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Fracture Characterization of Gap-Graded Asphalt Mixtures and Thin Bonded Wearing Courses

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Abstract: Thin bonded wearing courses (TBWC) provide an efficient treatment option for deteriorated rigid and flexible pavement systems. As a surfacing layer placed over existing, deteriorated pavement, the overlay system should be designed to resist various forms of cracking, including: thermal, block, reflective, and top-down. Recent developments in fracture testing and numerical simulation techniques have provided stronger links between material fracture properties and field cracking performances of asphalt pavements. However, little work has been directed towards applying these tools to thin bonded wearing courses and overlay systems. This paper describes fracture characterization of TBWC through testing of cored field samples and laboratory prepared specimens. The fracture characterization was performed using the ASTM D7313-07b test protocol, which is currently one of the most widely utilized test specifications for low temperature fracture energy measurement of asphalt concrete. Laboratory samples were prepared to evaluate the effects of the tack-coat application rate, compaction effort (air void level), and overlay thickness on the fracture properties of the gap-graded asphalt concrete mixes and TBWC. The fracture energy results for field cores are compared with laboratory compacted specimens of plant produced hot-mix asphalt mixture, which was sampled during construction. Moreover comparisons of fracture toughness are made between typical dense-graded asphalt mixtures, laboratory compacted gap-graded mixture, and TBWC samples. The results indicate a higher fracture resistance of the gap-graded TBWC when compared to the typical wearing course mixtures. This is a significant finding since the greater air void levels of gap-graded mixtures are typically associated with lower fracture toughness. More work is needed to further explore the fracture behavior in TBWC, especially to study the effects of crack propagation orientation. The fracture characterization results and the testing techniques presented herein provide a laboratory analysis tool for design, control, and characterization of TBWC.

Key words*: Fracture characterization; Fracture test; Gap-graded hot-mix asphalt; Pavement rehabilitation; Sustainable treatment; Thin bonded overlays.*

Introduction

Ultra-thin and thin bonded wearing courses offer an attractive alternative to conventional hot-mix asphalt (HMA) overlay systems, as they are thinner yet more strongly bonded to the underlying pavement as compared to HMA overlays. The division line between the total system thickness of ultra-thin and thin treatments is generally taken as 25*mm*. It can be argued that these TBWC offer a more sustainable approach to pavement preservation, as they utilize an environmentally friendly emulsion tack coat system and since they significantly prolong the time to major rehabilitation or reconstruction, which minimizes the amount of new materials and minimizes the energy required for material removal, the procurement and processing of new material, and material lay down. Use of thin treatments also minimizes the need for raising pavement shoulders and providing thickness transitions at intersections with adjacent pavement, which also results in reduced usage of new materials and associated energy for the construction of those materials. Given these benefits, the obvious question to ask is how these systems perform relative to conventional HMA overlay systems.

Fracture energy measurements from field procured and laboratory prepared samples are presented and analyzed in this paper. The gap graded asphalt mixtures are commonly utilized in TBWC due to their superior fractional characteristics in terms of pavement surface and the reliance of load transfer through larger size aggregates, which is important for overlays with small thicknesses. A typical gradation for a 9.5-mm nominal maximum aggregate sized mixture with dense-graded and gap-graded particle-size distributions are shown in Fig. 1.

The field samples represent a bonded wearing course constructed using a spray paver machine, which is capable of sequentially placing a heavy tack coat followed immediately by a lift of asphalt concrete mixture. This results in increased binder content near the bottom of the wearing course with a gradual gradient in material properties through the thickness of the wearing course. Laboratory prepared samples were used to represent the wearing course material without the tack coat to provide reference properties for the evaluation of the in-situ system, which is expected to have superior crack resistance due to the presence of the heavy tack coat and its permeation (upward wicking) into the bonded wearing course lift. The results shown in this paper verify and quantify this increase in fracture resistance resulting from the use of polymer modified tack coat at a high application rate on various projects.

