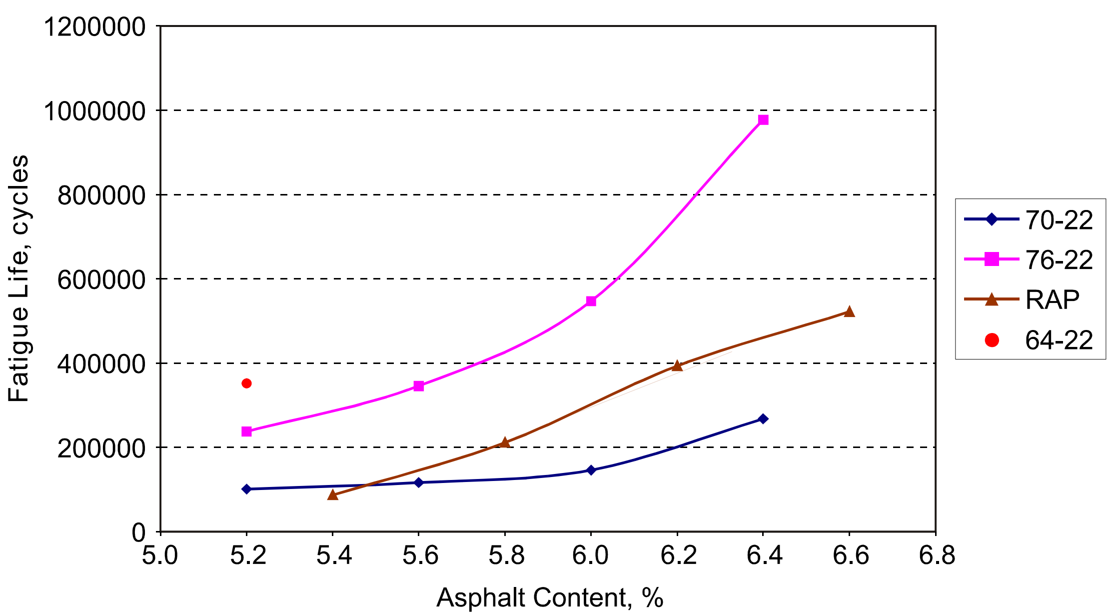

Figure 8. Fatigue Test Results

trended toward improvement as the AC increased for all mixtures. ACs more than 0.4 percent above optimum had the largest effect on fatigue life. The fatigue life at all ACs was the highest for the mixture containing PG 76-22 followed by the mixture containing RAP and then the mixture containing PG 70-22.

Unexplainably, the fatigue life of the original mixture containing an optimum amount of PG 64-22 was approximately 350,000 cycles, which was higher than that for any of the other mixtures at low AC. In a determination if a testing error had been made, retests on a duplicate set of beams verified the original values. Perhaps it is logical for the mixture with PG 64-22 to yield a relatively long fatigue life since it was the least stiff mixture. At higher than optimum AC, the fatigue life curve would probably have tended to level out much as it did with the mixture with PG 70-22.

The stiffness at the beginning of the fatigue test is plotted in Figure 9. For the mixtures containing PG 70-22 and PG 76-22, there was a slight increase in stiffness for the small increase in AC above optimum, after which the stiffness decreased with increasing AC. The mixture containing RAP displayed a plateau at optimum AC and immediately above optimum, and then the stiffness decreased with ACs more than 0.4 percent above optimum.

The phase angle measured at the beginning of each fatigue test for each mixture is provided in Table 6. The phase angle indicates the viscoelastic response of the loading and is the time delay of strain behind the load application. Low values indicate elastic behavior, and high values indicate viscous behavior. A value of 0 indicates a truly elastic material, and a value of 90 indicates a truly viscous material. As expected, the phase angle increased as binder stiffness decreased and AC increased.

