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Performance space diagram for the evaluation of high- and low-temperature asphalt mixture performance

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This paper presents a simple, yet powerful method for simultaneously evaluating the high- and low-temperature performance of asphalt paving mixtures for the purpose of mixture design, evaluation, and forensic investigation. A performance-space diagram approach is described, with an emphasis on Hamburg-DC(T) plots presented in this paper. Specifically, a plot of Hamburg wheel tracking results, plotted in reverse order on the y-axis using an arithmetic scale, along with DC(T) fracture energy results, plotted on the x-axis, constitutes the Hamburg-DC(T) plot. Plotting candidate mixture designs, research results, and so on yields a surprising amount of insight into mixture variables that affect overall performance. For instance, substitution of one straight-run binder grade for another results in a clear, predictable trade-off in the Hamburg-DC(T) performance space. Polymer-modified grades, on the other hand, provide a more beneficial shift in the Hamburg-DC(T) space. The benefits of using this approach in the design of mixtures containing recycled asphalt mixture and recycled asphalt shingles is also presented. Effects of rejuvenators and the benefits of stone-mastic asphalt designs are also demonstrated. Finally, a broad look at a large database of mixtures recently designed in Illinois is presented.

Keywords: Thermal cracking; fracture; asphalt; rutting; fracture energy; performance

1. Introduction

The Superpave mixture design procedure developed during the Strategic Highway Research Program made significant strides in modernising the way asphalt binders and aggregates are tested and specified, and how mixtures are compacted and analysed in the United States, and now, beyond. However, the replacement of mixture mechanical tests to supplement volumetric mixture design, for example, the replacement of the Marshall stability and flow test and Hveem stabilometer and cohesiometer, has been slow to develop. A number of key pavement distresses could arguably be considered for inclusion with mixture performance testing, possibly depending on factors such as project criticality (traffic level), climate, and the location of the mixture in the pavement structure (surface, binder course, shoulder, overlay, etc.). Those distresses could include rutting, moisture sensitivity, thermal cracking, block cracking, traditional fatigue cracking (bottom-up), top-down cracking, reflective cracking, and ravelling. However, it would be impractical to include separate tests for all of the aforementioned pavement distresses. Moisture sensitivity testing was recommended in Superpave mix design (AASHTO T-283 (2014)), and is also addressed in Hamburg wheel track testing of submerged specimens according to AASHTO

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T-324. But this still leaves a number of key distress types to be considered, including a number of cracking modes.

In the Superpave PG binder specification, the binder grade is established based on high-temperature (rutting) and low-temperature (thermal cracking) tests. Fatigue cracking is also controlled, although it is not directly incorporated into the two-grade designation scheme according to ASTM D-6373 (1999). A similar simplification appears to be happening in mixture design. Many agencies have now adopted a high-temperature rutting performance test as a first step towards controlling asphalt mixture performance as part of mix design. The Hamburg wheel-tracking device has emerged as a widely used high-temperature mixture performance test in the Unites States. A number of researchers have investigated cracking tests, and some of those tests have been used in major research studies, resulting in specifications, and in some cases, implementation and adoption by highway agencies such as Cooper, Mohammad, Kabir, and King (2014) and Zhou, Hu, and Scullion (2013).

Researchers have developed balanced mixture designs approaches applicable to the southern United States climates. Consequently, cracking considerations focused on intermediate-temperature monotonic and cyclic cracking modes. Cooper et al. (2014) demonstrated the use of the semi-circular bend (SCB) geometry to extract a critical J-integral value associated with monotonic intermediate-temperature cracking resistance in the state of Louisiana. This research found that balanced design criteria led to the use of higher quality materials when comparing performance from 2006 to 2013. Zhou et al. (2012) applied the Texas Overlay Tester (TEX-248-F) to consider intermediate-temperature cyclic fracture. Furthermore, Zhou et al. (2013) developed a Texas-specific design programme to determine a balanced design between Hamburg and Texas Overlay Tester laboratory performance.

For cold climates, significant research has been conducted to develop a low-temperature cracking test specified according to ASTM D7313 (2013), the disk-shaped compact tension (DC(T)), and associated thermal cracking specification over the past 15 years. This research is summarised in detail in the following section. This paper explores how the simultaneous use of high- and low-temperature mixture performance tests, plotted on a convenient performance-space diagram, provides a powerful tool to the mix designer in understanding how to assemble and adjust modern, economic, sustainable paving mixtures. Although the study focuses on high- and low-temperature tests as the “bookends” of performance, much like the Superpave binder specification, this would not preclude the use of additional mixture performance tests as needed to meet material and structural requirements. For instance, for new pavement designs with the potential for traditional fatigue cracking, a fatigue performance test could be added. For reflective cracking, additional DC(T) test limits could be imposed, or another test linked to reflective cracking could be added to the testing suite, and so on.

2. Testing methods

2.1. *DC(T) test*

The DC(T) fracture test was used to evaluate the crack propagation potential for the asphalt mixtures in this study at low temperatures. Generally, temperature-induced transverse (or thermal cracking) in asphalt pavements is thought to predominantly occur in a Mode I (pure tension at the crack tip) opening manner. This is supported by field observations, where evidence of fracture mode-mixity (curvilinear crack trajectory) is fairly minimal. In other words, thermal cracks are generally found to propagate perpendicular to the direction of traffic and vertically through the pavement depth. 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

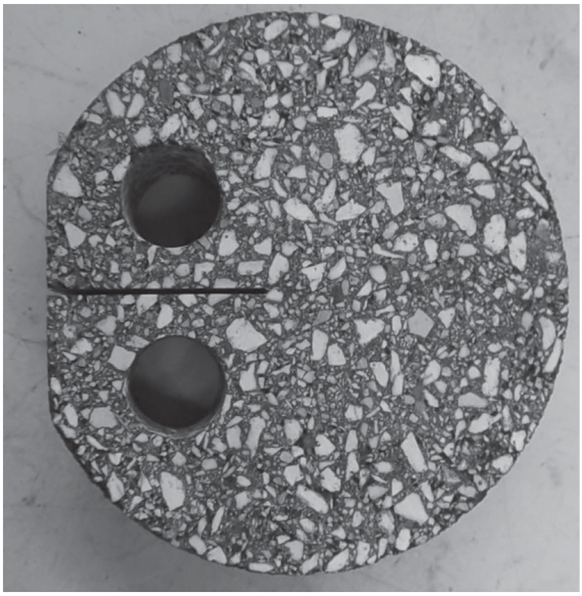

Figure 1. DC(T) test specimen.

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, such as block cracking. Wagoner, Buttlar, and Paulino (2005) determined that the most viable test configuration available for asphalt mixture Mode I fracture was the DC(T) geometry. This configuration, shown in Figure 1 and adjusted from ASTM E-399 (2007) 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, Ahmed, Buttlar, Bausano, and Lynn (2010) demonstrated that the DC(T) test can accurately capture the thermal cracking potential of asphalt concrete mixtures. In 2006, ASTM specified the DC(T) test as ASTM D7313 (2013).

An FHWA national pooled fund study on low-temperature cracking involving the participation of 10 states and over $1M of funding to 4 universities (led by the university of Minnesota) investigated several mixture cracking performance tests (DC(T), hollow cylinder, SCB, and notched beam) and selected the DC(T) as the most effective and practical cracking performance test (Marasteanu et al., 2007, 2012). During the pooled fund study, an adjustment to the recommended minimum crack mouth opening displacement (CMOD) fracture energy was made such that short-term oven-aged samples could be tested in lieu of long-term oven-aged samples. Three minimum thresholds were created to consider project levels for low-, medium-, and high-trafficked roads as an added measure of risk avoidance in areas of heavier traffic volume. The thresholds for low-, medium-, and high-traffic asphalt pavement mixtures were set at 400, 460, and 690 J/m^2, respectively. These thresholds, developed solely for low-temperature cracking, are currently being modified to include values to help control reflective cracking. The DC(T) test along with these limits has been used in thermal cracking mixture specifications in Minnesota, Iowa, Wisconsin, and the City of Chicago.