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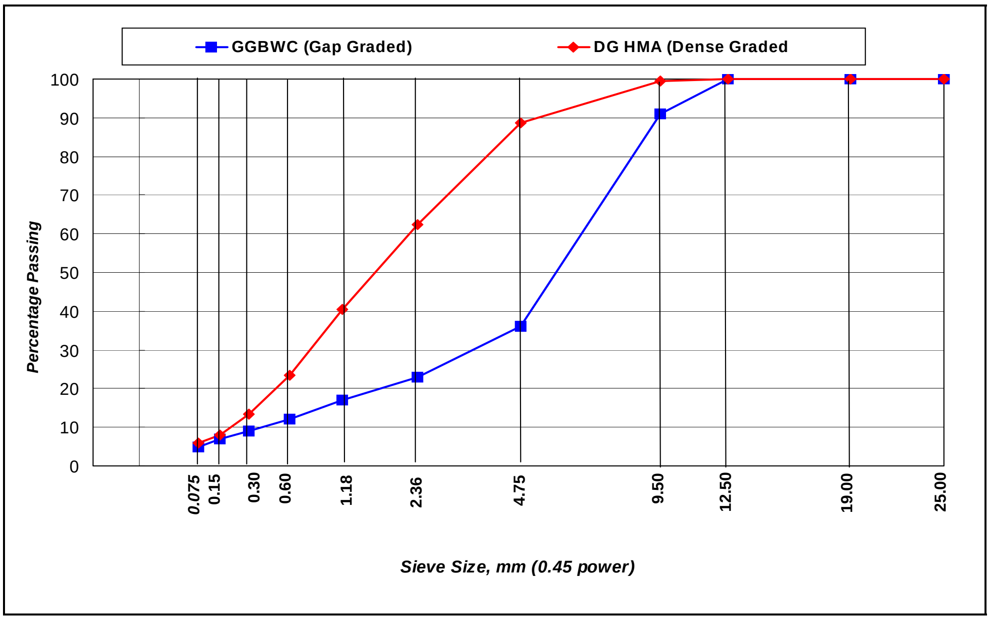


Fig. 1. Aggregate Gradations for Gap-Graded and Dense-Graded Mixtures.

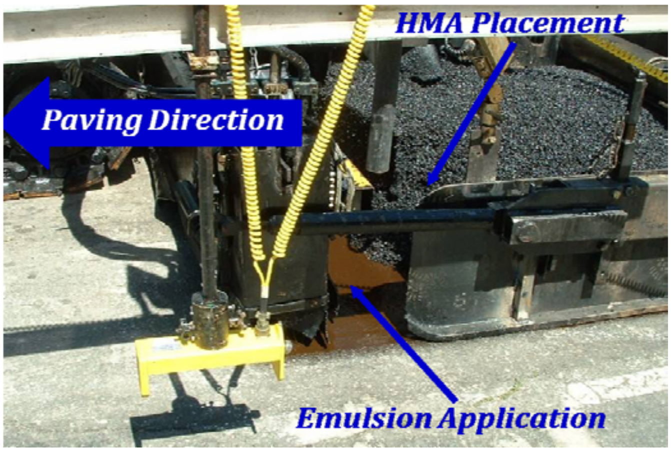


Fig. 2. Simultaneous Application of Emulsion and Placement of HMA.

Fig. 3. Construction Train (left to right: Dump Truck Delivering Hot-Mix Asphalt, Material Transfer Device, and Spray Paver).

Fig. 4. Finished Wearing Course.

Construction and Project Information

Thin bonded overlay systems are constructed through a spray paver in a single pass paving process as presented in Fig. 2. The paving equipment employed and finished pavement surface are shown in Figs. 3 and 4. The conventional HMA paving process entails application of a tack coat emulsion through a distributor, followed by HMA paving and its subsequent compaction. This arrangement often results in loss of tack coat emulsion by the passage of construction equipment such as dump trucks, material transfer devices, and the paver itself on the primed surface. On the other hand, the spray paver places HMA just inches following the tack coat emulsion via a spray bar mounted behind the paver wheels. Simultaneous application of tack coat emulsion and HMA precludes the loss of tack emulsion through tracking and makes it available for better interface bonding. Placement of HMA on uncured/wet emulsion facilitates the process of emulsion curing. The quick curing caused due to heat from the HMA facilitates the upward migration of asphalt cement from the tack coat into the wearing course. Upward permeation of emulsion results in richer binder contents in approximately the lower third of the wearing course. The rate of upward wicking process depends upon the HMA mixture properties, existing pavement condition, and the type and application rate of the tack coat emulsion.