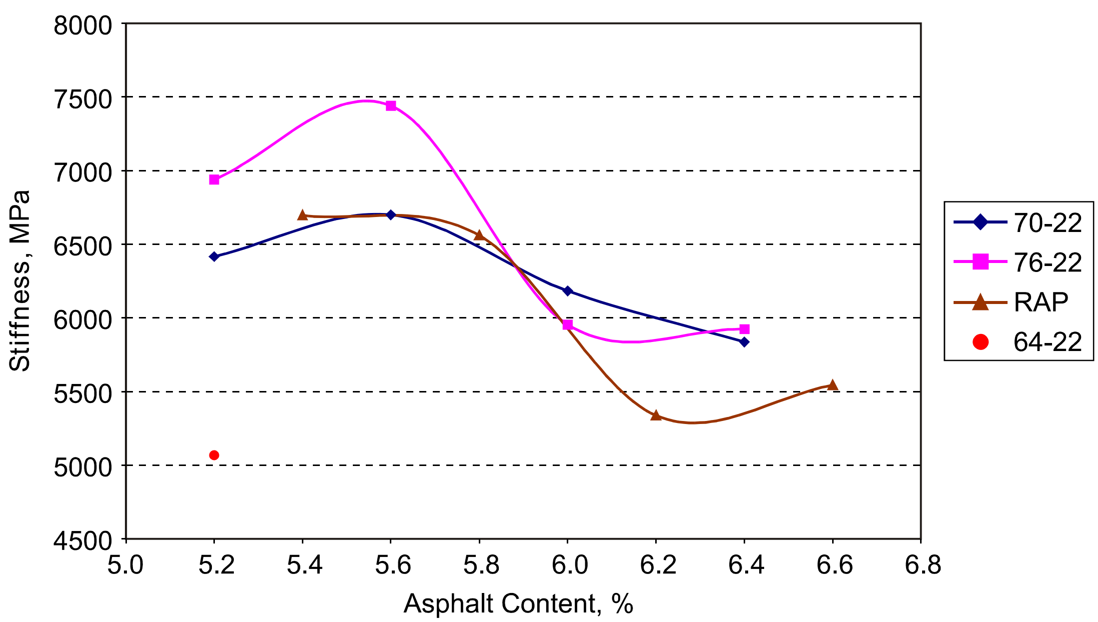

Figure 9. Flexural Stiffness Results

Table 6. Phase Angle

Mixture	Asphalt Content, %	Phase Angle, °
PG 70-22	5.2	34.8
	5.6	39.0
	6.0	39.9
	6.4	40.8
PG 76-22	5.2	33.1
	5.6	34.5
	6.0	38.5
	6.4	38.6
25% RAP	5.4	37.3
	5.8	37.7
	6.2	39.3
	6.6	40.6
PG 64-22	5.2	40.6

Rut Tests

The results of the rut tests are shown in Figures 10, 11, and 12. Each figure shows the test results at several increments of AC for both mixtures containing PG 70-22 and PG 76-22 binders and 25 percent RAP and a single value for the mixture at optimum AC using the conventional PG 64-22 binder. The mixture containing PG 64-22 was used for comparison since it had been placed and had performed well as an intermediate mixture in the field. The rut depth/AC curves resemble a sinusoidal shape in which the rut depth increases slightly at the first addition of asphalt, decreases at the second addition, and increases again at the third addition. As expected, the PG 76-22 binder provided the most rut resistance of the three binders used with rut depths at all ACs well below that produced by the conventional PG 64-22 binder at the optimum AC. In addition, the mixture with 25 percent RAP produced rut depths at all ACs below that produced by the PG 64-22 binder at optimum AC. It might be noted that the VDOT maximum allowable laboratory rut depth is 7.0 mm for a surface mixture containing PG 64-22 binder and would probably be slightly higher for an intermediate mixture since the loading stresses are lower for intermediate and base layers. The mixtures containing PG 70-22 binder and RAP had values slightly above the allowable value at the first increment of asphalt.

