Evaluating Thin, Ground-Tire Rubber Asphalt Overlay Alternatives to Traditional Hot-Mix Asphalt Overlays for Lower Traffic Volume Applications

by

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Introduction

Much attention has been given to the structural design methodology and materials characterization required to design new pavements in a more fundamentally sound manner. Such was the goal in producing the relatively new AASHTO Pavement M-E software. Ironically, most of the asphalt placed in the US in recent years is in the form of maintenance or rehabilitative overlays, with the goal of restoring surface characteristics. This restoration of surface characteristics includes increased smoothness, reduced noise, reduced rutting, increased friction, and reduction of surface cracking. Although the restoration of surface characteristics is temporary and often shorter in duration compared to the lifespan of the original surface, it is nevertheless an attractive and cost-effective way to restore pavement serviceability and to protect the underlying pavement foundation (Chou *et al.* 2008, Son and Al-Qadi 2015, FHWA TechBrief 2019). However, traditional thin lift overlays should not be considered over existing structures with significant structural deficiencies/failures, such as: fatigue/alligator cracking, rutting, moisture damage in underlying flexible pavement systems, and underlying concrete pavements with excessive slab cracking and/or joint deterioration (NAPA IS 117-E 1994).

There are a number of approaches that can be used to evaluate the relative merits of different combinations of overlay thicknesses and materials with varied properties (complex modulus, creep compliance, fracture energy, fatigue resistance, rutting resistance). At some point in the life of a pavement, structural capacity has deteriorated and/or traffic intensity has increased such that either a rehabilitative overlay or full depth pavement replacement is necessary. In either case, pavement design software can be used determine the appropriate thickness required to achieve the necessary pavement structure for the new design scenario. The decision regarding overlay or replacement will be influenced by the presence of severe localized deficiencies, such as cracks, ruts, potholes, etc., leading to pavement roughness, noise, moisture ingress, and safety concerns (Chou *et al.* 2008, Brown and Heitzman 2013), but one of the key considerations is pavement life cycle cost. The use of overlays as a way to substantially reduce the life cycle cost of paved roads has made overlays both a necessity and a preferred option in many road maintenance programs.

When sufficient pavement structure exists to support an overlay, desirable overlay system characteristics include:

- Rut resistance
- Reflective crack resistance
- Block crack resistance
- Thermally-induced transverse crack resistance
- Proper bonding to the underlying pavement in order to avoid interface sliding, which could lead to either shoving or top-down cracking
- Moisture resistance.

Adding to the overlay design challenge, modern, heterogeneous asphalt mixtures now contain a proliferation of newer ingredients as compared to state-of-practice before the turn of the last century (e.g., in the pre-2000's). It is not uncommon to see a mix design containing a mixture of recycled materials (RAP, RAS, GTR, REOB), along with rejuvenators, PPA, liquid antistrip, fibers, heterogeneous blends of soft and hard (and temperature susceptible) asphalt binder components, and even antioxidants (TRB 2014, Bressi *et al.* 2019). It is widely believed that asphalt mixes have become more brittle over the past few decades, possibly due to the combined effects of increased recycled material content and attention building rut resistance through high gyration SuperPave mix design targets. Increased brittleness (or 'dryness') in mixes has been blamed for the observed increase in various pavement cracking forms. To be fair, blame can also be assigned to increased tire pressures, tire stiffness, deferred maintenance, poor overlay bonding, and changes in asphalt binder supply. Some have also hypothesized the effects of changing climate. Regardless of the causes, there is clearly a critical need for new tools to aid in the design of thin, high-performance, economical maintenance overlays. Ground Tire Rubber ("GTR") additions can serve as such a tool.

Promising field data exists that supports the use of GTR in thin, maintenance overlays (Chou *et al.* 2008, Walubita and Scullion 2008, Scullion *et al.* 2009, Zhou *et al.* 2009, Hu *et al.* 2014). Potential benefits include:

- Greater resistance to cracking and rutting;

- Resistance to pavement "bleaching" and loss of color shortly after paving,

- Extension of pavement life-span with reduced overlay thickness and;

- Quieter, smoother pavements.

Unfortunately, a universally-accepted method for designing asphaltic maintenance overlays is not presently available. Nevertheless, advanced performance tests and numerical models are available to researchers to delve deeply into the question of thickness vs. material properties. This is a timely question in light of new, high performance recycled material systems, including those revolving around chemically-treated, dry-process GTR. For instance, although overlay life extension has been clearly demonstrated with GTR overlays (Hefer *et al.* 2008, Hu *et al.* 2014, Chen *et al.* 2019), the optimal design in terms of overlay thickness and target materials properties remains elusive. Optimal design strategies may vary from agency to agency, however, it is clear that life extension, lower life cycle cost, and increased pavement sustainability are the parameters to be optimized. Again, a truly mechanistic design scheme to arrive at this goal is yet unavailable for use by practitioners. However, recent advances in asphalt performance tests have opened the door for the development of a simple - yet robust - method for determining the break-even thickness and/or the predicted life-extension to be expected when using GTR in thin asphalt overlays.

This report provides strategies for the design of GTR overlays using modern, dry-process, chemically treated engineered crumb rubber (ECR). The motivation for this narrow scope is driven by the relatively lower cost associated with ECR and subsequent increased usage over the past fifteen years, for instance, on the Illinois Tollway (Buttlar and Rath 2017, Rath *et al.* 2019). That notwithstanding, the work presented herein could be extended to the design of wet-process GTR mixes, and more traditional polymer-modified mixes.

Overlay Strategies Evaluated

A number of agencies have policies for minimum asphalt overlay thicknesses and/or set guidelines for standard or 'policy' asphalt overlay thickness. For the purposes of this study, we focus on low-traffic, municipal asphalt overlay applications. This is an often overlook, yet critically important portion of our nation’s roadway system, as low-volume roads encompass roughly three-fourths of the road and highway system mileage in the US. The Asphalt Institute defines Thin Lift Overlays as typically 1.5” or less in compacted thickness and are not intended to strengthen the pavement structure, but instead to address pavement function problems as part of a Pavement Preservation Strategy.

Depending on geographical location, asphalt overlays may be used for the rehabilitation of either existing flexible (asphalt) or rigid (concrete) pavements. Thus, both types of existing pavement are considered herein. Standard overlays may range anywhere from 1.0 to 4.0 inches in thickness or beyond, but in the experience of the authors, most local agencies routinely specify asphalt overlays in the range of 1.0 to 2.5 inches. In this analysis, we have focused most of our evaluations on four primary asphalt overlay strategies:

- A control overlay of 2.0 inches in thickness, consisting of a dense-graded asphalt mixture using PG64-22 binder;
- Three thickness of GTR-modified mixtures are considered (utilizing ECR, dry-process GTR, provided by Asphalt Plus), namely 1.0”, 1.5”, and 2.0”.

The composition and estimated cost of the mixtures investigated are shown below. The results indicate that, although the addition of GTR as a performance-enhancing modifier along with a softer base binder adds $8/ton to mix cost (at a 10% add rate, GTR additives typically cost about $7.00 per mix ton, all-in – material plus construction costs). A 43% savings could be realized if a 1” thick GTR overlay can be shown as a viable alternative to a traditional 2” thick HMA overlay.

Mix Name	Thickness	Binder	GTR Type	Cost $/ton	Cost$/sq-yd	Diff*
Control HMA	2.0”	PG 64-22	None	60	6.60	0
ECR 2.0	2.0”	PG 58-28	ECR, 10%	68	7.48	+13%
ECR 1.5	1.5”	PG 58-28	ECR, 10%	68	5.61	-15%
ECR 1.0	1.0”	PG 58-28	ECR, 10%	68	3.74	-43%

*Difference in cost/sq-yd relative to control HMA; PG58-28 assumed to add $1/mix ton to cost as compared to PG64-22 (rack prices range from equal to $25/ton higher for one grade softer than standard base grade in most markets); ECR at 10% dosage rate assumed to add a net $7/mix ton.

Methods

Summaries of the asphalt mixture performance tests conducted are now presented.

<u>Mixtures Investigated</u>

For our laboratory investigation, we chose a recently sampled MoDOT-approved Superpave mixture available at the Mizzou Asphalt Pavement and Innovation Laboratory (MAPIL). The mixture is a dense-graded, 12.5mm Nominal Maximum Aggregate Size (NMAS) mixture, with 5.2% total asphalt content (PG58-28 binder), 25% reclaimed asphalt pavement (RAP), and 15.0% voids in the mineral aggregate (VMA). Although the 80-gyration Superpave mixture (Note: Many states like GA, VA and Carolina use 65 gyrations for all Superpave mixes) has relatively high compaction requirements for a low-volume road application, it affords the possibility to extend this investigation to moderate traffic levels in a planned, second phase of this study. Furthermore, it is not uncommon for local agencies to utilize stiffer, higher gyrations Superpave mixes if they are made available by the local contractor at a similar price as a lower gyration mix. The trade-off is enhanced rutting resistance with the possibility of reduced durability. Lower durability can be caused by the lower asphalt content resulting from the higher compaction effort, and from less consolidation under traffic, leading to higher void content (and oxidative hardening) during the life of the pavement. Regardless, the selected mixture allows a relative comparison of overlay system performance to be evaluated, especially in light of the fact that the pavement simulation software used (Pavement ME) does not directly account for mixture design gyration level.

For the ECR mixtures, three main modifications were made to the MoDOT mix that follow the recommendations from the supplier (Asphalt Plus):

- 10% ECR was added by weight of virgin binder;
- A 0.2% increase in binder content was used to account for the uptake of light ends by the dry GTR, and; A PG 58-28 binder was used, where the lower, -28C low temperature grade was selected to enhance low-temperature cracking resistance, and the 10% GTR level was selected to promote both rutting resistance and overall cracking resistance, while promoting mixture sustainability.

