IAPA SCHOLARSHIP

DETAILED LABORATORY INVESTIGATION ON LOW TEMPERATURE PERFORMANCE OF STONE MATRIX ASPHALT MIXTURES WITH VARIED LEVELS OF ASPHALT BINDER REPLACEMENT

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1. INTRODUCTION

Reclaimed asphalt materials have become more and more commonly used in the asphalt pavement community for both economic and environmental reasons. Incorporating reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS) reduces virgin asphalt and aggregate content, leading to cost savings. While the presence of RAP and RAS might have a positive effect on the rutting resistance of asphalt mixtures, the low temperature performance of the mixes may be negatively influenced because of the aged and oxidized binder involved in the reclaimed asphalt materials (Behnia *et al.* (2011), Hill *et al.* (2013), McDaniel *et al.* (2000)), leading to increased material brittleness. If the mixture contains greater than 20% RAP, the binder system will be much stiffer than that of the virgin binder alone. McGraw *et al.* (2010) showed that the addition of RAS reduces the relaxation capabilities of the binder and stiffens it, making it susceptible to fatigue cracking at intermediate temperatures. In general, mixtures containing high percentages of asphalt binder replacement (ABR) from RAP/RAS are thought to be more susceptible to thermal and block cracking as compared to virgin asphalt mixtures, unless specific measures are taken to counterbalance the recycled materials with a softer virgin binder base grade and/or through the use of a rejuvenating-type modifier. Such countermeasures have been taken in the design of Illinois Tollway (Tollway) high-traffic, stone-mastic asphalt (SMA) mixtures; however the design of theses mixtures pre-dated the existence of modern low temperature mixture cracking tests.

The primary objectives of this study were to evaluate the low temperature characteristics and expected performance of cores obtained from seven Tollway projects constructed between 2008 to 2012 using stone-mastic asphalt (SMA) mixtures with varying ABR levels and virgin materials. Creep compliance and disk-shaped compact tension (DC(T)) tests were performed to evaluate creep compliance and fracture energy of the surface SMA layers taken from the cores. The ILLI-TC thermal cracking prediction model was used to estimate thermal cracking potential under typical Chicago climatic conditions. A Hamburg-DC(T) performance space diagram was used to analyze the results, leading to recommendations on how future mix designs might be adjusted to yield even longer life with little-to-no extra cost.

2. MATERIALS

Twelve cores from seven Tollway pavement sections around the Chicagoland area (Figure 1) were provided by S.T.A.T.E. Testing for creep and fracture behavior characterization of the SMA surface layers by UIUC researchers. These pavements were constructed to the specifications applicable at the time, as part of a pavement rehabilitation or reconstruction. A summary of details pertaining to the seven sections, as taken from coring information and mixture design sheets, are summarized in Table 1.

Figure 1. Coring locations

Table 1. Summary of coring locations and general mixture composition

Section	Location	Yr. Placed	ABR	Surface Thickness (in)	Binder	Aggregate
A	I-90 WB in Rockford	2009	14	2	PG 76-22 GTR	Gravel
B	I-90 EB in Rockford	2008	16	2	PG 76-22 GTR	Diabase
C	I-90EB near Newberg Rd	2009	36*	2	PG 76-22 SBS	Quartzite
D	I-90 WB in Rt. 25 in Elgin	2011	33*	1.75	PG 70-28 SBS	Quartzite
E	I-88 EB, East of DeKalb	2012	37*	1.5	PG 70-28 SBS	Gravel
F	I-355 NB at 63rd St.	2009	0	1.75	PG76-22 GTR	Slag
G	I-294 BB, N. of Cermak Toll	2012	31*	2	PG 70-28 SBS	Quartzite

*These mixes include RAS

3. TESTING METHODS

In this report, creep compliance of the surface layer was measured to characterize the bulk mixture viscoelastic behavior at low temperatures. The DC(T) fracture energy test was conducted to evaluate the fracture behavior of the surface layer of each section. Using both creep and fracture properties, the ILLI-TC model was used to simulate cracking behavior under cyclic loading conditions. This was done as an alternative to conducting cyclic DC(T) tests, for three main reasons: 1) at the time of the research, a standard did not yet exist for cyclic DC(T) testing; 2)links to field performance are still under development, and; 3) the repeatability of the cyclic DC(T) test is not nearly as good as the standard DC(T) test and creep compliance test. Thus, it was determined that creep, followed by fracture testing and modeling with ILLI-TC would be an effective low temperature cracking analysis approach to garner additional insight from the valuable field cores obtained for this research.