The DC(T) test has demonstrated an ability to differentiate recycled material contents from reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS), warm mix asphalt (WMA) additives, asphalt binder grades, and oven ageing levels. Cascione et al. (2011), Behnia,

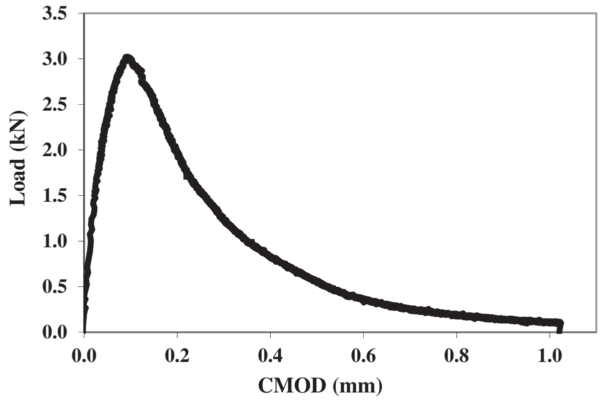

Figure 2. Typical load-CMOD plot.

Dave, Ahmed, Buttlar, and Reis (2011), and Hill, Behnia, Buttlar, and Reis (2012a) found that increasing contents of RAP and/or RAS led to reduced CMOD fracture energies if virgin binder grades were not adjusted. Hill, Behnia, Hakimzadeh, Buttlar, and Reis (2012b) determined that the DC(T) test differentiated between HMA and WMA mixtures and demonstrated that WMA chemical additives led to improvement in fracture resistance. Wagoner, Buttlar, Paulino, and Blankenship (2005) found improvement in CMOD fracture energy in the presence of progressively lower Superpave performance grades. Finally, Braham, Buttlar, Clyne, Marasteanu, and Turos (2009) determined that CMOD fracture energy was sensitive to ageing level.

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-CMOD gauge curve, shown in Figure 2, and normalising it by the fractured surface area as shown in the following equations:

$$A = \int_0^{\delta_{max}} P(\delta)\,\mathrm{d}\delta, \tag{1}$$

$$G_f = \frac{A}{bL}, \tag{2}$$

where G_f, δ, δ_{max}, A, b, L, and $P(\delta)$ are the CMOD fracture energy, CMOD, maximum CMOD, area under the load-CMOD curve, fracture area width, fracture area length, and the load at a specific CMOD value, respectively.

Researchers in this study tested all specimens at $-12°C$ which corresponded to the ASTM recommendation for asphalt mixtures placed in Illinois. The fracture specimens were held at $-12°C$ for a minimum of 2 h prior to testing. Furthermore, all tests were completed at a CMOD opening rate of 1.0 mm/min. Testing equipment included an Instron 8500 servo-hydraulic load frame with a 10 kN load cell and an Epsilon 3541 CMOD gauge. All equipment met the ASTM D7313 specifications for testing equipment resolution. A minimum of two replicates per mixture were tested to evaluate the average fracture properties. Samples were compacted to approximately 7.0% air voids in accordance with the ASTM standard.

2.2. *Hamburg wheel tracking test*

The Hamburg Wheel Tracking test was used to evaluate the permanent deformation characteristics of the asphalt mixtures investigated. The Hamburg test, shown in Figure 3 and specified

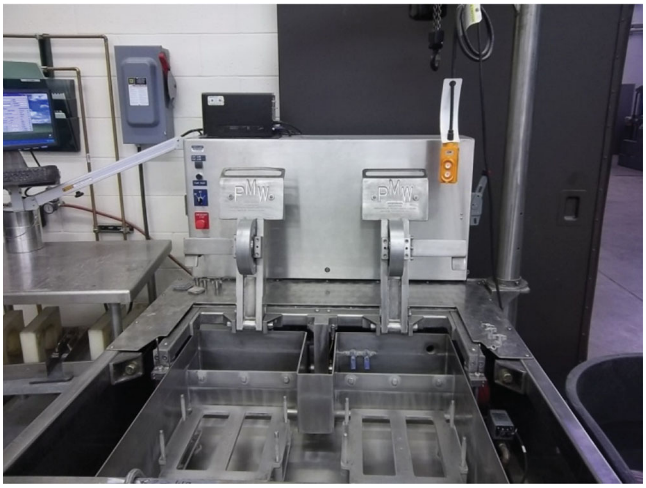

Figure 3. Hamburg wheel tracking device.

in AASHTO T-324 (2014), is conducted in a water-immersed state at 50°C to induce both permanent deformation and moisture damage. A steel wheel applied a load of approximately 702 N (158 lbs.) to each specimen and external linear variable differential transformers measure the rut depths at regular intervals during each pass of the wheel. Texas Department of Transportation was the first state to apply the Hamburg test as a mixture performance tool. Numerous states, including the state of Illinois, have implemented Hamburg specifications for their asphalt mixtures. The Illinois Department of Transportation (IDOT) has three requirements for asphalt mixtures in the Hamburg test. First, mixtures with PG 58-28 asphalt binder were required to resist a 12.5 mm rut depth for at least 5000 wheel passes. Second, mixtures with PG 64-22 asphalt binder needed to resist a 12.5 mm rut depth for a minimum of 7500 wheel passes. Third, mixtures in the Chicago land area were required to resist a 12.5 mm rut depth for 20,000 wheel passes. These modified AASHTO T-324 requirements were chosen based on available local aggregate, expected traffic level, and the asphalt binder performance grade.

The Hamburg test, similar to the DC(T) test, has shown the propensity to differentiate mixtures with RAP, RAS, WMA, and aggregate and binder type. Doyle, Mejias-Santiago, Brown, and Howard (2011) and Ozer, Al-Qadi, Kanaan, and Lippert (2013) found that increased levels of RAP and RAS, respectively, led to increased rutting resistance in the presence of the same virgin asphalt grade. Furthermore, Hill et al. (2012a) found the Hamburg test to be sensitive to various WMA additives as compared to a volumetrically similar HMA mixture. Finally, Solaimanian, Pendola, and Kennedy (2002) determined that softer virgin aggregate and asphalt binder led to reduced rutting resistance in the Hamburg test.

Gyratory specimens in the current study, 130 mm in height, were cut in half, and sawn along one edge to produce a flat face to produce a geometry suitable for the Hamburg test (using a the cylindrical geometry option). The heights of the two sides of each gyratory specimen were adjusted to reach equal heights to avoid dynamic loading. All Hamburg tests were conducted until either 20,000 passes were reached or 20.0 mm of rut depth was induced. Finally, all specimens were compacted to approximately 7.0% air voids to comply with AASHTO T-324 standards and four replicates per mixture were tested.

3. Mixture designs

Five 9.5 mm nominal maximum aggregate size mixtures were used in the current study to evaluate variables such as aggregate type, RAP and RAS contents, and asphalt binder grade. In addition, two RAS contents (2.5% and 5.0%), one RAP content (45% RAP), and three asphalt performance grades (PG 64-22, 58-28, 76-22) were considered. The mixtures contained crushed limestone and natural sand fine aggregate and crushed gravel and dolomitic limestone coarse aggregate. The two coarse aggregate types were approximately similar in terms of gradation and absorption properties. Therefore, the two coarse aggregates were considered interchangeable, as they did not significantly mixture volumetrics in the current study.