(Note: Dense Graded mix designs may or may not require the 0.2% binder additional based on fines content and whether or not softer binders with significantly more light ends are employed).

Please note that the PavementME simulation used PG64-22 as a base binder while laboratory mixes used PG58-28 as the base binder. This is due to the incorporation of recycled content in the mix. The 25% RAP modification in the mixture is assumed to bump up the grade to PG64-22.

Indirect Tensile Asphalt Cracking Test (IDEAL-CT)

The IDEAL-CT (Indirect Tensile Asphalt Cracking Test) is a simple cracking test for asphalt mixtures that computes a load-displacement based index, shown to have good correlation with expected mixture performance trends (Zhou *et al.* 2017). The IDEAL-CT is run at room temperature and a loading rate of 50 mm/min. The IDEAL-CT was compared to the Texas OT and Illinois SCB tests using over 25 laboratory and field plant mixes. All three tests ranked all of these mixes in the same order with respect to crack resistance. The IDEAL-CT showed a strong correlation with the field distresses of fatigue, reflective, and thermal cracking. According to the authors, the IDEAL-CT is straightforward to perform, requires minimal training, and is fast as the test can be performed within one minute.

The cracking parameter for the IDEAL-CT is derived from the load vs. displacement curve. The parameters used in calculation of the index are shown in Fig. 1.The larger the CT-index, the better cracking resistance of the mixture. The CT index equation for a specimen of 62 mm thick is as follows.

$$CT_{index} = \frac{G_f}{|m_{75}|} \times \left(\frac{l_{75}}{D}\right) \times \left(\frac{t}{62}\right) \text{ -----(1)}$$

where,

G_f = Fracture energy (area under the curve normalized by the area fractured)

$AREA$= Area under the load – displacement curve, until the terminal load of 0.1 kN is reached

m_{75} = Modulus parameter (absolute value of the slope at 75% of peak load)

l_{75} = Vertical displacement when the load is reduced to 75% of peak load

l_{75}/D = Strain tolerance parameter (when load is reduced to 75% of peak load)

D = Diameter of the sample

t = Specimen thickness

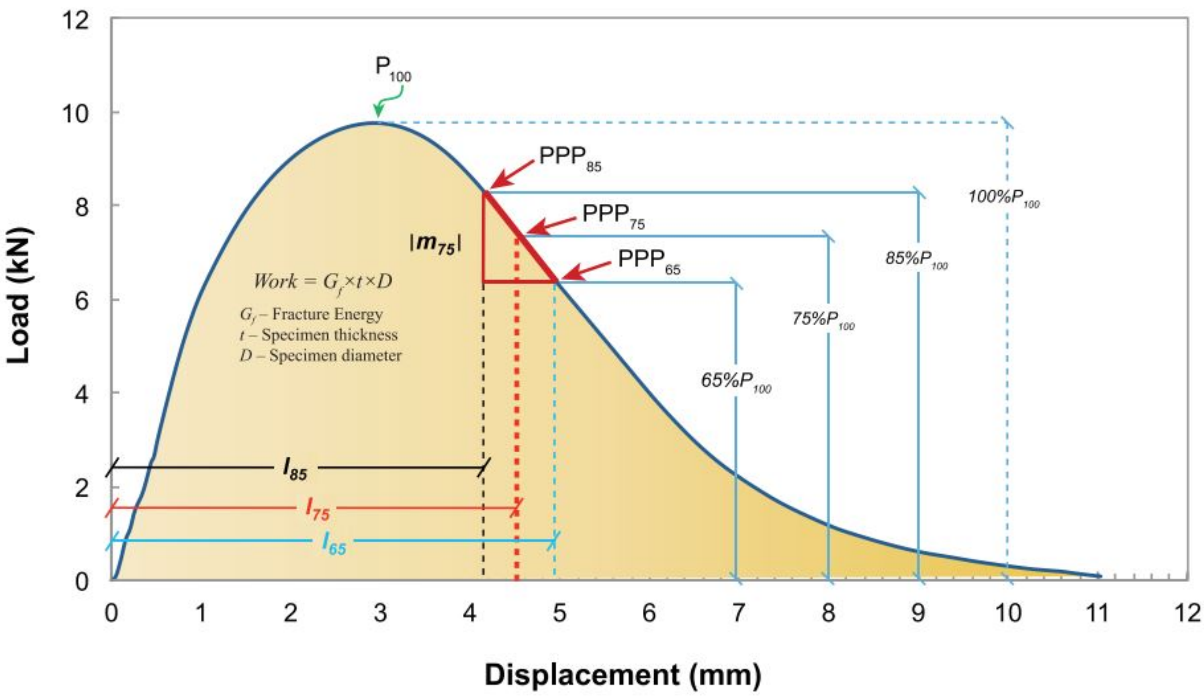

Figure 1. Parameters used in IDEAL CT index calculation (after Zhou et al. 2017).

<u>Illinois Flexibility Index Test (I-FIT)</u>

Researchers at the University of Illinois, Urbana-Champaign developed the Flexibility Index parameter derived from testing a semi-circular bend (SCB) test specimen at 25°C at a constant load-line displacement rate of 50 mm/min (Al-Qadi *et al.* 2015). The Flexibility Index was developed based on the observations that the post-peak slope of the load-displacement curves obtained from SCB tests was dependent on the mixture type. Flexibility Index (FI) was thus formulated as the fracture energy (area under load-displacement curve divided by fracture ligament area) over the slope of the inflection point in the post-peak load part of the load-displacement curve, as shown in Fig. 2 (Ozer *et al.* 2016).

$$FI = \frac{G_f}{|m|} * A \text{ --------(2)}$$

where,

G_f = Fracture energy (AREA under the curve normalized by the ligament length and thickness of the specimen)

AREA = Area under the load – displacement curve, until the terminal load of 0.1 kN is reached

m = Slope parameter

A = Scaling coefficient (=0.01)

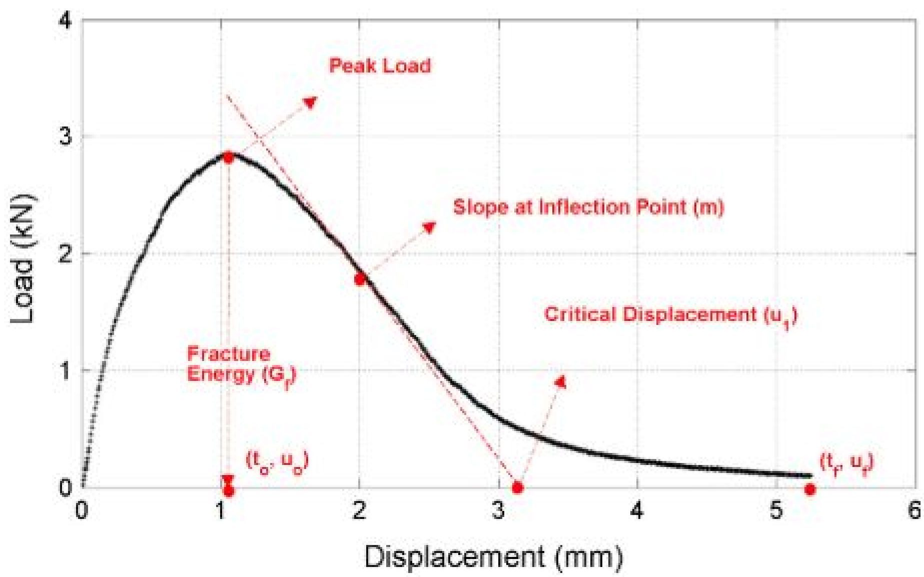

Figure 2. A typical load-displacement curve obtained from I-FIT testing (after Ozer et al. 2016).

<u>Disk-shaped Compact Tension Test (DC(T))</u>

The Disk-Shaped Compact Tension (DC(T)) (ASTM D7313-13) (ASTM 2013) test is used to measure the low-temperature cracking potential of the asphalt mixtures. Wagoner et al. developed a suitable configuration for this test using ASTM E-399 (ASTM E399-12 2012) as a starting point and then modifying it for asphalt materials (Buttlar *et al.* 2016). A significant advantage of the DC(T) test lies in its ability to test cylindrical cores obtained from field or compacted in Superpave Gyratory Compacter (SGC) and its large fracture surface area (Wagoner *et al.* 2005). The DC(T) test temperature is generally 10°C higher than the PG low temperature grade of the binder used in the asphalt mixture. The specimen is pulled with steel loading dowels through drilled holes, forcing a crack to propagate outward from the notch. The test is conducted at a constant Crack Mouth Opening Displacement (CMOD) rate of 1 mm/min (0.017 mm/s). The test is stopped when the post-peak loading reaches a nominal level of 0.1kN. A typical load-CMOD curve is shown in Fig. 3. The area under the curve, normalized by the initial fracture area of the specimen (Equation 3), is reported as the fracture energy of the asphalt mixture specimen. The standard method of testing is outlined in ASTM D7313-13 standard (ASTM 2013). DC(T) fracture energy has been a well-correlated indicator of transverse cracking on field, as shown in Figure 4.

$$G_f = \frac{AREA\ under\ load-CMOD\ curve}{thickness\ x\ ligament\ length} \text{-------(3)}$$

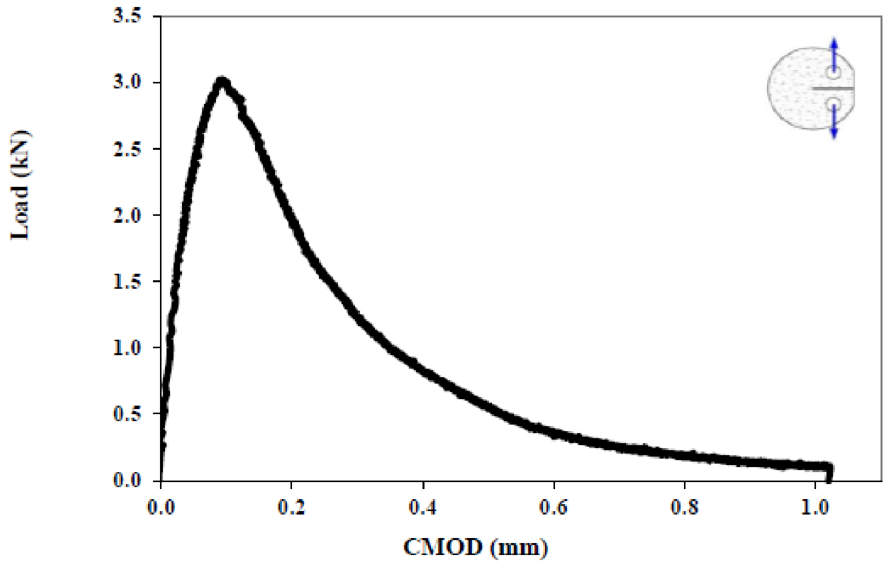

Figure 3. Typical load-CMOD curve obtained from a DC(T) test.