3.1 Creep Compliance Testing

Creep compliance is defined as time-dependent strain over stress, which is often used to evaluate the viscoelastic behavior of asphalt mixtures at low temperatures. Creep compliance of asphalt mixtures is influenced by many factors, such as performance grade of virgin binder, asphalt binder content, aggregate type, aging conditions, and RAP/RAS or ABR content. Creep compliance testing was conducted according to AASHTO T-322, as shown in Figure 2. In this test, three replicates were tested using a step-type creep load at -24, -12^{o}C and 0^{o}C for 1000 seconds. The horizontal and vertical displacements at the center of each side of the specimen were measured using Epsilon 3910 extensometers across a 38-mm gage length, and creep compliance was calculated using equation 1.

$$D(\mathrm{t}) = \frac{\Delta x \times D_{avg} \times t_{avg}}{P_{avg} \times L} \times C_c \quad (1)$$

Where, $D(\mathrm{t})$ = Creep compliance at time t

Δx = Trimmed mean of the normalized horizontal deflections at time t

D_{avg} = Average diameter of all replicates

t_{avg} = Average thickness of all replicates

P_{avg} = Average applied creep load

L = Gauge length

C_c = Correction factor to account for 3D stress and strain fields as a function of specimen aspect ratio (t/D) and Poisson's ratio

A creep compliance master curve produced using the principle of time-temperature superposition and a power-law model, as presented in equation 2, was used to smooth the raw data prior to master curve construction.

$$\mathrm{D}(t) = D_0 + D_1 t^m \quad (2)$$

Where:

$\mathrm{D}(t)$ = Creep compliance at time t

D_0, D_1 = Power law model parameters

m-value = A unit-less slope parameter which relates to the stress relaxation capabilities of the mixture

A least-squares fitting method was used to determine the parameters D_0, D_1 and m.

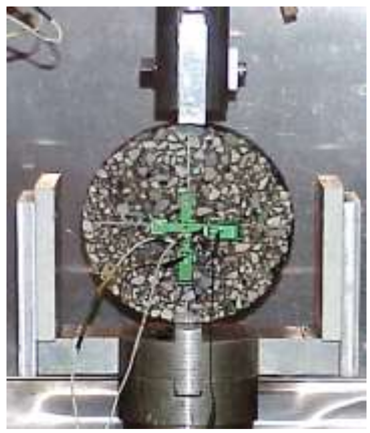

Figure 2. Indirect Tension Creep Compliance Test

3.2 DC(T) Fracture Energy Testing

To characterize the cracking behavior of the asphalt mixtures, DC(T) testing was performed. Generally, temperature-induced transverse (or thermal cracking) in asphalt pavements is thought to predominantly occur in a Mode I opening manner. In other words, thermal cracks are generally found to propagate perpendicular to the direction of traffic and vertically through the pavement depth. This is supported by field observations, where evidence of fracture mode-mixity (curvilinear crack trajectory) is fairly minimal. Since thermal cracks are easier to handle from an experimental and theoretical standpoint as compared to traffic-induced fatigue cracks or reflective cracks, they are directly addressed with the mode-I-type low-temperature tests selected for this study. However, it is likely that the mixture characteristics that promote higher resistance to thermal cracking will also tend to reduce other forms of pavement cracking. Wagoner *et al.* (2005) determined that the most viable test configuration available for asphalt mixture Mode I fracture was the DC(T) geometry. This configuration, adjusted from ASTM E-399 for metals, contains a sufficiently large fractured surface area to reduce test variation and is easily fabricated from field cores or laboratory-produced gyratory specimens. Furthermore, studies such as Dave *et al.* (2008) demonstrated that the DC(T) test can accurately capture the thermal cracking potential of asphalt concrete mixtures. In 2007, ASTM specified the DC(T) test as ASTM D7313. Fracture energy of asphalt mixtures is affected by a number of factors, including asphalt binder content, aggregate type, aggregate gradation, aging conditions, and RAP/RAS or ABR content.

