Investigation of the Fracture Resistance of Hot-Mix Asphalt Concrete Using a Disk-Shaped Compact Tension Test

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In recent years the transportation materials research community has focused a great deal of attention on the development of testing and analysis methods to shed light on fracture development in asphalt pavements. Recently it has been shown that crack initiation and propagation in asphalt materials can be realistically modeled with cutting-edge computational fracture mechanics tools. However, much more progress is needed toward the development of practical laboratory fracture tests to support these new modeling approaches. The goal of this paper is twofold: (*a*) to present a disk-shaped compact tension [DC(T)] test, which appears to be a practical method for determining low-temperature fracture properties of cylindrically shaped asphalt concrete test specimens, and (*b*) to illustrate how the DC(T) test can be used to obtain fracture properties of asphalt concrete specimens obtained from field cores following dynamic modulus and creep compliance tests performed on the same specimens. Testing four mixtures with varied composition demonstrated that the DC(T) test could detect the transition from quasi-brittle to brittle fracture by testing at several low temperatures selected to span across the glass transition temperatures of the asphalt binder used. The tendency toward brittle fracture with increasing loading rate was also detected. Finally, the DC(T) test was used in a forensic study to investigate premature reflective cracking of an isolated portion of pavement in Rochester, New York. One benefit of the DC(T) test demonstrated during testing of field samples was the ability to obtain mixture fracture properties as part of an efficient suite of tests performed on cylindrical specimens.

Asphalt pavement life span and rideability and the need for costly maintenance treatments are significantly affected by the type, extent, and rate of fracture that occurs in the surface layers of these pavements. Various forms of fracture are commonly observed, including thermal cracking (transverse to the direction of traffic), longitudinal surface or "top-down" cracking, and reflective cracking of asphalt overlays placed on existing jointed or cracked pavements (*1*). In recent years a great deal of effort has been directed toward the development of testing and analysis methods that can be used to study the mechanisms of crack initiation and propagation in asphalt pavements (*2–5*). Moreover, it has been shown that crack initiation and propagation in asphalt materials can be realistically modeled with cutting-edge computational fracture mechanics tools (*6, 7*). This approach incorporates a cohesive zone interface fracture model within a finite element modeling framework to describe the initiation and propagation of fracture (separation) of the material. An advantage of an integrated testing and modeling program is the ability to extract information from the laboratory results that cannot be determined from measurements alone. For instance, this approach can be used to gain insight into the isolation of crack formation energy from other sources of energy consumption in fracture tests. Furthermore, once a cohesive zone constitutive model is calibrated to laboratory test results, the extension of the model to field studies can be accomplished with reduced model calibration. That will not only lead to better prediction of field deterioration, but it will also provide more realistic insight into deterioration mechanisms.

To take full advantage of these new modeling approaches, advances in laboratory fracture tests for hot-mix asphalt (HMA) concrete are needed. In the cohesive zone fracture model, additional material parameters that cannot be obtained from conventional bulk material tests are required. For instance, the fracture energy, or the energy required to initiate and form a unit surface of a crack, is needed to describe the fracture resistance and softening behavior of the material (*8*). For an accurate determination of the fracture energy, the test should be a valid fracture mechanics test in which an initial crack is present.

On early development of a cohesive zone model for HMA concrete, a single-edge notched beam [SE(B)] was successfully employed to measure the fracture energy for input into the model (*9*). The SE(B) test has been used for determining various fracture characteristics of HMA concrete over a range of temperatures, specimen dimensions, and so on (*2, 10–13*). The SE(B) configuration is advantageous for investigating fracture for several reasons, as presented in Table 1. Foremost, the SE(B) allows for a stable crack growth after crack initiation. Also, the size of the beam can easily be varied in a laboratory setting to ensure that the fracture mechanisms are not affected by end effects. The SE(B) test is arguably the most versatile of testing modes, because mixed-mode (combination of tensile and shear opening) fracture tests can be performed by simply fabricating the notch away from the midpoint of the beam (*14*).

However, it is ultimately necessary to calibrate crack propagation models to observed field cracking, which requires the removal and testing of materials from constructed asphalt pavement layers. Typically, forensic investigations of in-place pavements are conducted by coring the pavement structure and obtaining the properties from those cores. The variability of the asphalt pavement layers (typically ranging from 25 mm up to 100 mm) could create a challenge for certain

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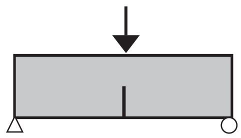
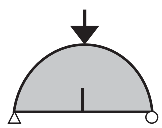
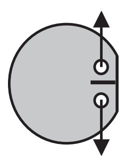
TABLE 1 Potential Fracture Specimen Geometries with Advantages, Disadvantages, and Potential Fracture Surface Area

Test Configuration	Advantages	Disadvantages	Potential Fracture Surface Area (mm^2)
Single-edge notched beam 	Pure Mode I loading Simple loading configuration Flexibility to investigate other areas (mix-mode fracture, specimen size effect, etc.)	Difficult to obtain field specimens	7500
Semicircular bending 	Easily obtained field specimens Simple three-point bending load	Complex stress state (arch effect arrests long cracks) Specimen size	3750*
Disk-shape compact tension 	Easily obtained field specimens Standard fracture test configuration	Application to HMA concrete unknown Crack deviation	5500*

*A specimen thickness of 50 mm was used in this calculation.

specimen geometries. Sawing beams from existing pavements may not be practical because excessive pavement damage may result or because insufficient layer thickness is present. Therefore, a practical fracture test for asphalt concrete should have the capability to test cylindrical specimens with thicknesses approaching as little as 25 mm. The Superpave® indirect tensile test has the capability to test field cores with varying layer thicknesses, but is limited to obtaining bulk material properties, such as creep compliance and tensile strength (*15*).