Fracture properties of gap-graded thin bonded asphalt concrete wearing courses paved on three projects were evaluated in the present study; these projects are identified herein as Projects 1, 2, and 3, respectively. All three projects were constructed using a spray paver and involved the placement of 9.5-mm nominal maximum aggregate sized gap-graded asphalt concrete mixes. All projects utilized a polymer modified asphalt emulsion (PMAE) tack coat. Projects 1 and 2 were constructed on an existing flexible pavement with Superpave PG 70-28 binder used in the TBWC. The TBWC in both cases was paved to be 19*mm* thick and a tack coat application rate of 0.2gal/yd^2 was utilized. The thickness of the bonded overlay on Project 3 was 55*mm* and was constructed with a PMAE tack coat applied at a rate of 0.4gal/yd^2. The HMA mixture on Project 3 was manufactured with PG 64-22 binder. The asphalt cement content on all three projects was 5.2%.

Field samples from each project were procured immediately following construction. The field samples were obtained through a coring operation, which yielded 150*mm* diameter cylindrical specimens. Moreover, asphalt concrete mixes from each project were also sampled during the paving process. Laboratory specimens were prepared from mix samples using the Superpave Gyratory Compactor (SGC) [1]. In order to study the effect of air void level, the laboratory specimens were prepared at two compaction levels.

Fracture resistance of the field and laboratory compacted specimens was determined using the disk-shaped compact tension (DC(T)) test. A brief description of the testing procedure is described in the following section.

Laboratory Fracture Characterization

A significant amount of research has been conducted in recent years in the field of cracking in asphalt concrete pavements [2-4]. Researchers have shown that asphalt concrete exhibits a quasi-brittle failure mode at intermediate and low temperatures [5, 6]. The quasi-brittle material failure is typically characterized by the growth of a damage region ahead of the macro-crack (visible crack). This region is typically called the fracture-process zone and it consists of micro-cracks and excessive material deformations prior to complete material separation. Depending on the material and the failure conditions, there is a length scale associated with the formation of this zone.

The fracture energy of a material is defined as the energy required for creating a new unit surface area in the material through the process of cracking. New test procedures have been developed in recent years for the fracture energy measurement of asphaltic materials [7-9]. The DC(T) test, proposed by Wagoner et al. [9], is being widely utilized for fracture energy measurements. It is currently the only ASTM recommended test protocol for the fracture energy measurement of asphalt concrete. The fracture energy measurements have been shown to be critical in development of integrated testing and analysis procedures using sophisticated fracture

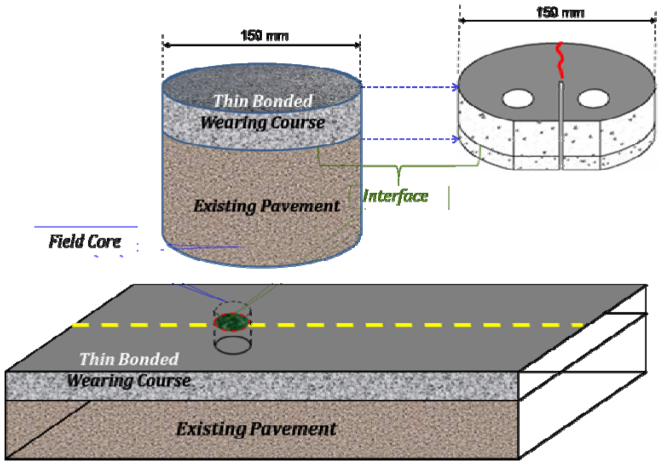


Fig. 5. DC(T) Specimen Configuration and Orientation within a Core.

simulation models [10]. These types of integrated systems have been deployed for the design and analysis of thermal and reflective cracking in asphalt pavements and overlays [11, 12]. It has been shown that the fracture energy from the DC(T) test is a better parameter for inferring crack-resistance of asphaltic pavement materials when compared with traditional parameters such as indirect tensile strength [13].

The DC(T) test can be readily used for the testing of pavement cores as well as cylindrical laboratory prepared samples, such as those obtained from the Superpave gyratory compactor. In the current study, both types of specimens were tested in the DC(T) geometry. As described in the introductory portion of this paper, one of the key benefits of thin bonded wearing courses is the presence of a heavy tack coat made possible by the use of a spray paver system. Details regarding sample preparation and test procedures are described in the next two subsections.

Specimen Fabrication

DC(T) specimens were prepared and tested in accordance with ASTM D7313-07b [14]. The testing of cored samples in the DC(T) test configuration simulates the formation of a crack that translates across the width of the wearing course. This type of crack formation in pavements is commonly referred to as a channeling crack and it is usually formed as a result of low-temperature thermal events. The term channeling crack is used to describe the type of pavement crack that is physically represented in the test, that is, a crack that is channeling across the pavement width or along a pavement in a horizontal plane as illustrated in Fig. 5.