The DC(T) test evaluates the fracture energy associated with propagating a crack perpendicular to the applied load through the asphalt mixture. Fracture energy can be calculated by measuring the area under the load-crack mouth opening displacement (CMOD) gauge curve, shown in Figure 3, normalized (divided) by the fractured surface area. S.T.A.T.E. Testing had already tested specimens at -12°C, which corresponded to the ASTM recommendation for asphalt mixtures placed in Illinois. The UIUC research team supplemented this data by testing at -24°C and 0°C. All tests were run at a CMOD opening rate of 1.0 mm/min, according to ASTM D7313. As recommended by the National Pooled Fund Study on Low Temperature Cracking Phase II (Marasteanu et al.), a fracture energy minimum for a high traffic volume road should be at least 690 J/m^2 at -12^{o}C. However, for long-term aged or heavily field-aged mixtures, a threshold value of 600 J/m^2 at -12^{o}C would be appropriate. This is consistent with the original recommendation from the Pooled Fund study, where the specification limits were originally developed with field cores. The threshold increase to 690 J/m^2 at -12^{o}C for short-term aged mixtures was done in order to facilitate design specimens, which are often only short-term oven aged. Thus a higher (more conservative) value is used for short-term aged design specimens. For field cores obtained somewhere between short-term and long-term aging periods (such as might be the case in this study), a minimum fracture energy between these numbers may be appropriate.

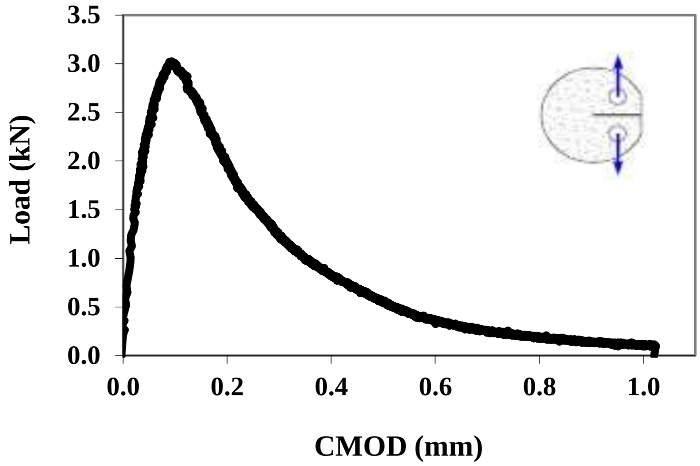

Figure 3. Typical Load-CMOD Plot

3.3 ILLI-TC Modeling

ILLI-TC is a mechanistic-empirical thermal cracking model developed by Professor Buttlar's research group, as detailed in Dave *et al* (2013). ILLI-TC uses viscoelastic finite element modeling framework with a built-in 2D, cohesive zone fracture modeling approach. In this model, creep compliance was considered to evaluate the stress relaxation behavior of the asphalt material. In addition, both strength and fracture energy are used as inputs to the model. In this project, ILLI-TC was used to simulate the thermal cracking of the surface layer of the Tollway sections. Parameters including project location, pavement structure, material properties, and design life are required to run the ILLI-TC software. In this project, intermediate temperatures for the State of Illinois were selected, which were considered the closest climatic location for the field sections. Since the thermal cracking software is not sensitive to pavement structure and since the sections had variable layering configurations, a default structure was used. This involved a 3-inch asphalt surface, which was selected in order to focus the evaluation on the thermal cracking performance of the SMA overlay. Creep compliance data, fracture energy and peak load results were also used to estimate critical events for thermal cracking, and the extent of pavement thickness damaged and cracked (if the pavement was predicted to crack) based on a 5-year analysis period (using climate data from 2000 to 2005). The critical events are pre-evaluated by the software to determine simulated days where the tensile stress of the surface layer exceeds 80% of the tensile strength of the asphalt mix. In this project, tensile strength was estimated from the peak load based on an empirical equation (Marasteanu et al., 2012). If the 80% threshold is reached, the program then performs a detailed finite element analysis to examine damage and cracking extent. In general, mixtures at the short-term aged level are to be used in the model (the model was calibrated to take into account the fact that most designers will only have short-term aged sample test results). However, since only field cores were provided, they were used with the rationale that conservative results should be obtained.

3.4 Hamburg Wheel Tracking Test

Hamburg Wheel Tracking test was completed by S.T.A.T.E Testing, and the results are reported herein. As specified by AASHTO T-324, Hamburg testing is conducted in water at 50^{o}C to induce both rutting and moisture damage. The load applied by the steel wheel is approximately 158 lbs and tests are conducted for a duration of 20,000 wheel passes. Tollway specifications require a rut depth less than 12.5mm (1/2") at 20,000 passes for SMA mixtures.