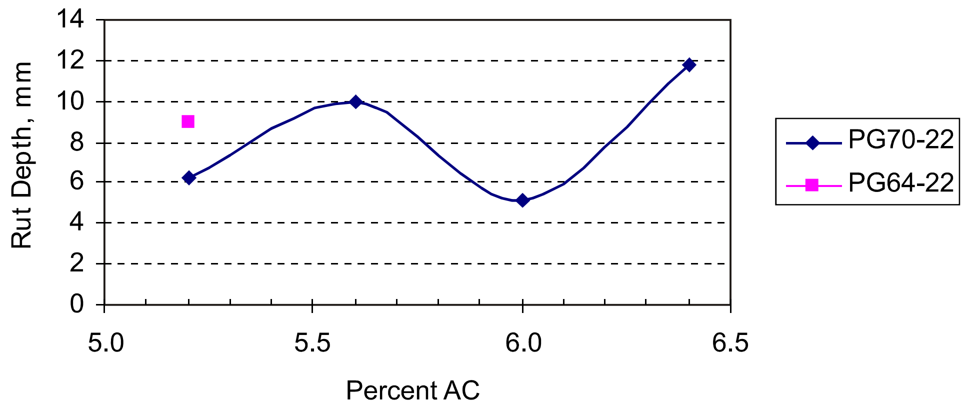

Figure 10. Rut Tests for Mixture Containing PG 70-22 Binder

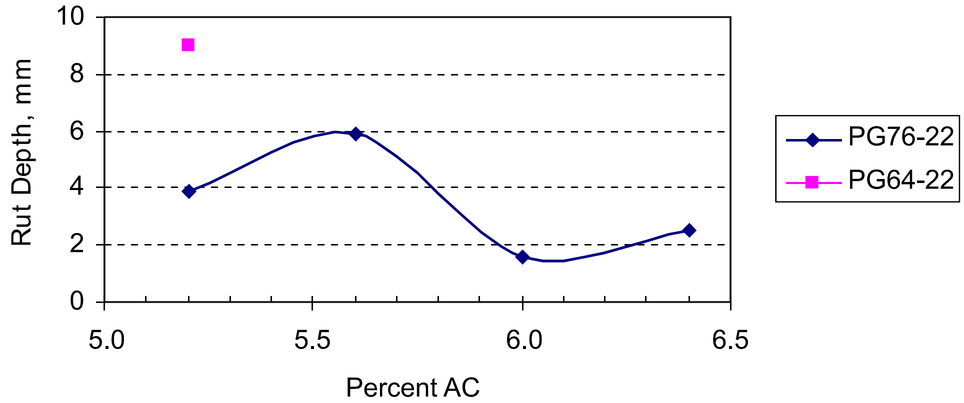

Figure 11. Rut Tests for Mixture Containing PG 76-22 Binder

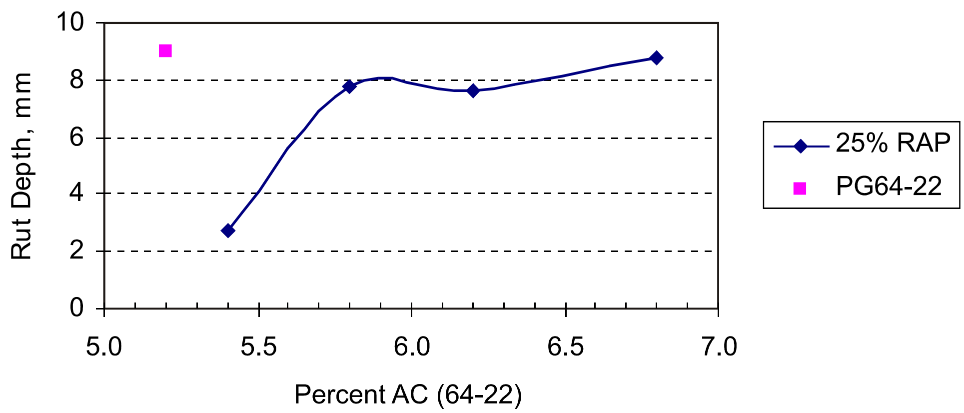

Figure 12. Rut Tests for Mixture Containing 25% RAP

Permeability Tests

The results of permeability tests performed on specimens at the optimum AC and at an AC slightly above optimum are provided in Table 7. The mixtures containing stiffer binders and RAP had low permeability, which was considerably lower than that obtained for the control mixture at optimum AC even though the air voids were similar. The additional AC seemed to decrease permeability slightly for the mixtures containing PG 70-22 binder and RAP.

Table 7. Permeability

Mixture	Asphalt Content, %	Air Voids, %	Permeability x 10^{-5} m/sec
PG 64-22	5.2	7.0	300
PG 70-22	5.2	7.0	30
PG 70-22	5.6	5.9	5
PG 76-22	5.2	7.0	10
PG 76-22	5.6	6.2	20
25% RAP	5.4	7.0	50
25% RAP	5.8	4.8	0

Stripping Tests

The stripping test results are provided in Table 8. The TSR results ranged from a low of 0.61 to a high of 0.78 with the exception of the single PG 70-22 mixture containing the antistripping additive, which had a TSR value of 0.91. VDOT's minimum TSR acceptance level is 0.80; therefore, only the mixture containing antistripping additive passed. This particular test did not indicate that additional asphalt and reduced voids would result in better predicted stripping performance. In this case, another type of test such as the Hamburg test would have been a better indicator of the beneficial effects of additional asphalt. In the TSR test, the specimens must be saturated to a certain degree of saturation; therefore, the fact that the specimens had more asphalt and reduced voids may not have necessarily influenced the severity of stripping. A Hamburg test subjects a specimen to repeated loadings under water; therefore, test specimens with more asphalt and reduced voids would probably have allowed less water to enter and have shown better performance. A Hamburg tester was not available for the experiment.

Table 8. Stripping

Mixture	Asphalt Content, %	Air Voids, %	Tensile Strength Ratio
PG 64-22	5.2	7.5	0.64
PG 70-22	5.2	7.4	0.74
PG 70-22 (Antistrip)	5.2	7.1	0.91
PG 70-22	5.6	5.7	0.64
PG 70-22	6.0	4.2	0.78
PG 76-22	5.2	7.2	0.61
PG 76-22	5.6	5.6	0.69
PG 76-22	6.0	5.2	0.72
PG 64-22 RAP	5.4	7.1	0.72
PG 64-22 RAP	5.8	5.6	0.65

Multilayer Elastic Analysis

A multilayer elastic analysis was performed using the software WESLEA for Windows to determine the tensile strain at the bottom of the HMA layers and the compressive strain at the top of the subgrade for the trial pavement design using typical truck loads. WESLEA calculates stresses, strains, and deflections at default or prescribed locations based on user-defined material properties, tire loads, and tire pressures. The analysis software assumes that the vehicle loading is applied by a circular load and that the HMA material behaves as a linear elastic material.

