Transportation Consortium of South-Central States

Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation

Development of Cost-Effective High-Modulus Asphalt Concrete (HMAC) Mixtures Using Crumb Rubber and Local Construction Materials in Louisiana

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16. Abstract

One of the emerging solutions to enhance the durability of asphalt pavements is the use of a French asphalt mix known as "High-Modulus Asphalt Concrete (HMAC)." This mix uses a hard asphalt binder, high binder content (about 6%), and low air voids content as compared to Superpave mixtures. The key objective of this study was to develop a cost-effective HMAC mixture using crumb rubber and local materials in Louisiana. To achieve this objective, four HMAC mixtures were prepared using two asphalt binders (PG 82-22 and PG 76-22 plus 10% crumb rubber) and two Reclaimed Asphalt Pavement (RAP) contents (20% and 40%); additionally, a conventional Superpave mixture in Louisiana was prepared as a control mixture. The laboratory performance of these five mixtures was evaluated in terms of workability, dynamic modulus, rutting resistance, and cracking resistance. The AASHTOWare Pavement ME Design software was also used to estimate the long-term field performance of these mixtures. Results indicated that the HMAC mixture prepared with 10% crumb rubber and 20% RAP successfully met the French mix design specifications for HMAC and LaDOTD specifications. This HMAC mix outperformed the control Superpave mix in terms of dynamic modulus, rutting resistance, and cracking resistance. Additionally, this HMAC mixture can reduce the required asphalt thickness by 1.5 or 2 inches based on traffic level. The cost-effectiveness analysis indicated that this HMAC mixture was more cost-effective than conventional Superpave mixtures in Louisiana. In addition, this mixture is environmentally-friendly since it can reduce the disposal of scrap tires in landfills.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Official
AMPT	Asphalt Mixture Performance Tester
ASTM	American Society for Testing and Materials
BBR	Bending Beam Rheometer
DOT	Department of Transportation
DSR	Dynamic Shear Rheometer
E^*	Dynamic Modules
FHWA	Federal Highway Administration
G_{mb}	Bulk Specific Gravity of the Mixture
G_{mm}	Maximum Specific Gravity of the Mixture
G^*	Complex Modulus
HMA	Hot-Mix Asphalt
J_c	Critical strain energy release rate
JMF	Job Mix Formula
LaDOTD	Louisiana Department of Transportation and Development
LTOA	Long-Term Oven Aging
LWT	Loaded Wheel Tracker
NMAS	Nominal Maximum Aggregate Size
RAP	Reclaimed Asphalt Pavement
RTFO	Rolling Thin Film Oven
SCB	Semi-Circular Bending
SGC	Superpave Gyratory Compactor
STOA	Short-Term Oven Aging
Superpave	Superior Performing Asphalt Pavement

EXECUTIVE SUMMARY

The term "High Modulus Asphalt Concrete- (HMAC)" or "Enrobé à Module Élevé- (EME)" refers to type of asphalt concrete that represents high modulus/stiffness, high durability, superior rutting performance and good fatigue resistance. This type of mix was developed in France in the 1980's. EME is a very good option to be used in lower and upper binder courses in the pavement structure which are subject to the highest levels of tensile and compressive stresses. HMAC offers several advantages over conventional binder course materials including reducing the thickness of the pavement structure with improved service life and reduction in raw materials consumption. The main objective of this project was to develop a cost-effective HMAC mixture using crumb rubber and local construction materials in Louisiana. To achieve this objective, the following tasks were accomplished:

- Develop four HMAC mixtures and compare their laboratory performance (workability, dynamic modulus, rutting resistance, and cracking resistance) against a conventional Louisiana Superpave mixture.

- Estimate the long-term field performance of HMAC mixtures as compared to a conventional Louisiana Superpave mixture.

- Assess the cost-effectiveness of HMAC mixtures as compared to a conventional Louisiana Superpave mixture.

1. INTRODUCTION

Asphalt concrete mixtures are primarily designed using the Superpave mix design procedure where the proportioning of asphalt mix components is primarily based on volumetric properties *(1)*. Early Superpave implementation mainly focused on rutting resistance. Mixture designs for moderate and high traffic pavements were designed for improved rutting resistance by specifying a higher grade of asphalt binder and higher quality aggregates. Most highway agencies now report that rutting problems have been virtually eliminated. However, there have been growing concerns that the primary mode of distress for asphalt pavements is cracking of some form or another *(1-2)*.

One of the emerging solutions to enhance the durability of asphalt pavements is the use of a French asphalt mix known as "High-Modulus Asphalt Concrete (HMAC)" or "Enrobé à Module Élevé (EME)" mix. This mix was developed in France in the 1980s using hard asphalt binders (typically PG 88 or higher for critical high temperature properties), relatively high binder content (about 6%), and relatively low air voids (close structure) as compared to conventional Superpave asphalt mixtures *(1)*. As such, HMAC mixes have high modulus/stiffness, high durability, superior rutting performance and reasonable fatigue resistance *(3)*. For these reasons, HMAC mixes are considered as an excellent option to be used in the binder course in the pavement structure, which is subjected to the highest levels of tensile and compressive stresses *(4)*. HMAC mixes have been successfully adopted by many other countries such as United Kingdom, Poland, Switzerland, South Africa, and Australia *(5, 6)*.

Generally, HMAC mixtures offer several advantages over conventional Superpave mixtures including reducing the required pavement thickness with improved service life as well as reducing the consumption of raw materials *(3)*. Yet, using HMAC mixes with high stiffness may raise some concerns related to fatigue cracking especially in cold climatic conditions. These concerns may be addressed by enhancing the elastic recovery (flexibility) of the utilized hard binder using some modifiers that enhance the fatigue cracking resistance of the binder *(7)*.

Some issues such as hot and humid climate, traffic, properties of available local construction materials, construction methods and standards are specific to Louisiana. Therefore, the development of a suitable HMAC mix design in Louisiana cannot be a duplicate copy of the French method or any other designs used in another country or jurisdiction. As such, this study aimed to develop a cost-effective HMAC mixture considering the needs and specificities of Louisiana while preserving the authenticity of the concept and the advantages of the original technology.

2. OBJECTIVES

The main objective of this research project was to develop a cost-effective HMAC mixture using crumb rubber and local construction materials in Louisiana. To achieve this objective, the following tasks were accomplished:

- Develop four HMAC mixtures and compare their laboratory performance (workability, dynamic modulus, rutting resistance, and cracking resistance) against a conventional Louisiana Superpave mixture.

- Estimate the long-term field performance of HMAC mixtures as compared to a conventional Louisiana Superpave mixture.

- Assess the cost-effectiveness of HMAC mixtures as compared to a conventional Louisiana Superpave mixture.

3. LITERATURE REVIEW

3.1. French Mix Design Method

Unlike the Superpave mix design procedure, the French mix design approach is not driven by volumetric properties as much as it is driven by trying to meet performance-based specifications *(1)*. In general, two classes of HMAC mixes exist, Class 1 and Class 2. Class 2 has an excellent fatigue and rutting resistance, while Class 1 is a "low-cost" mixture with lower binder content, thus having similar stiffness and rutting resistance to Class 2 but with a relatively lower fatigue resistance *(3)*. Figure 1 shows a flowchart of the steps in the French mix design procedure. The following subsections will briefly explain the key steps in the flowchart.

3.1.1. Design the Mix Gradation

Similar to the Superpave mix design procedure, the French mix design has specified particle size limits (grading envelopes) for HMAC mixes, which depend on the maximum sieve size of the mix (D). In general, there are three HMAC gradation categories based on D as follows:

- 0/10 gradation for D of 10 mm
- 0/14 gradation for D of 14 mm
- 0/20 gradation for D of 20 mm

The grading curves and envelopes for these three categories could be found elsewhere *(6)*.