3.5 Performance-Space Diagram

In order to present DC(T) and Hamburg results in a more visualized way, a performance-space diagram was utilized to evaluate the high and low temperature performance of asphalt mixtures, as detailed in Buttlar *et al.* (2016). This performance space diagram is a two-dimensional plot of Hamburg rut depths (on a reverse, arithmetic scale, y-axis) versus DC(T) CMOD fracture energy (arithmetic scale, x-axis). A Hamburg-DC(T) diagram, as shown in Figure 4, can be divided into four sections: a. Upper-Left (good rutting resistance, poor cracking resistance – not recommended); b. Lower-Left (poor rutting resistance, poor cracking resistance – not recommended); c. Upper-Right (good rutting resistance, good cracking resistance – recommended, which can be further divided into three sections based on different facture energy thresholds for different traffic volumes), and; d. Lower-Right (Poor rutting resistance, good cracking resistance – not recommended).

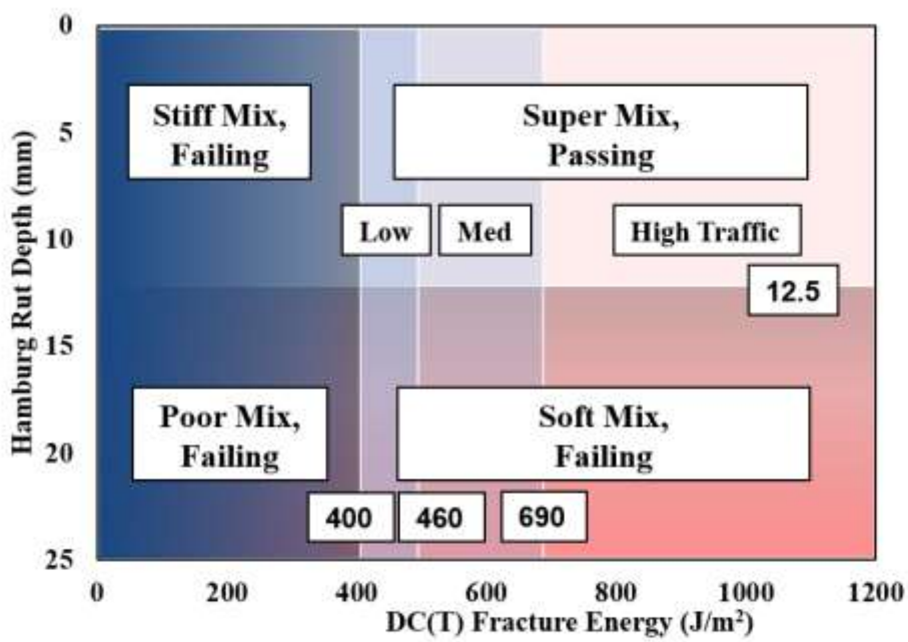

Figure 4. Performance-Space Diagram concept, with typical specification limits superimposed

4. RESULTS AND DISCUSSION

4.1 Creep Compliance Test

The creep compliance of the surface layer of each core was measured to characterize the low temperature viscoelastic behavior of the seven Tollway sections. Creep compliance master curves were produced using the principle of time-temperature superposition and a power-law model, with power-law model parameters provided in Table 2. It was found that high ABR mixtures tend to have lower m-values due to the presence of RAP, and in one case (Section D), RAP and RAS. In particular, RAS materials are thought to lower the m-value (slope of the right side of the master curve), both for binders and mixtures. Our data follows this trend, however, the absolute value of the creep compliance itself is reasonably high for the Section D mixture. The ILLI-TC model takes the full viscoelastic behavior into account. The Section D mixture is further examined in a later section of the report.

Table 2. Power-law model parameters from creep compliance master curves

Section	Location	D_0	D_1	m
A	I-90 WB in Rockford	0.03029	0.00773	0.330
B	I-90 EB in Rockford	0.04938	0.00239	0.390
C	I-90EB near Newberg Rd	0.03968	0.00115	0.330
D	I-90 WB in Rt. 25 in Elgin	0.03489	0.00687	0.295
E	I-88 EB, East of DeKalb	0.05133	0.00131	0.340
F	I-355 NB at 63rd St.	0.04108	0.00061	0.365
G	I-294 BB, N. of Cermak Toll	0.04307	0.00318	0.295

As shown in Figure 5, Sections C and Section F have the lowest creep compliance as compared to other sections, possibly resulting from the longer aging period associated with these sections. In addition, Section E and G were found to have low-to-intermediate creep compliance values, possibly as a result of the higher ABR levels