Unpublished data from VDOT's Traffic Division was used to determine the typical loading for a Class 9 truck (five-axle tractor with semi-trailer), the predominant heavy vehicle on Virginia's highways. The data were taken from an in-lane weigh-in-motion (WIM) scale located in the travel lane of I-66 in Fauquier County during June 2005. The data for I-66 were used since no in-lane WIM scale is available at the trial pavement design location to give a true representation of the truck traffic on I-81. The average, standard deviation, and 95th percentile value of the loading for the steering axle, drive axle group, and trailer axle group from the WIM data for June 15, 2005, are presented in Table 9.

Table 9. Representative Axle Loading for Multi-Layer Elastic Analysis

Axle or Axle Group	Average Axle Load, lb	Standard Deviation Axle Load, lb	95th Percentile Axle Load, lb	95th Percentile Tire Load, lb
Steering Axle (single axle, single tire)	10,770	1,310	12,930	6465.0
Drive Axle Group (tandem axle, dual tire)	23,270	8,630	37,500	4687.5
Trailer Axle Group (tandem axle, dual tire)	21,870	10,570	39,320	4915.0

The trial pavement design was used in WESLEA to calculate the strains at the critical locations using the representative tire loading (the 95th percentile values) shown in Table 9 for the steering axle and the trailer axle group. Since WESLEA is limited to analyzing up to five layers, the surface and upper intermediate HMA layers were combined into one 5-in-thick layer and the lower intermediate and base HMA layers were combined into one 9-in-thick layer. The materials properties used as inputs in the multilayer elastic analysis are shown in Table 10. The layer moduli values were estimated based on Figures 2.5 and 2.6 from the AASHTO 1993 pavement design guide[22] using the typical VDOT layer coefficient values.[15]

The results of the multilayer elastic analysis using the representative tire loadings (at a tire pressure of 120 psi) are presented in Table 11. Table 11 shows that the developed pavement design, using the assumptions for material properties and tire loads, meets the suggested strain criteria for both the horizontal tensile and vertical compressive strains for both the steering axle and the trailer axle group. The results in Table 11 show that the trailer axle group is more damaging than the steering axle. Although the steering axle is usually given as the most damaging component, the large standard deviation of the trailer axle group pushed the 95th percentile axle load to a high value. If the same analysis were run with values at the 50th percentile, the steering axle would be found to be the most damaging.

Table 10. Materials Properties Inputs for Mutli-Layer Elastic Analysis

Material Input	Estimated Layer Modulus, psi	Poisson's Ratio	Thickness, in
AC	470,000	0.35	5.0
AC	390,000	0.35	9.0
Granular Base	42,000	0.35	8.0
Soil	12,000	0.25	12.0
Soil	8,000	0.40	infinite

Table 11. Results of Multi-Layer Elastic Analysis

Axle or Axle Group	Tensile Strain at Bottom of HMA Layers, $\mu\varepsilon$	Compressive Strain at Top of Subgrade, $\mu\varepsilon$
Critical Strain Value	70	200
Steering Axle	55.2	75.0
Trailer Axle Group	64.2	109.0

Mechanistic-Empirical Pavement Design Guide Analysis

Following this analysis, the Mechanistic-Empirical Pavement Design Guide Software (Version 0.900), developed under NCHRP Projects 1-37A and 1-40D,[7] was used to evaluate the trial pavement design in addition to several design alternatives. The purpose of the MEPDG software is much different than that of other traditionally used pavement design software in that its purpose is to *analyze* a pavement design rather than to develop one based on traffic loading or other criteria. All inputs (materials and traffic) were performed at Level 3, the lowest level of specificity. Level 3 default values are often regionalized values taken from previous work such as the Long-Term Pavement Performance (LTPP) program. Tables 12 and 13 show the specific values of traffic and materials, respectively, which were included in the MEPDG analysis. Traffic data that corresponded to the trial design location on I-81 were used. Gradation inputs for the MEPDG analysis were taken from average values of the corresponding mixes recently collected and tested at the Virginia Transportation Research Council (VTRC) laboratories. The average of three to four gradations was used as the input gradation for each mix during the MEPDG analysis. From Table 13 it is seen that the intermediate HMA layer is split into two layers. This allows for an independent analysis of the upper intermediate layer, where the highest compressive stresses are expected, from the bottom intermediate layer. In this way, it is possible to determine if producing a stiffer mix by binder modification is necessary throughout the entire intermediate mix or only the upper portions, potentially reducing overall material costs.

