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Impact of Rich-Bottom Design in Asphalt Pavements

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Abstract: This paper evaluates the impact of rich-bottom design on the performance of HMA pavements. Based on national experience, the rich-bottom mix is defined as having a binder content that is 0.5% higher than the optimum binder content. Four optimum and four rich dense graded hot mix asphalt (HMA) mixes were designed and evaluated using unmodified and polymer-modified asphalt binders. An extensive laboratory evaluation was undertaken to determine the mixture's properties, such as resilient modulus, as well as its fatigue and rutting characteristics. Additionally, mechanistic analyses were conducted for a total of twenty-four pavement structures to first assess the gain in fatigue life for an additional cost in the rich-bottom mix and secondly to assess the relative cost in asphalt mixes for achieving the same fatigue performance as the control pavement structure. Based on the data generated from the laboratory experiment and the mechanistic analyses, several conclusions were made. The data show that the rutting resistance of the rich mix is similar to its corresponding optimum mix, supporting the use of polymer-modified mixes in the top lift. In general, the rich-bottom design increased the fatigue life of the pavement structure when compared to the conventional pavement structure. The cost analysis shows a cost-effective design for the rich-bottom pavement structures.

***Key words**: Benefit-Cost; Fatigue; HMA; Mechanistic; Polymer-modified; Rich-bottom layer; Rutting.*

Introduction

Rutting and fatigue cracking are among the most common mode of failures that hot mix asphalt (HMA) pavements experience under the combined action of traffic loads and environmental conditions. Rutting of HMA pavements can be caused by either the shear failure of the HMA mixture or the compressibility of the HMA and supporting layers (e.g. base course and subgrade or a combination of both). On the other hand, fatigue cracking is characterized by longitudinal and interconnected cracks in the wheel-tracks. The resistance of the HMA mixture to fatigue cracking is measured in terms of its ability to resist cracking under repeated loads generating a given level of a tensile strain. As the asphalt binder ages, it becomes brittle and incapable of absorbing the load-induced tensile strains at the bottom of the HMA layer.

The resistance of HMA pavements to these failures is dependent upon the proper selection of materials (asphalt binder and aggregates), good mixture design, adequate structural thickness design, and proper construction. Any defects in these components would lead to the failure of the pavement, which in turn would require additional funds for rehabilitation and cause unfavorable delays to users and significant financial losses to the surrounding businesses.

It is a challenge for the materials engineer to design an HMA mix that has superior resistance to both rutting and fatigue cracking. An HMA mix with superior rut resistance would be designed at lower binder content than an HMA mix that is designed for superior fatigue resistance. In other words, all other things being equal, the lower the binder content of the mix the better its resistance to rutting will be, while the higher the binder content of the mix the better its resistance to fatigue cracking will be.

One way of handling these two contradicting requirements is to design and construct the HMA layer in multiple lifts. This approach is plausible since the high shear strains generating rutting in the HMA layer are located near the top of the layer, while the high tensile strains generating fatigue cracking are located at the bottom of the HMA layer. Therefore, if the top lift is designed with a lower binder content, its rut resistance will be improved, and if the bottom lift is designed with a higher binder content, its fatigue resistance will be improved. However, additional concerns about the long-term durability of the HMA layer restrict the use of a low binder content mix near the surface. This leads to the use of the optimum mix design in the top lift and a rich mix in the bottom lift, hence the name of "rich-bottom design."

The rich bottom mixture is the standard mixture used in the pavement section with, typically, an additional 0.5% asphalt binder added. This mixture is then compacted in the field to 2-4% air voids. This compaction requirement is different from standard mixtures, which are typically only compacted to an air void level of 6-8%. This extra compaction, aided by the additional asphalt content, is expected to produce an increased modulus in the mixture that will improve the structural response of the section. Additionally, the added asphalt content is anticipated to provide a more fatigue resistant mixture.

Background

Asphalt mixtures in pavements are subjected to a wide range of load and environmental conditions. The response to these conditions is complex and involves the elastic, viscoelastic and plastic characteristics of the material. Thus, recommending satisfactory mixture and structural designs for HMA pavements requires an understanding of both the load deformation response and the

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strength properties of the materials to be used for the range of loading conditions.

HMA pavement materials, like all other paving materials, exhibit a variety of distresses. The mechanistic-empirical design method handles each failure criterion separately to take care of each specific distress. As pavements approach their design life, distresses are expected to occur as a result of the combined actions of the environment and repeated traffic loading. Permanent deformation (i.e. rutting) and fatigue cracking are the two primary distress mechanisms that can be present in asphalt concrete and are directly related to the combined actions of the environment and traffic loads.

The major factors influencing rutting failure are low mixture stiffness, high initial air voids, high asphalt content, excessive filler material, many round aggregates, heavy vehicle loads and high service temperature. Permanent deformation of more than 12.5 mm might cause water to pond on the pavement surface, which threatens safety and encourages other pavement distresses.

The major factors influencing fatigue cracking are low asphalt content, higher air voids, excessive repetition of heavy loads, insufficient pavement drainage, inadequate pavement thickness, and detrimental environmental factors. Fatigue cracking of the HMA layer initiates at the bottom of the layer, where the tensile strain is highest under a wheel load. The cracks propagate to the surface initially as one or more longitudinal or transverse cracks. After repeated traffic loading, the cracks connect and form many-sided, sharp angled pieces that develop a pattern resembling chicken wire or the skin of an alligator.

Over the last three to four decades in pavement technology, it has been common to assume that fatigue cracking normally initiates at the bottom of the asphalt layer and propagates to the surface (bottom-up cracking). This is due to the bending action of the pavement layer that results in flexural stresses to develop at the bottom of the bound layer. However, numerous recent worldwide studies have also clearly demonstrated that fatigue cracking may also be initiated from the top and propagate down (top-down cracking) [1]. This type of fatigue is not as well defined from a mechanistic viewpoint as the more classical “bottom-up” fatigue. However, with the current state of knowledge, it is a reasonable engineering assumption that this distress may be due to critical tensile and/or sheer stresses that develop at the pavement surface. These conditions, perhaps, are caused by extremely large contact pressures at the tire edge pavement interface coupled with a highly aged (stiff) surface layer that has become oxidized.