In case of field samples, the thickness of the DC(T) specimens was limited to the actual thickness of the TBWC. Cores were sliced just below the new interface in order to prevent damage to the interface. Specimen fabrication was accomplished using a wet masonry saw. SGC samples were compacted at two air void levels: 12% to match the as-constructed density of the TBWC and 7 to study the effect of air void level on fracture characteristics. Laboratory compacted samples were sliced to manufacture DC(T) specimens with two thicknesses: one group having standard DC(T) specimen thicknesses of 50*mm* and a second group to mimic the actual thickness of the TBWC. The variation of DC(T) specimen thicknesses along with air void levels were incorporated in this study to evaluate their significance on the fracture resistance of gap-graded asphalt mixtures and TBWCs.

It is important to note that, in the current study, tack coat was not added to the mixture during the preparation of the laboratory compacted samples. Thus, effectively three sets of variables were studied: (a) the effect of tack coat on fracture behavior of TBWC, (b) the effect of density or air void level on the fracture resistance of gap-graded asphalt mixtures, and (c) the effect of specimen thickness on the fracture properties of TBWC and gap-graded mixtures. After the specimens were sliced, the two loading holes were cored, the edge was flattened, and finally the notch was created using a tile-saw, all in accordance with ASTM D7313-07b.

Test Procedure and Analysis

Fabricated specimens were conditioned at -12°C for two hours in an environmentally controlled chamber before testing. The test temperature of -12°C was selected on basis of the required Superpave low temperature performance grade for the region where projects are located. The test temperature was selected to match the test temperature for the bending beam rheometer (BBR) test, which is 10°C warmer than the performance grade (PG) low temperature. Furthermore, the use of single temperature for all tests ensures that fracture energy comparisons are made on an equivalent basis.

DC(T) testing was performed with a constant crack mouth opening displacement (CMOD) rate of 0.017*mm/s*. Test set-up and DC(T) specimen from cores are shown in Fig. 6. Typical load verses CMOD data as obtained from the DC(T) test for the different mixes is plotted in Fig. 7. The work of fracture (S_f) was evaluated by integrating the imposed load (P) and the corresponding crack mouth displacement (u). The fracture energy (G_f) can be determined as the amount of fracture work required to generate a unit cracked surface area. This could be expressed in terms of following relationships:

$$S_f = \int P \cdot du\,; \qquad G_f = \frac{S_f}{W \cdot L}.$$

where, the length of the fracture face is L (ligament length) and the specimen thickness is W.

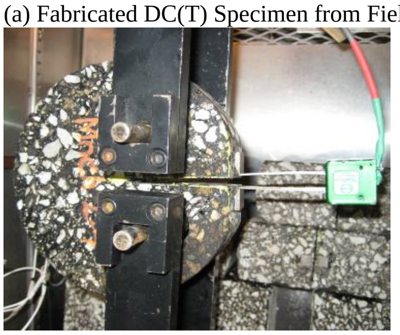
Results and Discussions

Project 1

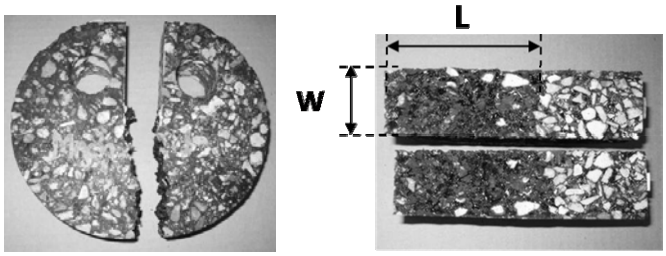
The fracture energy results for the field core and laboratory samples for Project 1 are shown in Fig. 8. The fracture energies for the field specimens ranged from 532 to 651J/m^2 for three replicates, with a coefficient of variation (CoV) of 11%. The same mixture was compacted in the laboratory without incorporating the tack coat. The volumetric properties of the laboratory compacted specimens were matched to those of the field samples. An average air void level of 12% was obtained in all the test specimens. The average fracture energy of laboratory compacted specimens as determined through the DC(T) test was 369J/m^2 compared to 583J/m^2 for field specimens. This result clearly shows the benefit of the tack coat on the fracture resistance of the TBWC, as the field cores demonstrated a 58% greater fracture energy compared to the lab compacted specimens. The primary difference between lab and field specimens is the presence of tack coat in TBWC and its upward migration into the lift.