Mixtures designed in the current study followed AASHTO M323 (2004) to meet Superpave volumetric requirements. All mixtures, except the PG 76-22 mixture, were mixed and compacted at 150°C while the PG 76-22 mixture was mixed at 170°C and compacted at 150°C. These temperatures were chosen in order to comply with the mixture design asphalt binder viscosity recommendations according to Roberts, Kandhal, Brown, Lee, and Kennedy (1996). All mixtures and subsequent performance test specimens were aged for approximately 2 h prior to compaction for short-term oven ageing. Additionally, all mixtures were stirred at approximately 1 h after introduction to the short-term ageing oven to avoid ageing gradients with the sample. The mixture gradations were chosen such that volumetric properties such as the voids in the mineral aggregate (VMA), voids filled with asphalt (VFA), and per cent effective binder (P_{be}) were approximately equal to avoid additional variables affecting performance in the DC(T) and Hamburg tests. The volumetric properties for the virgin aggregate and recycled material mixtures are provided in Tables 1 and 2. The recycled binder contents in percentage form were provided in terms of the asphalt binder replacement ratio (ABR).

Table 1. Virgin and RAS mixture designs.

	Mixture		
Volumetric property	Virgin	2.5% RAS	5.0% RAS
Total asphalt content (%)	6.6	6.6	6.6
ABR (%)	0.0	10.6	21.2
Air voids (%)	4.0	4.0	4.0
VMA (%)	15.2	15.3	15.2
VFA (%)	74.0	73.8	73.7
Effective asphalt content (%)	4.9	4.9	4.9
Dust/effective AC	1.1	1.3	1.7

Table 2. Virgin and RAP mixture designs.

	Mixture	
Volumetric property	Virgin	45% RAP
Total asphalt content (%)	6.6	6.2
ABR (%)	0.0	38.1
Air voids (%)	4.0	4.0
VMA (%)	15.3	15.3
VFA (%)	73.7	73.3
Effective asphalt content (%)	4.9	4.9
Dust/effective AC	1.2	1.4

Table 3. Chicago rejuvenator mixture designs.

	Mixture	
Volumetric property	N30	N70
Total asphalt content (%)	6.8	5.9
ABR (%)	66.2	50.0
Air voids (%)	3.0	3.5
VMA (%)	16.8	14.8
VFA (%)	82.2	76.4
Effective asphalt content (%)	6.0	4.9
Dust/effective AC	1.1	1.2

Four additional field mixtures were considered in the current study to evaluate the effects of a rejuvenator in high ABR mixtures. Both mixtures were placed in Chicago, IL at an asphalt construction facility and included an N30 low-volume and N70 intermediate-volume road mixtures. The N30 mixtures contained either PG 58-28 with rejuvenator or PG 46-34 with a chemical WMA additive and had a 67% ABR. The N70 mixtures also contained either PG 58-28 with rejuvenator or PG 46-34 with a chemical WMA additive, but had a 50% ABR (Table 3).

In addition, results from a recent major study conducted by Mogawer, Austerman, Buttlar, and Hill (2015) regarding recycled engine oil bottoms, a recycling agent, and two reference mixes are presented in a Hamburg-DC(T) space diagram and discussed. Finally, a number of mixtures from a database of recent mix designs in Illinois are plotted in the Hamburg-DC(T) space and briefly discussed.

4. Performance-space diagram hypotheses

The concept of plotting performance data in a performance-space diagram was recently introduced to capture high- and low-temperature performance properties at several expert task groups and forums (Innovations in Construction, Asphalt, and Transportation (ICAT) 2015 Buttlar (2015a), 2015 FHWA Mixtures ETG) Buttlar (2015b). When plotting Hamburg rut depths (on a reverse, arithmetic scale, y-axis) versus DC(T) CMOD fracture energy (arithmetic scale, x-axis), a two-dimensional view of high-/low-temperature mixture performance can be conveniently viewed. Moreover, adjustments/change to mix composition and design can be readily observed in the context of a vectoral shift (as denoted by arrows on the plots contained herein) in high-/low-temperature performance using this plot.

The general concept of a performance-space diagram can be applied to specific tests. In the upper Midwest, USA, a number of agencies are specifying the Hamburg wheel track device as the high-temperature mixture performance test, and the DC(T) as the low-temperature mixture performance test. The resulting performance-space diagram could then be conveniently titled as a "Hamburg-DC(T) performance-space diagram," or more simply, a "Hamburg-DC(T) plot." Rounding out the suggested nomenclature, data analysis/decision-making could be referenced to data plotted in the "Hamburg-DC(T) space." Figure 4 presents the Hamburg-DC(T) plot in a conceptual sense. As shown in Figure 4, there are four corners to the plot with performance implications:

- Lower-Right: High Rutting Potential, High Cracking Potential – not recommended.
- Upper-Left: Low Rutting Potential, High Cracking Potential – not recommended for pavement surfaces.

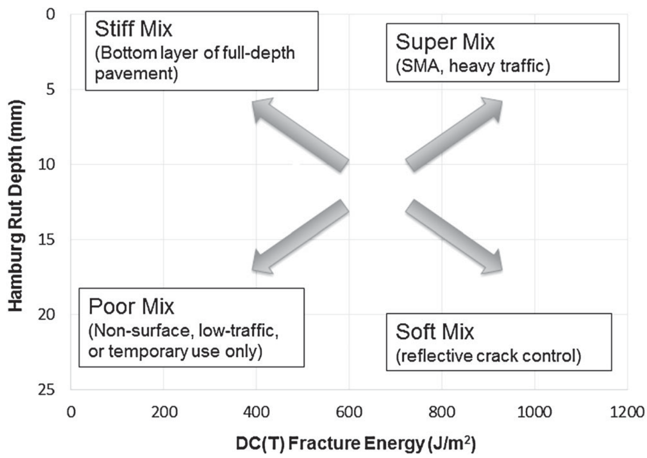

Figure 4. Hamburg-DC(T) plot concept and performance zones.

- Lower-Right: High Rutting Potential, Low Cracking Potential – not recommended for pavement surfaces.
- Upper-Right: Good Performance Zone, suitable for all mixtures, especially surface mixtures.

Figure 5 adds typical Hamburg and DC(T) performance limits to the plot, along with convenient gradient shading (deeper red for more rutting potential, deeper blue for more cracking potential). Since the DC(T) cracking test is usually accompanied with three levels of fracture energy thresholds based on traffic (400, 460, and 690 J/m^2 for low, med, and high traffic, respectively), these three zones have been identified on the plot. For low-traffic applications, data points residing in any of the three upper-right zones would acceptable. For medium-traffic applications, a higher DC(T) fracture energy threshold is required; thus, only data points residing in the two upper-right-most zones are allowable. For high traffic, only points residing in the upper-right-most zone are acceptable.

Several hypotheses of the effect of binder grade and aggregate change on mixture performance in the performance space can be made. The swapping of straight-run binder grades does not always give the designer much mixture improvement, as the movement of the mix is expected to be along a "performance-trade-off" axis (upper-left to lower-right, or vice-versa). For a weak aggregate system, this might mean that a soft mix failing the Hamburg (in the lower-right region of the plot) will be difficult to improve by simply substituting a harder virgin binder grade. Instead, a combination of recycled materials and polymer-modified binder may be a better solution. Polymer-modified binder tends to rotate the arrows on the plot away from the performance trade-off axis, and towards the desired upper-right portion of the performance space. Depending on the type of modification, the rotation of the shift (if plotted as an arrow) could be clockwise (harder, modified grade, or counter clockwise (softer, modified grade) as compared to the expected movement along the performance trade-off axis with the substitution of harder or softer unmodified grades, respectively. These trends will become more apparent by examining actual test data, which is the subject of the following section.