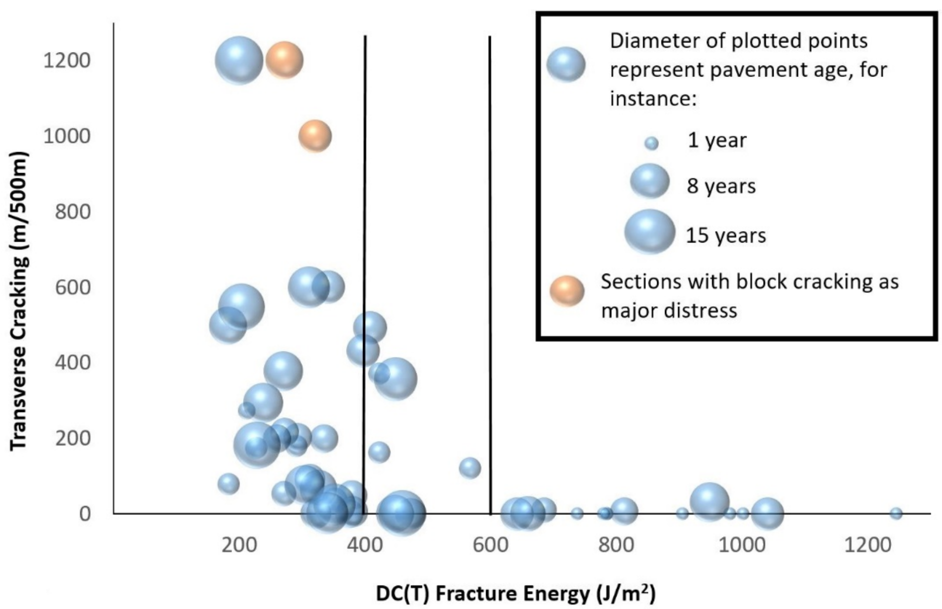

Figure 4. DC(T) fracture energy vs. transverse cracking (after Buttlar et al. 2019))

Hamburg Wheel Tracking Test (HWTT)

Wheel load tracking (WLT) tests are the most common performance tests for measuring rutting potential of HMA mixes. The WLT methods simulate traffic by passing over standardized wheels simulating real-life traffic loads on HMA specimen at a given temperature. The two most common WLT test devices are Hamburg Wheel Tracking Test (HWTT) and the Asphalt Pavement Analyzer (APA) (formerly known as Georgia-loaded wheel tester). The HWTT is performed in accordance to AASHTO T324 standard (AASHTO-T324 2017). A loaded steel wheel, weighing approximately 71.7 kg tracks over the samples placed in a water bath at 50°C. The vertical deformation of the specimen is recorded along with the number of wheel passes. Hamburg wheel tracking test is implemented by many researchers and agencies to address the permanent deformation and rutting problem of the mixtures. In addition, conducting the test at wet condition provides the opportunity to measure stripping potential. To this end, the concept of stripping inflection point (SIP) is defined and currently used by agencies such as California, Wisconsin, and Iowa DOTs. SIP is reported in number of passes and represents the point at which the rutting vs. wheel pass curve has a sudden increase in rut depth. This is believed to be the point where the asphalt binder starts to separate from aggregates. In this study, we implemented the IOWA method to calculate the SIP as follows.

- Fit a 6th degree polynomial curve on the rut depth vs. wheel pass curve.
- Take the first derivative of the fitted curve
- Determine the stripping line using the tangent at the point nearest the end of the test where the minimum of the first derivative of the fitted curve occurs.
- Determine the creep line using the tangent at the point where the second derivative of the fitted curve equals zero.
- Intersect the creep and stripping lines. The wheel pass at which these two lines intersect is the SIP.

For HWTT, apart from the standard 62 mm (~2.5”) thick specimen, two other specimen thicknesses- 1.5” and 1.0”- were tried to simulate the actual thickness of a thin overlay under the wheel passes. The non-standard specimens were supported beneath by a concrete cylinder of required depth. Table 1 below shows the rut depths of the control mix and the rubber modified mixes for different thicknesses. These rut depth values, and stripping inflection points for these specimens are used for comparison in subsequent sections of this report.

Table 1. Comparison of rut depth for Hamburg specimens with different thicknesses.

Mix ->	**Control Mix**	**Rubber-Modified Mix**
Specimen Thickness: 62 mm (~2.5”)		

1.5”		
1.0”		

<u>Cracking Test Thresholds</u>

Table 2 shows the recommended performance test result thresholds for different types of mixes for the cracking tests used in this study.

Table 2. Thresholds for IDEAL-CT, I-FIT, and DC(T) tests.

Test	**Mix Type**	**Minimum Value**	**From**
IDEAL-CT	Dense-Graded	65	Zhou 2018
	Superpave	105	

Test	**Mix Type**	**Minimum Value**	**From**
I-FIT	HMA	8.0	IDOT 2015
	SMA	8.0	

Test	**Traffic Level**	**Minimum Value**	**From**
DC(T)	Low	400 J/m^2	National Low-Temperature Cracking Pooled Fund Study (Marasteanu *et al.* 2012)
	Medium	460 J/m^2	
	High	690 J/m^2	

Pavement ME Simulation

In order to take a more holistic look at relative, predicted performance of a traditional HMA overlay and ECR, i.e., considering the effect of pavement layering (pavement structure), the AASHTOWare Pavement ME design/simulation software was used. These simulations allow a number of comparisons to be made, such as:

1. Comparison of control overlay strategy (2" HMA overlay) to ECR overlays of varying thickness (including a slender 1" thick, 'thinlift' overlay strategy);
2. Comparison of popular mixture cracking and rutting performance tests to Pavement ME simulation results; and;
3. Comparison of DC(T) fracture energy to simulation results from two thermal cracking modes.

The pros and cons of each comparison should be acknowledged, i.e., that the performance tests are easy to conduct (rapid, inexpensive) and have the advantage of testing the actual material being considered for use in the overlay, while the Pavement M-E simulation has the advantage of taking a more rigorous look at the effects of pavement structure on overlay performance but the disadvantage of usually being run using default data for the overlay mix, which are mainly based on the assumed PG binder grade equivalent.

The following summarizes some of the key inputs and assumptions used in this analysis:

- Version 2.3.1+66 of the software used
- Location/Climate: Champaign, Illinois
- 15-year simulation performed
- Low traffic setting (331,464 total heavy trucks over 15-year life, default truck/axle configurations used)
- Asphalt overlay, control section = 2" thick, dense-graded, PG 64-22 binder
- ECR asphalt overlays:
  - Three thicknesses studied (2", 1.5", 1.0"),
  - PG 76-22 binder equivalent used (following the assumed 2-binder-grade bump for a 10% ECR mix, when starting with a PG64-22 binder and modifying with ECR [Justification provided in the Appendix])
- 2 Pavement structures considered:
  - Asphalt-over-asphalt (ACC_ACC), and
  - Asphalt-over-concrete (ACC_JPCP), where JPCP = jointed-plain concrete pavement
- Granular bases used for both pavement structures, higher quality base used in ACC_ACC (more details provided below)
- Moderate/weak subgrade strength assumed (A-5 soil – silty-clay)

Pavement Structures

Scenario I. Asphalt-over-Asphalt (ACC_ACC)

(a) Control (2” HMA over 4” Deteriorated ACC)

Layer type	Material Type	Thickness (in)
Flexible (OL)	Default asphalt concrete	2.0
Flexible (existing)	Default asphalt concrete	4.0
NonStabilized	A-1-a	10.0
Subgrade	A-5	Semi-infinite

(b) ECR (2.0” ECR over 4” Deteriorated ACC)

Layer type	Material Type	Thickness (in)
Flexible (OL)	Default asphalt concrete	2.0
Flexible (existing)	Default asphalt concrete	4.0
NonStabilized	A-1-a	10.0
Subgrade	A-5	Semi-infinite

(c) ECR (1.5” ECR over 4” Deteriorated ACC)

Layer type	Material Type	Thickness (in)
Flexible (OL)	Default asphalt concrete	1.5
Flexible (existing)	Default asphalt concrete	4.0
NonStabilized	A-1-a	10.0
Subgrade	A-5	Semi-infinite

(d) ECR (1.0” ECR over 4” Deteriorated ACC)