Fig. 9 illustrates the effects of specimen thickness and air void level on fracture resistance of the gap-graded mixtures utilized in

(a) Fabricated DC(T) Specimen from Field Core



(b) DC(T) Test Set-up



(c) Specimen on Completion of DC(T) Test

Fig. 6. Specimen Preparation, Test Setup, and Fractured Specimen from DC(T) Test.

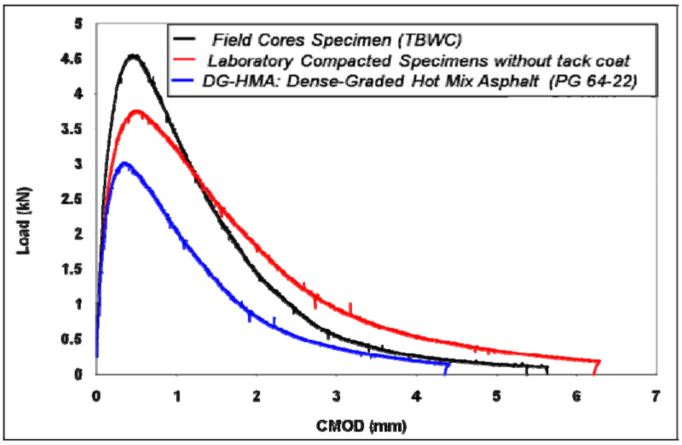


Fig. 7. Typical Load Crack Mouth Opening Displacement (CMOD) Plot.

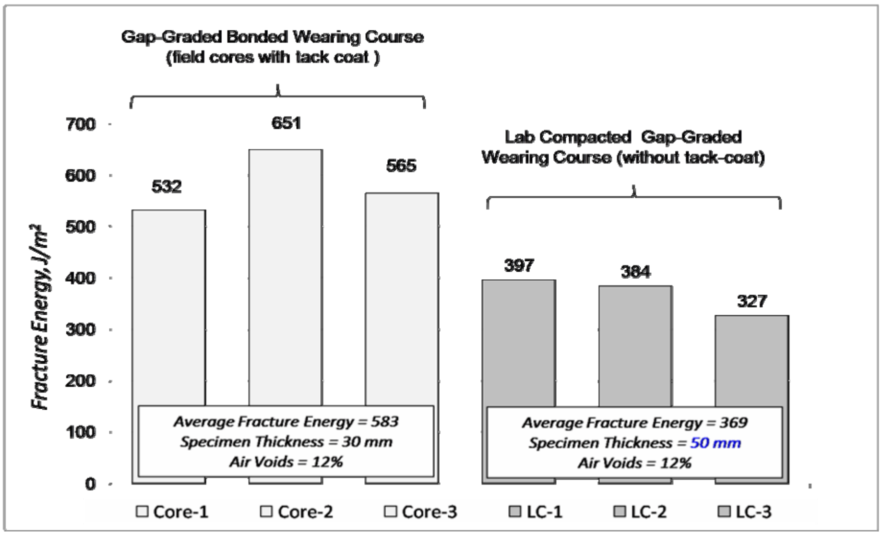


Fig. 8. Project 1 DC(T) Test Results of Field Cores and Laboratory Compacted Specimens.

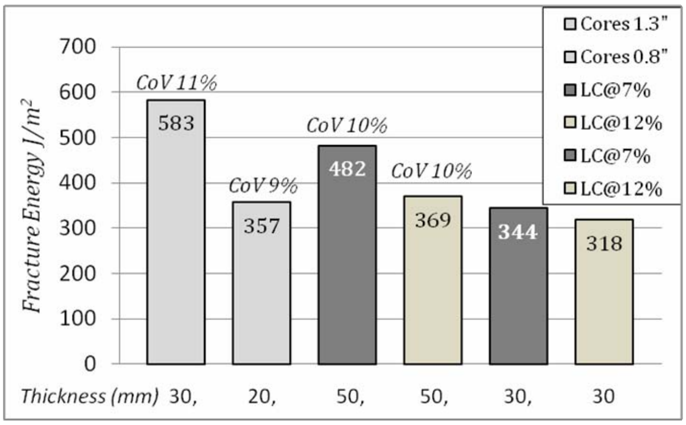


Fig. 9. Effect of DC(T) Specimen Thickness and Air Void on Fracture Energy.