The goal of this paper is twofold: (*a*) present a disk-shaped compact tension [DC(T)] test as a practical method for determining low-temperature fracture properties of cylindrically shaped asphalt concrete test specimens and (*b*) illustrate how the DC(T) test can be used to obtain fracture properties of asphalt concrete specimens obtained from field cores following dynamic modulus and creep compliance tests performed on the same specimens.

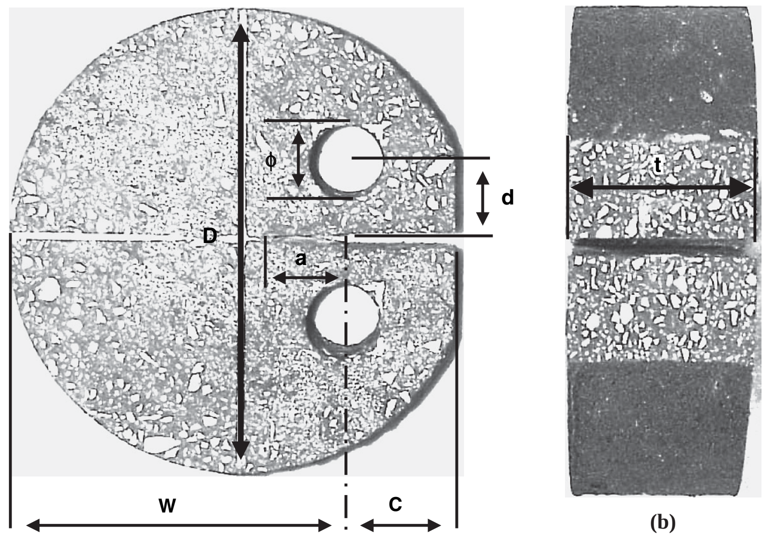
SELECTION OF FRACTURE TEST GEOMETRY

Before an experimental research campaign was conducted, two prospective fracture specimen configurations were identified in the literature that would be applicable to cylindrically shaped, thin pavement layers obtained from field cores. The semicircular bend (SCB) specimen has been successfully applied to measure the fracture resistance of HMA (*16*, *17*). The DC(T) specimen, which has been standardized in the ASTM E399 "Standard Test Method for Plane–Strain Fracture Toughness of Metallic Materials," would also satisfy the requirements (*18*). To select the most promising geometry for obtaining fracture energy from field cores, the advantages and disadvantages (Table 1) of each specimen geometry were considered.

The SCB test configuration has the potential to obtain two specimens from each field core, reducing the number of field cores needed to provide a representative sampling of test results. However, the specimen size of the SCB geometry could be a factor when analyzing the data. The initial ligament length, after the notch is fabricated, could create a constraint on the crack front for two reasons. First, even before crack propagation, the ligament is in proximity to the top rounded exterior of the specimen, in which high compressive stresses are located, because of the presence of an applied load and flexural bending effects. Although these factors are also present in other bending fracture tests, such as the SE(B) test, the effects appear to be more critical in the smaller, compact SCB specimen geometry. Also, the short initial ligament could adversely constrain the fracture process zone and provide added test variability because of the relatively small fracture surface created when testing in this configuration.

The DC(T) geometry (Figure 1), which has been used for testing metallic materials, has recently been adapted to HMA materials (*19*). Localized failure at the loading holes occurred during the initial development of the DC(T) geometry owing to insufficient material to carry the stress at those locations. However, the loading hole locations were modified to ensure that the probability of the undesired failures would be minimal. Currently, more than 100 tests have been performed in the new configuration without a localized failure. The recommended specimen dimensions, initially developed for 9.5-mm nominal maximum aggregate size mixtures, are shown in Figure 1.

One of the primary goals in developing the DC(T) geometry is to maximize the potential fracture area, thereby reducing the statistical variability of the fracture energy obtained from the test (*20*). The SE(B) test has been shown to provide a repeatable measure of fracture energy (*9*) and was therefore taken as a benchmark reference



(a) (b)

Recommended Dimensions (mm)	
D	150
W	110
ϕ	25
a	27.5
d	25
C	35
t	50

(c)

FIGURE 1 Recommended dimension (based on 9.5-mm NMAS) for laboratory-prepared disk-shaped compact tension geometry.