Layer type	Material Type	Thickness (in)
Flexible (OL)	Default asphalt concrete	1.0
Flexible (existing)	Default asphalt concrete	4.0
NonStabilized	A-1-a	10.0
Subgrade	A-5	Semi-infinite

Scenario II. Asphalt-over-JPCP (ACC_JPCP)

(a) Control (2” HMA over 8” Deteriorated PCC)

Layer type	Material Type	Thickness (in)
Flexible (OL)	Default asphalt concrete	2.0
PCC	JPCP Default	8.0
NonStabilized	A-2-5	6.0
Subgrade	A-5	Semi-infinite

(b) ECR (2.0” ECR over 8” Deteriorated PCC)

Layer type	Material Type	Thickness (in)
Flexible (OL)	Default asphalt concrete	2.0
PCC	JPCP Default	8.0
NonStabilized	A-2-5	6.0
Subgrade	A-5	Semi-infinite

(c) ECR (1.5" ECR over 8" Deteriorated PCC)

Layer type	Material Type	Thickness (in)
Flexible (OL)	Default asphalt concrete	1.5
PCC	JPCP Default	8.0
NonStabilized	A-2-5	6.0
Subgrade	A-5	Semi-infinite

(d) ECR (1.0" ECR over 8" Deteriorated PCC)

Layer type	Material Type	Thickness (in)
Flexible (OL)	Default asphalt concrete	1.0
PCC	JPCP Default	8.0
NonStabilized	A-2-5	6.0
Subgrade	A-5	Semi-infinite

Results

Results of laboratory performance testing and Pavement ME simulations are provided in the following tables. High-level interpretation of test and simulation results are provided in the tables. A more detailed discussion of results follows each group of tables. For the majority of the tables, the control 2.0" HMA overlay is compared against the three thickness levels investigated for the ECR mix (2.0", 1.5", and 1.0"). Additional testing was conducted for the specialized Hamburg rut/overlay tests conducted, where three, slightly difference thickness levels were considered for both the HMA and ECR modified mixes (approximately 2.5", 1.5" and 1.0"). This allowed the standard Hamburg test thickness to be included (62mm, or roughly 2.5"). It also allowed us to investigate the potential issues associated with using a standard (non-GTR-modified) mixture as a thin, 1" overlay placed on PCC.

Most tables include a side-by-side comparison of 'property-only' and 'pavement ME' or other simulation software results to be compared. The reader will notice that the property only results appear in multiple tables, i.e., in association with multiple deterioration (or 'distress') modes. This acknowledges the fact that the property-only mix performance tests are used by various researchers and agencies in an attempt to control more than one distress mode. For the purposes of this study, the DC(T) test was compared alongside thermal cracking simulation results, and reflective cracking results. The iFIT and IDEAL test results were shown along with fatigue and reflective cracking results. The reader will also notice that the simulation results allow direct investigation of thickness effect on pavement performance, while the performance tests in general do not allow thickness to be considered. The exception here is the modified Hamburg test, where asphalt mixes of varying thickness were placed on a PCC substrate. It is also noted that the Hamburg test was run up to 20,000 wheel passes, in order to evaluate the potential for stripping and interface debonding. While this is inconsistent with the low traffic used in the Pavement ME simulations (we used too many passes to evaluate the pavement samples), it was deemed as advantageous in exposing the differences in the structural integrity of the HMA and ECR-modified mixes under extreme conditions.

Figure 5 shows a flowchart of experimental methodology adopted in this study. The testing and modeling results presented in the following tables are supplemented with brief data analysis summaries and clarifying remarks in the form of: (a) summaries in the final table columns; (b) summaries in the final table rows; (c) footnotes, and; (d) color coding of numerical results (green = exceeding criteria ; yellow = marginal/conditional passing, and; red = failing to meet criteria).

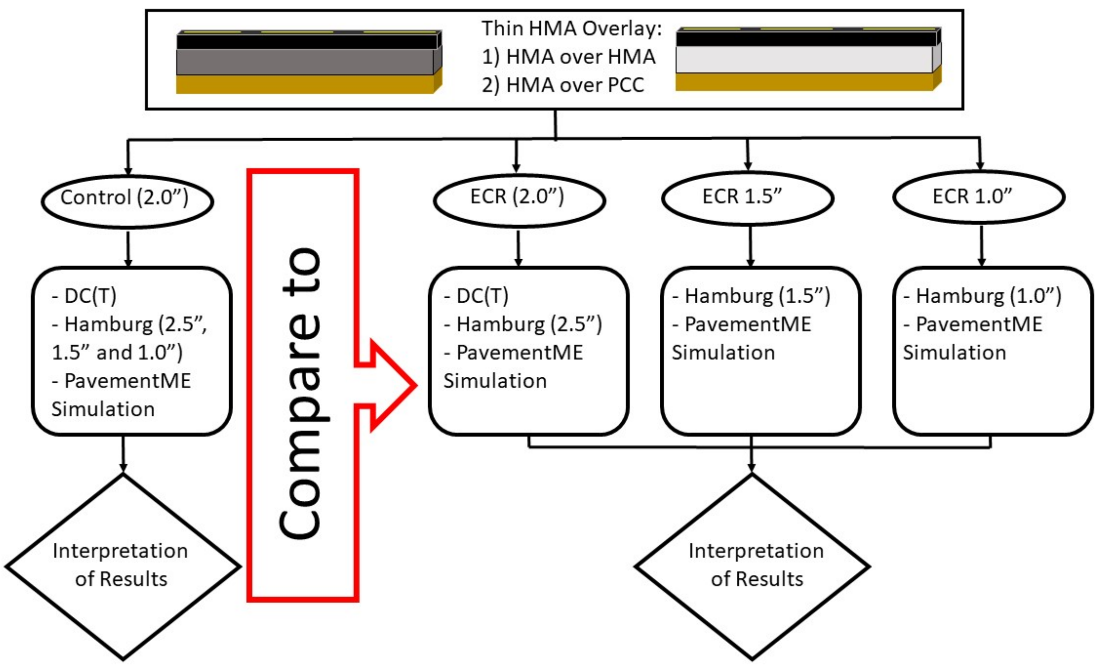

Figure 5. Flowchart showing the experimental methodology for the study

A. Thermal Cracking Analysis

Table A.1. HMA over PCC Overlay

Strategy	Property-Only Analysis		Pavement ME Thermal Cracking Prediction (Property plus Thickness Effect, Level 3*), ft/mile HMA over HMA	Pavement ME Thermal Cracking Prediction (Property plus Thickness Effect, Level 3*), ft/mile HMA over PCC	ILLI-TC Cracking Prediction (Property plus Thickness Effect)
	DC(T) Fracture Energy (J/m^2)	Interpretation			
Control (2” HMA)	436	Passing only low-volume traffic	1041	968	ECR Outperforms Control, All 3 Thicknesses** (on basis number of critical events calculated in Illi-TC (See Table A.2))
Control (1.5” HMA)			1484	1769	
Control (1” HMA)			889	1394	
ECR (2.0”)	474	Pass, low- and med-volume traffic	117	123	
ECR (1.5”)			594	463	
ECR (1.0”)			86	230	
Comparison	ECR possesses approx. 10% higher fracture energy than control	ECR Greatly Outperforms Control on Basis of Fracture Energy	ECR Greatly Outperforms Control, All 3 Thicknesses, on Basis of Pavement ME	ECR Greatly Outperforms Control, All 3 Thicknesses, on Basis of Pavement ME	

*Level 3 PG grades used in model: PG64-22 (control); PG76-22 (ECR). Criterion = 1000 ft/mile, max.

**Min thickness allowed in ILLI-TC is 3”. See table A.3 for detailed results.

Table A.2. ILLI-TC Thermal Cracking Analysis (Property Plus Thickness Effect)

Mix	Location	Peak Load (kN)	Tensile Strength (MPa)	Fracture Energy (J/m^2)	Mix CTE (mm/mm/°C)	Layer Thickness (in.)	Critical Events
Unmodified	MN	3.11	4.52	436	4.00E-05	3	6
Unmodified	MN	3.11	4.52	436	4.00E-05	4	5
Unmodified	MN	3.11	4.52	436	4.00E-05	5	6
Rubber-modified	MN	3.46	5.03	474	4.00E-05	3	4
Rubber-modified	MN	3.46	5.03	474	4.00E-05	4	3
Rubber-modified	MN	3.46	5.03	474	4.00E-05	5	5
Comparison	ECR Mix outperforms control mix in each scenario						

Tables A.1 and A.2. demonstrate that the ECR mix outperforms the HMA mixture across the thickness ranges considered, and in terms of property-only characterization in the DC(T) test, as well as by Pavement ME and ILLI-TC thermal cracking simulation. In terms of DC(T) testing, the ECR mix achieved a fracture energy level of 474 J/m^2, allowing it to pass both low- and medium-traffic level requirements. The HMA control mix had a measured fracture energy level of 436 J/m^2, allowing it to pass only the low traffic category. The Pavement ME software uses a thermal cracking prediction software originally developed at Penn State in the early 1990's called TCMODEL. It was later updated during NCHRP 1-37A, which led to the version used in the AASHTOWare, Pavement ME software. The lead author of this report oversaw the NCHRP 1-37A software updates, and also was a co-PI on the research contract that led to the development of the ILLI-TC software.