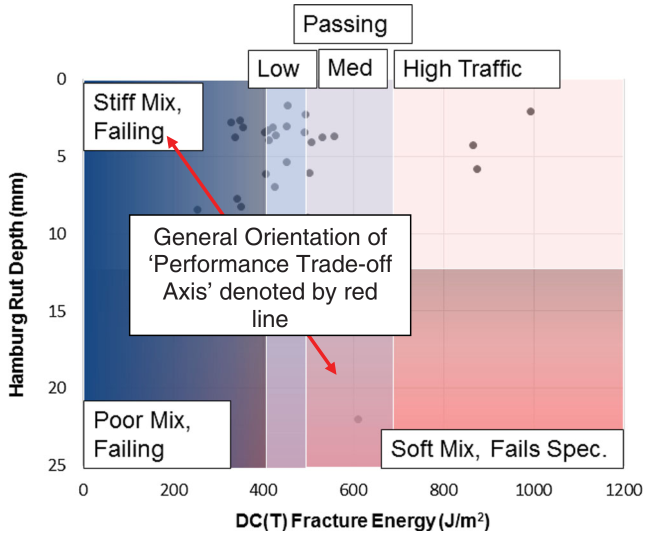

Figure 5. Hamburg-DC(T) plot with typical specification limits superimposed.

5. Study findings

5.1. *DC(T) and Hamburg test results*

The DC(T) and Hamburg test results for the various mixtures tested in the current study are provided below in Tables 4 and 5. The DC(T) fracture energy results have coefficients of variation (COV) less than 10% in all cases except three. In general, this is a common finding with the DC(T) test geometry at low temperatures as the fractured area of the test is typically larger than the representative volume element of the mixture. The CMOD fracture energy results follow expected trends for recycled content use, modification using a neat or polymer-modified binder, and a modified aggregate structure (change in coarse aggregate type). In the case of the recycled content use with both RAP and RAS, CMOD fracture energies decreased, which agrees with the results reported by Cascione et al. (2011) and Behnia et al. (2012). Furthermore, the use of a softer asphalt grade (PG 58-28 as opposed to PG 64-22) or a polymer-modified binder (PG 76-22

Table 4. DC(T) test results (− 12°C).

Mixture	PG grade	Fracture energy (J/m^2)	COV (%)
Virgin limestone I	64–22	377.3	9.3
45% RAP limestone	64–22	286.0	8.7
	58–28	347.7	18.1
	46–34	377.6	1.4
Virgin gravel	64–22	551.0	8.7
	76–22	614.5	9.2
Virgin limestone II	64–22	411.2	9.9
Virgin limestone	58–28	609.1	18.2
2.5% RAS limestone		502.3	8.9
5.0% RAS limestone		490.2	8.6
N30WMA	46–34	412.8	9.8
N30Rejuvenator	58–28	404.1	9.1
N70WMA	46–34	521.8	9.6
N70Rejuvenator	58–28	442.2	16.7

Table 5. Hamburg Test Results (50°C).

Mixture	PG grade	Rut depth (mm)
Virgin limestone I	64–22	> 20.0 (5850)
45% RAP limestone	64–22	2.9
	58–28	3.7
	46–34	10.2
Virgin gravel	64–22	7.2
	76–22	3.6
Virgin limestone II	64–22	8.5
Virgin limestone	58–28	> 20.0 (3000)
2.5% RAS limestone		12.1
5.0% RAS limestone		3.4
N30WMA	46–34	9.8
N30Rejuvenator	58–28	4.8
N70WMA	46–34	8.3
N70Rejuvenator	58–28	7.7

binder contained 4% styrene–butadiene–styrene (SBS)) led to increased CMOD fracture energy similar to Wagoner, Buttlar, Paulino, and Blankenship (2005). Finally, the use of an improved aggregate structure (substituting crushed gravel for crushed limestone coarse aggregate) led to increased fracture resistance, which agrees with the trends reported by Braham, Buttlar, and Marasteanu (2007). Virgin Limestone I and II are two different virgin limestone mixtures with volumetric properties shown in Tables 1 and 2, respectively. Mixture I was compared with the 45% RAP mixtures and Mixture II was compared to the PG 58-28 RAS mixtures.

Hamburg test results followed previously found trends for polymer-modification, recycled material use, and improved aggregate structure. The tabular results display the rut depths found after 7500 wheel passes which corresponded to the minimum wheel pass requirement for PG 64-22 mixtures in Illinois excluding Chicago. The rut depth at 7500 wheel passes is also used in the Hamburg-DC(T) plots shown in Figures 6–10. If the data shown in Table 5 have a rut depth greater than 20.0 mm, then the number of passes required to reach that rut depth is provided in parentheses. As shown in Table 5, polymer modification led to improved rutting resistance which supports the findings of Solaimanian et al. (2002). The use of recycled materials such as RAP and RAS also led to improvements in rutting resistance if no asphalt binder grade change was completed. Furthermore, an improved aggregate structure using gravel as opposed to dolomitic limestone also improved rutting resistance.

5.2. *Performance space diagram results*

5.2.1. *RAS content*

The use of RAS led to a trade-off of fracture resistance for rutting resistance and movement towards the upper left corner of the Performance Space Diagram. In the current study, the data shift more vertically than horizontally which would suggest that fracture resistance was not as sensitive as rutting resistance to the introduction of RAS in Figure 6. This type of trajectory is advantageous with recycled material use because mixtures could more easily meet the Hamburg minimum wheel pass requirement without becoming significantly low-temperature crack susceptible. Furthermore, the trajectory of mixture alteration in the diagram relative to the trajectory associated with virgin binder swapping is slightly more vertical, for example, black lines are rotated clockwise relative to the “binder trade-off axis,” which is represented by the red line. A

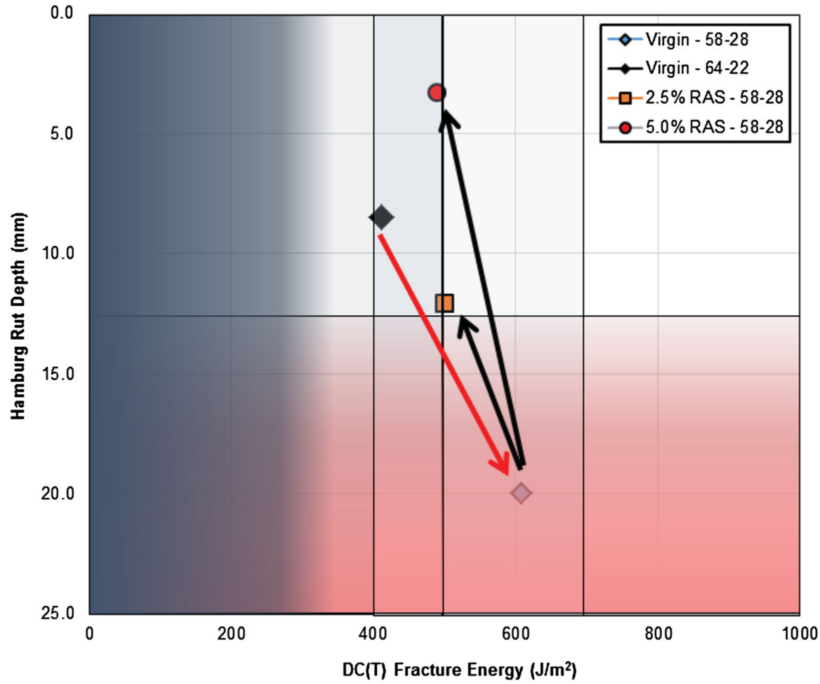

Figure 6. RAS mix designs illustrated in the hamburg-DC(T) space.