3.1.2. Binder Grade

Typically, hard binders (10/25 or 15/25 pen binders) have been used in HMAC mixes *(6)*. Since hard binders are not readily available in all locations, previous studies have used recycled materials in HMAC mixes *(9)*.

3.1.3. Binder Content

In the French mix design, the binder content is calculated not through volumetric properties like in the Superpave mix design, but through computing a minimum richness factor (k), which is an indicator of the minimum required asphalt film thickness. To determine the minimum required binder content, the specific surface area of the aggregate (Σ) should be first calculated as follows:

$$100\Sigma = 0.25G + 2.3S + 12s + 150f \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots,,,,(1)$$

where,
G = proportion of aggregate retained on and above the 6.3 mm sieve;
S = proportion of aggregate retained between the 0.25 mm and 6.3 mm sieves;
s = proportion of aggregate retained between the 0.063- and 0.25-mm sieves; and
f = percent passing the 0.063 mm sieve.

Then the minimum binder content can be calculated as follows:

$$\text{Minimum binder content} = k\alpha\sqrt[5]{\Sigma}\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(2)$$

where,

k = minimum richness factor (3.4 for Class 2 HMAC mixtures)
$\alpha = 2.65/G_{se}$
G_{se} = aggregate effective specific gravity
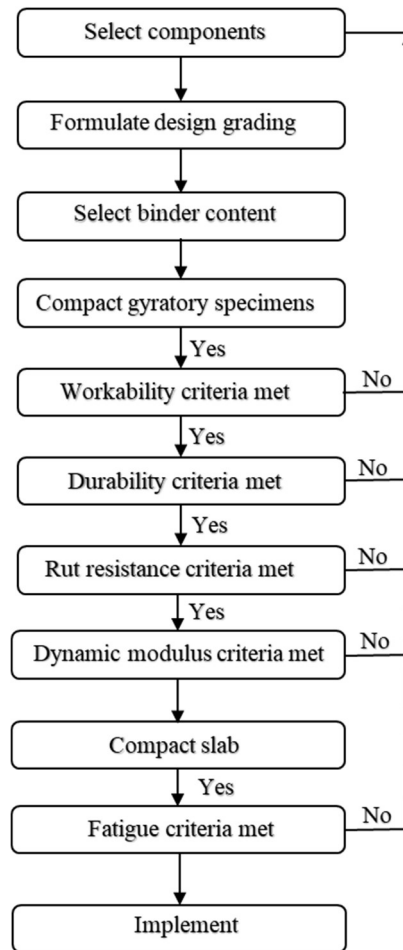
Figure 1 French mix design procedure *(6)*

3.1.4 Performance Tests

Once the binder content is calculated, the final step in the mixture design is to conduct five performance tests to ensure that the mixture will be durable in the field. These tests include *(1, 3)*:

1. **Gyratory Shear Compactor:** this test evaluates the compaction aptitude of the HMAC mixture using the French Gyratory Shear Compactor (called PCG). For HMAC Class 2 mixes, 0/14 mm gradation category, the air voids percentage after 100 gyrations in the PCG should be less than 6%.
2. **Duriez test:** this test evaluates the resistance of the HMAC mixture to moisture damage and is similar to the modified Lottman test conducted in the Superpave mix design procedure. For HMAC Class 2 mixes, the tensile strength ratio (TSR) should be greater than or equal to 0.75.
3. **Dynamic modulus test:** For HMAC Class 2 mixes, the dynamic modulus at 15°C and 10 Hz should exceed 14 GPa.

4. **Rutting test:** EN 12697-22 is the standard in Europe for assessing the rutting resistance of HMAC mixes using the French LCPC rutting tester. Other countries use their own standard rutting tests such as the Superpave Shear Tester (SST) and the Repeated Simple Shear Test at a Constant Height.
5. **Fatigue test:** EN 12697-24 is the standard in Europe for assessing the fatigue resistance of HMAC mixes using the two-point bending test. Other countries use their own standard fatigue tests such as the four-point bending test.

3.2. Performance of HMAC Mixes Based on Previous Studies

In 2010, Sybilski et al. evaluated the applicability of limestone aggregate for HMAC mixes in Poland *(10)*. Three HMAC mixtures were prepared in the laboratory using 20/30 grade bitumen obtained from Polish refineries. Two of the HMAC mixtures encompassed basalt aggregate and had binder contents of 4.6 and 5.1%, while the third HMAC mixture included limestone aggregate and had a binder content of 5.5%. Several laboratory tests were carried out to determine the dynamic modulus, resistance to moisture damage, fatigue resistance, and rutting resistance for the three HMAC mixtures. In terms of dynamic modulus and resistance to moisture damage, all three HMAC mixtures passed the requirements. On the other hand, only the limestone mixture with 5.5% binder passed the rutting resistance and fatigue resistance requirements. Therefore, it was concluded that limestone aggregate may be used in HMAC mixtures in Poland for base and binder courses. Similarly in Latvia *(11)*, Latvian dolomite aggregate was successfully incorporated into HMAC mixtures when used with polymer-modified binders.

In 2011, a research study was conducted to develop a new HMAC Class 2 mixture using local materials in Indiana *(12)*. In this study, HMAC mixture was developed using Indiana aggregates (crushed stone, dolomite, stone stand, and coarse RAP) and PG 64-22 asphalt binder mixed with 65% post-consumer shingles. The dynamic modulus of the HMAC mixture was measured in the laboratory and was compared to the dynamic modulus of a conventional Superpave mix in Indiana. Results indicated that the HMAC and Superpave mixtures had dynamic moduli (at 15°C and 10 Hz) of 15.1 and 11.5 GPa, respectively. The major limitation of this study was the fact that the fatigue resistance and rutting resistance of the proposed HMAC mixture were not experimentally evaluated providing incomplete assessment of this mixture.

In 2017, Villacorta et al. conducted a research study in Auburn, AL. to evaluate the laboratory performance of HMAC mixtures for use as base course *(1)*. The experimental plan included a French mixture with a stiff binder (PG 88-16), two mixtures containing 35% reclaimed asphalt pavement (RAP) both with polymer-modified binders, one with high polymer content (HiMA), another mixture containing 25% RAP and 5% reclaimed asphalt shingles (RAS) with a polymer-modified binder, and finally, a 50% RAP mixture with a polymer-modified binder. For these five mixtures, the dynamic modulus, fatigue resistance, and rutting resistance were evaluated. Results indicated that all the mixes had dynamic modulus (at 15°C and 10 Hz) that exceeded 14 GPa. Results also indicated that the 35% RAP HiMA mixture showed the highest resistance to permanent deformation followed by the 25%-5% RAS mixture based on the flow number test. In terms of fatigue resistance, the 35% RAP HiMA mixture was the most fatigue-resistant mixture based on the uniaxial tension fatigue test (S-VECD). Accordingly, it was concluded that the rutting and fatigue properties were improved for the high polymer-modified mixtures and decreased for the French mixture, which had a stiffer virgin binder (PG 88-16).

In 2018, Moghaddam *(3)* performed a research study in Ontario, Canada to develop a new approach for HMAC mix design that would achieve adequate performance at high, medium, and low temperatures. Two different mix types based on the NMAS were considered. In addition, three types of modified asphalt binders were used in this study, namely: PG 88-28, PG 82-28, and PG 58-28 plus 10% elastomer additives. Thermo-mechanical tests were conducted to evaluate the performance of HMAC mixes in terms of stiffness, rutting resistance, and fatigue-cracking resistance. Results showed that the developed mixes had acceptable performance at all levels, and that the mixes could satisfactorily perform at low temperatures in Ontario.

3.3. Advancements Based on Previous Research

Based on the reviewed literature, there is a general agreement that HMAC mixtures outperform conventional mixtures in terms of mechanical properties. Yet, this study is expected to address several shortcomings in previous studies as follows:

- Most of previous studies conducted in the United States, were conducted in Northern States with cold climates, since the main challenge with HMAC mixes is low-temperature cracking in cold climatic conditions. Yet, surface cracking is a major concern in hot and wet climates such as Louisiana. Therefore, this study developed HMAC mixtures using available local construction materials in Louisiana and considering the needs and standards of the state while preserving the advantages of the original technology.