For most pavement structures and typical traffic loads, fatigue cracking is assumed to begin at the bottom of the asphalt concrete layer, where tensile strains are usually largest. Here, large asphalt contents would be most beneficial [2].

The placement of fatigue resistant mixes near the bottom of the asphalt concrete layers of the pavement and the use of more rut resistant mix near the surface has been the standard practice in Australia for more than 15 years [2]. A variation on this type of structure is termed “rich bottom.” In order to simplify construction, the rich bottom structure uses the same asphalt binder grade and aggregates found in the upper layers of the asphalt concrete with the rich bottom layer asphalt content being 0.5% over the target determined for the upper layers [2].

The California Department of Transportation (Caltrans) needs to rehabilitate or reconstruct much of its network of urban freeway pavements. Elements of the strategy evaluated include the use of a rich bottom asphalt concrete layer with enhanced fatigue properties, improved compaction of the asphalt concrete, use of rut resistant mixes in the critical zone for mix rutting, and a subgrade rutting criteria. The replacement of the asphalt concrete includes a bottom layer 50 mm to 80 mm thick (rich bottom) that has improved fatigue properties. The enhanced fatigue properties of the bottom asphalt layer are achieved by increasing the asphalt content by about 0.5% over the optimum and compacting to an in-place density of about 98% [2].

Increased asphalt content means increased thickness of the binder film throughout the mix and an increased proportion of asphalt over a cross-section normal to the direction of tensile strain. Since bending strains are concentrated in the asphalt binder, which is much more compliant than the stiffer aggregate particles, thicker films result in smaller binder strain if the overall mixture strain is not altered by the added asphalt. Moreover, because tensile stresses must ultimately be transferred through the asphalt, more asphalt means more asphalt area in the cross-section and, hence, less stress in the asphalt [3].

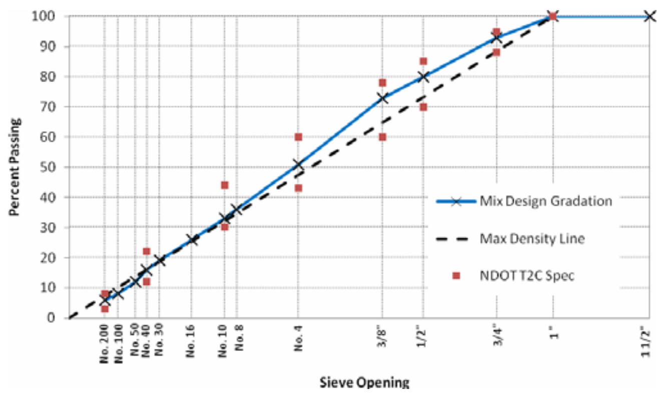
In 1996, researchers at the University of California at Berkley investigated the application of the rich bottom strategy in California [3]. The experimental laboratory program to study the effectiveness of air voids and asphalt content consisted of three air void contents, five asphalt contents, two strain levels and three replicates. An AR-4000 California Valley asphalt binder and Watsonville granite aggregate were used in this experiment. Laboratory prepared specimens compacted to the target air void contents were tested for fatigue resistance using the controlled-strain flexural beam fatigue test at a temperature of 19±1°C and a loading frequency of 10Hz. Based on the produced fatigue test data, the following conclusions were made. For controlled strain testing, an increase in asphalt content resulted in an increase in laboratory fatigue life, whereas an increase in air void contents resulted in a decrease in laboratory fatigue life.

Objective

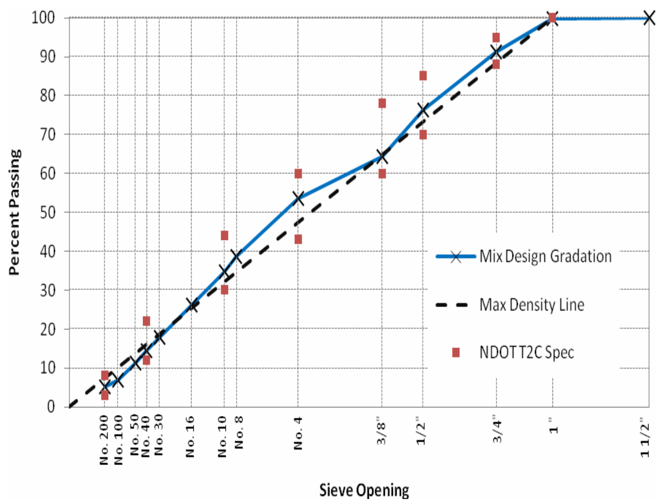
The objective of this paper is to evaluate the impact of rich bottom design on the performance of HMA pavements. Based on national experience, the rich bottom mix was defined as having a binder content that is 0.5% higher than the optimum binder content. The comparative performance of HMA pavements were evaluated through a mechanistic-empirical pavement analysis process.

Materials and Mix Designs

This study evaluates the typical mixtures used in the state of Nevada, U.S. Typically used aggregate sources from the northern and southern parts of Nevada were used in this research. The northern and southern aggregates were sampled from the Lockwood and Sloan pits, respectively. Each source was sampled from the available stockpiles at the time of the research’s conduct. Standard unmodified and polymer-modified asphalt binders were used with each aggregate source obtained from common suppliers in the north



(a)



(b)

Fig. 1 Aggregate Blend Gradations for a) Lockwood and b) Sloan.

and south:

- PG64-22: unmodified asphalt binder commonly used in the northern part of the state.
- PG64-28: polymer-modified asphalt binder commonly used in the northern part of the state.
- PG70-16: unmodified asphalt binder commonly used in the southern part of the state.
- PG76-22: polymer-modified asphalt binder commonly used in the southern part of the state.