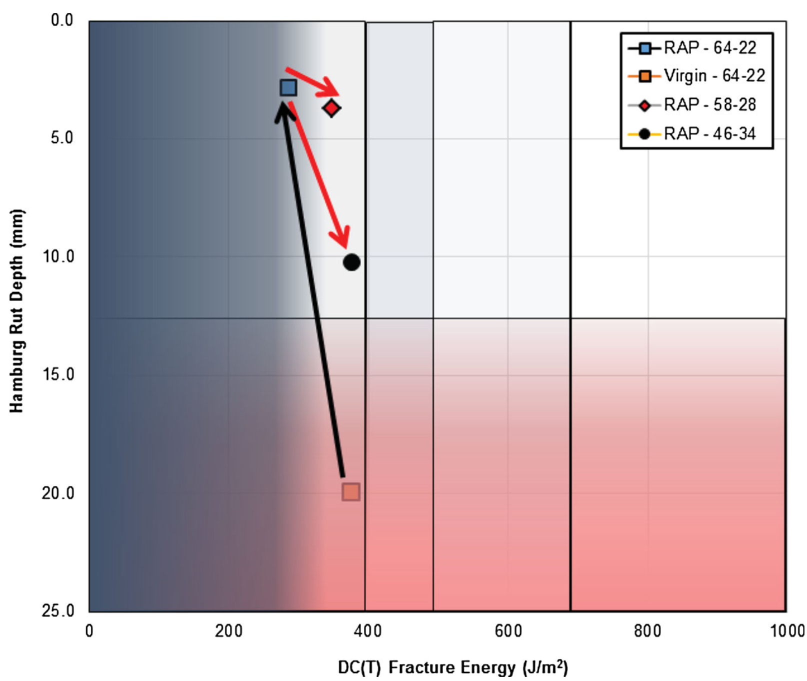

Figure 7. RAP mix designs illustrated in the Hamburg-DC(T) space.

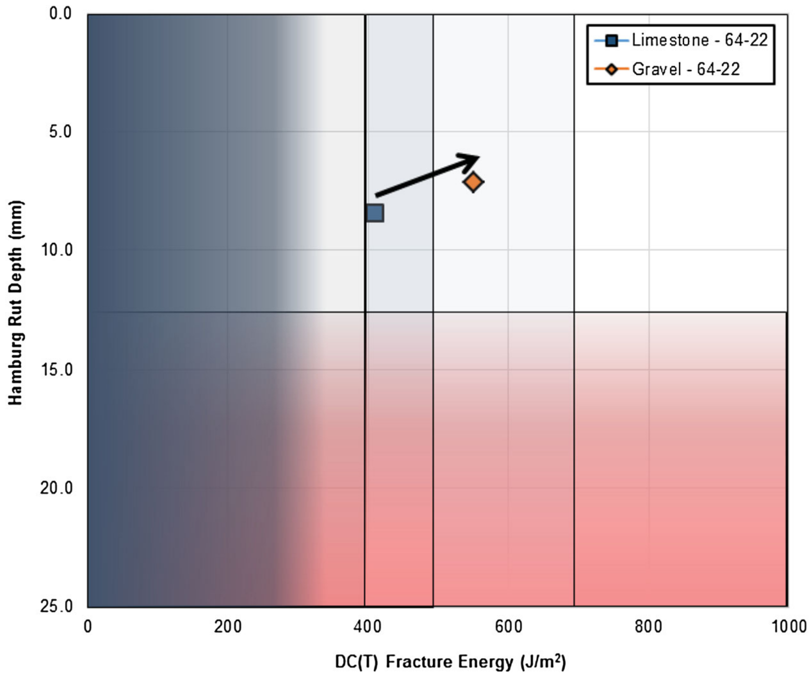

Figure 8. Aggregate structure effects on the Hamburg-DC(T) diagram.

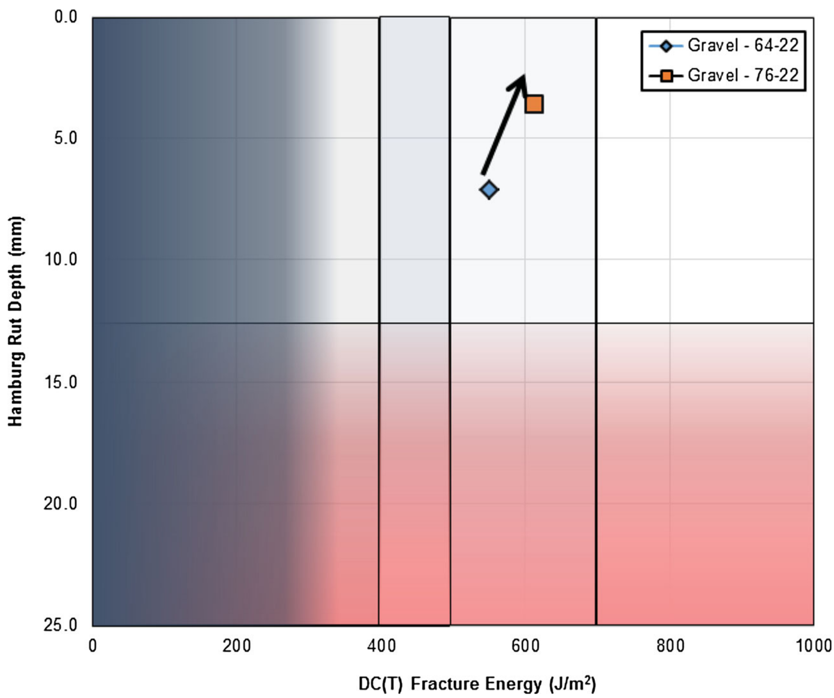

Figure 9. Polymer modification effects on the performance space diagram.

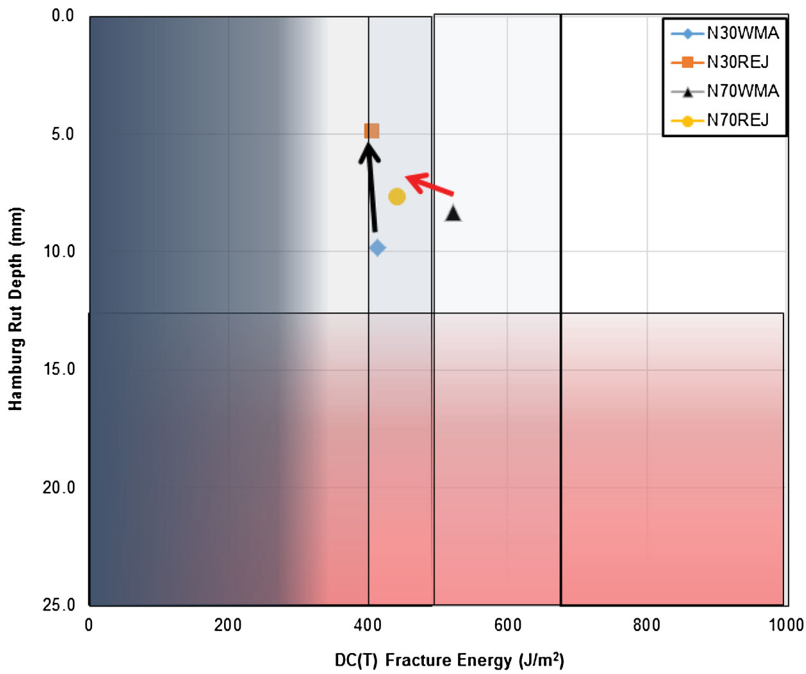

Figure 10. Rejuvenator effects on the performance space diagram.

rotation towards the upper-right corner of the plot away from the trade-off line represents a shift which is more preferential than simple binder grade adjustment. This might be interpreted such that the RAS is acting as a slightly modified material, perhaps due to the heterogeneity of the resulting mix (composite materials are known for their strength), and/or perhaps due to the presence of fibres in the pulp material or the hard aggregate added. In any case, the use of 5.0% RAS in conjunction with a softer asphalt grade of PG 58-28 led to a mixture meeting low-to-medium volume road requirements for low- and high-temperature performance in this particular case.