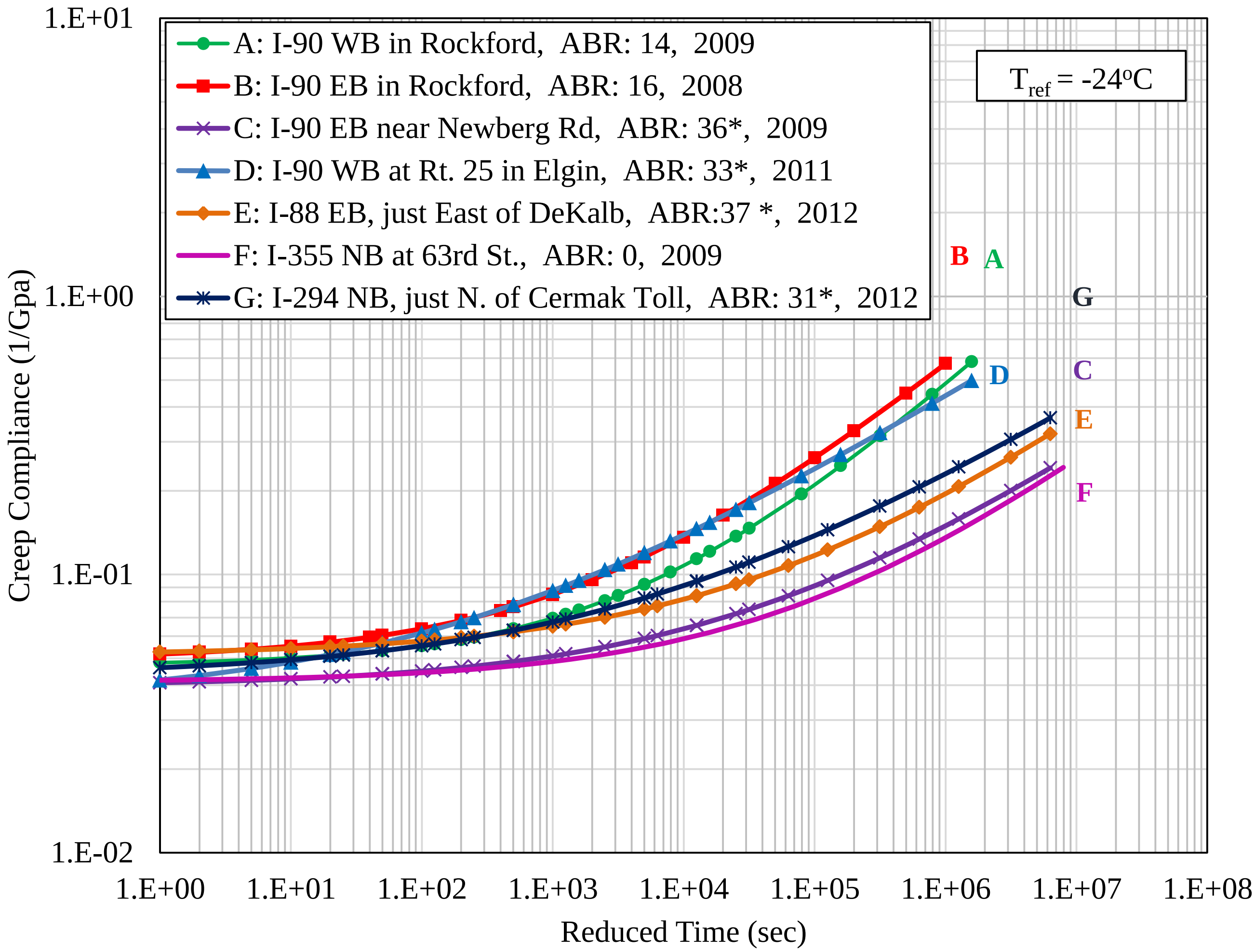

Figure 5. Creep compliance results

found in these mixtures. Sections A, B and D potentially have better stress relaxation potential as compared to the other sections (highest creep compliance, and largest master curve slope or ‘m-value’). This could possibly translate into a very high resistance to thermally-induced transverse cracking. As these sections are monitored for future performance, it is recommended to correlate any future thermal or block cracking to these creep compliance and mixture m-value numbers, as well as results from the thermal cracking predictions presented in section 4.3.

4.2 DC(T) Fracture Energy Test

The DC(T) fracture energy test was conducted to evaluate cracking resistance of asphalt materials. Two replicates were used for DC(T) test at 0^oC and -24^oC accordingly, and fracture energy of the materials for each surface layer at -12^oC was provided by S.T.A.T.E Testing (Figure 6). As expected, all the materials had lower fracture energy values at the lower temperature. To be specific, it was found that Section C has the lowest fracture energy at 0^oC due to longer aging time/ service life, which agreed with the aforementioned creep compliance result. The asphalt mixture in Section C displayed some effects of medium- to long-term aging. Sections A and E had the lowest fracture energy at -24^oC, probably as a result of oxidization and higher ABR. However, the fracture energy of these two sections at higher temperatures were satisfactory, perhaps as a credit to their good stress relaxation properties (higher creep compliance). Note that testing was conducted in two labs, which may explain why some of the test results at -12^oC did not fall in between the tests results at 0^oC and -24^oC. However, the results overall appear to be quite reasonable.