Following the Nevada Department of Transportation (NDOT) specifications, all four mixtures were designed using the Hveem method as outlined in the NDOT mix design specifications. Fig. 1 shows the blend gradations for the Lockwood and Sloan aggregate sources. It should be noted that both blend gradations followed the NDOT Type 2C specifications for dense graded asphalt mixtures. Table 1 shows the optimum binder contents for all four mixes at the design air voids, which ranged between 4% and 5.5%. The rich bottom mixes were produced by increasing the optimum asphalt binder content by 0.5% (see Table 1).

Pavement Structures

For each aggregate source the following pavement structures were evaluated. The pavement structures included two different asphalt layer thicknesses: 150 mm and 200 mm.

- Full depth un-modified asphalt binder at optimum binder contents.
- HMA layer with un-modified asphalt binder at optimum binder content in the top lift and an unmodified rich bottom lift.
- Full depth polymer-modified asphalt binder at optimum binder contents.
- HMA layer with polymer-modified asphalt binder at optimum binder content in the top lift and a polymer-modified rich bottom lift.
- HMA layer with polymer-modified asphalt binder in the top lift and an un-modified asphalt binder in the bottom lift at optimum binder contents.
- HMA layer with polymer-modified asphalt binder at optimum binder content in the top lift and an un-modified rich bottom lift.

In summary, a total of twenty-four pavement structures were analyzed. Table 2 shows the layout of the various pavement structures for the northern and southern parts of the state.

Laboratory evaluation

The objective of the laboratory evaluation was to measure the properties of the mixtures that will be used in the mechanistic-empirical analysis process. The mechanistic-empirical analysis models the pavement structure as a multi-layer elastic system with each layer represented by its elastic modulus and Poisson's ratio. The responses of the multi-layer system under a standard axle are calculated in terms of deformations, stresses, and strains.

The Poisson's ratio is defined as the ratio of the lateral strain over the axial strain. The Poisson's ratio of the HMA mixture is assumed at a constant value of 0.35. The elastic moduli of the various HMA mixtures were measured in the laboratory using the resilient modulus (Mr) test at 25°C following ASTM D7369 [6]. The assumed Poisson's ratio and the measured stiffness of each layer in the pavement structure are used in the multi-layer elastic solution to calculate the responses of the pavement structure under traffic loading.

In order to evaluate the impact of rich bottom design on the fatigue performance of the HMA pavement, the fatigue characteristics of each mixture were measured following AASTHO T21 [7]. Additionally, The Asphalt Pavement Analyzer (APA) was used to evaluate the impact of rich bottom design on the rutting performance of the HMA mix.

Analysis of Laboratory Data

This section examines the resilient modulus (*Mr*) property and the fatigue and rutting characteristics of all four mixtures at the optimum binder content and at the optimum plus 0.5% (i.e. rich mix).

Resilient Modulus

The repeated load indirect tension test for determining the *Mr* property of HMA mixtures was used in this research [6]. The test is

Table 1. Asphalt Mixtures Properties

Mix ID*	Binder Grade	Binder Content (%)	Resilient Modulus at 25°C (MPa)	Fatigue Model+	APA Rut Depth After 8,000 Cycles at 60°C (mm)
L6422-Opt	PG64-22	4.13	3,482	$N_f = 9.513\times10^{-11}\left(\frac{1}{\varepsilon}\right)^{4.335}$	3.81
L6422-Rich	PG64-22	4.63	4,206	$N_f = 1.774\times10^{-7}\left(\frac{1}{\varepsilon}\right)^{3.425}$	4.32
L6428-Opt	PG64-28	4.31	1,517	$N_f = 4.146\times10^{-13}\left(\frac{1}{\varepsilon}\right)^{5.484}$	1.52
L6428-Rich	PG64-28	4.81	1,689	$N_f = 4.127\times10^{-20}\left(\frac{1}{\varepsilon}\right)^{7.986}$	1.02
S7016-Opt	PG70-16	3.67	7,033	$N_f = 1.516\times10^{-9}\left(\frac{1}{\varepsilon}\right)^{3,847}$	3.81
S7016-Rich	PG70-16	4.17	7,757	$N_f = 2.573\times10^{-11}\left(\frac{1}{\varepsilon}\right)^{4.389}$	2.79
S7622-Opt	PG76-22	3.67	1,655	$N_f = 2.752\times10^{-8}\left(\frac{1}{\varepsilon}\right)^{3.957}$	1.27
S7622-Rich	PG76-22	4.17	2,551	$N_f = 1.373\times10^{-7}\left(\frac{1}{\varepsilon}\right)^{3.705}$	0.76

* L denotes Lockwood, S denotes Sloan, Opt denotes Optimum Binder Content, and Rich denotes Rich Mix.

Table 2. Pavement Structures.

HMA Mix Type (Northern Mixes - Lockwood)					
150 mm HMA Layer on Top of CAB*			200 mm HMA Layer on Top of CAB*		
Top Lift (50 mm)	Bottom Lift (100 mm)	Pavement Structure ID	Top Lift (50 mm)	Bottom Lift (150 mm)	Pavement Structure ID
L6422-Opt	L6422-Opt	N1Opt	L6422-Opt	L6422-Opt	N4Opt
L6422-Opt	L6422-Rich	N1Rich	L6422-Opt	L6422-Rich	N4Rich
L6428-Opt	L6428-Opt	N2Opt	L6428-Opt	L6428-Opt	N5Opt
L6428-Opt	L6428-Rich	N2Rich	L6428-Opt	L6428-Rich	N5Rich
L6428-Opt	L6422-Opt	N3Opt	L6428-Opt	L6422-Opt	N6Opt
L6428-Opt	L6422-Rich	N3Rich	L6428-Opt	L6422-Rich	N6Rich
HMA Mix Type (Southern Mixes - Sloan)					
150 mm HMA Layer on Top of CAB*			200 mm HMA Layer on Top of CAB*		
Top Lift (50 mm)	Bottom Lift (100 mm)	Pavement Structure ID	Top Lift (50 mm)	Bottom Lift (150 mm)	Pavement Structure ID
S7016-Opt	S7016-Opt	S1Opt	S7016-Opt	S7016-Opt	S4Opt
S7016-Opt	S7016-Rich	S1Rich	S7016-Opt	S7016-Rich	S4Rich
S7622-Opt	S7622-Opt	S2Opt	S7622-Opt	S7622-Opt	S5Opt
S7622-Opt	S7622-Rich	S2Rich	S7622-Opt	S7622-Rich	S5Rich
S7622-Opt	S7016-Opt	S3Opt	S7622-Opt	S7016-Opt	S6Opt
S7622-Opt	S7016-Rich	S3Rich	S7622-Opt	S7016-Rich	S6Rich