ILLI-TC was developed as part of a Pooled Fund Low Temperature Cracking study (#776), led by the University of Minnesota and MnDOT, and also involving the University of Illinois at Urbana-Champaign (UIUC), Iowa State, and the University of Wisconsin. The Pavement ME simulation predicts roughly 2 times to 10 times more thermal cracking in the control mixture as compared to the ECR mixture, depending on pavement thickness. It was somewhat counter-intuitive that the middle thickness category of the ECR mix had the highest thermal cracking, but a similar trend was observed for other distresses as well. The effect of the existing pavement below the overlay had minimal effect on predicted thermal cracking, with slightly higher cracking predicted in the HMA-over-HMA structures. The ILLI-TC analysis conducted was limited to the prediction of # of critical cracking events, showing a slight improvement in number of critical cracking events for the ECR mix relative to the control mix. One can also conclude from this data set that the DC(T) property-only analysis is in general agreement with the simulation results, where both predict moderate thermal cracking resistance in the mixtures, with the ECR possessing the better low-temperature cracking resistance.

In our experience, thermal and block cracking mechanisms are quite inter-related (see H. Wang, PhD thesis, 2018, UIUC). The two orange dots shown earlier on Figure 4 demonstrate how low fracture energy can lead to high block cracking. However, current simulation software does not allow for direct prediction of block cracking. That notwithstanding, the DC(T) test results obtained suggest that the ECR mix should also be more resistant to block cracking as compared to the control mix.

B. Fatigue Cracking Analysis (Bottom-up)

Table B.1 HMA over HMA Overlay

Strategy	Property-Only Analysis			Pavement ME Fatigue Cracking Prediction (Property plus Thickness Effect), % lane area cracked HMA over HMA	Pavement ME Fatigue Cracking Prediction (Property plus Thickness Effect), % lane area cracked HMA over PCC
	iFIT Flex. Index	IDEAL CT Index	Interpretation		
Control (2" HMA)	7.6	68.2	Failing iFIT, Passing IDEAL only at low traffic level	0	1.4
Control (1.5" HMA)				0	1.4
Control (1" HMA)				0	1.4
ECR (2.0")	1.9	24.6	Failing iFIT, Failing IDEAL	0	1.4
ECR (1.5")				0	1.4
ECR (1.0")				0	1.4
Comparison	Control greatly outperforms ECR mix	Control greatly outperforms ECR mix	Both Mixes Mostly Failing Criteria, Exception Control/IDEAL/Low Traffic	Control and ECR Identical, No Bottom-Up Fatigue	Control and ECR Identical, No Bottom-Up Fatigue

Note: Lack of correlation from Pavement ME software predictions to IFIT and IDEAL test results

Tables B.1 summarizes the predicted fatigue cracking performance of the mixtures investigated. In the case of property-only characterization, the iFIT test characterized both the control and ECR mix as failing in cracking resistance, with the control mix scoring much higher on the flexibility index test. The IDEAL test also scored the control mix higher, with a passing result for a dense-graded, low-volume mix (but failing the Superpave mix category). Thus, a yellow-shaded box was used. In the case of the HMA-over-HMA pavement structure, the Pavement ME software predicted zero fatigue cracking in all cases considered. Clearly, the IFIT and IDEAL tests greatly overpredict the amount of bottom-up fatigue cracking predicted by the Pavement ME software. This may owe to the fact the Pavement ME simulation directly takes into account pavement structure, while the IFIT and IDEAL property-only tests do not. This may also be partially due to the fact that the Pavement ME software has been calibrated to a large, national dataset, while IFIT and IDEAL criteria are based on very limited field data at this time.

The Pavement ME software also predicted near-zero fatigue cracking in the HMA-over-PCC pavement structure. Given the fact that so much tonnage of asphalt is used in HMA overlays placed on PCC pavements, the results suggest that the overly-conservative nature of the iFIT and IDEAL cracking tests for HMA-over-PCC pavement structures might lead to improper adjustments/decisions during mix designs (over-estimation of asphalt content bumps required, improper characterization of GTR mixes).

Further discussion of this point will be made following the presentation of the reflective cracking results. It should be noted that GTR mixes are not directly available in Pavement ME software predictions, so the ECR results shown are actually based on the PG76-22 default mixture available in the software. Thus, actual fatigue resistance of the GTR mix may differ from the predicted levels. Research has shown that GTR mixes may be more fatigue resistant than traditional, polymer-modified mixes.

The other type of fatigue cracking noted in modern, asphalt pavement surfaces is top-down cracking. Because the top-down fatigue cracking model in Pavement ME was added late in the NCHRP 1-37 A project and is largely empirical, its accuracy is deemed questionable. Thus, results from the Pavement ME top-down cracking model are not presented herein.

C. Reflective Cracking (R.C.) Analysis

Table C.1 HMA over HMA Overlay

Strategy	Property-Only Analysis				Lytton R.C. Prediction (Property plus Thickness Effect), ft/mile*
	Fracture Energy (J/m^2)	iFIT Flex. Index	IDEAL CT Index	Interpretation	
Control (2" HMA)	436	7.6	68.2	Passing DC(T), Failing iFIT, Passing IDEAL only at low traffic level	842
Control (1.5" HMA)					924
Control (1" HMA)					809
ECR (2.0")	474	1.9	24.6	Passing DC(T), Failing iFIT, Failing IDEAL	492
ECR (1.5")					729
ECR (1.0")					459
Comparison	ECR mix outperforms control mix	Control greatly outperforms ECR mix	Control greatly outperforms ECR mix	Both Mixes Failing iFIT and IDEAL Criteria, Exception Control/IDEAL/Low Traffic, DC(T) Test Most Predictive	ECR Outperforms Control, all 3 thicknesses, All Pass

*Using 1500 ft/mile as criterion, max

Table C.2 HMA over PCC Overlay

Strategy	Property-Only Analysis				Lytton R.C. Prediction (Property plus Thickness Effect), ft/mile*
	Fracture Energy (J/m^2)	iFIT Flex. Index	IDEAL CT Index	Interpretation	
Control (2” HMA)	436	7.6	68.2	Scores Insufficient to Eliminate R.C.	4703
Control (1.5” HMA)					5018
Control (1” HMA)					4993
ECR (2.0”)	474	1.9	24.6	Scores Insufficient to Eliminate R.C.	4413
ECR (1.5”)					4619
ECR (1.0”)					4489
Comparison	ECR mix outperforms control mix	Control outperforms ECR mix	Control outperforms ECR mix	Scores From All 3 Tests insufficient to Eliminate R.C., Both Mixes	ECR Slightly Outperforms Control, all 3 Thicknesses, All Sections Eventually Fail in Reflective Cracking

*Using 1500 ft/mile as criterion, max

The reflective cracking results shown in Tables C.1. and C.2. have all three cracking test results represented alongside Pavement ME simulation results. Oshone et al. proposed DC(T) fracture energy threshold for various thicknesses according to the needed performance of the overlay. The authors investigated a set of 15 field cores and the corresponding PMS (Pavement Management System) data including only two AC over PCC overlays, to propose a preliminary fracture energy threshold. The values are reproduced from the authors’ published paper in Table 3 (Oshone, Dave, and Sias 2019).

Table 3. Preliminary Recommendations for DC(T) Fracture Energy for Asphalt Overlays for Lower Performance Need (after Oshone, Dave, and Sias 2019)

Overlay Thickness (cm)	**Overlay Thickness (inches)**	**DC(T) Fracture Energy (J/m^2)**
2.5	1	730
3.75	1.5	490
5	2	370
6.25	2.5	290

Previous work on reflective cracking resistance thresholds for the DC(T) derived from accelerated pavement testing of HMA-over-PCC overlay systems suggested that very high fracture energy levels and multi-layered overlay systems are required to greatly mitigate reflective cracking in these structures (I. L. Al-Qadi and Wang 2009). Values of 850 J/m^2 for the surface layer, and 1300 J/m^2

for the stress-absorbing membrane interlayer placed directly above PCC were recommended for the rehabilitation of runway 9R-27L at Chicago's O'Hare airport in recent years. These values were obtained from the Accelerated Pavement Testing of various asphalt mixtures meant to be placed on different depths (I. L. Al-Qadi and Wang 2009). For the purposes of the study herein, we simply apply the fracture energy requirement for thermal cracking, although in the future, slightly higher thresholds may be deemed appropriate to account for stress intensities introduced in the cracking, underlying flexible pavement. Following this practice, both mixes pass the DC(T) requirement, with the ECR mix ranking as more reflective cracking resistant.

Table C.1. shows that the DC(T) test correctly ranks the control and ECR mix in terms of their reflective cracking resistance for the HMA-over-HMA structure, as compared to the Pavement ME simulation results. The DC(T) also correctly predicts a passing result for both mixes. On the other hand, the iFIT and IDEAL show a reversed ranking as compared to the Pavement ME result. Both iFIT and Ideal show failing results, despite passing results being predicted by the software. This suggests that the iFIT and IDEAL test criteria may be too severe for the purposes of evaluating reflective cracking resistance of HMA overlays placed over PCC. In their current forms, it appears that the IFIT and IDEAL tests may be inappropriate for characterization of mixes containing GTR. This may be due to the fact that the loading rate for stiffer, less viscous mixes (such as GTR) is actually higher than for softer mixes, due to the use of very rapid, load line displacement control in these tests. Thus, every mix tested in these devices experiences a different stressing rate, which invokes a high peak load/high stored energy response in the GTR mixes. Since the IFIT and IDEAL cracking indexes largely ignore the concept of material strength and focus most heavily on post-peak unloading behavior, the use of differing stressing rates for each material appears to put GTR mixes at a distinct disadvantage. This may explain why the results obtained from these tests for GTR mixes do not appear to match field experience or Pavement ME predictions.