5.2.2. *RAP content*

The introduction of RAP and the effects of virgin binder grade adjustment are demonstrated below in Figure 7. Similar to the use of RAS, RAP in the current study led to a fairly steep, and in this case, long vertical shift towards the upper left region of the diagram due to the high percentage of RAP used (45%). This shifted the mixture from failing in terms of rutting resistance to failing in terms of fracture energy. In order to adjust the mixture, the virgin binder grade was altered from a PG 64-22 to a PG 58-28 and a PG 46-34. For this particular mix, the use of PG 46-34 with the 45% RAP mixture yielded approximately equal low-temperature cracking resistance and approximately half the rutting depth as compared to a PG 64-22 virgin dolomitic limestone coarse aggregate mixture. Therefore, recycling may be an effective method to employ with a softer virgin asphalt binder to shift a rutting-prone virgin mixture which fails the Hamburg requirement into a mixture passing both Hamburg and DC(T) test standards.

It is also interesting to compare the effect of the two different, softer virgin binder grades. When substituting the PG 58-28 binder for the PG 64-22, both the high-temperature grade and low-temperature grade were dropped by one grade (6°C). This caused a slight increase in rut depth, and a moderate increase in fracture energy. In the case of the PG 46-34 substitution for

PG 64-22, the high-temperature grade was dropped by three, and the low-temperature grade was dropped by two. This led to a longer arrow in the Hamburg-DC(T) space; that is, significant change in the high- and low-temperature grades led to significant changes in rut and cracking mix performance, as expected. It is also interesting to note that the PG 58-28 binder is less "temperature susceptible," has a wider PG spread (difference between high- and low-temperature grades), as compared to the PG 46-34 binder. It was expected that lower temperature susceptibility binders would tend to rotate more towards the upper-right corner of the Hamburg-DC(T) plot, while more temperature susceptible binders would be rotated more towards the lower-left corner. This was in fact the case observed here.

5.2.3. *Aggregate structure modification*

The use of an improved aggregate structure led to movement towards the upper right corner of the Performance Space Diagram. This type of movement, shown in Figure 8, is very desirable, as it stems from improvements in both the rutting and low-temperature cracking resistance of the mixture. In the current study, a local dolomitic limestone coarse aggregate yielded acceptable results for low-volume roads, but lacked the fracture resistance to meet the specification requirements for higher traffic levels. For comparison, a crushed gravel source was substituted as the primary coarse aggregate, which led to increased resistance in both rutting and cracking, meeting the cracking criteria for the medium-traffic category. It is hypothesised that this type of diagram movement would also occur with stone matrix asphalt (SMA) mixtures, which will be demonstrated with supporting data in a following section. The use of more angular and durable aggregate in conjunction with a polymer-modified binder would push mixtures towards the high traffic upper right corner. The possible trade-off in the use of stronger, more durable aggregate would be the associated cost in regions where a stronger aggregate source is not locally available. Based on these results, the use of the Hamburg-DC(T) diagram may be a useful tool in determining if the cost of high-quality aggregate is justified in terms of high- and low-temperature performance, and meeting specification limits.

5.2.4. *Polymer modification in virgin binder*

The use of polymer-modified binder led to movement in the upper-right direction of the Hamburg-DC(T) diagram, similar to the use of improved coarse aggregate (Figure 9). The movement on the diagram was more vertical in the case of the polymer-modified binder as compared to the aggregate modification. This predominantly vertical movement was due to the "two grade bumps" on the high-temperature grade of the binder, and the identical low-temperature grade (-22°C). The polymer modification led to a slight improvement in peak load capacity in the DC(T) test which manifested into a slightly higher CMOD fracture energy, due to the beneficial effects of the SBS polymer. However, as expected, the primary effect of the polymer modification in this case (the PG 76-22 has double-bump on the high-temperature grade, no bump on the low-temperature grade) was the improvement in rutting resistance. As shown in Figure 9, the rut depth for the PG 76-22 mixture was approximately half of that of the PG 64-22 binder. The results suggest that designer might want to instead consider a PG 70-28 binder. Assuming that the PG 70-28 binder would have roughly the same cost as the PG 76-22 binder (it possesses the same spread between the high- and low-temperature grades), it would have likely provided more benefit in fracture resistance, while slightly improving rut resistance (which was already in the passing range).

5.2.5. *Rejuvenator effects in high ABR mixtures*

The field mixtures tested in this section of the study demonstrated that the use of a rejuvenator with a stiffer virgin asphalt grade (PG 58-28 base binder) as compared to a WMA-modified softer virgin asphalt grade (PG 46-34 base binder) led to higher rutting resistance and lower cracking resistance. In both the N30 and N70 high ABR mixtures (as described earlier), the use of rejuvenator along with PG 58-28 binder tended to produce a more rut-resistant, yet less crack-resistant mix, as compared to the PG 46-34 counterparts. On the Hamburg-DC(T) diagram, the PG 58-28 plus rejuvenator mixtures are shifted up and to the left as compared to the mixtures with the PG 46-34 binder. In the case of the N70 mixtures, the movement was more horizontal as compared to the N30 mixture. This result likely occurred due to the difference in ABR for the N70 mixture (50% ABR for the N70 mixture, as compared to 66% ABR for the N30 mixture). This figure demonstrates the options available to the mixture designer if the mixtures fall in the upper right corner of the diagram. In this case, since all mixtures meet the Hamburg requirement, it may be advantageous to simply use the softer virgin binder grade (PG 46-34) to take advantage of increased low-temperature cracking performance. However, if an issue arose such as a PG 46-34 binder was not available at the time of construction or if it was not economical, the designer could employ the PG 58-28 with rejuvenator and still meet specification requirements.

6. Massachusetts evaluation of the Performance Space Diagram

Recently, Mogawer et al. (2015) conducted a study to address some of the New England state transportation agencies concerns associated with the use of Re-refined Engine Oil Bottoms (REOB) in asphalt binders and mixtures. The effect of REOB obtained from two sources (REOB 1 and REOB 2) on the physical and rheological properties of an asphalt binder was investigated. Also, the effect of REOB-modified binders on the performance of asphalt mixtures after short- and long-term ageing was evaluated in terms of moisture damage, rutting, and cracking at intermediate and low temperatures. Two straight run binders (PG58-28 and PG64-22), a typical PG64-28, two sources of REOB, an aromatic oil, and PPA were utilised. Binder rheology results showed that the addition of REOB at the dosage required to attain the PG58-28 caused the binders to age more relative to the straight run binder. The results also indicated that the use of higher dosages of REOB that still provide the same PG can cause increased binder ageing. Hamburg-DC(T) Space Diagrams indicated that the REOB-modified mixtures remained within the passing zone in a Hamburg Wheel Tracking-Disc Shaped Compact Tension DC(T) tests diagram for low- to medium-traffic level. The rutting tests showed that generally the REOB did not cause the mixtures to fail. Low-temperature cracking evaluations detected minor effects on low-temperature fracture properties associated with various combinations of REOB tested.

Figure 11 shows a set of results obtained in the recent REOB study by Mogawer et al. (2015), plotted in the Hamburg-DC(T) space, along with arrows to highlight key trends when plotted in this space (REJ stands for rejuvenator in Figure 11). The key observations are summarised as follows:

- For the virgin, straight-run mixtures, the arrow between the PG 64-28 short-term oven-aged (STOA) mixture and PG 58-28 STOA mixture indicate a softening effect, although along a steeper trajectory than the typical performance trade-off axis. This is because of the larger spread between the high- and low-temperature grade of the PG 64-28 binder relative to the PG 58-28 binder. With the drop in PG high-temperature grade, the PG 58-28 binder clearly led to higher rut depth than the PG 64-28 binder. With nearly identical low-temperature binder grades, very little difference in DC(T) fracture energy was noted.