- Few previous studies incorporated crumb rubber in HMAC mixtures. The use of crumb rubber as an additive in asphalt pavement construction is of interest to the paving industry due to its economic and environmental benefits such as resource recovery by creating a use for recycled waste tires. Therefore, this study developed HMAC mixtures using crumb rubber enhancing pavement sustainability.

- Most of the previous studies emphasized the superior performance of HMAC mixtures without considering the cost-effectiveness of this technology. It is well recognized that using harder binders with higher binder contents will increase construction costs. As such, this study evaluated the cost-effectiveness of HMAC mixtures as compared to conventional Superpave mixtures.

4. MATERIALS USED

In this study, one RAP stockpile (binder content of 4.9%), one fine sand stockpile, and three limestone aggregate stockpiles; #89, #11, and #78 were collected from a contractor located in Lafayette, Louisiana.
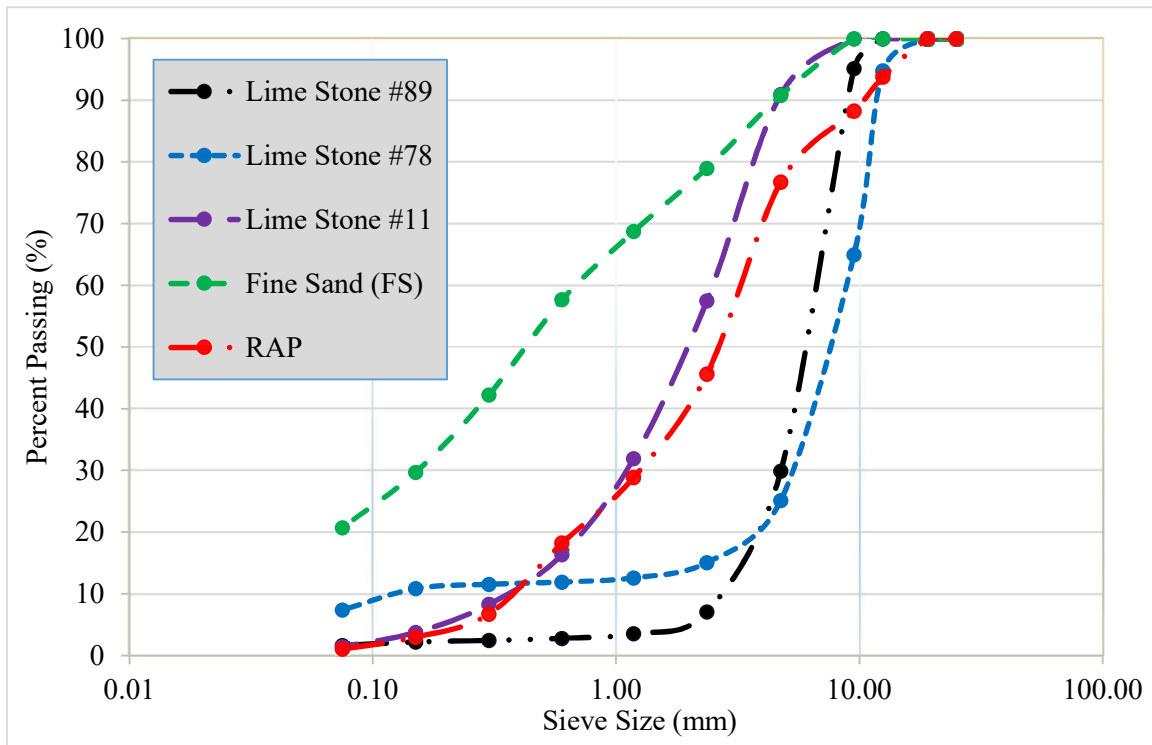
Figure 2 Aggregate gradation for the stockpiles used in this study

illustrates the aggregate gradation for these stockpiles. Three asphalt binders were used in this study as follows:

1. Styrene-Butadiene-Styrene (SBS)-modified PG 76-22 binder

2. Styrene-Butadiene-Styrene (SBS)-modified PG 82-22 binder

3. Styrene-Butadiene-Styrene (SBS)-modified PG 76-22 binder mixed with 10% (by mass of asphalt binder) 30 mesh crumb rubber (CR). The mixing was conducting through the wet process where the crumb rubber was mixed with the liquid binder for 45 minutes at 180°C and resulted in a binder with PG of 94-16.

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Figure 2 Aggregate gradation for the stockpiles used in this study

5. MIXTURE DESIGN

5.1. Experimental Design

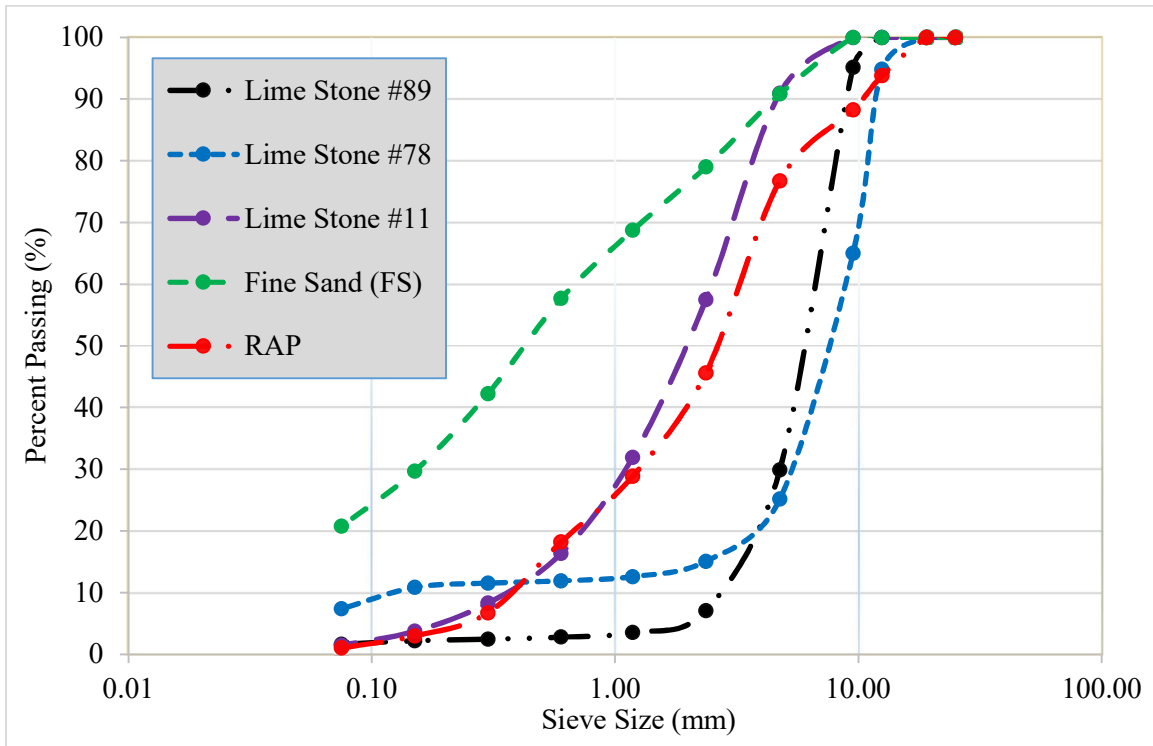In this study, four HMAC mixtures (Class 2 and 0/14 gradation) were prepared in addition to a conventional Superpave mix in Louisiana (NMAS of 12.5 mm) to be used as a control mix. Table 1 summarizes the details of these asphalt mixtures. As shown in Table 1, two design aggregate gradations were developed for mixtures with 20% RAP and 40% RAP (by aggregate mass) to meet both the requirements of the Superpave and French mix design procedures, see Figure 3. These two mixtures were defined in this study as Blend 1 and Blend 2, respectively. The Superpave mix design procedure was performed to select the optimum binder content for the control Superpave mix, while the minimum richness factor (k) specified in the French mix design procedure (k=3.4) was used to compute the required binder content for the HMAC mixes. Table 1. Details of the asphalt mixtures prepared in this study