Table 12. MEPDG Analysis Traffic Inputs

Parameter	Value
AADTT	18,700
Number of lanes in design direction	2
Percent of trucks in design direction	50
Percent of trucks in the design lane	90
Operational speed	65 mph
Growth rate	6.4% (compound)

Table 13. MEPDG Analysis Materials Inputs

Layer No.	Material	Binder PG[a]	Thickness, in	Air Void, %	Eff. Binder Content (vol.), %	Unit Weight, lb/ft^3	% Retained			% Passing No. 200	Modulus, psi
							¾ in	3/8 in	No. 4		
1	SMA 12.5	70-22	2.0	6.0	16.1	152	0	38.1	68.9	11.7	
2	IM 19.0	64-22	3.0	6.0	10.3	152	1.1	25.0[b]	49.0[b]	6.0	
3	IM 19.0	64-22	3.0	6.0	10.3	152	1.1	25.0[b]	49.0[b]	6.0	
4	BM 25.0	64-22	6.0	6.0	11.3	148	14.9	35.0[b]	57.0[b]	5.2	
5	21-B		8.0								42,000
6	A-7-6 Subgrade (treated)		12.0								12,000
7	A-7-6 Subgrade		infinite								8,000

[a]Performance grade.
[b]Estimated.

Twenty-one trial designs, including the default pavement design, were processed using the MEPDG software. Each trial design represents the variation of only one property from the default design to determine the influence of each modification. Through conversations with VDOT officials statewide, it is generally recognized that fatigue cracking and rutting are the most prevalent distresses observed on Virginia's flexible pavements; therefore, the analysis was tailored to determine the influence of design changes on these distresses. Descriptions of the trial runs are as follows:

- Trial 1: Default pavement design
- Trial 2: Layer 1: PG 76-22 binder
- Trial 3: Layer 2: PG 70-22 binder
- Trial 4: Layer 2: PG 76-22 binder
- Trial 5: Layer 2: Increased binder content (optimum + 0.6%)
- Trial 6: Layer 2: Increased binder content (optimum + 1.2%)
- Trial 7: Layer 2: Increased binder content (optimum + 1.8%)
- Trial 8: Layer 4: PG 70-22 binder
- Trial 9: Layer 4: Increased binder content (optimum + 0.6%)
- Trial 10: Layer 4: Increased binder content (optimum + 1.2%)
- Trial 11: Layer 4: Increased binder content (optimum + 1.8%)
- Trial 12: Layer 4: Increased binder content (optimum + 2.4%)
- Trial 13: Layers 2 and 3: PG 70-22 binder
- Trial 14: Layers 2 and 3: PG 76-22 binder
- Trial 15: Layers 1, 2, and 3: PG 76-22 binder
- Trial 16: All HMA Layers: 4 percent voids
- Trial 17: Layer 1: 4 percent voids
- Trail 18: Layer 4: 4 percent voids
- Trial 19: All HMA Layers: 8 percent voids
- Trial 20: Layer 1: 8 percent voids
- Trial 21: Layer 4: 8 percent voids.

The MEPDG software calculated the anticipated deterioration and International Roughness Index (IRI) for each month of the analysis period using an incremental approach to calculate these parameters based on the traffic data and historical climatic data. The trial runs were designed to determine the predicted deterioration by varying specific materials properties. For this study, the results were focused on the calculated fatigue cracking and rutting of the HMA layers. The air void content default value of 6 percent was used since it is the default within the MEPDG software, typical in-place air void content values range from 6 to 10 percent. The calculated distress quantities for these criteria using the default pavement design (Trial 1) are presented for month 1 and years 5, 10, 15, and 20 in Table 14.

Table 14. Results of MEPDG Pavement Design Analysis for Trial 1 (Default Pavement Design)

Year	Calculated Distress	
	Fatigue Cracking, %	HMA layers rutting, in
0.08	0.00	0.06
5	0.14	0.23
10	0.33	0.34
15	0.59	0.44
20	0.95	0.55

Table 15 presents the results from the MEPDG trials in terms of the percent difference in fatigue cracking and HMA layers rutting at year 20 as compared to the default pavement design (Trial 1). For all distress criteria, a negative percent increase in deterioration indicates an improvement in pavement performance.