Table C.2 indicates a high level of reflective cracking predicted by all tests for the HMA-over-PCC structure (except, moderate cracking predicted in the case of the IDEAL/control mix), which agrees with the prediction of high reflective cracking rate by the Pavement ME software. The Pavement M-E software uses the reflective cracking prediction system developed at Texas A&M University by Professor Bob Lytton and colleagues. These findings support typical field observations, which nearly always show that reflective cracking is virtually impossible to stop in the case of HMA overlays placed on PCC pavements. These results also suggest that, unless extreme measures are taken, reflective cracking will probably occur in HMA overlays placed over PCC. This again brings into question the usefulness of the iFIT and IDEAL tests for these overlay systems, since criteria do not exist for the design of systems to effectively mitigate reflective cracking in HMA-over-PCC overlay systems. Although the DC(T) criteria for multi-layer reflective crack resistant systems (SAMI plus high fracture energy surface) exist, they have only been evaluated and shown to work well in accelerated pavement testing at Chicago O'Hare Airport and should therefore be further evaluated.

D. Rutting (and Stripping) Analysis

Table D.1 HMA over HMA Overlay

Strategy	Property-Only Analysis				Pavement M-E Rut Prediction (Property plus Thickness Effect), in.* HMA over HMA	Pavement M-E Rut Prediction (Property plus Thickness Effect), in.* HMA over PCC
	Rut Depth @ 20k Passes (mm)	Stripping Slope	Stripping Inflection Point	Interpretation		
Control : ~2.5” (62 mm) HMA**	2.62	<2.0	-	No Stripping	0.56	0.04
Control : 1.5” HMA	4.05	<2.0	-	No Stripping	0.59	0.03
Control : 1” HMA**	4.77	2.5	13370	Stripping	0.62	0.01
ECR : ~2.5”	1.64	<2.0	-	No Stripping	0.56	0.04
ECR : 1.5”	2.03	<2.0	-	No Stripping	0.59	0.02
ECR : 1.0”	1.74	<2.0	-	No Stripping	0.62	0.01
Comparison	ECR mix outperforms control mix	Control, 1” Triggers Stripping Analysis	Control, 1” Has a Stripping Inflection Point	Control, 1” Fails Stripping Inflection Point for Med and High Traffic	Control and ECR Practically Identical, All thicknesses, Moderate Rut, All Passing	Control and ECR Practically Identical, Very Low Rut

*Using 0.75” as max rutting criterion, 2” HMA Thickness. 1 inch = 25.4 mm.
**2 wheel paths instead of 3

Table D.1 presents the results of the property-only Hamburg testing and the Pavement ME simulation results. In all cases, the ECR mixes outperformed the HMA mixes, with less than half the rutting depth measured in some cases. The most dramatic difference was observed in the 1.0” thickness trials (of HMA or ECR overlays tested over a PCC substrate in the Hamburg test). Refer back to Table 1 for a side-by-side comparison of rutting profiles in the modified Hamburg test. In the case of the HMA-over-PCC 1.0” overlay system, a relatively deeper rut depth was observed, along with an indication of a stripping inflection point at 13,370 wheel passes. Although the rut depth and # of cycles to stripping inflection should be viewed as passing for a low traffic setting, it nevertheless points out the difference between the control HMA and ECR mix. It is surmised that the ECR mix is stiffer and more elastic at higher temperatures, allowing the mix to withstanding rutting, shear movement, and interface shear sliding at the HMA-PCC interface. This also suggests a benefit in using GTR-modified mixes for thin overlay applications, especially where lateral forces may exist due to braking, accelerating, and turning operations (intersections, ramps, hills, etc.). It is not appropriate to directly compare the Hamburg rut depth estimate to the Pavement ME rut depth estimate, for a number of obvious reasons. However, low rut depths and similar predictions were obtained for both mixes with Pavement ME.

E. International Roughness Index (IRI) Rating

Table E. Overall Pavement Performance by IRI (Both Pavement Structures)

Strategy	Pavement M-E IRI Prediction, Asphalt-Over-Asphalt*, in/mile	Pavement M-E IRI Prediction, Asphalt-Over-Concrete*, in/mile	Interpretation
Control (2" HMA)	168	111	Control and ECR Similar in Terms of Overall Performance, All Thicknesses Passing, ECR Slightly Lower Roughness in Asphalt-over-Asphalt Pavement Structure
Control (1.5" HMA)	174	112	
Control (1" HMA)	169	112	
ECR (2.0")	158	110	
ECR (1.5")	165	110	
ECR (1.0")	161	110	
Comparison	ECR Slightly Better in Terms of Overall Performance, All Thicknesses. Control 1.5" only iteration that fails IRI	Control and ECR Virtually Identical in Terms of Overall Performance, All Thicknesses	

*Using 172 as max IRI criterion

Table E presents overall pavement performance in terms of the predicted International Roughness Index (IRI) after 15 years of simulated traffic (low traffic volume) and environmental exposure. The overarching observation from these results, somewhat surprisingly, is that the pavement ME software does not predict much difference in IRI between the various overlay materials and thicknesses investigated. In the case of the Asphalt-Over-Asphalt overlay system, the ECR mixes at all three levels showed a slightly better (lower) IRI prediction than the control mixture. The similar IRI predictions were not expected, since the ECR strategies evaluated had better performance in terms of thermal cracking resistance, and reflective cracking resistance, and similar performance in terms of fatigue cracking and rutting. Very similar results were also obtained for IRI in the asphalt-over-PCC systems.

In the larger picture, it is important to note that the 1" thick ECR overlay system outperforms the 2" thick control section in terms of IRI, in addition to the individual performance category benefits outlined earlier. This has positive implications for local road authorities, as the 1" ECR system is expected to cost approximately 44% less than a 2" thick traditional HMA overlay, but is predicted to have a lower deterioration rate (for thermal, block and reflective cracking), therefore suggesting a longer life. As discussed earlier, even when comparing a 1" ECR overlay to a 1.5" thick traditional overlay system, a 26% cost savings can be realized, with an even bigger relative performance difference expected.

The similarity in IRI prediction is probably driven by the fact that wheel path fatigue cracking more adversely affects ride quality as compared to thermal and reflective cracking. However, if the individual distress types and severity levels were fed into another pavement rating system, such as PASER (Walker *et al.* 2013), one would expect to see more distinct differences between the ECR and control mix. This analysis has been carried out in the following section.

F. PASER Evaluation of Overall Pavement Performance

As mentioned in the previous section, Pavement ME IRI ratings of the various overlay strategies were found to reside in a narrow range, despite the fact that the GTR mixes were predicted to have fewer overall distresses and higher scores in the DC(T) test. In reality, most owner-agencies tend to use overall pavement serviceability rating systems such as PASER rather than IRI in the management of their road networks. Therefore, the predicted Pavement ME distresses were compared to the subjective PASER rating scale to obtain PASER serviceability ratings. PASER rates pavements on a 10-point scale, with newly constructed pavements given a rating of 10, newly constructed asphalt overlays typically given a rating of 9, and deteriorated pavements given ratings of 8 or less, depending on the type, extent and severity of distresses present. Although numerous comparisons could be made with the data generated in this study, for the sake of simplicity two scenarios are evaluated herein: (1) Equal thickness HMA and GTR overlays (2"), and; (2) HMA overlay with 2" thickness vs. GTR overlay with 1" thickness. To further simplify the analysis, a linear rate of PASER serviceability decline vs. time was assumed.

The results from scenario #1 are presented in Figures 5a and 5b. In the case of Figure 5a, the following points can be made:

- GTR extends overlay life by 5 years (20 years vs. 15 years), for overlay placed on existing PCC

- 33% life extension requires only 13% more initial investment

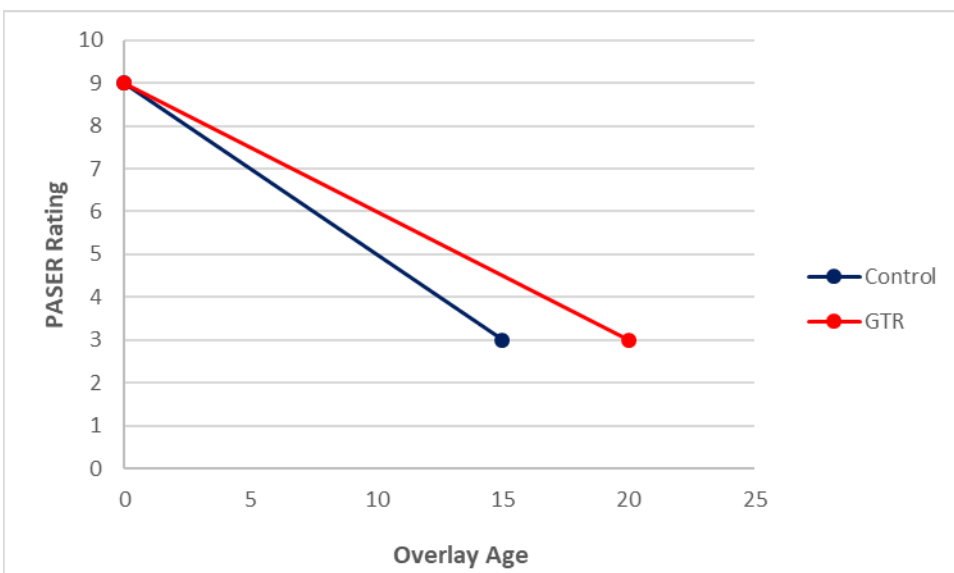

Figure 5a. PASER ratings for HMA and GTR overlays: Scenario 1a: 2" HMA and 2" GTR Overlays placed over Existing HMA