*Crushed Aggregate Base (CAB)

conducted by applying a compressive load with a haversine waveform (loading = 0.1 sec and rest = 0.9 sec) on the vertical diametral plane of a cylindrical specimen. The mixtures at the optimum binder content were compacted using the Superpave gyratory compactor to 7±0.5% air voids, while the rich mixtures were compacted to 3±0.5% air voids. The two air voids level were selected to mimic the in-place air voids of optimum and rich designs. Table 1 summarizes the Mr property for the various mixtures at 25°C. The 25°C temperature was selected to simulate the environmental condition that is critical to fatigue cracking and to correspond with the temperature of the laboratory fatigue testing.

The data in Table 1 shows a higher stiffness for the rich mix when compared to the corresponding optimum mix design. Additionally, the polymer-modified mixtures exhibited a significantly lower stiffness than the unmodified mixtures.

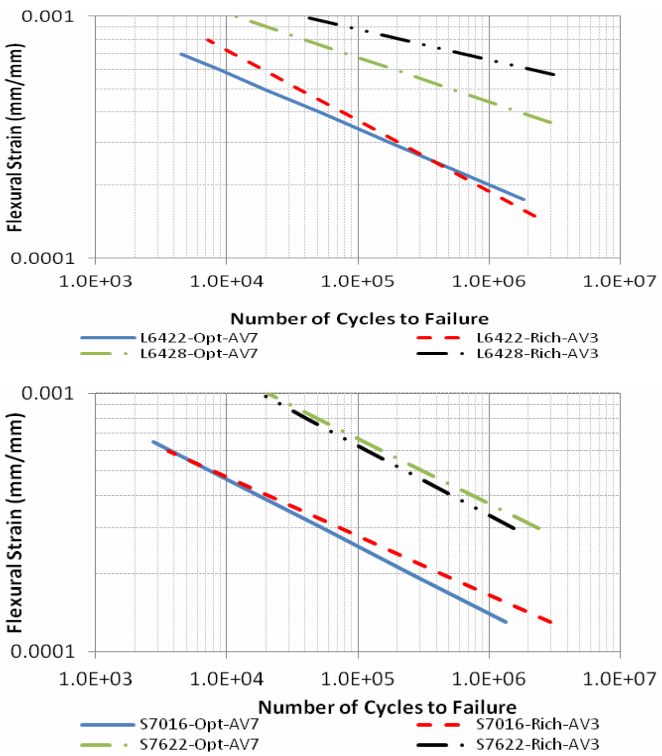


Fig. 2. Fatigue Relationships for all Mixtures

Fatigue Characteristics

The resistance of the HMA mixtures to fatigue cracking was evaluated using the flexural beam fatigue test standardized under AASHTO T321 [7]. The beam specimen is subjected to 4-point bending with free rotation and horizontal translation at all load and reaction points. This produces a constant bending moment over the central portion of the specimen. The test can be run in either a constant strain mode or a constant stress mode. Experience has shown that pavements with an asphalt layer thickness larger than 200 mm generally perform closer to a constant stress mode in the field, while pavements with asphalt layer thickness less than 200 mm generally perform closer to a constant strain mode in the field. In this research, the constant strain tests were conducted at different strain levels using a repeated pulse load at a frequency of 10 Hz and a test temperature of 25ºC. The initial flexural stiffness was measured at the 50th load cycle. Fatigue life or failure was defined as the number of cycles corresponding to a 50% reduction in the initial flexural stiffness. The controlled strain mode model shown below was used to characterize the fatigue behavior of each of the evaluated HMA mixtures:

$$N_f = k_1 \left(\frac{1}{\varepsilon_t} \right)^{k_2} \tag{1}$$

where N_f is the fatigue life (number of load repetitions to fatigue failure), ε_t is the applied tensile strain, and k_1 and k_2 are experimentally determined regression coefficients. The models require field calibration in order to provide the in-service fatigue life of an asphalt pavement.

The fatigue models for the various mixtures are shown in Table 1. Fig. 2 shows the relationship between the strain and the number of cycles to failure for all the mixtures at 25°C. There is a logarithmic inverse relationship between the level of strain and the number of cycles to failure. In other words, the higher the strain the lower the number of cycles to failure.

Fig. 2 indicates similar fatigue relationships between the optimum and the rich mixtures, except for the rich PG64-28 mix that exhibited better fatigue resistance than the PG64-28 mix at all strain levels. Additionally, the polymer-modified mixes exhibited significantly better fatigue resistance than the unmodified mixtures.

However, a significant difference in the laboratory fatigue resistance will not necessarily translate to the same difference in fatigue performance in the field. The fatigue life of an asphalt pavement is highly dependent on the modulus, the fatigue characteristics of the HMA mixture, and their interaction. In a mechanistic pavement analysis, an HMA layer with a higher stiffness will show a lower laboratory fatigue life, but on the other hand, it will produce a lower tensile strain under field loading. Therefore, depending on the magnitude of strain reduction, the HMA layer with the higher stiffness may result in a longer fatigue life in the field or vice-versa. Therefore, a full mechanistic analysis is needed to effectively evaluate the impact of rich bottom design on the fatigue performance of an HMA pavement.

Rutting Characteristics

The various mixtures were evaluated for rutting resistance using the asphalt pavement analyzer (APA) test in accordance with AASHTO TP63 [8]. The test consists of subjecting compacted HMA specimens to a loaded concave wheel that travels along a pressurized rubber hose that rests upon the HMA sample. Cylindrical samples with 150 mm diameter were compacted for each mix using the Superpave Gyratory Compactor (SGC) to a height of 76.2 mm. Four replicates were prepared and tested at the same time for each mixture. Samples were secured within form-fitting acrylic blocks during testing. The APA wheel load was 444.8 N, and the hose pressure was 690 kPa. The samples were conditioned for six hours at the testing temperature before being tested in the dry condition at 60°C under 8,000 cycles. A data acquisition program recorded rut depth at two points within each sample, and their average is reported.