Table 15. Results of MEPDG Pavement Design Analysis for All Trials at Year 20

Trial No.	Description	% Difference in Calculated Distress from Default (Trial 1) at Year 20[a]	
		Fatigue Cracking, %	HMA layers rutting, in
2	Layer 1, 76-22	**-1.8**	**-8.4**
3	Layer 2, 70-22	**-1.5**	**-7.8**
4	Layer 2, 76-22	**-2.6**	**-13.9**
5	Layer 2, + 0.6%	0.7	2.7
6	Layer 2, + 1.2%	1.5	5.5
7	Layer 2, + 1.8%	2.1	8.0
8	Layer 4, 70-22	**-4.6**	0.7
9	Layer 4, + 0.6%	**-26.1**	**-0.2**
10	Layer 4, + 1.2%	**-42.0**	**-0.4**
11	Layer 4, + 1.8%	**-53.1**	**-0.5**
12	Layer 4, + 2.4%	**-63.9**	**-0.7**
13	Layers 2 & 3, 70-22	**-3.6**	**-7.3**
14	Layers 2 & 3, 76-22	**-6.8**	**-12.8**
15	Layers 1, 2, & 3, 76-22	**-8.6**	**-21.7**
16	All HMA, 4% voids	**-67.3**	**-12.4**
17	Layer 1: 4% voids	**-3.8**	**-7.8**
18	Layer 4: 4% voids	**-64.8**	**-0.5**
19	All HMA, 8% voids	152.6	17.9
20	Layer 1: 8% voids	4.5	10.9
21	Layer 4: 8% voids	130.5	0.4

[a]Improvement shown in bold.

DISCUSSION

Laboratory Test Results

The tests that were performed predicted change of field performance when asphalt was added to a conventional 19mm Superpave asphalt mixture that had actually been used as an intermediate mix layer under traffic. Additional asphalt can obviously have interactive effects where it may improve one characteristic but worsen another. Stability and rutting are two primary concerns as asphalt is increased above the amount of the conventional design. For this particular experiment, the laboratory rut tests showed that the rutting for the mixtures containing stiffer binder increased slightly when a small amount of asphalt was added. However, the rutting of those mixtures was generally less than the rutting of the conventional mixture containing PG 64-22 binder at optimum AC. The flexural stiffness measured in the fatigue tests showed a slight increase when the AC was increased approximately 0.5 percent. The fatigue tests also showed a considerable decrease in stiffness as the AC was increased further. If one optimizes the flexural stiffness, the additional asphalt should be limited to approximately 0.5 percent.

Potential change in durability at higher ACs was predicted using the fatigue, permeability, and stripping tests. The anticipated primary benefits of additional asphalt were to increase fatigue life and decrease air voids, which would, it is hoped, decrease permeability and aid in the prevention of stripping. The addition of asphalt benefited the fatigue life to some degree for all mixtures, although the most benefit occurred when the AC was increased more than 0.8 percent. It could not be explained why the fatigue life of the original mixture with an optimum AC tended to have a comparatively high fatigue life; however, except for polymer-modified mixtures, mixtures with lower stiffness will generally yield better fatigue properties under this type of test.

Substantially higher permeability was obtained with the conventional mixture containing PG64-22 binder at 7.0 percent air voids than with the other mixtures with stiffer asphalt binder and the mixture with 25 percent RAP at 7.0 percent air voids. Even though the air void content was equal for the mixtures, the degree of interconnectivity between air voids, which affects permeability, evidently differed. The permeability of the mixtures containing stiff binder and RAP was relatively low; therefore, there was room for little improvement when asphalt was added. However, some decrease in permeability occurred for two of the mixtures. The improvement would probably have been more impressive if the mixtures at optimum AC were very permeable.

The stripping tests did not indicate that additional asphalt was beneficial. Potentially, it was thought that a reduction in voids would allow less water to enter the mixture and reduce the stripping. Since the TSR test method requires that the conditioned test specimens be saturated to 70 to 80 percent, water is necessarily forced into the available voids; therefore, the beneficial effect of additional asphalt may not have been indicated by this particular test. In retrospect, a wheel load test underwater, similar to the Hamburg test, would possibly have been more appropriate for this investigation, but the TSR test was the only stripping test available in the VTRC laboratory.

Theoretical Pavement Analysis Results

MEPDG Analysis

With respect to this study, the MEPDG analysis predicted an increase in both fatigue cracking and rutting of the HMA layers if the binder content of an intermediate layer is increased beyond the optimum. Although the increase is small, it would not be advisable to increase the binder content of the intermediate layer unless some other significant improvement in pavement performance was offered. However, the MEPDG analysis showed that increasing the high-temperature performance grade would reduce both the amount of predicted fatigue cracking and rutting of the HMA layers. The change in predicted fatigue cracking was small (less than 3%). However, the change in predicted rutting of the HMA layers was up to nearly 14 percent when a PG 76-22 binder was used in Layer 2 versus the default PG 64-22 binder. A decrease in predicted rutting of nearly 8 percent was noted when a PG 70-22 binder was used versus the default PG 64-22 binder. Further analysis of the results indicated that performance improvements might be realized if the properties of other layers are optimized.