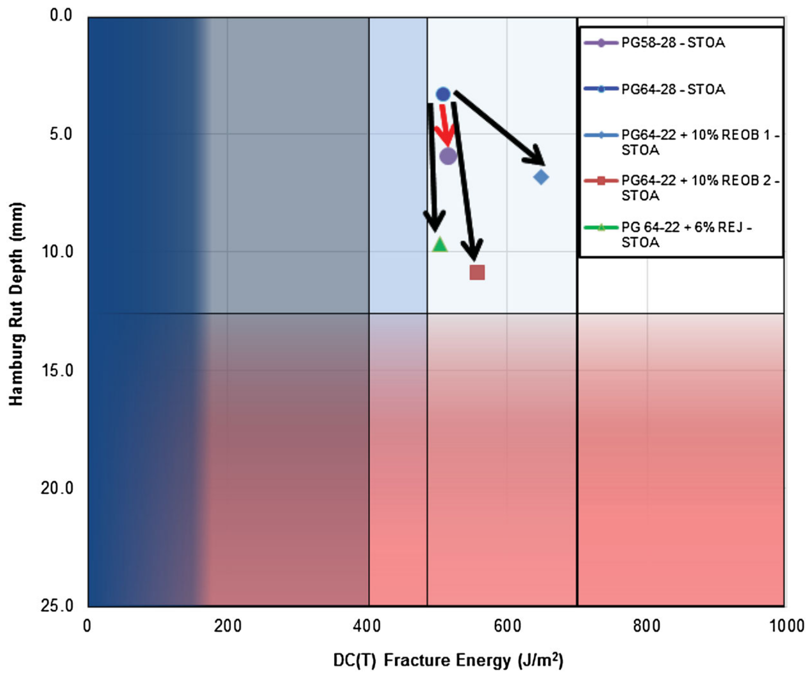

Figure 11. Selected REOB study results illustrated on a Hamburg-DC(T) plot.

- The remaining three shifts in the Hamburg-DC(T) space are comparisons of the mixtures containing PG 64-22 plus REOB or rejuvenator, in reference to the PG 64-28 control mixture.

  For the mixture with rejuvenator, a nearly vertical, downward shift was noted. This suggests that the rejuvenator material tended to soften the mixture, thereby lowering the rut resistance without increasing fracture resistance. This trend is steeper than the typical performance trade-off axis.

  For the mixture with REOB source #2, a trend in the softening direction was also observed, this time more along the direction of the performance trade-off axis. Thus, the mix was softened overall, but some gain in fracture energy was associated with the loss in rut resistance, much like substitution with a softer binder grade would yield.

  For the mixture with REOB source #1, the softening trend had a shallower trajectory, more counter-clockwise than the typical shift along the trade-off axis. Thus, the REOB source #2 produced a better overall shift in the Hamburg-DC(T) space relative the other two additives in the short-term oven ageing condition.

In general, all of the additives tended to soften the mixtures, creating different mixture rather than a more exact substitute for the reference mixture. All four mixtures (control plus three modified mixtures), passed the Hamburg and DC(T) specifications in the same performance categories. However, the mixtures were clearly situated in different zones within the 2D performance space, and in some cases, close to specification limits. Thus, the designer, in a follow-up iteration, might have adjusted the various mixtures differently to give a better factor of safety away from specification limits. For instance, one mix was close to the cracking limit (rejuvenator), one was close to the rutting limit (REOB#2), and one appeared to require no further adjustment (REOB

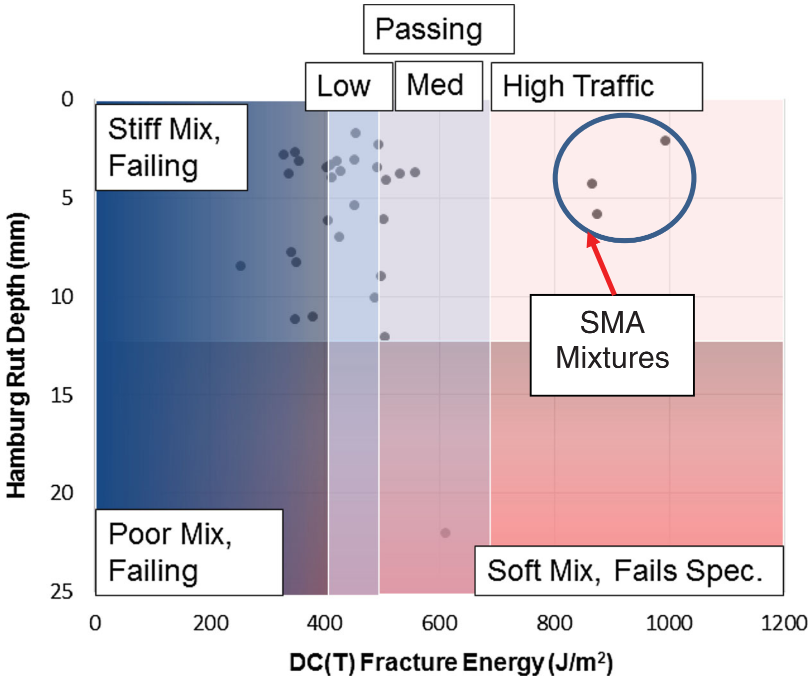

Figure 12. Hamburg-DC(T) plot for recent mixtures tested in Illinois, with typical specification limits superimposed.

#1). This data set provides another example of how the Hamburg-DC(T) plot can be used in the design and evaluation of modern, heterogeneous asphalt paving mixtures.

7. Hamburg-DC(T) plot trends for recent Illinois asphalt mix designs

Figure 12 presents a number of recent performance tests collected in Illinois, plotted in the diagram. In addition to the data presented earlier, additional data from recent mixture design trials provided courtesy of State Testing, LLC, of Skokie, IL, are provided. In particular, the additional data plots demonstrate some salient features of SMA mixtures, and high RAP/RAS content (high ABR) mixtures. First, however, note that all but one mixture was found to pass the Hamburg test, but cracking performance data fell into all categories, including failing. This is not unexpected, since the Hamburg specification has been in place for a number of years in Illinois, while the DC(T) test is just now being incorporated into specifications, such as for high ABR mixtures as specified by the Chicago Department of Transportation. In Figure 12, three SMA appear in the upper-right corner of the Hamburg-DC(T) space diagram. Recent experience in Chicago suggests that SMA mixtures are a good approach to achieving both high rut and crack resistance in performance tests. Based on the results presented earlier, this is very likely due to their use of high-quality crushed stone, with coarse aggregate particles in contact, along with a heavy mastic coating of highly polymer-modified binder in the mixtures. Moreover, these mixtures have been found to perform exceptionally well in the City of Chicago and on the Illinois State Toll Highway system under extremely heavy traffic (and in a cold, wet-freeze environment).