Table 1 summarizes the average rut depth data from the APA test at 60°C for all mixtures. A maximum of 8.0 mm rut depth after 8,000 cycles at 60°C has been used as a general failure criterion by the Nevada DOT. The APA data in Table 1 show that the rich mixes exhibit statistically similar resistance to rutting as the corresponding mixes at optimum design. For example, the rich PG64-22 mix exhibits a rut depth of 4.3 mm, while the PG64-22 mix at optimum binder content exhibits a rut depth of 3.8 mm. On the other hand, the PG64-28 polymer-modified mix exhibits a significantly better resistance to rutting than both the PG64-22 optimum and rich design. Similarly, the PG76-22 polymer-modified mix exhibits a significantly better resistance to rutting than both the PG70-16 optimum and rich design. This data support the use of the polymer modified mixture (PG64-28 and PG76-22) in the top HMA lift where rutting potential is normally high.

Pavement Performance Analysis

The objective of this analysis is to evaluate the impact of the rich bottom lift on the performance of HMA pavements. The mechanistic-empirical analysis was used in conjunction with the fatigue characteristics data that were measured on all eight mixtures to assess the fatigue performance of HMA pavements. Table 2 summarizes the pavement structures evaluated.

The mechanistic-empirical method of analysis is based on the multi-layer elastic solution that relates an input, such as a wheel load, to pavement responses, such as stresses, strains, and deflections. This research used the ELSYM5 program to analyze the structures. ELSYM5 provides a multi-layer elastic solution for a pavement subjected to static loads. In this analysis, the axle load was assumed at 98 kN/single axle and dual tires at an inflation pressure of 860 kPa. These conditions represent the most common legal load limits in the U.S. The modulus properties of the base course and subgrade were assumed at 207 MPa and 55 MPa, respectively. The Poisson's ratio of the base course and subgrade were assumed at 0.40 and 0.45, respectively. The laboratory measured resilient moduli were assigned to the corresponding HMA layers in the various mechanistic analyses (Table 1).

The tensile strain at the bottom of the HMA is calculated for each pavement structure. The calculated tensile strains from each structure are input into the corresponding fatigue relationship to calculate the number of load repetitions to fatigue failure. It should be mentioned that the developed fatigue performance models are statistical relationships based on the laboratory analysis of the asphalt mixes. Therefore, field shift/adjustment factors are required to provide reasonable estimates of the actual performance in the field. The field shift factors are outside the scope of this research, and the laboratory based performance models were only used for a relative comparison. The mechanistic analysis was conducted to achieve the following two objectives:

1. Assess the gain in fatigue life for an additional cost in rich HMA mixes.
2. Assess the relative cost in asphalt mixes to achieve the same fatigue performance.

In order to achieve the first objective, the numbers of load repetitions to fatigue failure from each pavement structure were

Table 3. Number of Load Repetitions to Fatigue Failure.

			Northern Mixes		
Pavement Structure ID	Top Lift (50 mm)	Bottom Lift (100 mm)	Tensile Strain at the Bottom of HMA Layer, (Micro-strain)	Number of Repetitions to Fatigue Failure, N_f	Increase in Fatigue life, N_f
N1Opt	L6422-Opt	L6422-Opt	242	455,380	32%
N1Rich	L6422-Opt	L6422-Rich	220	600,985	
N2Opt	L6428-Opt	L6428-Opt	378	2,436,000	> 1130%
N2Rich	L6428-Opt	L6428-Rich	362	> 30,000,000	
N3Opt	L6428-Opt	L6422-Opt	263	315,680	40%
N3Rich	L6428-Opt	L6422-Rich	240	443,335	
Pavement structure ID	Top Lift (50 mm)	Bottom Lift (150 mm)	Tensile Strain at the Bottom of HMA Layer, (Micro-strain)	Number of Repetitions to Fatigue Failure, N_f	Increase in Fatigue life, N_f
N4Opt	L6422-Opt	L6422-Opt	169	2,156,620	-2%
N4Rich	L6422-Opt	L6422-Rich	152	2,104,780	
N5Opt	L6428-Opt	L6428-Opt	272	14,717,300	> 105%
N5Rich	L6428-Opt	L6428-Rich	260	> 30,000,000	
N6Opt	L6428-Opt	L6422-Opt	183	1,512,040	5%
N6Rich	L6428-Opt	L6422-Rich	166	1,583,325	
			Southern Mixes		
Pavement structure ID	Top Lift (50 mm)	Bottom Lift (100 mm)	Tensile Strain at the Bottom of HMA Layer, (Micro-strain)	Number of Repetitions to Fatigue Failure, N_f	Increase in Fatigue Life, N_f
S1Opt	S7016-Opt	S7016-Opt	154	698,325	150%
S1Rich	S7016-Opt	S7016-Rich	146	1,747,780	
S2Opt	S7622-Opt	S7622-Opt	362	1,136,095	36%
S2Rich	S7622-Opt	S7622-Rich	300	1,542,865	
S3Opt	S7622-Opt	S7016-Opt	184	356,255	125%
S3Rich	S7622-Opt	S7016-Rich	175	801,880	
Pavement Structure ID	Top Lift (50 mm)	Bottom Lift (150 mm)	Tensile Strain at the Bottom of HMA Layer, (Micro-strain)	Number of Repetitions to Fatigue Failure, N_f	Increase in Fatigue Life, N_f
S4Opt	S7016-Opt	S7016-Opt	105	3,047,930	212%
S4Rich	S7016-Opt	S7016-Rich	99	9,525,110	
S5Opt	S7622-Opt	S7622-Opt	260	4,209,955	32%
S5Rich	S7622-Opt	S7622-Rich	212	5,566,255	
S6Opt	S7622-Opt	S7016-Opt	123	1,665,240	188%
S6Rich	S7622-Opt	S7016-Rich	116	4,789,060	

Table 4. Equivalent Bottom HMA Lift Thicknesses of all Structures.