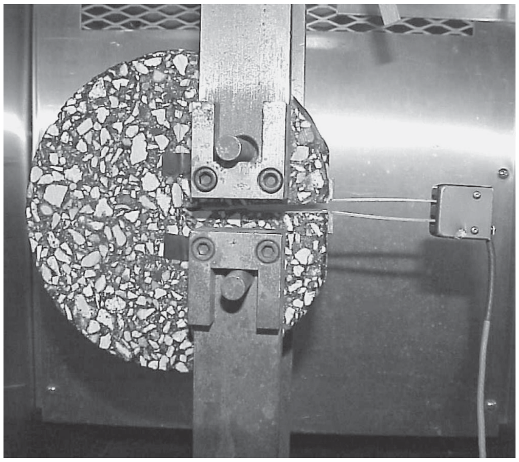
for the evaluation of experimental results obtained from the surrogate DC(T) testing geometry. Compared with the SE(B), the DC(T) produces 35% less potential fracture area and the SCB produces 50% less area. Although variable, the thickness for both the SCB and DC(T) specimens was considered to be 50 mm for the purposes of this comparison.

Compact tension tests (both rectangular and disk-shaped) can provide erroneous results if the crack front significantly deviates from a straight (pure Mode I) crack path. Wagoner et al. (*19*) noted that crack deviation occurred during some tests using the DC(T) configuration and that the average deviation angle from 50 specimens was 5°. A solution to the crack deviation is the fabrication of shallow side grooves in the specimen (*21*), but that would create a fabrication issue that would result in a less practical test. The crack deviation observed during the testing did not statistically correlate with the fracture energy obtained from the tests (*19*). However, further analysis should be performed, using cohesive zone model and finite element analysis, to obtain guidelines to determine when a valid fracture result has been obtained from the test when the crack deviates.

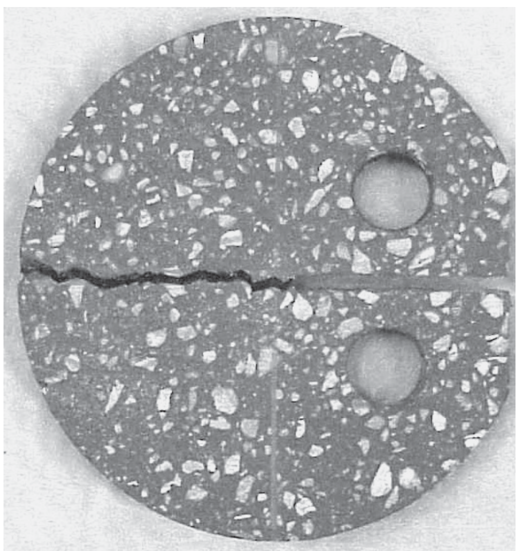
On the basis of the comparison between the SCB and DC(T) geometries, the DC(T) was selected as the most promising test geometry for obtaining the fracture energy directly from field cores. Although each specimen has distinct pros and cons, the deciding factor was judged to be the larger potential fracture surfaces associated with the DC(T) test. Furthermore, it appears that one of the potential disadvantages of the DC(T) test, deviation from a Mode I crack path, might be all but eliminated in the future with continued progress in the integration of numerical analysis with the analysis of test results. It is believed that as more research is conducted to better account for the effects of size and material heterogeneity on the interpretation of fracture test results, the SCB geometry may indeed provide a more efficient method for obtaining fracture energy from field cores, because twice as many test specimens can be generated from a given number of cylindrical field cores or laboratory-compacted cylinders.

EXPERIMENTAL STUDY USING DC(T)

The test development and procedures for the DC(T) test are provided by Wagoner et al. (*19*). The DC(T) test is performed under tensile loading at the loading holes, and the crack mouth opening displacement (CMOD) is measured with a clip-on gauge (Figure 2). The test is controlled through a constant CMOD rate to provide a stable postpeak fracture. The fracture energy is calculated by determining the area under the load–CMOD curve normalized by initial ligament length and thickness. An experimental design was developed to investigate the fracture energy variation of four distinctly different mixtures. The mixtures were tested at



(a)



(b)

FIGURE 2 (*a*) Experimental setup of DC(T) test with loading pins inserted and CMOD gauge and (*b*) typical fractured DC(T) specimen.

three temperatures (–20°C, –10°C, and 0°C) and a single CMOD loading rate of 1 mm/min. Also, a single mixture was tested at four loading rates to investigate the fracture response of the material.

Materials Used in Study

Four mixtures were selected to provide distinctly different fracture characteristics. The relevant mixture properties are described in Table 2. The four mixtures represent a variety of mixture types from typical Illinois surface mixtures to polymer-modified interlayer mixtures to large aggregate binder mixtures. For the experimental study two specimens were fabricated from each standard gyratory-compacted specimen prepared.

TABLE 2 Properties of Mixtures Used for Experimental Study

Mixture ID	NMAS (mm)	Asphalt Binder	Tensile Strength[1] (kPA)	Fracture Energy[2] (J/m^2)
LR19	19	PG 64-22	—	445
LR9.5	9.5	PG 64-22	3580	448
PIA	9.5	PG 58-22	3560	351
AST (polymer-modified interlayer mixture)	4.75	Polymer-modified	2670	1769

[1]Obtained from Superpave indirect tensile test (IDT) at –10 °C.
[2]Obtained from disk-shaped compact tension test at –10 °C.