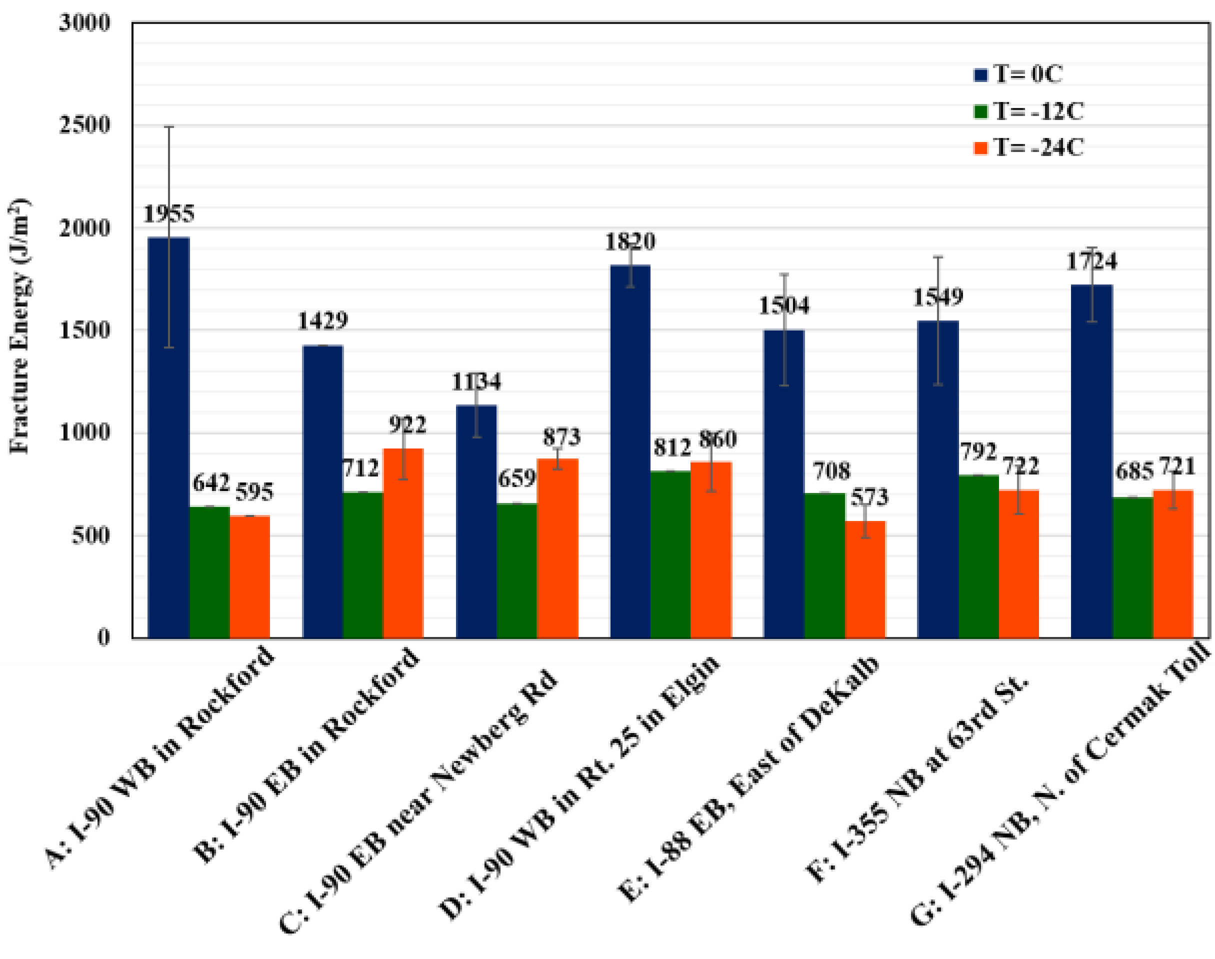

Figure 6. Fracture energy results of testing sections

As stated in the Pooled Fund Study Phase II, fracture energy at -12°C for a high traffic volume road is recommended to be a minimum 690J/m^2. It was found that the surface layers of most sections satisfied the fracture energy requirement except sections A, C and G, which indicates that the surface SMA layers of section B, D, E and F should be very resistant to thermal cracking (note that sections D and E contain RAS). Because the fracture energy values for A, C and G were within 10% of the stringent criterion, and because the cores had already experienced some field aging (suggesting that a long-term aged criterion somewhere between 600 and 690 J/m^2 may be more appropriate), it is believed that these sections will also be very resistant to thermal and block cracking.