Figure 13 highlights several of the recent, high ABR mixtures used in the Chicago area for various traffic volume facilities. Three medium traffic level mixtures (N90 and N70) are shown, all having just under 30% binder replacement. The N90 mixtures used a combination

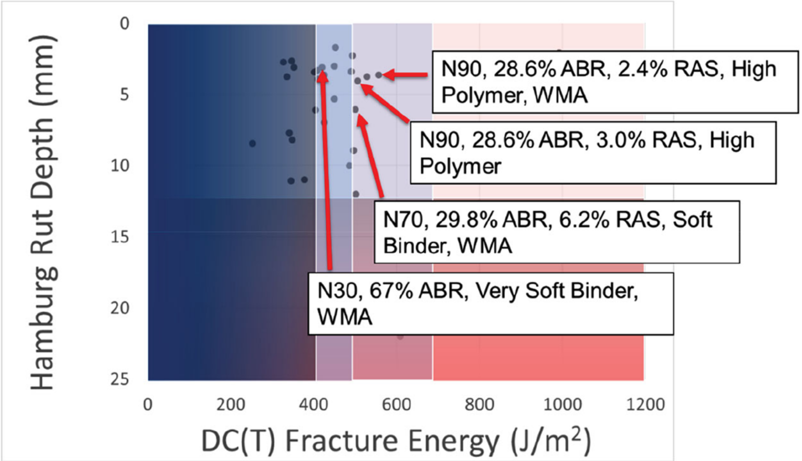

Figure 13. Hamburg-DC(T) plot for recent mixtures tested in Illinois, high asphalt binder replacement (ABR) mixtures indicated.

of recycled asphalt shingles (RAS) and RAP, along with polymer-modified binder to meet performance specifications. The N70 mixture used only RAS for binder replacement and mixture stiffening/toughening, along with a soft base binder grade and warm-mix additive. The more economical, low-volume N30 mixture utilised an impressive 67% binder replacement, along with a very soft binder and WMA additive. Although this mixture is borderline on the DC(T) fracture energy and might experience light thermal cracking over time, it is likely to be used as a thin overlay placed on an existing, cracked pavement. Thus, since reflective cracking is likely to occur anyways (propagation of exiting cracks/joints in underlying PCC pavement), a more rut-resistant, high recycled content mix with moderate cracking resistance may be the most economical strategy for a temporary maintenance-type overlay in this application.

8. Concluding remarks

This paper presented a new performance-space diagram approach – a simple, yet powerful method for simultaneously evaluating the high- and low-temperature performance of asphalt paving mixtures, for the purpose of mixture design, evaluation, and forensic investigation. The data presented herein emphasised the Hamburg-DC(T) approach for the control of high- and low-temperature mixture properties, in a somewhat analogous manner to the Superave PG binder specification. Of course, additional mixture tests could be added to this suite to control other pavement distresses, such as fatigue cracking and reflective cracking. The Hamburg-DC(T) space diagram involves plotting Hamburg wheel tracking results, plotted in reverse order on the y-axis using an arithmetic scale, along with DC(T) fracture energy results, plotted on the x-axis, also using an arithmetic scale. The Hamburg-DC(T) plots yield a surprising amount of insight into mixture variables that affect overall performance. Variables such as the recycled material content, asphalt binder substitution using neat or polymer-modified binders, aggregate structure change using crushed gravel instead of crushed dolomitic limestone, and rejuvenator effects on high ABR mixtures were considered in this study.

Based on the findings of this study, the following conclusions were drawn:

- The use of recycled material such as RAP or RAS led to shifting towards the upper-left corner of the diagram, which demonstrates an increase in rutting resistance and a decrease in low-temperature cracking resistance. The use of RAS tended to have a more vertical shift on the diagram, suggesting the possible benefits of the fibre pulp and/or the composite nature of the resulting heterogeneous mixture. As commonly done, it was shown that this can be addressed in mixture design by counterbalancing with a softer virgin binder grade. The amount and direction of shifting in the Hamburg-DC(T) space caused by recycled materials and softer virgin binder grades should be of great use to mix designers in cutting down on mix design iterations to meet performance criteria.

- Polymer-modified binders, which had the same low-temperature asphalt grade as the neat asphalt binder, led to shifts towards the most desirable upper-right corner of the diagram, as they increased both rutting and cracking resistance. The PG 76-22 used in the current study shifted the mixture in a more vertical direction as the low-temperature grade was equal to the PG 64-22 binder used as the baseline. Polymer modification using a binder with a lower low-temperature grade would likely shift the mixture in a more diagonal fashion. On the other hand, substitution of one straight-run binder grade for another results in a clear, predictable trade-off in the Hamburg-DC(T) performance space.
- In the current study, the substitution of crushed gravel for crushed dolomitic limestone led to both increased fracture energy and rut resistance, indicating how harder aggregates can benefit a mixture design with Hamburg and DC(T) mixture performance specifications.
- Rejuvenators in the presence of a stiffer virgin binder led to higher rut resistance and lower fracture resistance in the current study for high ABR mixtures used in the Chicago area.
- Plotting and analysing data from a recent study by Mogawer et al. (2015), the Hamburg-DC(T) results showed how three binder blending agents, two REOB materials and one rejuvenator, used in conjunction with a PG 64-22 binder, compared with respect to mixtures produced with the PG 64-28 reference binder. In general, all of the additives tended to soften the mixtures, creating a different mixture rather than a more exact substitute for the reference mixture. All four mixtures (control plus three modified mixtures), passed the Hamburg and DC(T) specifications in the same performance categories. However, the mixtures were clearly situated in different zones within the 2D performance space, and in some cases, close to specification limits.
- In addition, a broad look at a large database of mixtures recently designed in Illinois was also presented. This demonstrated the potential benefits of stone-mastic asphalt mixtures, and illustrated how several mixtures containing high recycling contents were designed to successfully meet high- and low-temperature mixture specifications.

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03-16d William Buttlar

ISWANDARU WIDYATMOKO: Thanks very much for the presentation. It’s very, very interesting and I like the idea of having these space diagrams. Very easy to follow. We don’t use the same parameters in the UK, but the idea is very, very good. I think there are a lot of potentials in there. My question here is – I can see the usefulness of this diagram to allow a contractor or any designer to do a spot check where they are with their mix design and how that mix design might be performing or how the performance has been achieved by that mix design – but then what would be your vision in the future, how this space diagram will be taken for? What it is going to be like in the future? It’s going to be a threshold failure that needs to be achieved on the installed product, like every two years, these products must not show a certain crack or rutting or something like that.

WILLIAM BUTTLAR: You know, these tests have been designed around extensive field performance studies, but it is going to be useful that when others start using the tests as the specs get modified. You certainly have to continue to track field performance. The other thing is I would say, at least in the case of the DCT, it really wasn’t developed, at least the simple specification, for like RAS. It wasn’t developed for . . . We didn’t have really high polymer mixes or REOB, things like that. So, you know, it may be that some will use a more complicated version of these cracking specifications. They might imbed a model, they might look at two parameters, so then this space diagram may evolve and then you would have to go back and recalibrate to field performance. And so using it as-is here, I think it’s kind of calibrated, it works pretty well, but making it even more sophisticated and considering more variables, newer materials, yeah, then we have to keep moving forward.

ISWANDARU WIDYATMOKO: Thank you.

MIHAI MARASTEANU: Very nice work, Bill. Really great work. I really enjoyed it, and the comment that I have is not a question but just a comment. And I’m so happy you showed also the plot on the PG grade. If you look back – and we’ve done that some time ago – if you look back at how the PG actually specs were developed in these limits, it’s quite interesting. They were developed from mixture testing, actually. So, obviously, they had these field experiments in Canada for low temperature, and then they had the mixture tested. And then they used in one case Van der Poel Nomograph to back calculate the binder. So it is quite interesting that actually the whole thing came from mixture but then for 40 years we did not have a mixture specification, so we just extracted the binder parts out of it. So basically what you can do from the binder spec that they have today, you could do the back calculation the other way and get mixture properties, find out, for example, what does stiffness of 300 MPa mean for a mixture. Of course, it gets more complicated. But that’s why I think the study that you showed, it’s so important because, as you said, you followed the same idea, and maybe one day we’ll have some sort of a PG for asphalt mixtures. Of course, it is bit more complicated. And I think why is this important? Because for many years binder and mixtures were kind of different, as I said, different material, and by doing this, we understand better what the role of the binder is,