Mixture Code	Mixture Type	Number of Specimens	Asphalt Binder	Aggregate Blend	Total Binder content
SP	Superpave	13 specimens (8 for volumetric properties [optimum Ac content and G_{mm}]; 4 for rutting testing; 2 for dynamic modulus test; and 3 for cracking evaluation)	PG 76-22	Blend 1 (RAP 20%)	5.7%
H 1	HMAC	For each HMAC mixture, 13 specimens	PG 82-22	Blend 1 (RAP 20%)	6%
H 2	HMAC	were prepared (2 for volumetric properties	PG 94-16 (PG 76-22+10% CR)	Blend 1 (RAP 20%)	6%
H 3	HMAC	[G_{mm}]; 2 for workability; 4 for	PG 82-22	Blend 2 (RAP 40%)	6%
H 4	HMAC	rutting testing; 2 for dynamic modulus test; and 3 for cracking evaluation)	PG 94-16 (PG 76-22+10% CR)	Blend 2 (RAP 40%)	6%

Figure 3 Aggregate gradation for blend 1 and blend 2
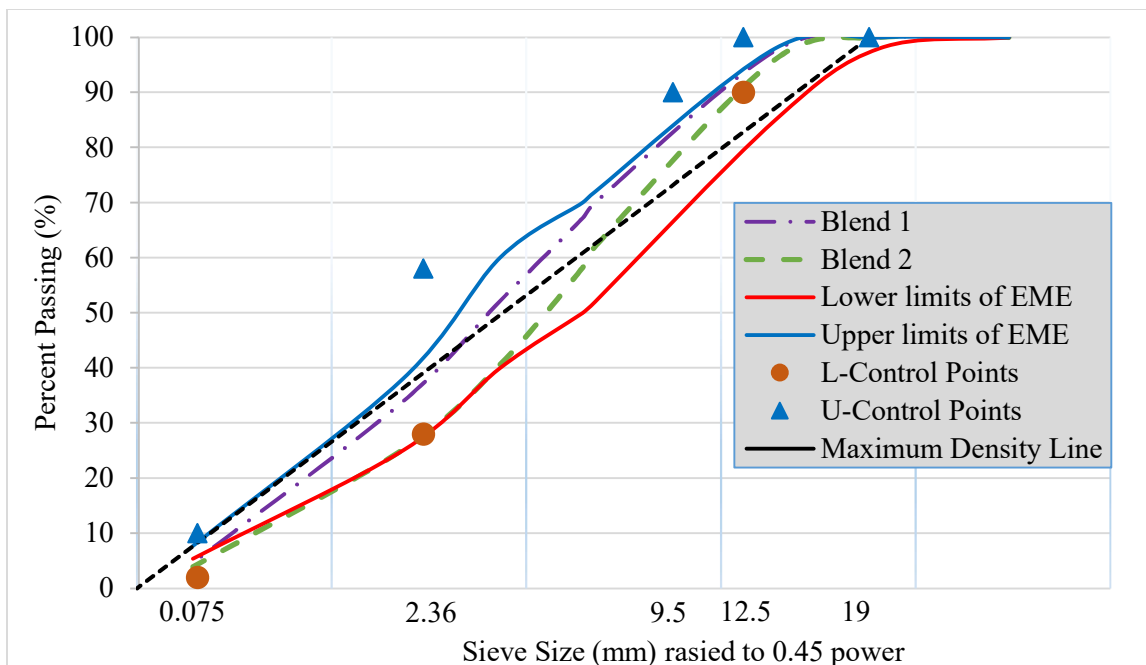
5.2. Sample Preparation

Given that all the samples in this study included RAP, the mixing procedure was based on the recommendations of a study conducted in Louisiana *(13)* to ensure 100% of the available recycle binder is utilized within the asphalt mixture. Mixture blending and compacting steps are summarized below:

1. 5% of moisture content was added to the RAP.

2. Virgin aggregates were superheated to a minimum temperature of 383°F (195°C) for 3 hours, while the mixing tools were heated to 325°F (163°C).
3. Moisture-laden RAP was placed at the bottom of the heated mixing bucket and the superheated virgin aggregates were placed on the top of the RAP. Superheated virgin aggregates and RAP were mixed resulting in steaming. Mixing was continued until steam seized.
4. Blended aggregate and RAP were placed into 325°F (163°C) oven till the blended aggregate reached the suitable temperature for mixing with asphalt binder.
5. Heated asphalt binder and blended aggregate were mixed in a heated mixing bucket. After mixing, the mixture was spread in a pan and short-term oven-aged for 2 hours at 275°F (135°C).
6. Compacted cylindrical specimens were then prepared using the Superpave gyratory compactor (SGC) to the specified dimensions for each particular test procedure.

6. PERFORMANCE TESTS

6.1. Volumetric Properties

Eight specimens were prepared to determine the optimum asphalt content and the volumetric properties of mixture SP. Table 2 presents the final job mix formula for mixture SP. As shown in this table, mixture SP satisfied the volumetric criteria in accordance with the Louisiana Standard Specifications for Roads and Bridges *(14)*. For 12.5 mm NMAS asphalt concrete mixtures, these criteria are as follows:

- Air voids percentage (AV%) should be in the range of 2.5 to 4.5%;
- Voids in mineral aggregate (VMA) should be greater than 13.5%;
- Voids filled with asphalt (VFA) should be between 69 and 80%.

Table 2 Job mix formula for the control mixture SP

Mix code		SP
NMAS (mm)		12.5
Aggregate blend		20 % #89 LS 36% #11 LS 10% #78 LS 14% FS 20% RAP
Binder type		PG 76-22
Number of gyrations in SGC	N_i	7
	N_d	65
	N_f	105
Design volumetric Properties	$G_{mm,\ N_d}$	2.456
	%AC	5.7
	% air voids	4.0

Mix code		SP
	%VMA	14.8
Gradation (% passing)	%VFA	73
	25.0mm - 1"	100
	19.0mm - 3/4"	100
	12.5mm - 1/2"	96.8
	9.5mm - 3/8"	84.3
	4.75mm - No. 4	58.9
	2.36mm - No. 8	37.6
	1.18mm - No. 16	25.6
	0.600mm - No. 30	18.1
	0.300mm - No. 50	12.1
	0.150mm - No. 100	8.7
	0.075mm - No. 200	5.5

As previously mentioned, the French mix design approach is not driven by volumetric properties as much as it is driven by trying to meet performance-based specifications. In the French mix design, the performance-based specification that governs the mixture volumetric properties is the PCG test that evaluates the mixture workability. This specification requires HMAC Class 2 mixes, 0/14 mm gradation category, to have an air voids percentage less than 6% after 100 gyrations in the French Gyratory Shear Compactor (called PCG). Previous studies *(13)* indicated that 80 gyrations in the Superpave gyratory compactor (SCG) produced similar compaction as 100 gyrations in the French compactor.