Test Results

Previous work with portland cement concrete has shown that the specimen size has an effect on the fracture energy obtained from the test (*8, 22*). Because the layer thickness of pavements can vary and would reflect on the thickness of the DC(T) specimen, the effect of the specimen thickness on the fracture energy should be understood so that equal comparisons can be drawn when the thickness varies between specimens. A brief study was conducted to develop an initial understanding of the thickness effect. For this study a single mixture (LR9.5) was tested, with specimen thickness ranging from 25 mm to 75 mm. The tests were conducted at –10°C with a 1-mm/min loading rate. Figure 3 shows the average fracture energy obtained from the five replicates, along with the variation of fracture energy, by plotting the maximum and minimum deviation as error bars. The fracture energy tended to increase as the specimen thickness increased, which agrees with the findings of Duan et al. (*22*). Also, the variability of the test results was not affected by the specimen thickness. However, further work needs to be done to develop a more rigorous understanding of the effect of thickness on the fracture properties of asphaltic materials. A single thickness of 50 mm was selected as the standard thickness for the rest of this study.

With a "standard" specimen thickness decided, the four mixtures were tested at the temperatures described in the section above with three replicates tested at each temperature. As shown in Figure 4, with increasing temperature the fracture energy increases, that is, the material becomes less brittle. The increase in fracture energy with increasing temperature can be attributed to two causes. First, the material becomes more ductile as the temperature increases, causing more energy to be consumed to initiate and propagate a crack. Also, the interaction between the aggregate stiffness and mastic stiffness varies with temperature. At the lower temperatures, the crack tended to propagate through both the aggregates and the mastic. The crack at the higher temperatures propagates around the aggregates. More energy is consumed due to aggregate bridging and interlock when the crack follows the more tortuous path around the aggregates. The increase in fracture energy with increasing temperature agrees with the findings of Wagoner et al., in which a statistical analysis of the data showed a significant temperature influence on the fracture energy (*19*).

The maximum and minimum deviation from the average fracture energy is also shown in Figure 4. The coefficient of variation

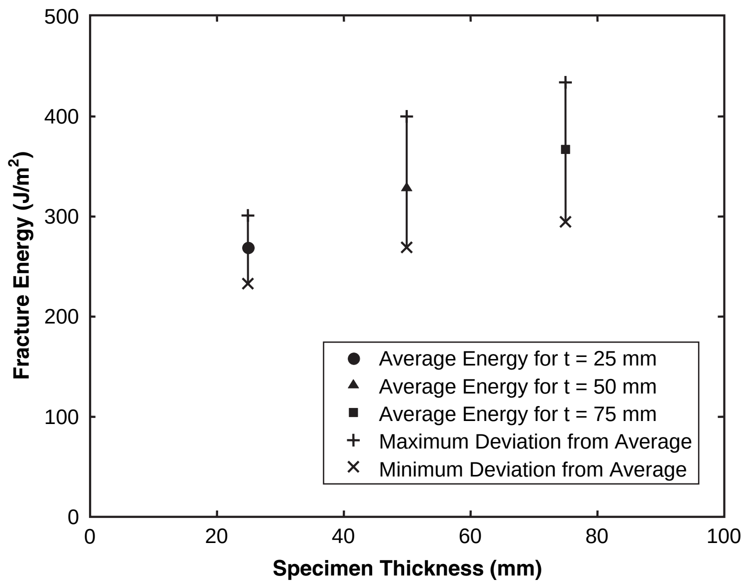


FIGURE 3 Specimen thickness (t) effect on average fracture energy of five replicates for LR9.5 mixture tested at −10°C.

for the data shown in Figure 4 ranges from 3% to 28%. When comparing the coefficient of variation from the DC(T) with data that were reviewed in the literature for the SE(B) (*10*) and SCB tests (*17*), the variability of the DC(T) was within the range of variation from those tests. For example, the coefficient of variation of the SE(B) test ranged from 3% to 28%, and for the SCB it ranged from 15% to 34%. As shown in Figure 4, the mixture with the largest deviation from the average was the LR19 mixture at 0°C. A contribution to the large variation in the test results with the 19-mm mixture could be that the specimen size, particularly the specimen thickness, may be below the representative volume of the mixture. When a specimen size that is below the representative volume of the material is used, a significant number of replicates may be required and the averaging process may be invalid, creating significant errors (*20*). Also, the crack propagation can influence the fracture energy, as stated above, by requiring more energy to grow the crack