Pavement Structure ID	Top Lift (50 mm)	Mix Type	Bottom Lift: Equivalent Bottom HMA Lift Thickness (mm)	Bottom Lift: Round up of bottom HMA lift thickness to the nearest 5 mm (mm)	Total HMA Thickness (mm)
Northern Mixes					
N1Opt*	L6422-Opt	L6422-Opt	100		150
N1Rich	L6422-Opt	L6422-Rich	95	95	145
N2Opt*	L6428-Opt	L6428-Opt	100		150
N2Rich	L6428-Opt	L6428-Rich	38	40	90
N3Opt*	L6428-Opt	L6422-Opt	100		150
N3Rich	L6428-Opt	L6422-Rich	89	90	140
Pavement Structure ID	Top Lift (50 mm)	Mix Type	Equivalent Bottom HMA Lift Thickness (mm)	Round up of Bottom HMA Lift Thickness to the Nearest 5 mm (mm)	Total HMA Thickness (mm)
N4Opt*	L6422-Opt	L6422-Opt	150		200
N4Rich	L6422-Opt	L6422-Rich	159	160	210
N5Opt*	L6428-Opt	L6428-Opt	150		200
N5Rich	L6428-Opt	L6428-Rich	70	70	120
N6Opt*	L6428-Opt	L6422-Opt	150		200
N6Rich	L6428-Opt	L6422-Rich	150	150	200
Southern Mixes					
Pavement Structure ID	Top Lift (50 mm)	Mix Type	Equivalent Bottom HMA Lift Thickness (mm)	Round up of Bottom HMA Lift Thickness to the Nearest 5 mm (mm)	Total HMA Thickness (mm)
S1Opt*	S7016-Opt	S7016-Opt	100		150
S1Rich	S7016-Opt	S7016-Rich	76	80	130
S2Opt*	S7622-Opt	S7622-Opt	100		150
S2Rich	S7622-Opt	S7622-Rich	95	95	145
S3Opt*	S7622-Opt	S7016-Opt	100		150
S3Rich	S7622-Opt	S7016-Rich	83	85	135
Pavement Structure ID	Top Lift (50 mm)	Mix Type	Equivalent Bottom HMA Lift Thickness (mm)	Round up of Bottom HMA Lift Thickness to the Nearest 5 mm (mm)	Total HMA Thickness (mm)
S4Opt*	S7016-Opt	S7016-Opt	150		200
S4Rich	S7016-Opt	S7016-Rich	121	125	175
S5Opt*	S7622-Opt	S7622-Opt	150		200
S5Rich	S7622-Opt	S7622-Rich	145	145	195
S6Opt*	S7622-Opt	S7016-Opt	150		200
S6Rich	S7622-Opt	S7016-Rich	127	130	180

* Control pavement structures

compared. Table 3 summarizes the tensile strain at the bottom of the 150 mm and 200 mm HMA layers and the number of load repetitions to fatigue failure for all evaluated structures.

In general, Table 3 shows that the rich bottom design significantly increases the fatigue life of the pavement structure more than the structure that has a bottom lift with the optimum mix. For example, the number of cycles to fatigue failure in the 150 mm HMA layer of structure N1Rich shows a higher number of cycles to fatigue failure than structure N1Opt by 32%. Only in the case of 200 mm HMA layer for the northern mix does the PG64-22 rich bottom and optimum designs (i.e. N4Rich and N4Opt) show very similar number of cycles to fatigue failure.

In the case of northern mixes, the number of cycles to fatigue failure increased significantly when the polymer-modified PG64-28 mix was used in the top and bottom lifts (i.e. N2Opt and N5Opt pavement structures). Additionally, the use of the PG64-28 rich design in the bottom lift (i.e. N2Rich and N5Rich pavement structures) further improved the fatigue resistance of the pavement.

In the case of southern mixes, the increase in fatigue life was more significant for the PG70-16 rich designs (i.e. S1Rich and S4Rich) when compared to the PG76-22 rich designs (S2Rich and S5Rich).

When polymer-modified mixes (i.e. L6428-Opt and S7622-Opt) were used in the top lift to improve rutting resistance and the corresponding unmodified optimum mixes (i.e. L6422-Opt and S7622-Opt) were used in the bottom lifts, lower resistance to fatigue cracking was observed when compared to all other pavement structures. However, an increase in the fatigue life was observed when the corresponding unmodified rich designs were used in the bottom lifts. Except for the case of pavement structure N6Rich, the

Table 5. Ratio of Percent Increment in Fatigue Life to Additional Cost for Northern Mixes.

Pavement Structure	Description	Lift Thickness (mm)	Cost /km/lift (USD$)	Total Cost/km (USD$)	Comments	Ratio of % Increment in Fat. Life to Additional Cost/km
150 mm HMA layer						
N1Opt	L6422-Opt	50	37,280	111,841	32% Increase in Fatigue Life for Additional $2,485/km	1.3%
	L6422-Opt	100	74,561			
N1Rich	L6422-Opt	50	37,280	114,327		
	L6422-Rich	100	77,046			
N2Opt	L6428-Opt	50	42,251	126,754	> 1130% Increase in Fatigue Life for Additional $9,942/ km	> 11.4%
	L6428-Opt	100	84,503			
N2Rich	L6428-Opt	50	42,251	136,696		
	L6428-Rich	100	94,445			
N3Opt	L6428-Opt	50	42,251	116,812	40% Increase in Fatigue Life for Additional $2,485/ km	1.6%
	L6422-Opt	100	74,561			
N3Rich	L6428-Opt	50	42,251	119,298		
	L6422-Rich	100	77,046			
200 mm HMA Layer						
N4Opt	L6422-Opt	50	37,280	149,122	2% Decrease in Fatigue life for Additional $3,107/km	0.06%
	L6422-Opt	150	111,841			
N4Rich	L6422-Opt	50	37,280	152,228		
	L6422-Rich	150	114,948			
N5Opt	L6428-Opt	50	42,251	169,005	105% Increase in Fatigue Life for Additional $14,292/km	0.73%
	L6428-Opt	150	126,754			
N5Rich	L6428-Opt	50	42,251	183,296		
	L6428-Rich	150	141,045			
N6Opt	L6428-Opt	50	42,251	154,093	5% Increase in Fatigue Life for Additional $3,107/km	0.16%
	L6422-Opt	150	111,841			
N6Rich	L6428-Opt	50	42,251	157,199		
	L6422-Rich	150	114,948			

use of a polymer-modified mix on top of a rich unmodified mix exhibits similar or better resistance to fatigue cracking when compared to the corresponding full depth unmodified mix.