In this study, the workability of the four HMAC mixtures (H1 to H4) was evaluated by measuring the degree of compaction of eight specimens (2 specimens for each mixture). The evaluation was conducted using the SGC in which the air voids percentage was measured after 80 gyrations, Figure 4. As shown in Figure 4, the percentages of air voids after 80 gyrations were 1.3%, 2.0%, 2.9%, and 3.8% for mixtures H1, H2, H3, and H4, respectively. Since all the HMAC mixes had percentage air voids less than 6% after 80 gyrations, it can be concluded that the workability requirement of the HMAC mixes was achieved.
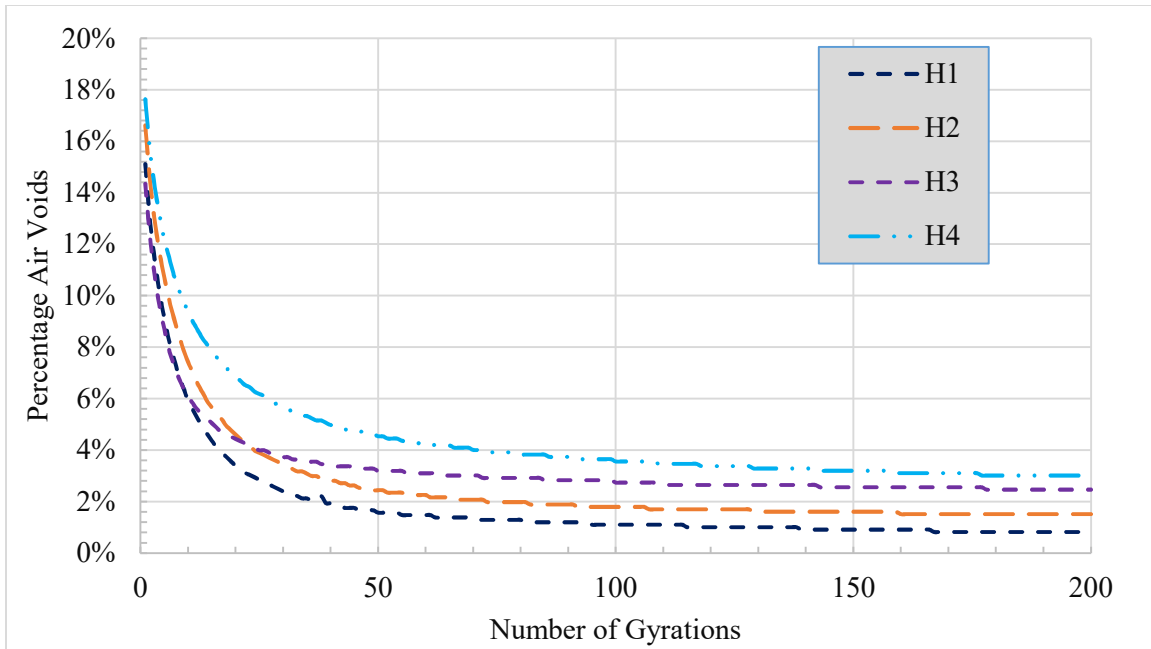
Figure 4. Degree of compaction of the HMAC mixes.

6.2. Permanent Deformation

Since the test procedure to evaluate the rutting resistance in Louisiana is not the same as the French method (which uses the French LCPC rutting tester), the currently-used performance testing procedure and standards in Louisiana were adopted in this study. As such, the ability of the five asphalt mixtures to resist permanent deformation was evaluated using the Loaded Wheel Tracking (LWT) test in accordance with AASHTO T324-17 *(15)*. The Hamburg Double Wheel Tracker was used in this study. In this test, the prepared mixtures were short-term oven-aged as per AASHTO R30 *(16)*. After that, the mixtures were compacted using SGC to 60 ± 1 mm. The average percentage of air voids for mixture SP was 6.5% to meet the requirements of the Superpave which specifies a range of allowable air voids of 7 ± 1% for all performance tests. The average percentages of air voids for mixtures H1, H2, H3, and H4 was 4.7%, 5.6%, 4.3%, and 5.5%, respectively, to meet the requirements of the French mix design procedure, which specifies a range of allowable air voids between 3 and 6% for all performance tests.

For each of the five mixtures, four specimens were prepared and tested (a pair for each LWT test). Specimens were conditioned in a 122ºF (50ºC) water bath for 45 minutes before running the test for 20,000 passes (52 passes/min), per AASHTO T324 standard procedure *(15)* and Louisiana Department of Transportation and Development (LaDOTD) specification *(14)*. Based on LaDOTD specifications, the maximum allowable rut-depth value at 20,000 passes is 6 mm or 10 mm based on the design traffic level *(14)*. Figure 5 presents the LWT output (number of passes versus average rut depth of the right and left wheel paths) for the five mixtures. Based on Figure 5, the following findings were observed:

- The average rutting depth after 20,000 cycles was 5.0, 3.6, 3.3, 2.9, 1.7 mm, and the coefficient of variation was 3.8%, 17.7%, 2.0%, 17.3%, and 2.0% for mixtures SP, H1, H2, H3, and H4, respectively.

- While the control mix had the least rutting resistance, all the five mixtures met LaDOTD rutting requirements by experiencing an average rut depth less than 6 mm after 20,000 passes. Mixture H4 exhibited the highest rutting resistance (lowest average rut depth).
- To evaluate the impact of adding RAP on the rutting resistance of HMAC mixtures, mixture H1 was compared versus mixture H3, and mixture H2 was compared versus mixture H4. As expected, and as reported by previous studies *(17)*, increasing the RAP content in the asphalt mixture enhanced the rutting resistance.
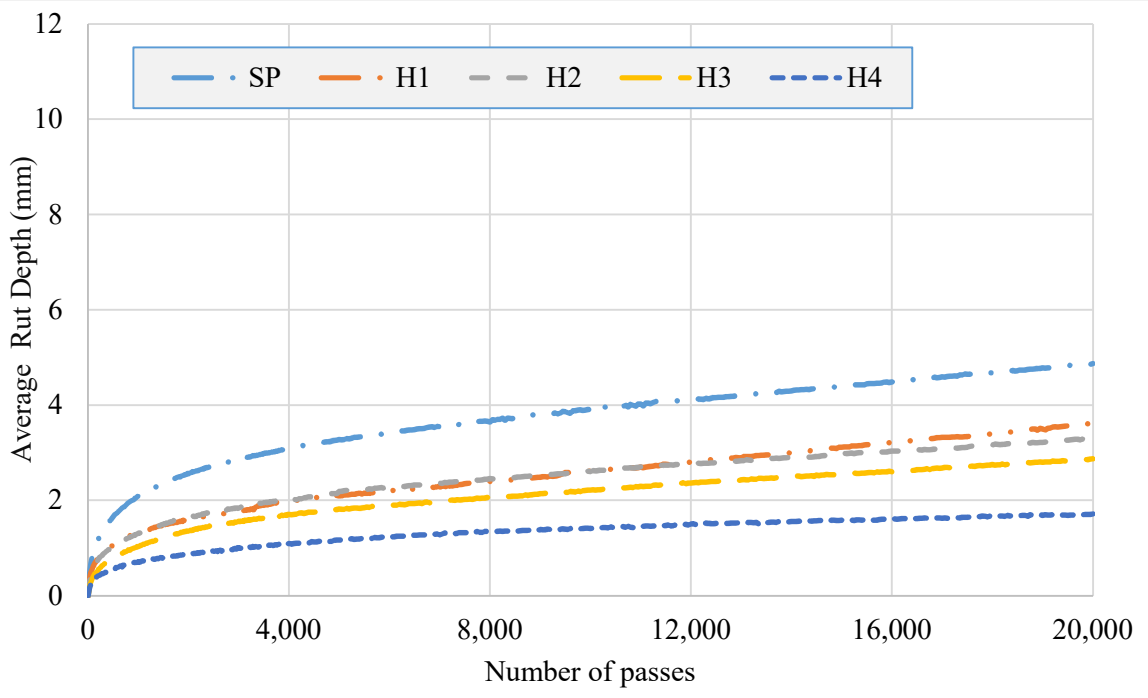