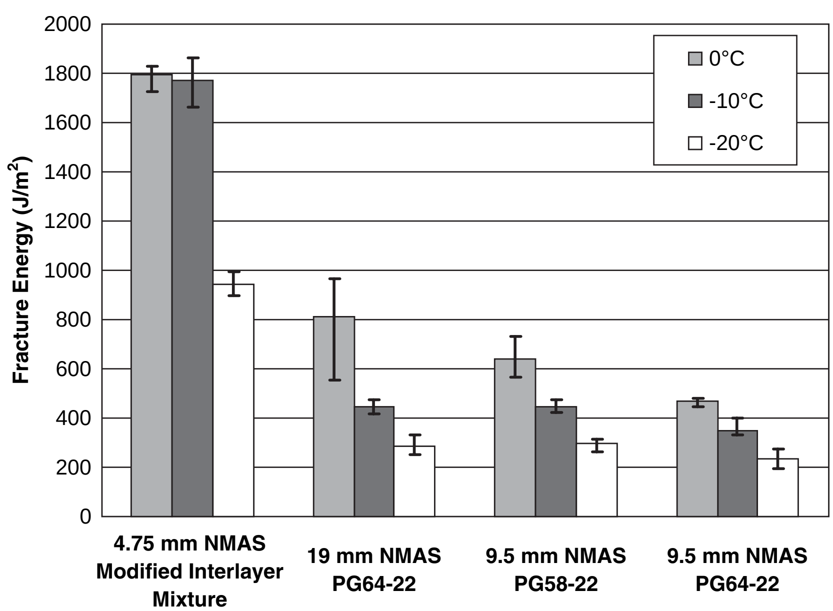


FIGURE 4 Average fracture energy for four mixtures tested at 0°C, −10°C, and −20°C along with maximum and minimum deviation from the average.

around the larger aggregates. That would be more prevalent at the highest temperature tested (0°C) and, thus, the variation of the results would be higher at that temperature.

For the fracture energy obtained from the DC(T) test to provide relevant information, the test should be sensitive to changes in mixture properties, especially the asphalt binder. The fracture energy ranked the mixtures reasonably well, with the AST mixture having the highest fracture energy. The AST mixture has high asphalt content and polymer-modified binder and was expected to provide a better resistance to fracture. When the PIA (PG 58-22) and LR9.5 (PG 64-22) mixtures were compared, the test was able to differentiate between the different binders, with the softer PG 58-22 binder having the higher fracture energy, as was expected from previous studies (*17*).

The fracture energy obtained from the DC(T) test was compared with the fracture energy obtained by Wagoner et al. (*9*) using the SE(B) for the same mixtures. The fracture energy obtained from these different test modes should be different owing to the boundary conditions, crack front constraints, specimen size, and so on, but the two tests should rank the materials consistently (*8, 23*). As shown in Figure 5, the two test configurations ranked the materials in a consistent manner and, in general, the fracture energy obtained from the DC(T) test is higher than the fracture energy obtained from the SE(B) test. Two discrepancies are shown for the correlation between the DC(T) and SE(B). First, the LR19 mixture tested at 0°C shows that the fracture energy obtained from the DC(T) is higher than that obtained from the SE(B). The second instance occurred with the 4.75-mm modified interlayer mixture at −10°C and 0°C. For this mixture, the failure mechanisms were slightly different where large amounts of crack branching occurred, which suggests that the material experienced an area of distributed damage ahead of the crack tip. As explained above, the thickness of the specimen might affect the results of the DC(T) test, whereas the size of the SE(B) specimen is large enough to provide repeatable test results.

The fracture energy was able to differentiate these mixtures, but the tensile strength obtained from the Superpave IDT was essentially the same for the mixtures (see Table 2). The tensile strength considers the bulk material response, which may not be as sensitive to the localized failure of the material. From previous work, the tensile strength obtained from the Superpave IDT and hollow cylinder tensile test can show large discrepancies between the tests (*24*). Part of the reason for the differences in strength can be attributed to the stress concentration at the loading heads of the IDT, causing considerable distortion in the specimen under the loading heads, which influences or even prevents visible tensile failure from occurring in the center of the specimen.

The modulus and strength of HMA concrete vary with loading rate and, therefore, the fracture energy should vary with loading rate (*25*). A single mixture (LR9.5) was initially tested at three temperatures (0°C, –10°C, and –20°C) and four loading rates (10, 5, 1, and 0.1 mm/min), with three replicates at each temperature and loading rate. As shown in Figure 6, the fracture energy increases with decreasing loading rate. For the fastest loading rate at –20°C, the material exhibited a brittle failure without a softening response after peak load. The transition of the material from a softening quasi-brittle material to a brittle material can be related to the glass transition temperature. If the brittle transition is related to the glassy transition, then the same phenomenon should be exhibited at a lower temperature and slower loading rate. Therefore, a fourth temperature, –30°C, was added with only two loading rates, 5 and 1 mm/min. Results from the lower temperature, also shown in Figure 6, exhibited the same brittle transition except at a slower loading rate (5 mm/min). Thus, the brittle transition of HMA concrete depends on both testing temperature and loading rate.

USE OF DC(T) TEST WITH FIELD CORES

This section provides specific examples to demonstrate how the DC(T) test has been incorporated into recent field investigations that sought