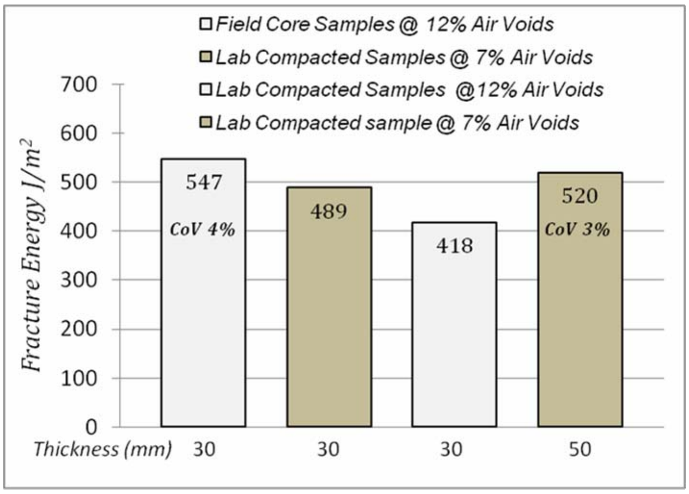


Fig. 10. Project 2 DC(T) Test Results of Field Cores and Laboratory Compacted Specimens.

TBWC. Field cores procured from two locations on this project had thickness variation of 10*mm*. Fracture energy of TBWC samples with 30*mm* thickness resulted in 583J/m^2 compared with 357J/m^2 for the 20-mm thick field specimens. Although the thickness variation of the bonded overlay systems at the two locations was 50%, the resulting variation in the fracture energy was 63%. Comparison of field cores with laboratory compacted specimens of same thickness (30*mm*) and air voids (12%) resulted in 83% greater fracture energy. Once again, the main difference between field and laboratory specimens is the spray paver construction technique in the case of TBWC and the use of tack coat. Similar to previously discussed results, the TBWC specimens showed significantly greater fracture toughness when compared with the laboratory compacted (LC) gap-graded mixture specimens of similar thickness and density. Fracture energy measured from laboratory compacted specimens with 50*mm* thickness was 369J/m^2 compared to 344J/m^2 for 30*mm* thickness. Wagoner et al. [13] reported a similar trend of decreasing DC(T) fracture energy with reduced specimen thicknesses for dense-graded HMA. Results presented in Fig. 9 shows that thicker (50*mm*) laboratory compacted gap-graded mixture specimens at lower air voids (7%) have 58% lower fracture energy when compared with 30*mm* thick field specimens with 12% air voids.

Project 2

Fracture energy results from this project were used to compare field cores with laboratory compacted specimens for two thicknesses and two air void levels. The first set of LC specimens was prepared with similar thickness and volumetric properties as the TBWC. Results presented in Fig. 10 shows that fracture energy of field core specimens (TBWC) are 30% higher than LC specimens with same thickness and similar air voids. LC specimens with same thickness but 5% lower air voids (12 vs. 7%) resulted in 12% decrease in fracture energy (547 vs. 489J/m^2) as compared with TBWC.

Fracture energy of 50*mm* thick LC specimens at 7% air voids was 520J/m^2 compared to 547J/m^2 for 30*mm* thick field specimens at 12% air voids, which are not significantly different. These results further reinforce that the specimen thickness and compaction effort are significant factors affecting fracture properties of gap graded mixes that are typically used for construction of TBWC.

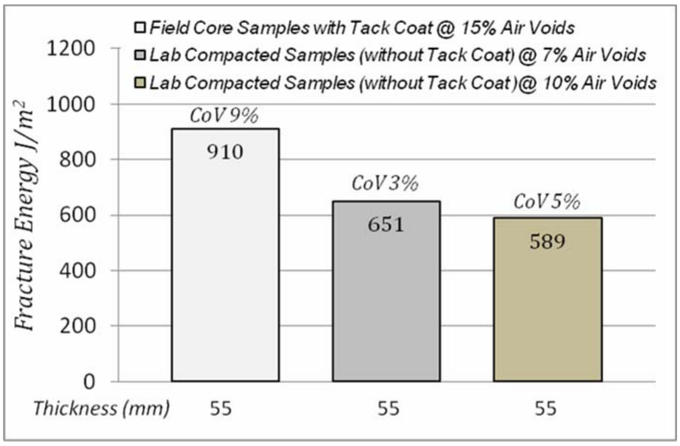


Fig. 11. Project-3 DC(T) Test Results of Field Cores and Laboratory Compacted Specimen.