Figure 5. LWT results for the five mixtures

6.3. Dynamic Modulus

For the dynamic modulus test, two specimens were prepared for each of the five mixtures. The specimens were aged at 135ºC (short-term oven aging) for four hours before SGC compaction to a height of 170 mm and diameter of 150 mm. The samples were then cored using a portable core drilling machine and grinded from each end using a grinding machine to have a height of 150 mm and a diameter of 100 mm. The average percentages of air voids were 7.1%, 5.7%, 5.9%, 4.1%, and 5.2% for mixtures SP, H1, H2, H3, and H4, respectively to meet the Superpave and French specifications. The dynamic modulus test was then conducted in accordance with AASHTO Provisional Standard T 378 (equivalent to EN 12697-26 in the European standards) using a Universal Testing Machine. During the test, a sinusoidal axial compressive stress with different loading frequencies (0.1, 0.5, 1, 5, 10, and 25 Hz) was applied to the sample at specific temperatures (4.4, 25, 37, and 54˚C). The applied stress and the resulting strain response of the specimen were measured continuously during the test using a data acquisition system. The dynamic complex modulus values were then calculated as follows:

$$|E^*| = \frac{\sigma_o}{\varepsilon_o} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \quad (3)$$

where,

22

$|E^*|$= absolute value of the dynamic complex modulus;
σ_o= peak dynamic stress amplitude; and
ε_o= Peak recoverable strain amplitude.

Figure 6 illustrates the average dynamic modulus for all the mixtures versus temperature at a frequency of 10 Hz. Based on the obtained results, the following was observed:

- The average dynamic modulus was 10.5, 13.5, 15.6, 14.8, and 17.7 GPa, and the coefficient of variation was 16.8%, 1.0%, 10.2%, 12.5%, and 8.0% for mixtures SP, H1, H2, H3, and H4, respectively.
- Mixtures SP and H1 did not meet the minimum stiffness HMAC requirement of 14.0 GPa at 15˚C and under 10 Hz loading.
- Mixture H4 had the highest dynamic modulus (17.6 GPa) at 15˚C and under 10 Hz loading, which could be attributed to the use of 40% RAP in addition to using a stiff binder with 10% crumb rubber. Previous studies indicated that including RAP *(18)* and crumb rubber *(19)* in the asphalt mix increase its dynamic modulus.
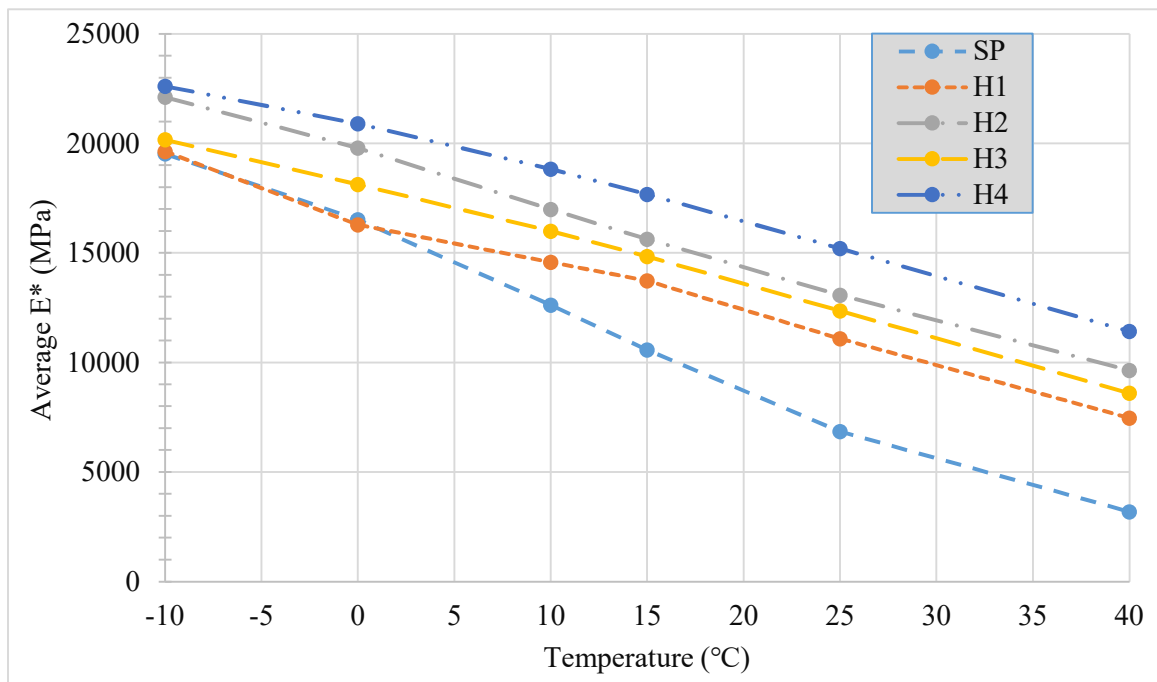

Figure 6. Average dynamic modulus for all mixtures versus temperature at a frequency of 10Hz

6.4. Semi-Circular Bending (SCB) Test

Since the test procedure to evaluate the fatigue cracking resistance in Louisiana is not the same as the French method (which uses the two-point bending test), the currently used performance testing procedure and standards in Louisiana were adopted in this study. As such, the ability of the five asphalt mixtures to resist cracking at intermediate temperature was evaluated using the Semi-circular Bending (SCB) test in accordance with the ASTM D8044 *(20)*. In this test, the samples were short-term oven-aged as per AASHTO R30 *(15)*. Afterward, the samples were compacted using SGC to a height of 57 mm and 150 mm diameter, and 7.1% air voids for mixture SP and 4.2%, 4.7%, 3.1%, and 5.9% air voids for H1, H2, H3, and H4 mixtures, respectively. The

compacted samples were then long-term oven-aged for 120 h ± 0.5 hr. at a temperature of 85 ± 3°C before testing. For this test, two sets of samples with two different notch depths (25.4 and 38.1 mm) were prepared for each mixture. Each set included three semi-circular samples, resulting in a total of six semi-circular notched samples for each mixture. Using a three-point bending set-up, the semi-circular samples were loaded monotonically at a loading rate of 0.5 mm/min at 25 ± 0.3°C to measure the critical strain energy release rate, also called the critical value of J-integral (J_c). According to LaDOTD specifications, a minimum J_c value of 0.6 kJ/m^2 is recommended for adequate cracking performance *(14)*. Figure 7 presents the J_c values for each mixture. Based on Figure 7, the following was observed:

- Mixtures SP, H2, and H4 met LaDOTD cracking requirements, while mixtures H1 and H3 failed to meet LaDOTD cracking requirements because of the hard binder (PG 82-22) combined with RAP (20 or 40%).
- To evaluate the impact of adding RAP on the cracking resistance of HMAC mixtures, mixture H1 was compared versus mixture H3, and mixture H2 was compared versus mixture H4. As expected, and as reported by previous studies *(21)*, increasing the RAP content in the asphalt mixture reduced the cracking resistance.
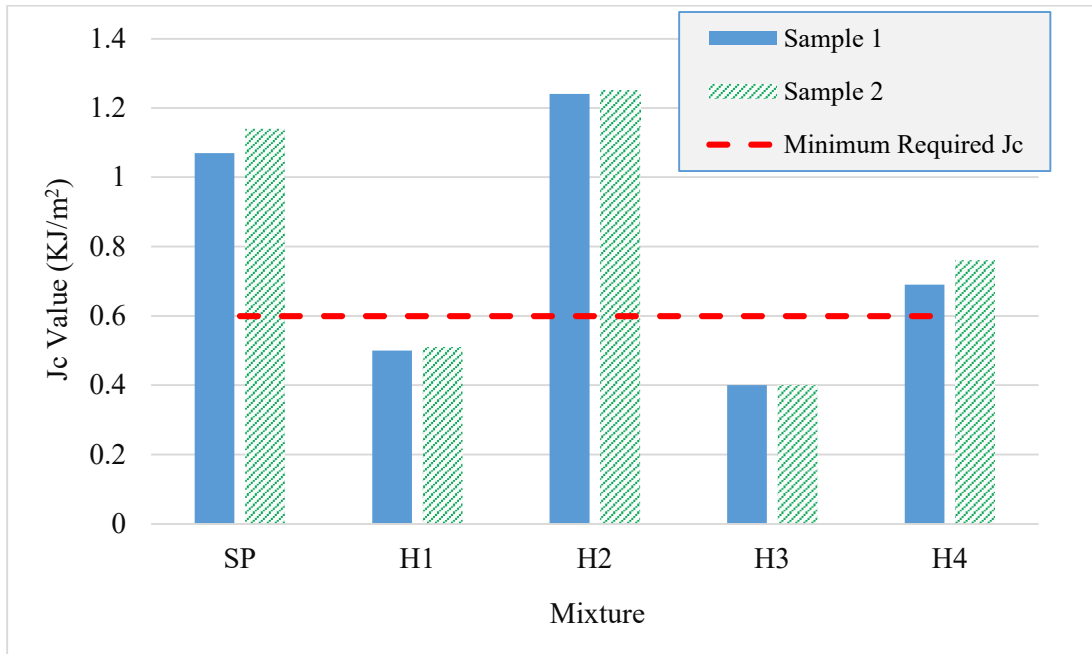