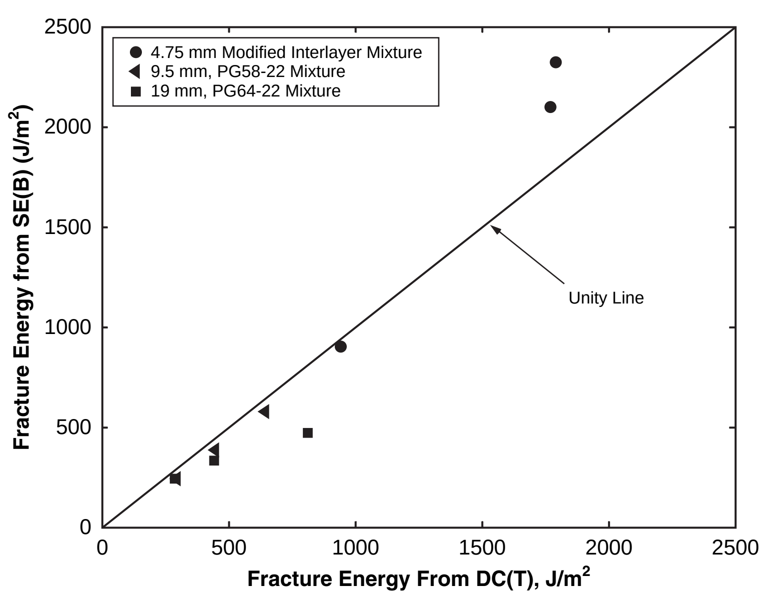


FIGURE 5 Comparison of fracture energy obtained from SE(B) and DC(T) tests at 0°C, −10°C, and −20°C for AST, PIA, and LR19 mixtures.

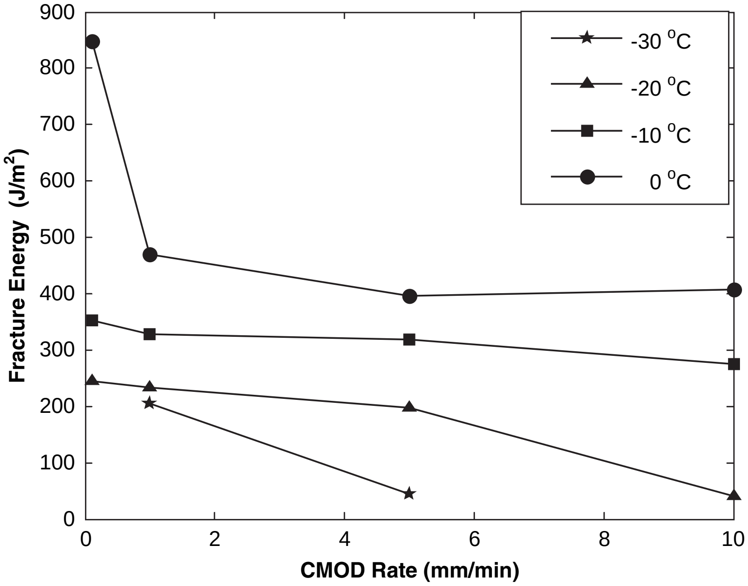


FIGURE 6 Fracture energy as function of loading rate and temperature for LR9.5 mixtures.

fracture properties of asphalt concrete paving layers. The application of the DC(T) test in a recently completed project and planned use of the device in a series of upcoming projects are described in the following sections.

DC(T) Fracture Testing of Rochester, New York, Pavement Section

The DC(T) test was recently used to study overlay mixtures placed on Route 33 in Rochester, New York. After the first winter, the New York State Department of Transportation (New York SDOT) observed premature cracking in an isolated section of an overlay system placed on Route 33. The overlay system consisted of three layers with a 12.5-mm nominal maximum aggregate size (NMAS) surface course, 9.5-mm NMAS truing and leveling course, and a reflective crack relief interlayer. The total overlay thickness was 95 mm. It was hypothesized that a possible explanation of the cracking in the Route 33 overlay system involved the occurrence of extremely cold winter conditions acting on a surface mixture containing reclaimed asphalt pavement (RAP). Because typically RAP contains very stiff, field-aged binder, there is a possibility that the inclusion of RAP in a surface mixture might lead to an excessively brittle mixture. Although some research has been directed toward the study of how RAP affects the low temperature properties of the binder in the RAP mixture, current mix design specifications do not have a direct method for considering the final mixture low-temperature fracture properties in the procedure for selecting the base asphalt grade and design RAP percentage.

Researchers at University of Illinois at Urbana–Champaign (UIUC) have successfully used the DC(T) test on field cores from Route 33 to examine the fracture properties of the surface course and truing and leveling (T&L) overlay materials. The surface course contained PG 58-28 binder with 19% RAP; the truing and leveling course contained the same PG 58-28 binder, but without RAP. The reflective crack relief interlayer was composed of an asphalt-rich (minimum of 7% binder) polymer-modified asphalt binder with a fine aggregate gradation. The T&L course had slightly higher in-place air voids than the surface mixture (11.0% versus 8.4%) and incorporated similar virgin aggregates, but with a different blend and gradation. The 150-mm-diameter field cores were first sawn into test specimens approximately 25 mm thick.