Table 15 shows that the design factors offering the largest improvement in fatigue cracking was reducing the air void content and increasing the binder content in the HMA base layer. Reducing the void content in all HMA layers from the default value of 6 percent to a value of 4 percent decreased the amount of predicted fatigue cracking by approximately two-thirds. When comparing Trial 18 vs. Trial 16, reduction of the air void content in Layer 4 alone accounted for nearly all the improvement in fatigue performance. This suggests placing an emphasis on improving in-place density of HMA base mixes, in addition to the current focus on surface mixes, is greatly beneficial to pavement performance. Increasing the binder content in Layer 4, the HMA base layer, also showed a significant improvement in fatigue cracking performance. The MEPDG analysis suggested that increases in binder content improved the fatigue cracking performance versus the default design from optimum + 0.6 percent all the way to optimum + 2.4 percent with decreased predicted fatigue cracking of approximately 26 percent and 64 percent, respectively. This increase in fatigue resistance was offered without a corresponding increase in rutting; although an additional 2.4 percent is higher than recommended amounts by others.[4,23] Increasing the stiffness of the various HMA layers by increasing the high-temperature binder performance grade also showed some influence on reducing the amount of predicted fatigue cracking; however, none of the trials reduced the amount predicted by more than 10 percent.

Table 15 also shows that the design factors offering the largest potential improvement in rutting performance was increasing the stiffness of the HMA layers by increasing the binder high-temperature performance grade and reducing the void content. The most influential areas to increase the stiffness and thus reduce the amount of predicted rutting in the HMA layers, according to the MEPDG trials, occurred when the binder performance grades of the surface and both intermediate layers were varied from 70-22 and 64-22, respectively, to 76-22 for all three layers. This change resulted in a predicted rutting reduction of approximately 23 percent from the default design. Increasing the binder performance grade of the upper-most intermediate HMA layer (Layer 2), from 64-22 to 76-22, decreased the predicted rutting by approximately 14 percent. Reducing the air void content in all HMA layers from 6 to 4 percent resulted in a predicted rutting decrease of approximately 12 percent. It is interesting to note that improvement from PG 64-22 to PG 70-22 in Layer 2 only (Trial 3) offered nearly the same improvement in rutting performance as increasing the high-temperature performance grade of Layer 1 from PG 70-22 to PG 76-22 (Trial 2). Given the high cost of PG 76-22 binder relative to an unmodified binder, it may be more cost-effective to employ PG 70-22 binder within the upper intermediate layers than to use PG 76-22 binder in the surface mix. When comparing Trials 3 and 13, it can be seen that nearly the same reduction in predicted rutting occurs when the binder performance grade is increased to 70-22 vs. 64-22 for the upper intermediate layer only (Trial 3) compared to increasing the binder performance grade in both intermediate layers (Trial 13). Therefore, the same performance may be achieved at a lower total cost. With a predicted rut depth of 0.55 in at year 20, it is likely that only the binder performance grade increase in all layers will result in a measurable difference in the field, as the maximum predicted reduction of 23 percent is approximately equal to one-eighth of an inch. However, designs of thinner pavement structures may produce a more measurable difference.

Table 15 also shows that an increase in voids in all HMA layers from 6 to 8 percent (Trial 19) increased the predicted fatigue cracking and rutting of the HMA layers by 1.5 times and approximately 18 percent, respectively. When the void content in all HMA layers decreases from 6 to 4 percent (Trial 16), the predicted fatigue cracking and rutting of the HMA layers decreases by approximately two-thirds and 12 percent, respectively. Specifically, when the void content of Layer 1 only (Trial 20) was increased to 8 percent, a nearly 11 percent increase in the rutting was predicted versus the default design. When the void content of Layer 4 only (Trial 21) was increased to 8 percent, an increase of approximately 130 percent was predicted for the fatigue cracking versus the default design. Conversely, Trial 17 indicates that if the void content of Layer 1 is reduced to 4 percent, the predicted rutting decreases by nearly 8 percent versus the default design. In addition, Trail 18 indicates that if the void content of Layer 4 is reduced to 4 percent, the predicted fatigue cracking decreases by approximately 65 percent. Trials 17 through 21 show the importance of minimizing excessive void contents in the field, especially within the HMA surface and base layers.

Considerations for In-place Air Voids Specifications

VDOT's current specifications for in-place air voids of HMA vary depending on the mix being placed.[24-26] For SMA mixes, the specifications require an in-place air void content of 2 to 6 percent (as measured from five cored or sawn samples from each day's production). However, VDOT's traditional Superpave mixes allow a higher in-place air void content. VDOT requires that a compacted course of Superpave material have an in-place air void content (by measuring the density) that is 98 to 102 percent that of the control strip. The maximum control strip in-place air void content for surface, intermediate, and base mixes ranges from 7.5 to 8.5 percent, depending on the mix type (based on an average of 10 readings). Since VDOT accepts an in-place air void content (based on density measurements) as a percentage of the control strip, VDOT could theoretically accept a pavement having an in-place air void content as high as 9.3 to 10.3 percent depending on mix type.