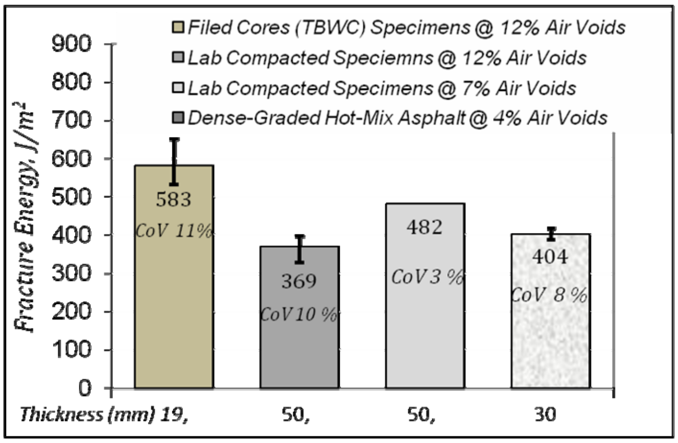


Fig. 12. Comparison of Fracture Energies of Different HMA Mixes.

Project 3

Project 3 was paved with a 55*mm* thick gap-graded asphalt concrete mixture with PG 64-22 binder, which was placed on an existing concrete pavement. PMAE tack coat was applied at an effective rate of 0.4gal/yd^2 using the spray paver. Fracture test results presented in Fig. 11 indicates that the field core DC(T) specimens at 15% air voids have 40 and 55% higher fracture energy when compared to the laboratory compacted specimens at 7 and 10% air voids. Although the TBWC was compacted with at least 50% higher air voids compared to the LC specimens, 55% greater fracture energy is observed in the case of TBWC. This improvement in fracture resistance is thought to have resulted from the heavy application of polymer modified tack coat and its migration into the TBWC from the spray paver construction technique.

Comparison of Gap-Graded Thin Bonded Wearing Course Fracture Properties with Traditional Hot-Mix Asphalt Material

As discussed earlier, the fracture energy of asphalt concrete provides a good indication of its cracking resistance. In order to make comparison with typical dense-graded hot mix asphalt (DG-HMA), the fracture energy results from a 9.5-mm nominal maximum aggregate sized (NMAS) dense-graded mix were selected for comparison purposes. The dense-graded HMA was designed and manufactured as per the Superpave mix design criteria with 4% air voids. The gap-graded mixture was designed with PG 70-28 having 5.2% binder content at two air void levels (7 and 12%), and the dense-graded mix was designed with 7% binder content and contained PG 64-22.

The averaged DC(T) fracture energy measurements from three test replicates for each of the mixes have been plotted in Fig. 12. The LC gap-graded mix at 7% air voids has 19% higher fracture energy than a conventional PG 64-22 mix (DG-HMA). The LC gap-graded mix at 12% air void resulted in 10% lower fracture energy as compared to gap-graded mix. The results indicate that the gap-graded mixture at 3% higher air voids (7 vs. 4%) has higher fracture resistance compared to a similar dense-graded mixture and that the TBWC, which would also derive additional fracture resistance from upward migration of the polymer modified tack coat, would be expected to have further improvement in the fracture resistance when compared to dense-graded mixtures. The statistical analysis of the test data was conducted using the paired t-test. The statistical analysis showed that fracture energy of field-cored TBWC specimens is significantly greater than laboratory compacted gap-graded mixes and DG-HMA. The difference between the fracture energies for gap-graded mixture was found to be insignificant when compared with the DG-HMA. The range of air voids evaluated within the gap-graded mixture resulted in significant variation in their fracture properties.

Conclusions and Recommendations

The fracture characterization presented in this study indicates that the presence of tack coat, the amount of air voids, and specimen thickness significantly affects fracture properties of gap graded mixtures and thin-bonded wearing courses. The results also indicate that the use of a spray paver system to apply a high rate of polymer modified tack coat and construct TBWC enhances the fracture resistance of the overlay system.

This is an important finding, as due to their high air void content, it is often presumed that gap graded mixtures have lower fracture energies. For similar air void levels and thicknesses, up to 83% improvement in fracture energy was observed. This encompasses the samples procured from field and compacted in the laboratory. The main difference between field and laboratory compacted samples was presence and lack of tack coat and the use of spray paver technology. Enhancement in the fracture properties are hypothesized to be caused by upward migration of the modified binder from tack coat into the wearing course. Thus, the use of polymer modified tack coat at a higher application rate not only ensures good bonding, but also improves the fracture resistance of the newly constructed layer. Although preliminary, this work suggests that thin bonded wearing courses may provide a more sustainable approach to pavement preservation as compared to treatment with conventional thin overlay systems.