The specimens were first subjected to low-strain creep testing in the Superpave indirect tension test (IDT) to characterize their creep compliance at three test temperatures. The specimens were then further fabricated into DC(T) specimens according to the protocols described earlier in this paper. Results of the DC(T) testing are shown in Figure 7. For all test temperatures (−30°C, −20°C, and −10°C), the interlayer mixture displayed the highest fracture energy of all the mixtures. Figure 7*a* illustrates the load–CMOD curves for the mixtures at −30 C. At the extremely low test temperature of −30°C, the fracture energy of the T&L layer was actually slightly smaller than that of the surface layer. The most likely explanation of that result is that the PG 58-28 binder is below its glass transition temperature at this temperature, and so both mixtures would behave in a brittle fashion, but the presence of higher air voids in the T&L mixture is more discernible in this case. The surface mixture containing RAP showed significantly lower fracture energy than the T&L layer at −20°C and −10°C (see Figures 7*b* and 7*c*, respectively); this suggests that the surface mixture is more susceptible to fracture at these temperatures. The interlayer mixture at −10°C did not show a single fracture, but did show an area of distributed cracking (see Figure 7*d*). Clearly, the valid range of the fracture energy test was exceeded in this instance. Future work should be conducted to establish criteria for determining the range of validity of fracture test results.

One outcome of the research was the recommendation that New York SDOT consider evaluating its design procedures for mixtures including RAP, particularly with respect to the adjustment of base binder grade (e.g., selecting a softer base binder) to compensate for

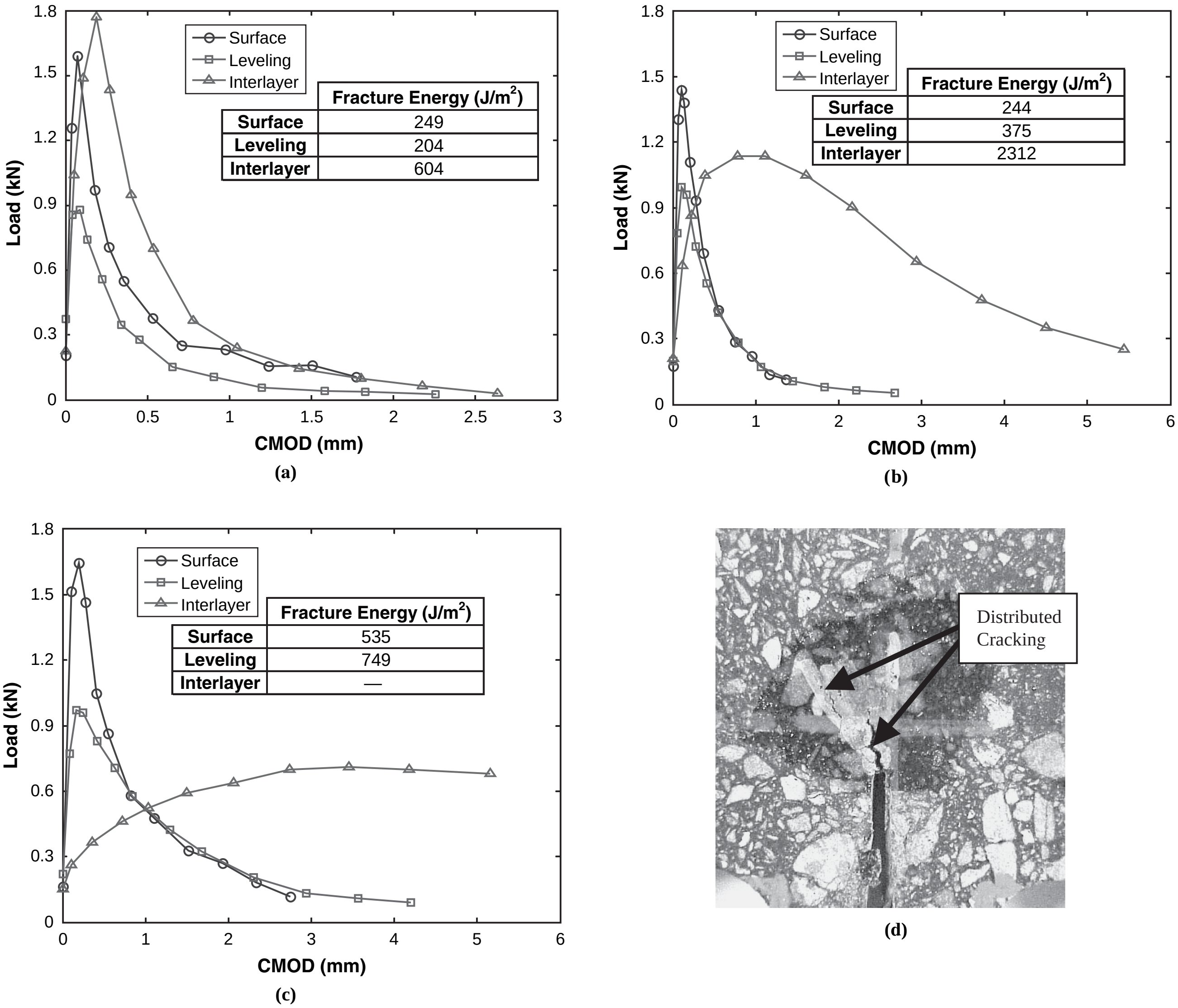


FIGURE 7 Fracture energy of Route 33, New York, overlay mixtures: (*a*) −30°C, (*b*) −20°C, (*c*) −10°C, and (*d*) area of microcracking in front of notch tip for interlayer mixture at −10°C.

the stiffening and embrittlement caused by RAP and the limitation of the maximum amount of RAP allowed in surface mixtures. New York SDOT's current procedures for using RAP follow the recommendations of NCHRP 9-12, Incorporation of Reclaimed Asphalt Pavement in the Superpave System (*26*).