Figure 7. SCB test results for the five mixtures

6.5. Overall Performance Evaluation

Based on the aforementioned results of the performance tests, mixtures H2 and H4 met the French mix design specifications as well as LaDOTD specifications. Therefore, only these two HMAC mixtures (H2 and H4), as well as the control mix (SP), were considered in the following analysis. It is worth noting that mixture H4 had higher RAP content (40%) than mixture H2 (20%), and therefore had higher dynamic modulus and rutting resistance but lower cracking resistance. Given the fact that LaDOTD allows only 20% of RAP in asphalt mixtures with a NMAS of 12.5 mm, mixture H2 would be preferable and recommended to LaDOTD.

7. COST-EFFECTIVENESS OF HMAC MIXTURES

To assess the cost-effectiveness of HMAC mixtures as compared to conventional Superpave mixtures, it is important to evaluate the predicted field performance of each type of mixture while considering the associated costs. In this study, the field performance was predicted using the AASHTOWare Pavement ME Design software, while the associated costs were obtained from local sources.

7.1. Predicted Field Performance

A pavement structure that was constructed on route LA 1077 (control section 852-13) in Louisiana was selected in the analysis to predict the field performance of mixtures SP, H2, and H4. Pertinent design information for this route was obtained from a previous study in Louisiana *(22)*. The

pavement structure of this control section consisted of 50.8 mm (2 in.) wearing course (PG 76-22), 50.8 mm (2 in.) binder course (PG 70-22), 304.8 mm (12 in.) cement-treated base, and a subgrade. The pavement was subjected to an initial Average Annual Daily Truck Traffic (AADTT) of 405 trucks per day (tpd) with a growth rate of 2.1%. In this study, two analysis approaches were conducted as follows:

1. **Approach 1 (constant thickness):** three simulation runs were conducted where mixtures SP, H2, and H4 were incorporated into the 50.8-mm (2-in.) binder course to evaluate the impact of using HMAC mixes on reducing rutting and fatigue distresses.

2. **Approach 2 (constant distresses):** four simulation runs were conducted where mixture SP was incorporated into the binder course having four different thicknesses (76.2 mm [3 in.], 88.9 mm [3.5 in.], 101.6 mm [4 in.], and 114.3 mm [4.5 in.]) to estimate the thickness equivalent (constant distress) to using 50.8-mm (2-in.) binder course including H2 and H4 mixtures. This would allow predicting the effect of using HMAC mixes on the required asphalt thickness.

To consider the impact of traffic loading, approaches 1 and 2 were conducted at two different traffic levels (initial AADTT of 405 and 7000 tpd) resulting in a total of 14 runs (6 runs for approach 1 and 8 runs for approach 2). For each of the 14 simulation runs, the total permanent deformation (in.) and AC bottom-up fatigue cracking (% lane area) were predicted. Table 3 presents the constant and variable inputs used within the 14 simulation runs.

Table 3. AASHTOWare input data

Input	Variation within the 14 Runs	Input in the MEPDG
Wearing course T*	Constant for all the runs	50.8 mm (2 in.)
Binder course T	Approach 1: constant	Approach 1: 50.8 mm (2 in.)
	Approach 2: variable	Approach 2: 76.2 mm [3 in.], 88.9 mm [3.5 in.], 101.6 mm [4 in.], and 114.3 mm [4.5 in.]
Base course T	Constant for all the runs	50.8 mm (2 in.)
Wearing course MP**	Constant for all the runs	Input level 3 through defining binder type and mixture gradation
Binder course MP	Variable in approach 1 and constant in approach 2	Input level 1 through defining the corresponding master curve
Base course MP	Constant for all the runs	Input level 3 through defining a resilient modulus of 80,000 psi
Subgrade MP	Constant for all the runs	Input level 3 through defining a resilient modulus of 18,000 psi
Initial AADTT	Variable	Two levels (405 and 7,000 tpd)

Input	Variation within the 14 Runs	Input in the MEPDG
Climate File	Constant for all the runs	A station was selected in Louisiana having the following location (latitude of 30.5 ft., longitude of -91.875 ft., and elevation of 16 ft.)
Analysis Period	Constant	20 years

*: Thickness
**: Material properties

7.1.1. Results of Approach 1

Figures 8 and 9 present the results of the 6 simulation runs conducted in approach 1. Based on these figures, the following was observed:

- As expected, for all the runs, the permanent deformation and bottom-up cracking at the end of the analysis period were higher for higher traffic.

- For low initial AADTT (405 tpd), all the mixtures had almost the same permanent deformation and bottom-up cracking at the end of the analysis period.

- For higher initial AADTT (7000 tpd), mixtures H2 and H4 had relatively lower permanent deformation at the end of the analysis period when compared to mixture SP. Yet, all the three mixtures had permanent deformation at the end of the analysis period below the threshold (0.5 in.). This agrees with the experimental results of this study which indicated that mixtures SP, H2, and H4 met LaDOTD rutting requirement with mixture SP showing the least rutting resistance while mixture H4 showing the highest rutting resistance.

- For higher initial AADTT (7000 tpd), mixtures H2 and H4 had relatively lower bottom-up fatigue cracking at the end of the analysis period when compared to mixture SP. Yet, all the three mixtures had bottom-up fatigue cracking at the end of the analysis period below the threshold (25% of the lane area).