The second objective was achieved by decreasing the thickness of the bottom lift of the HMA layer in all the pavement structures to maintain the same fatigue performance provided by the control design. Table 4 summarizes the control and reduced designs for the 150 mm and 200 mm HMA layers.

For the northern mixes, and in the case of the 150 mm HMA control section, the use of a rich bottom layer resulted in a 5 mm to 60 mm reduction in the bottom HMA lift. In the case of the 200 mm HMA control section, only the use of a rich bottom layer with full-depth polymer-modified asphalt mixture resulted in a reduction (80 mm) in the bottom HMA lift (i.e. N5Rich design structure). The highest reduction in the bottom lift was observed when the optimum polymer-modified mix was used in the top lift and the rich polymer-modified mix was used in the bottom lift.

For the southern mixes, and in the case of the 150 mm HMA control section, the use of a rich bottom layer resulted in a 5 mm to 20 mm reduction in the bottom HMA lift. In the case of the 200 mm HMA control section, the use of a rich bottom layer resulted in a 5 mm to 25 mm reduction in the bottom HMA lift. The least reduction in the bottom lift was observed when the optimum polymer-modified mix was used in the top lift and the rich polymer-modified mix was used in the bottom.

Benefit-cost analysis

A benefit cost analysis was conducted to determine and compare the cost of all structures. The analysis consists of determining the cost of paving a 1.0 km long by 3.65 m wide asphalt section. Currently, the plant cost of one ton of polymer-modified HMA mix is $85 USD, whereas the plant cost of one ton of unmodified HMA mix is $75 USD. Tables 5 and 7 summarize the costs and the percent increase in fatigue life for the additional cost in material for the northern and southern mixes, respectively. On the other hand, Tables 6 and 8 summarize the savings/costs in materials for the same fatigue performance for the northern and southern mixes, respectively. These costs were calculated based on 7% air voids for the HMA layers with optimum binder content and 3% air voids for the rich bottom mixtures.

Based on the results in Table 5 for the northern mixes, in both 150 mm and 200 mm HMA layers, the largest ratio of percent increment in fatigue life to additional cost is when the polymer-modified PG64-28NV mix is used in the top lift and the rich polymer-modified PG64-28NV mix is used in the bottom lift (i.e. N2Rich and N5Rich). Additionally, the largest savings of $46,974/km and $60,456/km for an equivalent fatigue life were

Table 6. Pavement Structure Costs for Constant Fatigue Life (Northern Mixes).

Pavement Structure	Description	Lift Thickness (mm)	Cost /km/lift (USD$)	Total Cost/km (USD$)	Comments
Constant fatigue life for 150-mm HMA layer					
N1Rich	L6422-Opt	50	37,280	110,599	Equivalent Fatigue Life for a Saving of $1,242/km
	L6422-Rich	95	73,319		
N2Rich	L6428-Opt	50	42,251	79,780	Equivalent Fatigue Life for a Saving of $46,974/km
	L6428-Rich	40	37,529		
N3Rich	L6428-Opt	50	42,251	111,531	Equivalent Fatigue Life for a Saving of $5,281/km
	L6422-Rich	90	69,280		
Constant Fatigue Life for 200-mm HMA Layer					
N4Rich	L6422-Opt	50	37,280	175,591	Equivalent Fatigue Life for a Cost of $26,470/km
	L6422-Rich	160	138,311		
N5Rich	L6428-Opt	50	42,251	108,549	Equivalent Fatigue Life for a Saving of $60,456/km
	L6428-Rich	70	66,297		
N6Rich	L6428-Opt	50	42,251	157,199	Equivalent Fatigue Life for a Cost of $3,107/km
	L6422-Rich	150	114,948		

Table 7. Ratio of Percent Increment in Fatigue Life to Additional Cost for Southern Mixes.

Pavement Structure	Description	Lift Thickness (mm)	Cost /km/lift (USD$)	Total Cost/km (USD$)	Comments	Ratio of % Increment in Fat. Life to Additional Cost/km
150 mm HMA Layer						
S1Opt	S7016-Opt	50	37,280	111,841	150% Increase in Fatigue Life for Additional $2,485/km	6.0%
	S7016-Opt	100	74,561			
S1Rich	S7016-Opt	50	37,280	114,327		
	S7016-Rich	100	77,046			
S2Opt	S7622-Opt	50	42,251	126,754	36% Increase in Fatigue Life for Additional $9,942/ km	0.4%
	S7622-Opt	100	84,503			
S2Rich	S7622-Opt	50	42,251	136,696		
	S7622-Rich	100	94,445			
S3Opt	S7622-Opt	50	42,251	116,812	125% Increase in Fatigue Life for Additional $2,485/ km	5.0%
	S7016-Opt	100	74,561			
S3Rich	S7622-Opt	50	42,251	119,298		
	S7016-Rich	100	77,046			
200 mm HMA Layer						
S4Opt	S7016-Opt	50	37,280	149,122	212% Increase in Fatigue Life for Additional $3,107/km	6.8%
	S7016-Opt	150	111,841			
S4Rich	S7016-Opt	50	37,280	152,228		
	S7016-Rich	150	114,948			
S5Opt	S7622-Opt	50	42,251	169,005	32% Increase in Fatigue Life for Additional $14,292/km	0.2%
	S7622-Opt	150	126,754			
S5Rich	S7622-Opt	50	42,251	183,296		
	S7622-Rich	150	141,045			
S6Opt	S7622-Opt	50	42,251	154,093	188% Increase in Fatigue Life for Additional $3,107/km	6.1%
	S7016-Opt	150	111,841			
S6Rich	S7622-Opt	50	42,251	157,199		
	S7016-Rich	150	114,948			

observed for the 150 mm and 200 mm HMA layer when the polymer-modified PG64-28 mix is used in the top lift and the rich PG64-28 mix is used in the bottom lift, respectively (see N2Rich and N5Rich pavement structures in Table 6). The use of a rich polymer-modified HMA layer in the northern part of the state proves to be a cost effective alternative. Additionally, the use of a rich unmodified HMA layer in the bottom lift was also effective but only for the case of 150 mm HMA layer, regardless of the type of