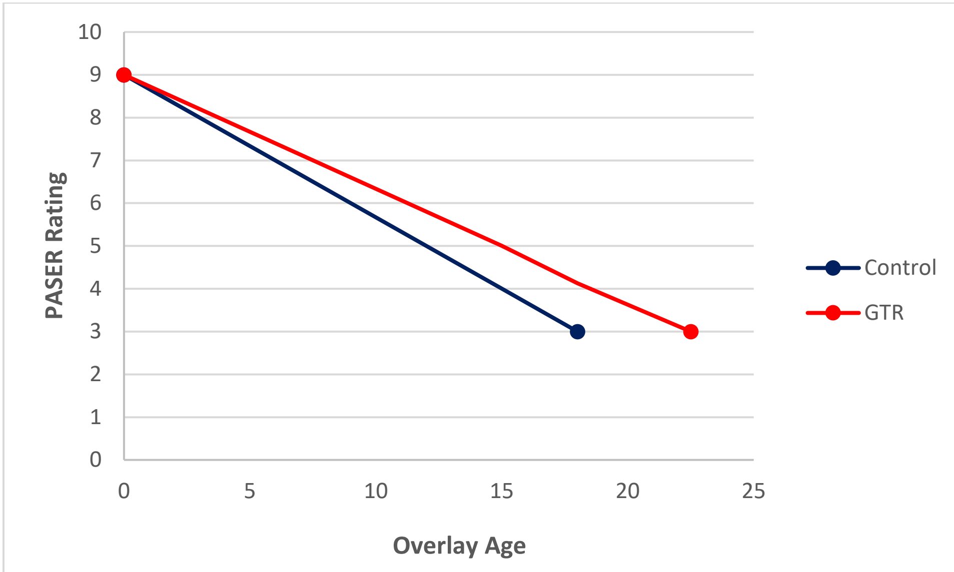

Figure 5b. PASER ratings for HMA and GTR overlays: Scenario 1a: 2" HMA and 2" GTR Overlays placed over Existing PCC

In the case of Figure 5b, the following points can be made:

- GTR extends overlay life by 4.5 years for rehabilitation of existing PCC
- 25% life extension requires only 13% more initial investment

The results from scenario #2 are presented in Figures 6a and 6b. In the case of Figure 6a, the following points can be made:

- Even at half the thickness, GTR still outperforms control (1.36 year life extension, 9%)
- In this scenario, ***the GTR overlay strategy saves 43% on initial costs***

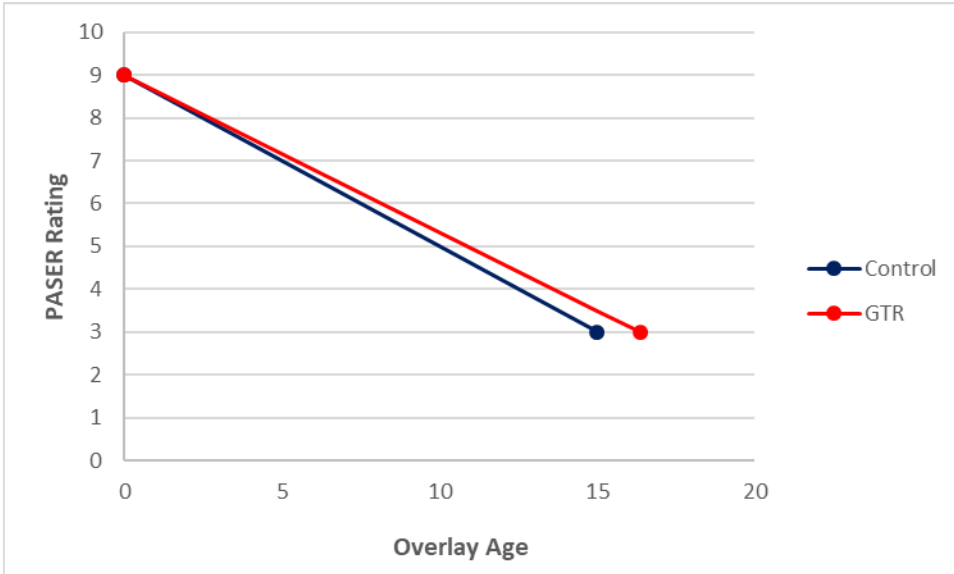

Figure 6a. PASER ratings for HMA and GTR overlays: Scenario 1a: 2" HMA and 1" GTR Overlays placed over Existing HMA

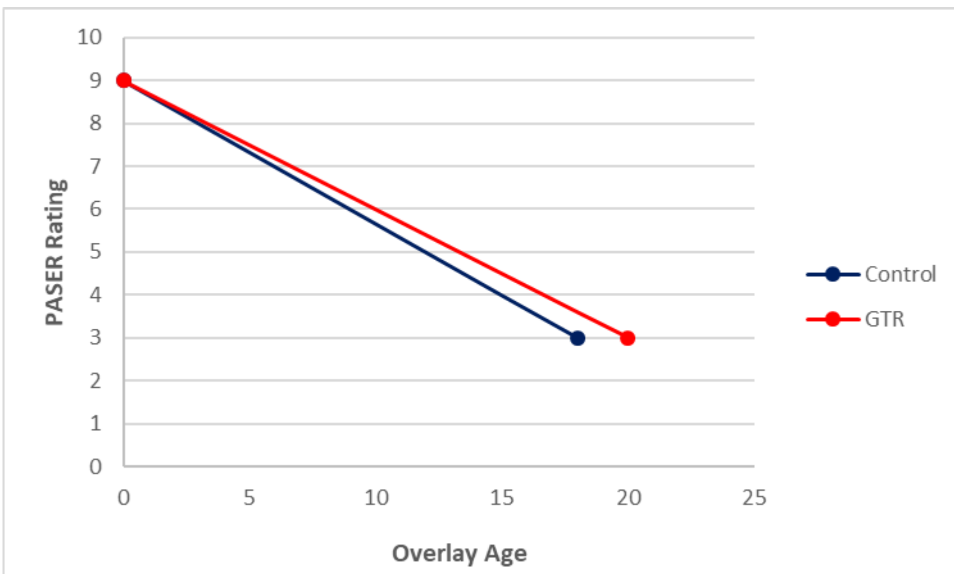

Figure 6b. PASER ratings for HMA and GTR overlays: Scenario 1a: 2" HMA and 1" GTR Overlays placed over Existing PCC

In the case of Figure 6b, the following points can be made:

- Even at half the thickness, GTR still outperforms control (2 year life extension, 11%)

- In this scenario, the GTR overlay strategy saves 43% on initial costs

Overall, for this particular analysis (asphalt mixtures investigated, selected existing pavement structures and materials, climate (Midwest), and traffic level (low-volume), scenario #2 appears to be the best strategy. In this case, using a half-thickness (1” thick) GTR overlay saves 43% on initial costs, while providing, on average, 10% more life than a traditional HMA overlay placed at 2” thickness.

Additional savings may also be possible, considering the fact that the GTR overlay strategy will likely involve less maintenance over time. This is not only because less surface distresses will be present – lower thermal and block cracking, but also because the use of a thinner overlay with a tougher mix will reduce crack spalling width and depth (due to the thinner overlay used), which will reduce crack sealing quantities. Road users will also benefit from reduced surface roughness, reduced noise (due to fewer distresses and the acoustic benefits of GTR mixes), and a better overall surface appearance (less distresses, less bleaching of road surface).

Conclusions and Recommendations

A comprehensive laboratory testing and simulation study was conducted to provide a quantitative evaluation of thin, ground tire rubber modified asphalt concrete overlay systems as economical alternatives to traditional hot-mix asphalt overlays for low traffic volume applications. Based on the results obtained, the following conclusions were drawn:

1. **Based on AASHTO Pavement ME simulation results, A 1” thick GTR-based overlay mixture (dry-process, ECR investigated herein) will:**
    - **Yield superior field performance;**
    - **Exhibit a longer service life**
    - **Exhibit a lower up-front cost, and;**
    - **Generate a lower life-cycle cost, all relative to a 2” traditional HMA overlay.**

    This strategy is estimated to provide a 43% cost savings on a per square yard basis, while extending pavement life by 10% on average. Due to reduced thermal, block and reflective cracking formation and delayed, tighter cracks in a thinner overlay, less required crack sealant is expected. Thus, additional cost savings may be realized.

2. **ECR overlay mixes showed superior performance in terms of thermal, block and reflective cracking resistance, as estimated by physical property testing in the DC(T) and as predicted by the Pavement ME software.** Significant improvements in reflective cracking resistance was noted for the asphalt-over-PCC pavement structure, and similar results were obtained for the asphalt-over-PCC system. This performance enhancement is expected to reduce maintenance costs (reduced crack sealing) and extend overlay life. Interestingly, the Pavement ME IRI prediction did not capture the benefits of reduced cracking in these categories, probably because wheel path fatigue cracking and effects of variable rut depths might drive the IRI model in Pavement ME.

3. **Unlike the DC(T), the iFIT and IDEAL tests did not agree with the ranking of HMA and ECR mixes in terms of reflective cracking resistance as predicted by the Pavement ME software.** Although more validation is needed, different criteria are available for the DC(T) in terms of pavement structure criteria: i.e. reflective crack control for overlays placed on asphalt vs. those placed on PCC. For the iFIT and IDEAL, pavement-structure-based criteria do not exist, which

seems to lead to overly-conservative results for asphalt-over-asphalt overlay systems. In general, Pavement ME predicted a moderate reflective cracking rate in the asphalt-over-asphalt overlay systems (with ECR mixes cracking at a significantly lower rate than the HMA control), and a high reflective cracking rate was predicted for asphalt-over-PCC for all systems evaluated. This concurs with field observations, which indicate the difficulty in slowing down reflective cracking in HMA overlays placed over PCC.