The results of the MEPDG analysis show that the predicted fatigue cracking when all HMA layers have 6 percent voids increases by approximately 150 percent when all HMA layers contain 8 percent voids; the increase appears to be accounted for mostly within the base HMA layer. Previous work suggests that air void contents should not exceed 6 to 7 percent to avoid excessive permeability in the mix.[14,27] Based on these findings, it is recommended that VDOT review the allowable in-place densities for HMA materials in pavements designed in accordance with long-life principles. In addition, the specifications are based on average values only and thus do not account for any variance in individual readings. The addition of a uniformity component to the current density specification (e.g., specifying a coefficient of variation) would aid in ensuring a uniformly long-lasting pavement.

CONCLUSIONS

Laboratory Study of Design of Asphalt Mixture with More Than Normal Amount of Binder and High Stiffness

- Predicted field voids decrease approximately 1.0 to 1.5 percent for each 0.4 percent increase in AC.

- The maximum stiffness occurs at an AC approximately 0.5 percent above the optimum AC.

- Fatigue properties improve with an increase in AC although the improvement is not major until the AC is increased approximately 1.0 percent above the optimum AC.

- Mixtures with PG 76-22 binder are associated with the greatest fatigue life of any of the mixtures that were tested.

- Some improvement in permeability over the mixture containing conventional PG 64-22 binder is achieved for mixtures containing stiff binders and RAP.

- There seems to be no advantage of adding binder and decreasing voids. The Hamburg test would probably have been more appropriate for this study.

- The laboratory rut depths are generally less than that of the conventional mixture containing PG 64-22 binder that has been used in field construction; therefore, rutting is unlikely.

Theoretical Analysis of Developed Pavement Design Using MEPDG Software

- Increasing the binder content of the HMA intermediate layer beyond the design optimum slightly increases the predicted fatigue cracking and predicted rutting of the HMA layers.

- Increasing the high-temperature binder performance grade of the HMA intermediate layer decreases the predicted rutting of the HMA layers but only slightly reduces the predicted fatigue cracking.

- Increasing the high-temperature binder performance grade of the upper intermediate layer (Layer 2) offers a similar decrease in predicted rutting of the HMA layers than if the same modification was made to both intermediate layers (Layers 2 and 3), thus a cost savings may be realized by modifying the binder of only one layer.

- Increasing the high-temperature performance grade of both intermediate layers (Layers 2 and 3) slightly decreases the predicted fatigue cracking versus increasing the high-temperature performance grade of the upper intermediate layer (Layers 2) only, again a cost savings may be realized if the binder of only one layer is modified.

- A similar reduction of both the predicted fatigue cracking and predicted rutting of the HMA layers was noted when the high-temperature binder performance grade of the upper intermediate layer (Layer 2) was changed from PG 64-22 to PG 70-22 as when the high-temperature binder performance grade of the surface layer (Layer 1) was changed from PG 70-22 to PG 76-22. A cost savings may be realized if the difference in price between a PG 64-22 and a PG 70-22 is less than the difference in price between a PG 70-22 and a PG 76-22 binder.

- Increasing the binder content of the HMA base layer beyond the design optimum greatly decreases the predicted fatigue cracking.

- Reducing the void content of all HMA layers significantly reduces the predicted fatigue cracking and slightly reduces the predicted HMA layer rutting; most of the improvement in fatigue cracking performance is gained in the base HMA layer.

RECOMMENDATIONS

1. *VTRC should quantify the difference in fatigue performance of HMA base mixes when the binder content is increased beyond the optimum versus HMA base mixes produced at the optimum binder content.*

2. *VTRC should quantify the difference in fatigue performance of HMA base mixes at varying air void contents and develop recommendations for acceptance of in-place materials.*

3. *VTRC should study the statistical variation of HMA in-place density to assess the effects of non-uniformity.*

4. *VDOT's Materials Division and VTRC should study the current criteria for in-place air voids to determine if they are providing the desired pavement performance based on pavement modeling, laboratory study, and the results of previous research.*

COSTS AND BENEFITS ASSESSMENT

This project provides a stepping stone to achieve long-lasting perpetual-type flexible pavement. Designs with a high binder content offer the potential to reduce fatigue cracking 20 to 60 percent by incorporating additional asphalt binder and reducing the void content of asphalt base. The use of RAP to maintain the necessary stiffness for high binder contents should provide comparable stiffness to an increasingly expensive PG 70-22 binder for base material. Some effort is underway to reduce the air voids in HMA base mixes through specification revision; however, quantification of the economic benefits from that endeavor will be a future goal.

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