Table 8. Pavement Structures Costs for Constant Fatigue Life (Southern Mixes).

Pavement Structure	Description	Lift thickness (mm)	Cost /km/lift (USD$)	Total Cost/km (USD$)	Comments
Constant Fatigue Life for 150-mm HMA Layer					
S1Rich	S7016-Opt	50	37,280	98,793	Equivalent Fatigue Life for a Saving of $13,048/km
	S7016-Rich	80	61,513		
S2Rich	S7622-Opt	50	42,251	132,471	Equivalent Fatigue Life for a Cost of $5,717/km
	S7622-Rich	95	90,219		
S3Rich	S7622-Opt	50	42,251	107,803	Equivalent Fatigue Life for a Saving of $9,009/km
	S7016-Rich	85	65,552		
Constant Fatigue Life for 200-mm HMA Layer					
S4Rich	S7016-Opt	50	37,280	133,091	Equivalent Fatigue Life for a Saving of $16,030/km
	S7016-Rich	125	95,811		
S5Rich	S7622-Opt	50	42,251	177,142	Equivalent Fatigue Life for a Cost of $8,137/km
	S7622-Rich	145	134,890		
S6Rich	S7622-Opt	50	42,251	141,791	Equivalent Fatigue Life for a Saving of $12,302/km
	S7016-Rich	130	99,539		

mix in the top lift. Additional costs were observed for an equivalent fatigue life for the case of 200 mm HMA layer when a rich unmodified HMA layer in the bottom lift was used.

The data in Table 7 show, for southern mixes, that the use of the unmodified PG70-16 mix in the top lift and a rich PG70-16 mix in the bottom lift exhibits, for both the 150 mm and 200 mm pavement structures, the largest ratio of percent increment in fatigue life to an additional cost of 6.0% and 6.8%, respectively. Nonetheless, the structures with the polymer-modified PG76-22 in the top lift and the rich unmodified PG70-16 mix in the bottom lift exhibit, for both the 150 mm and 200 mm pavement structures, a ratio close to the aforementioned structures. Hence, when rutting is a concern, S3Rich and S6Rich will provide better rutting resistance than S1Rich and S4Rich without jeopardizing the pavement resistance to fatigue cracking. On the other hand, the full depth polymer modified pavement sections (i.e. S2Rich and S5Rich) did not offer significant advantages.

In the case of the southern mixes and when compared to the 150 mm HMA layer control section, savings of $13,048/km and $9,009/km for an equivalent fatigue life are observed in Table 8 when the unmodified PG70-16 or polymer-modified PG76-22 mix is used in the top lift, respectively, and the rich PG70-16 mix is used in the bottom. On the other hand, for the 200 mm HMA layer control section, the use of unmodified PG70-16 or polymer-modified PG76-22 mix in the top lift and the rich PG70-16 mix in the bottom offered savings of $16,030/km and $12,302/km, respectively. For the southern mixes, it is clear that the use of a rich bottom polymer-modified mix is not a cost-effective pavement structure, whereas the use of a rich bottom unmodified mix offers an evident economical advantage.

Conclusions

The objective of this research is to evaluate the impact of a rich bottom design on the rutting and fatigue performance of HMA pavements. This objective was achieved through a combination of a laboratory based experiment that evaluated the rutting and fatigue characteristics of optimum and rich mixtures and a mechanistic-empirical analysis that evaluated the impact of these characteristics on the design life of HMA pavements. The flexural beam fatigue test in the strain controlled mode of testing at 25°C was used to evaluate the mixtures' resistance to fatigue cracking. The rutting resistance of the various mixtures was evaluated using the APA test at 60°C. A mechanistic analysis was conducted using laboratory measured resilient moduli for the various mixtures to evaluate the fatigue performance of different pavement structures. Two asphalt layer thicknesses were considered in this study: 150 mm and 200 mm. A benefit cost analysis was also conducted to determine and compare the cost of all evaluated pavement structures. Based on the data generated from the laboratory experiment and the mechanistic analysis, the following conclusions can be made:

- The rutting resistance of the rich mix and its corresponding optimum mix are similar. The rutting resistance of the polymer-modified optimum and rich mixes is significantly better than the unmodified mixes and is significantly lower than the 8.0 mm NDOT failure criterion. This data support the use of the polymer-modified mix in the top lift.
- In general, the rich bottom design significantly increased the fatigue life of the pavement structure more than the structure that has a bottom lift with the optimum mix design.
- The mechanistic-empirical analysis shows that the use of polymer-modified mix throughout the HMA layer offers significant advantages in the fatigue and rutting performance of HMA pavements. On the other hand, the use of the rich bottom design offers a noticeable advantage in the fatigue performance of HMA pavements.
- The cost analysis of the northern mixes shows that the rich bottom PG64-28 polymer-modified pavement structure will offer the most cost-effective pavement structure.
- The cost analysis of the southern mixes shows that the rich bottom PG70-16 unmodified mixture with either an unmodified PG70-16 mix or a polymer-modified PG76-22 mix in the top lift will provide the most cost-effective pavement structure when compared to the polymer-modified rich bottom design.

The use of the PG76-22 mix in the top lift will offer a better resistance to rutting.

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