4.3 ILLI-TC Modeling

ILLI-TC was used to predict thermal cracking severity of the sections. In this model, cracking severity is expressed as the number of critical events and length of transverse/thermal cracking per 500m of pavement (if cracked). As provided in the Table 3, all sections have 0 critical events, which indicates that no transverse cracking / a very low density of transverse cracking should be expected in these pavement surfaces. It is interesting that the lowest thermal cracking potential (as expressed by Peak Tensile Stress/Tensile strength (%)) is predicted in section D, which is the one of the sections that contained RAS. This is probably due to the high fracture energy, higher tensile strength, and relatively low computed thermal stress. The low computed thermal stress indicates that when the full viscoelastic nature of the mixture is taken into account, the predicted thermal stress is relatively low. This should be viewed as a more rigorous assessment of the stress relaxation potential of the pavement, as compared to simply looking at the m-value from the power law model, as presented earlier. These results suggest that properly designed mixtures containing RAS can have suitable thermal and block cracking resistance for the Chicagoland area.

Table 3. Critical events as predicted by ILLI-TC

Section	Cores Location	Input		Output			
		Fracture Energy (J/m^2)	Peak Load (kN)	Calculated Tensile Strength (MPa)	Peak Tensile Stress (MPa)	Peak Tensile Stress/ Tensile strength (%)	Critical Events
A	I-90 WB in Rockford	1275	3.38	4.92	1.15	23.4	0
B	I-90 EB in Rockford	1176	2.76	4.01	0.96	23.9	0
C	I-90 EB near Newberg Rd	1003	3.61	5.25	3.53	67.2	0
D	I-90 WB in Rt. 25 in Elgin	1340	4.10	5.96	1.09	18.3	0
E	I-88 EB, East of DeKalb	1038	2.47	3.59	2.72	75.8	0
F	I-355 NB at 63rd St.	1135	3.64	5.29	2.87	54.3	0
G	I-294 NB, N. of Cermak Toll	1222	2.84	4.13	2.32	56.2	0

4.4 Hamburg Wheel Tracking Test

Hamburg Wheel Tracking results provided by S.T.A.T.E Testing are shown in the Table 4. It was found that all mixtures were well below the requirement of <12.5mm rutting @ 20,000 passes, which indicates that the surface layers of these sections possess excellent rutting resistance.

Table 4. Hamburg Wheel Tracking Test provided by S.T.A.T.E Testing

Section	Cores location	Rut depth @ 20,000 passes (mm)
A	I-90 WB in Rockford	2.4
B	I-90 EB in Rockford	1.8
C	I-90 EB near Newberg Rd	2.2
D	I-90 WB in Rt. 25 in Elgin	2.5
E	I-88 EB, East of DeKalb	1.8
F	I-355 NB at 63rd St.	1.3
G	I-294 NB, N. of Cermak Toll	2.0

4.5 Performance-Space Diagram

As shown in Figure 7, Hamburg rut depth results at 20,000 passes and DC(T) fracture energy results at -12^{o}C were plotted in the performance-space diagram to simultaneously evaluate the high and low temperature performance of the seven tollway sections. It was found that all of the dots fell in the upper-right zone, which is the desired zone for high-traffic applications, representing appropriate levels of rutting and cracking resistance for the tollway. As mentioned previously, a DC(T) fracture energy threshold of between 600 and 690 J/m^2 might be more appropriate for these materials, which have a field aging level somewhere between short- and long-term aging. Thus, all of the sections investigated can be considered as being in an appropriate performance zone.

Since some of these sections were borderline on fracture energy, but possessed a large factor of safety with respect to rutting, it might be worth exploring the use of a slightly softer overall virgin binder grade for future mix designs. To keep costs down, an identical Usable Temperature Range (UTR) binder could be used, which should have similar cost to the virgin binder grades used in these mixtures (i.e., selecting a virgin binder that is one grade softer on both the high and low temperature side). This would have the tendency of pushing the points on the Hamburg-DC(T) plot down and to the right, firmly in the pink square (refer to the blue line, which is based on results presented in Buttlar et al, 2016). This could be attempted during mix design, and if the softer grade results in an excessive shift or trade off to the lower-right (i.e., the mix becomes borderline on rutting), then a second option might be to explore additives that could create a modest shift in the desired direction, such as WMA additives or rejuvenators.