- Comparing mixtures H2 and H4 for the high initial AADTT level (7000 tpd), both mixtures had similar permanent deformation at the end of the analysis period. Yet, mixture H2 (20% RAP) had lower bottom-up cracking at the end of the analysis period, due to the lower RAP content used in mixture H2. This supports the laboratory results presented in Figure 7, and validates that mixture H2 may be an alternative for state agencies.
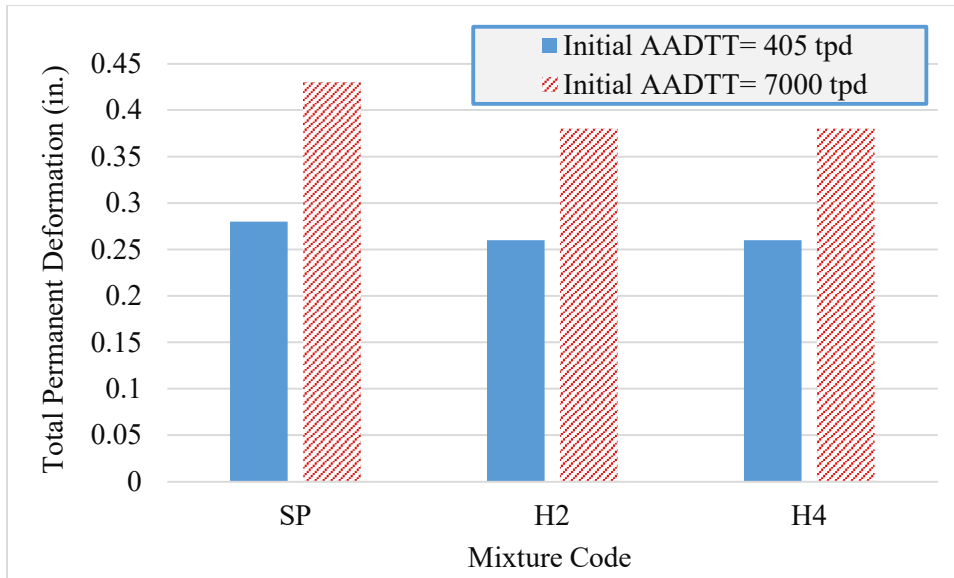
Figure 8. Total permanent deformation for the three mixtures under different initial AADTT levels
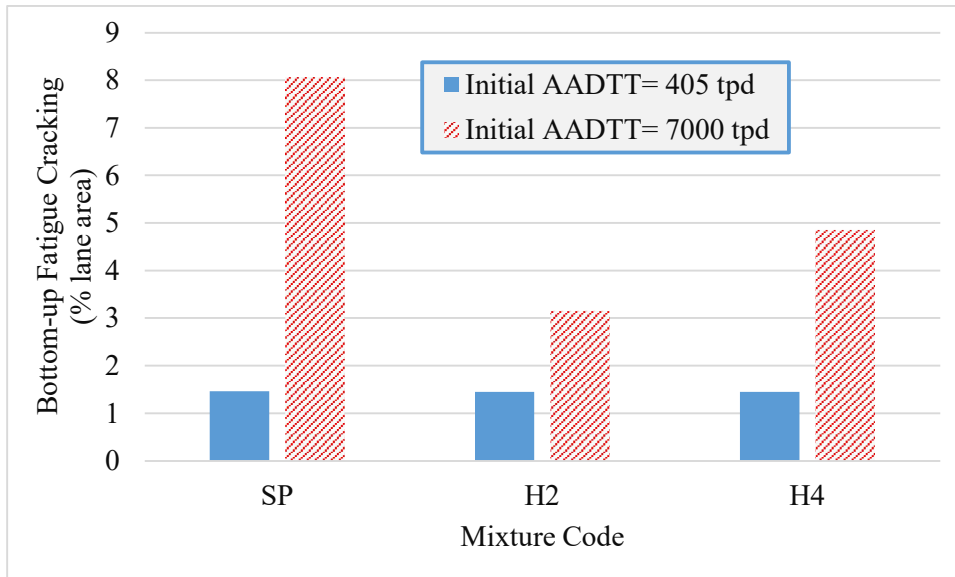

Figure 9. Bottom-up fatigue cracking for the three mixtures under different initial AADTT levels

7.1.2 Results of Approach 2

The runs of approach 2 resulted in equivalent thicknesses of 88.9 mm (3.5 in.) and 101.6 mm (4 in.) for initial AADTT of 405 tpd and 7000 tpd, respectively. This means that for initial AADTT of 7000 tpd, a 101.6-mm (4-in.) binder course including mixture SP will have almost the same structural capacity as a 50.8-mm (2-in.) binder course including mixture H2 or H4 (reduction in asphalt thickness by 50.8 mm [2 in.]). This is comparable to a previous study *(12)* that reported a reduction in asphalt thickness by 63.5 mm (2.5 in.) when HMAC mixtures were used instead of a conventional Indiana Superpave asphalt mixture subjected to initial AADTT of 18,454 tpd and growth rate of 1.7%.

7.2. Associated Material Costs

The material costs for the three mixtures SP, H2, and H4 were estimated. To do so, the following estimates (as of 2009) were obtained from Louisiana Asphalt Pavement Association and used in this study *(23)*:

- Cost of virgin aggregates: $22/ton
- Cost of PG 76-22: $538/ton
- Cost of RAP: $15/ton
- Cost of crumb rubber: $270/ton

Using these estimates, the material cost of H4 ($/ton) was calculated as follows:

- Cost of virgin aggregates=60%×94%×22= $12.4/ton
- Cost of RAP= 40%×94%×15= $5.6/ton
- Cost of virgin binder (PG 76-22) = 90%×6%×538= $29.1/ton
- Cost of crumb rubber= 10%×6%×270= $1.6/ton
- Total cost= 12.408+5.64+29.052+1.62=$48.7/ton

Similarly, the material cost of mixtures SP and H2 were computed, see Table 4.

Table 4. Total material costs for the three mixtures

Mixture Code	SP	H2	H4
Cost of virgin aggregates ($/ton)	16.6	16.5	12.4
Cost of RAP ($/ton)	2.8	2.8	5.6
Cost of virgin binder ($/ton)	30.7	29.1	29.1
Cost of crumb rubber ($/ton)	0.0	1.6	1.6
Total material cost ($/ton)	**50.1**	**50.0**	**48.7**

7.3. Cost-Effectiveness

The previous section indicated that mixtures H2 and H4 had relatively lower materials costs and higher benefits (reduction in asphalt thickness by 1.5 or 2 in. based on the traffic level). Additionally, comparing mixtures H2 and H4 to mixture SP, the use of crumb rubber in mixtures H2 and H4 is expected to offer additional disposal cost savings (as of 2020, the cost for the Central Landfill to dispose tires was about $150/ton). As such, it can be concluded that the HMAC mixtures proposed in this study using crumb rubber and local construction materials in Louisiana were more cost-effective than conventional Louisiana Superpave mixtures. In addition, they are more environmentally-friendly since they reduce the disposal of scrap tires in landfills.

8. CONCLUSION

This study developed a cost-effective HMAC mixture using crumb rubber and local construction materials in Louisiana. Based on the experimental results and structural analysis, the following conclusions and recommendations were drawn:

- Two HMAC mixtures (mixtures H2 and H4) were successfully developed using crumb rubber and local materials in Louisiana. These two mixtures met the French mix design specifications as well as LaDOTD specifications.

- Mixture H2 outperformed the conventional Superpave mix in Louisiana (mixture SP) in terms of dynamic modulus, rutting resistance, and cracking resistance.

- Mixture H4 had higher dynamic modulus and rutting resistance, but lower cracking resistance than mixture SP. Yet, mixture H4 successfully met LaDOTD cracking requirements.

- Mixture H4 had higher RAP content (40%) than mixture H2 (20%), and therefore had higher dynamic modulus and rutting resistance but lower cracking resistance. This conclusion was validated using the AASHTOWare Pavement ME Design software. Given the fact that LaDOTD allows only 20% of RAP in asphalt mixtures with a NMAS of 12.5 mm, mixture H2 may be an alternative for LaDOTD.

- For initial AADTT of 7000 tpd, a 101.6-mm (4-in.) binder course including mixture SP is expected to have almost the same structural capacity as a 50.8-mm (2-in.) binder course including mixture H2 or H4 (reduction in asphalt thickness by 50.8 mm [2 in.]). For initial AADTT of 405 tpd, an 88.9-mm (3.5-in.) binder course including mixture SP is expected to have almost the same structural capacity as a 50.8-mm (2-in.) binder course including mixture H2 or H4 (reduction in asphalt thickness by 38.1 mm [1.5 in.]).

- HMAC mixtures proposed in this study using crumb rubber and local materials in Louisiana were more cost-effective than conventional Louisiana Superpave mixtures. In addition, they are more environmentally-friendly since they reduce scrap tires in landfills.

While the results of the AASHTOWare Pavement ME Design software support the laboratory results, it should be noted that the Pavement ME only considers the mixture stiffness (E*), not its flexibility, ductility, or brittleness. As such, it is essential to support the results of this study through field testing.

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