Permeation of the tack emulsion through the thickness of bonded wearing course makes it graded in nature. Thus, there is need to study the effect of crack propagation orientation for such bonded overlay systems. Furthermore, in order to quantify the extent and amount of binder translation from tack coat in the bonded wearing courses, future extensions of the present work are recommended. The improvement of interface bond characteristics due to the presence of a high amount of tack coat in conjunction with the benefits afforded by the spray paver construction technique also needs to be evaluated.

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References

1. ASTM, (2007). Preparation and Determination of the Relative Density of Hot Mix Asphalt (HMA) Specimens by Means of Superpave Gyratory Compactor, ASTM D 6925, ASTM, Philadelphia, PA, USA.
2. Wagoner, M.P., (2006). Fracture Tests for Bituminous-Aggregate Mixtures: Laboratory and Field Investigation, *PhD Dissertation*, University of Illinois, USA.
3. Wagoner, M.P., Buttlar, W.G., Paulino, G.H., and Blankenship, P.B., (2006). Laboratory Testing Suite for Characterization of Asphalt Concrete Mixtures Obtained from Field Cores, *Association of Asphalt Paving Technologists - Proceedings of the Technical Sessions 2006 Annual Meeting, Association of Asphalt Paving Technologist*, Vol. 75, pp. 815-852.
4. Al-Qadi, I., Scarpas, A., and Loizos, I. (eds.), (2008). *Pavement Cracking: Mechanisms, Modeling, Detection, Testing, and Case Histories*, CRC Press, London, UK.
5. de Souza, F.V., Soares, J.B., Allen, D.H., and Evangelista, Jr.. F., (2004). Model for Predicting Damage Evolution in Heterogeneous Viscoelastic Asphaltic Mixtures, *Transportation Research Record*, No. 1891, pp. 131-139.
6. Song, S.H., Paulino, G.H., and Buttlar, W.G., (2006). A Bilinear Cohesive Zone Model Tailored for Fracture of Asphalt Concrete Considering Rate Effects in Bulk Materials, *Engineering Fracture Mechanics*, 73(18), pp. 2829-2848.
7. Wagoner, M.P., Buttlar, W.G., and Paulino, G.H., (2005a). Development of a Single-Edge Notched Beam Test for Asphalt Concrete Mixtures, *Journal of Testing and Evaluation*, 33(6), pp. 452-460.
8. Wagoner, M.P., Buttlar, W.G., and Paulino, G.H., (2005b). Disk-Shaped Compact Tension Test for Asphalt Concrete Fracture, *Experimental Mechanics*, 45(3), pp. 270-277.
9. Li, X., Marasteanu, M.O., Iverson, N., and Labuz, J.F., (2006). Observation of Crack Propagation in Asphalt Mixtures with Acoustic Emission, *Transportation Research Record*, No.1970, pp. 171-177.
10. Dave, E.V., Song, S.H., Buttlar, W.G., and Paulino, G.H., (2007). Reflective and Thermal Cracking Modeling of Asphalt Concrete Overlays, In I. Al-Qadi, A. Scarpas, and A. Loizos (eds.). *Advance Characterization of Pavement and Soil Engineering Materials*, CRC Press, London, UK.
11. Dave, E.V., Braham, A.F., Buttlar, W.G., Paulino, G.H., and Zofka, A., (2008). Integration of Laboratory Testing, Field Performance Data, and Numerical Simulations for the Study of Low-Temperature Cracking, In I. Al-Qadi, A. Scarpas, and A. Loizos (eds.). *Pavement Cracking: Mechanisms, Modeling, Detection, Testing, and Case Histories*, CRC Press, London, UK.
12. Dave, E.V., Wagoner, M.P., Buttlar, W.G., Todd, L., and Bausano, J., (2008). Integrated Testing and Modeling Approach to Develop Accelerated Testing Sections for Asphalt Overlay-Interlayer Systems over PCC, In E. Beuving (ed.). *Proceedings of Eurasphalt & Eurobitume Congress*, Copenhagen.
13. Wagoner, M.P. and Buttlar, W.G., (2007). Influence of Specimen Size on Fracture Energy of Asphalt Concrete, *Association of Asphalt Paving Technologists-Proceedings of the Technical Sessions 2007 Annual Meeting, Association of Asphalt Paving Technologist*, Vol. 76, pp. 391-426.
14. ASTM, (2007).Standard Test Method for Determining Fracture Energy of Asphalt Concrete-Aggregate Mixtures using the Disk-Shaped Compact Tension Geometry, ASTM 7313-07(b), ASTM, Philadelphia, PA, USA.