DC(T) Fracture Testing for NSF Reflective Cracking Study

The DC(T) test has recently been included in the experimental design of a National Science Foundation (NSF) study on reflective crack control treatment and design procedures through the program titled Grant Opportunities for Academic Liaison with Industry (GOALI). Researchers from the University of Illinois at Urbana–Champaign and their industry partner Koch Materials Company are seeking to develop a better understanding of the mechanisms of reflective cracking of asphalt overlays. The key to the research approach is the integration of laboratory tests, computer simulation, and analysis of field materials and field performance. The early stages of the research, now complete, focused on the development of new fracture tests for asphalt concrete, such as the SE(B) and DC(T) tests, and the development of finite element–based fracture models, particularly the cohesive zone model, as described earlier. The next stage of the project will involve field calibration and validation of the fracture models. The DC(T) test will be used to obtain fracture properties of in-place field materials in a manner similar to that used on the Rochester Route 33 project. Cylindrical cores will be fabricated for bulk material tests, such as dynamic modulus and creep compliance, and then refabricated into DC(T) specimens. In that way, the same specimen can be used to obtain dynamic modulus, viscoelastic creep, and fracture information, which can be used to model pavement response and distress under field conditions.

Along with the integration described above, the NSF project will allow for further investigation of the experimental procedures of the DC(T) fracture test. One such area is the initial notch. The current procedure assumes that the narrow mechanical notch represents the precracking requirement associated with typical fracture test standards (*18*). The precracking would provide for a sharp crack tip. However, the measurement of the precrack length is not straightforward and would require further analysis. Other areas that will be investigated during the NSF project are extending the fracture properties from laboratory-scale specimens to full-scale pavements. Also, work is under way to develop a procedure to isolate the energy associated with material separation (fracture) from other energy contributions that can enter into the current experimentally determined fracture energy, such as the effects of material elasticity and viscoelasticity on CMOD measurements.

SUMMARY AND CONCLUSIONS

Reflective cracking mechanisms of hot-mix asphalt (HMA) concrete are currently being investigated by integrating laboratory experimentation and numerical analyses with field studies to provide a mechanistic evaluation of the pavement structure. The inclusion of the field investigations would require that the in-place material properties be determined for an accurate representation. An area of concern is obtaining the fracture energy from field cores, because the method up to the present has been using the single-edge notched beam [SE(B)] test. A review of the literature revealed that two potential specimen geometries could be used to obtain the fracture energy from field cores, the semicircular bend and disk-shaped compact tension. Although each geometry had advantages and disadvantages, the disk-shaped compact tension [DC(T)] geometry was selected as the most promising test configuration based on the potential fracture surface being larger than the semicircular bend (SCB) configuration.

The DC(T) test was used to obtain the fracture energy of HMA concrete at different temperatures and loading rates. From the study, the following can be concluded:

- On the basis of limited data, the thickness of the specimen influences the fracture energy obtained from the test. The specimen size effect is well documented for portland cement concrete, but further work needs to be performed on HMA concrete to quantify the size effect not only on fracture energy, but also on other material properties, to ensure that the bench-scale material parameter represents the quantity found in full-scale pavements (*8, 22*).
- For the range of temperatures tested (0°C, −10°C, and −20°C), the fracture energy increases as the temperature increases. The crack path also appears to be affected by the temperature. At the lower temperatures, the crack tended to propagate through both aggregates and mastic. At the higher temperatures, the crack propagated around aggregates, increasing the potential of aggregate interlocking and bridging.
- The coefficient of variation of the test results were within the range of variation found in other fracture tests of HMA concrete.
- The fracture energy appears to be a much better indicator for determining the resistance of the material to fracture than other indirect measures such as tensile strength. The fracture energy approach clearly distinguishes between the materials according to differences in binder properties, whereas the indirect tensile strength was shown to greatly underestimate the tensile strength of highly ductile mixtures.

The specific mixtures investigated were shown to be rate sensitive in the sense that the fracture energy decreases with increases in loading rate (i.e., CMOD rate). As temperature decreases, the mixtures appear to exhibit a distinct transition from quasi-brittle fracture with softening response to brittle fracture with minimal softening after peak. The loading rate associated with this transition to brittle behavior was found to decrease with decreasing temperature.

Finally, the DC(T) test was applied to a field investigation of an asphalt overlay system, which experienced fracture in an isolated area during the first winter of service. The case study illustrated how the DC(T) test could be used to obtain mixture fracture energy as part of an efficient suite of tests performed on cylindrical specimens from field cores. With additional work, similar progress could be made in the area of mechanistic pavement design, to provide a more direct link between material properties and predicted pavement distress, particularly thermal, reflective, and fatigue cracking.

Further investigations are necessary to fully develop and interpret results from the DC(T) test. During the development of the DC(T) test, limited HMA mixtures were used and further work is needed on more mixtures to determine the effects of mixture properties on the fracture energy. Along with the extension to more mixtures, more fundamental aspects of the test should be investigated, including precracking, energy analysis, energy decomposition due to various effects, and size effect.

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