4. **For fatigue cracking, the Pavement ME software predicted identical performance between all of the overlay systems investigated.** A zero bottom-up fatigue cracking rate was predicted for the asphalt-over-asphalt overlay systems, and a near-zero rate for the asphalt-over-PCC systems was estimated by Pavement ME. However, the IFIT and IDEAL property-only tests predicted a high rate of cracking in the mixes investigated. The results suggest that the IFIT and IDEAL tests may be too severe or simply inappropriate for the analysis of GTR mixes in their current forms.

5. **It is evident that the underlying, pre-existing pavement system plays a dominate role in fatigue cracking rate, similar to what was observed for reflective cracking.** When compared to the ME analysis, the iFIT and IDEAL tests both correctly predicted high reflective cracking potential in the asphalt-over-asphalt overlays systems, but incorrectly predicted bottom-up fatigue cracking potential in the overlay systems. In fact, neither system allows the user to delineate between these pavement structures (only one set of criteria is available). As expected, the reflective cracking rate was higher in the case of the PCC underlying pavement structure.

6. **The fact that the underlying pavement type appears to be a dominating factor in the development of reflective and fatigue cracking brings into question the merit of incorporating iFIT or IDEAL testing in the design of asphalt overlay mixtures.** For instance, reflective cracking is likely to occur in HMA-over-PCC pavement overlays regardless of overlay mix properties. By employing iFIT or IDEAL in the design of these systems, the mix design might be driven to a more expensive, higher asphalt content design, but where reflective cracking is still likely to occur. A higher incidence of rutting potential would also exist for such mix alterations.

7. **In terms of physical testing (HLWT), the ECR mix showed much lower rutting potential when compared to the HMA control.** Similar results were obtained Pavement ME simulations (i.e., virtually no rutting predicted for any of the systems). The most pronounced result was for the case of the 1" thick control mix tested over PCC in the Hamburg apparatus in a modified test arrangement, where higher rutting and stripping was observed. Although the stripping occurred at over 13,000 wheel passes (which is associated with a moderate to high traffic level), it nevertheless points out the advantage of GTR-modified mixes in producing stable, thin overlay systems. Such mixtures may be especially advantageous in areas of high shear, such as intersections, curves, and hills. The use of GTR in thin overlay systems may prevent rutting, shoving, and tearing distress in these areas, due to enhanced mixture tensile strength, stiffness, and fracture energy.

Future investigations should be conducted to evaluate higher traffic level applications. More work is also needed to quantify life extension gained by utilizing GTR-modified overlay mixes. This can be perhaps accomplished by feeding the individual pavement distress predictions vs. time into the PASER rating system, leading to non-linear PASER rating vs. time predictions (a linear assumption was used herein). Furthermore, advanced lab testing should be conducted and integrated with Pavement ME simulations, especially in the case of the GTR systems, which are not currently well-represented by default material properties available in the software. The appendix elaborates on this point, and provides recommendations for future studies to address these research gaps.

Users of iFIT and IDEAL should be aware of test method limitations when designing overlay systems, as these methods do not account for pavement structure and can lead to overly-conservative designs. These tests also seem to improperly characterize GTR mixes, perhaps by placing too much penalty in the stiffness and elasticity imparted by the presence of GTR, while overlooking the cracking pinning benefits associated with these mixtures. In cold climates and in locations where significant pavement aging and temperature cycling exists, consideration should be given to using the DC(T) in asphalt mixture design. DC(T)-based designs can be tailored to limit thermal and block cracking development, oftentimes without significant increases in mix costs. The DC(T) can also be used to help mitigate reflective cracking, especially as separate criteria exist for designing asphalt-over-asphalt and asphalt-over-PCC overlays systems.

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Appendix

Selecting Material Property Inputs for Pavement ME Simulations for GTR Mixes

A.1. Introduction

Pavement ME allows three levels of property input, depending on the amount of laboratory testing results available for input to the software simulation program. The analysis levels are:

- **Level 1**: The most detailed, fundamental information regarding binder, aggregate, and mixture physical properties are available, with testing conducted over a range of temperatures and loading rates. For instance, data to allow the construction of asphalt mixture master curves for dynamic modulus (E*) and low temperature creep compliance (D(t,T)) must be provided for a Level 1 analysis. This is not a commonly used input level, as the cost and time associated with the testing equipment, sample preparation, and sample testing is probably only feasible for research studies aimed at model validation and calibration, and for very high criticality projects (such as long-term warranty projects).
- **Level 2**: A subset of data required for Level 1 is needed for a Level 2 analysis. For instance, some level 2 inputs involve providing fundamental mixture properties at a single temperature. This is not a rarely used input level, since the equipment and time investment for fundamental testing is nearly the same as level 1, which has more accuracy than level 2 simulations.
- **Level 3**: This is by far the most commonly used input level, as it requires only commonly known materials properties and allows the use of many default values. The main drawback of this level, besides the lower accuracy associated with using additional default values, <u>is the lack of calibrated/relevant input values for modern, heterogeneous recycled asphalt mixtures such as GTR-modified mixtures</u>. At the time of development, only PG binders with likely polymer grades (generally, those with a Useful Temperature Interval (UTI) above 90, as calculated as the spread in degrees Celsius between the low and high PG grades) were available as inputs that could positively affect performance predictions in Pavement ME, as would be expected with GTR modified mixes.

Because of the relative inability to characterize modern, heterogeneous asphalt paving mixtures in Pavement ME using level 3, it is logical to conclude that a Level 1 analysis might be worth the additional testing and time for evaluating GTR mixes and overlay systems relative to unmodified control mixes. However, even if level 1 inputs (master curves) were available, the resulting simulation results obtained will likely not reflect the actual performance benefits of GTR. This is because the current Pavement ME system heavily relies on the ‘response side’ of mechanistic-empirical pavement simulation. In ME simulations, inputs for traffic, climate, and material properties are first used so simulate pavement response, that is, stresses, strains and deflections at known critical response locations. Next, these critical responses are fed into distress models - or more appropriately, calibrated transfer functions. While the response 'side of the equation' involves highly accurate, mechanistic simulations requiring little or no calibration, the distress 'side of the equation' involve physics-poor models, often simple power-law-type models. The current distress models in Pavement ME are very light on actual material inputs, and quite heavy on empirical calibration factors, including both national and regional parameters.

Therefore, even if the researcher goes to the effort of measuring E* and D(t,T) master curve data, mixture tensile strength as a function of temperature, and the like, there will be little reward in doing so at the current time. This is because, while the response models might be more accurate than those obtained using Level 3 default values, the distress models would not be expected to fully capture the benefits of modified mixes such as dry-process GTR, where the presence of discrete rubber particles has been shown to provide crack pinning, which in turn provides significant rutting, fatigue and thermal cracking resistance. Since the current pavement ME model contains level 3 PG binder inputs that go beyond UTI values of 90, and since some of those materials have been calibrated nationally, it was decided to utilize the level 3 input level in the current simulations, and to save level 1 simulation research until a later time, when pairs of materials property and field performance data sets can be used to create accurate, local calibration parameters for GTR mixes.

To proceed in the aforementioned direction, it was necessary to develop a systematic approach for selecting an appropriate PG binder grade for rubber-modified mixes at various GTR dosage levels.

A.2. Selecting Appropriate Pavement ME Inputs for ECR GTR Mixes

Research conducted at the MAPIL lab during the period of 2016-2019 led to a number of binder and mixture data sets, which were evaluated to determine an appropriate binder bump factor for use in Pavement ME simulations. These are summaries as follows:

1) Binder studies: Testing of a PG 58-28 neat binder modified with 10% ECR led to an increased spread in the binder UTI by nearly 11 degrees Celsius (the PG low temperature grade was improved by 2.1 degrees Celsius [-29.0 neat, -31.1 ERC modified], while the PG high temperature grade was improved by 8.8 degrees Celsius [55.8 C neat, 64.6 C ECR]. Since the improvement is binder-specific, these results suggests that ECR-modification in the range of 10-12% by weight of binder would be needed to incur a 2 grade UTI bump (12 degrees Celsius widening in PG spread) in the Superpave binder grading system.

2) Mixture studies: Illinois Tollway SMA designs require a 2-grade bump in Superpave PG grade for surface mixes under heavy traffic (PG 76-22). In recent years, this requirement is often met in an economical fashion using ECR-modified mixes with between 10 and 12 percent GTR by weight of mixture (Buttlar and Rath [2017], Rath et al. [2019]). A recent study conducted for the Missouri Department of Transportation concluded similar results for ECR-modified mixtures [Buttlar et al., 2019], where the ECR-modified SMA mixture outperformed the control modified mixture for heavy traffic in all three cracking tests evaluated, while easily meeting Hamburg wheel tracking requirements.

Following these results, the ECR-modified mixture simulated in the present study was assigned a PG 70-28 binder grade, while the control mixture was assigned a neat PG 64-22 binder grade.

A.3. Recommended Future Work

As modern, heterogeneous recycled mixture containing performance-enhancing modifiers such as GTR gain popularity, their inclusion in future revisions of Pavement ME is imperative. However, this will require significant efforts in:

- Developing a database of fundamental material properties for GTR and control mixtures in situations where both mixtures were placed in the field
- Monitoring the field performance of these sections, especially in applications where multiple thickness overlay strategies were attempted, including thin, GTR-modified overlays, and;
- Calibrating Pavement ME to accurately reflect the field performance of GTR-modified overlay systems.

In addition, there is a critical need to improve the distress models in Pavement ME, especially in the areas of:

- Composite pavement overlay performance prediction
- Inclusion of modern cracking test data in distress models for overlay performance prediction, and;
- Inclusion of reference data and ability to model (in level 3 designs), modern, heterogeneous pavement mixtures including those designed with GTR.