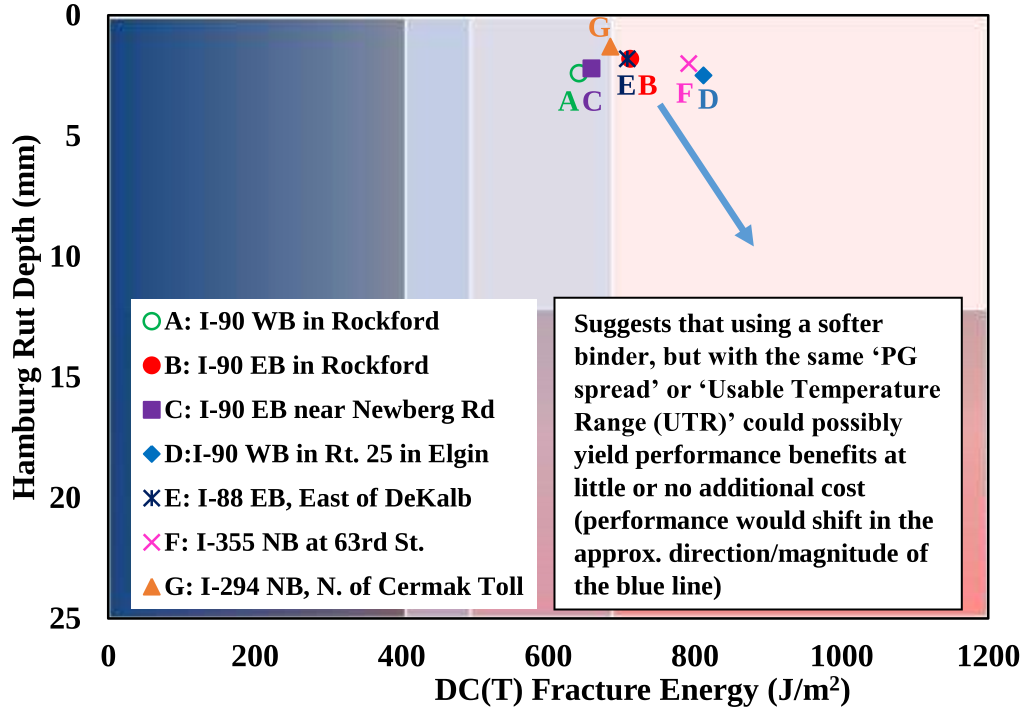

Figure 7. Performance-Space diagram of testing sections

5. CONCLUSIONS

In this report, creep compliance testing, DC(T) fracture energy testing, Hamburg Wheel Tracking testing, and the performance-space diagram were utilized to characterize and evaluate mixture behavior of field cores from seven Illinois Tollway pavement sections, and ILLI-TC modeling was used to predict thermal cracking tendencies in the field. It was found that the fracture energy of most sections satisfied the stringent fracture energy criteria suggested by Pool Fund Study Phase II report, and all sections easily passed Hamburg rutting criteria. It was found that the surface layers of most sections satisfied the most stringent fracture energy requirements except sections A, C and G. However, because the fracture energy values for A, C and G were within 10% of the most stringent criterion, and because the cores had already experienced some field aging (suggesting that a long-term aged criterion of between 600 and 690 J/m^2 may be more appropriate), it is believed that these sections will also be very resistant to thermal and block cracking. This appears to be the case since, based on performance of these sections to date, only reflective cracking has been found.

According to ILLI-TC model results, the predicted critical events in a five-year analysis period were zero, further reinforcing the conclusion that the sections will experience little-to-no thermal cracking throughout their lifetime, which is being confirmed by field performance. Additionally, no high-ABR-induced performance issues were found, suggesting that proper design at higher ABR levels can lead to durable asphalt surfaces for the Tollway, including mixtures containing RAS. In fact, one of the sections containing RAS (section D), had the highest fracture energy at -12 ^{o}C.

Since some of these materials were borderline on fracture energy, but possessed a large factor of safety with regards to rutting, it might be worth exploring the use of a slightly softer overall virgin binder grade for future mix designs. To keep costs down, an identical Usable Temperature Range (UTR) binder could be used, which should have similar cost to the virgin binder grades used in these mixtures (i.e., selecting a virgin binder that is one grade softer on both the high and low temperature side). This could be attempted during mix design, and if the softer grade results in an excessive shift or trade off to the lower-right (i.e., the mix becomes borderline on rutting), then a second option might be to explore additives that could create a more slight shift in the desired direction, such as WMA additives or rejuvenators.

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