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FRACTURE ENERGY DENSITY OF INTERSTITIAL COMPONENT OF ASPHALT MIXTURES

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ABSTRACT.

Interstitial component (IC), referring to the finer portion of asphalt mixture, is primarily responsible for tensile properties and thereby strongly affects mixture cracking performance. Whereas mixture tests are usually complex and labor-intensive, determination of fracture properties with a simpler test on the IC portion will add values in terms of ranking mixtures and predicting mixture fracture properties. An interstitial component direct tension (ICDT) test, which was derived from the dog bone direct tension test originally developed for asphalt mixtures, was applied to determine the fracture energy density (FED) of mixture IC portion. FED describes the damage tolerance before fracture occurs and it is also a component associated with crack propagation. Two methods of strain determination were evaluated including a digital image correlation (DIC) system and a predictive equation derived from finite element analysis with load-head displacement as input. ICDT tests were conducted on the IC portion of two sets of four mixtures, which had identical coarse aggregate structure. The DIC system yielded greater failure strain than those based on load-head displacement. However, the ratios between the two values for all mixtures were almost constant, supporting the use of the predictive equation as a surrogate. Moreover, IC FED ranked these mixtures in the same order as mixture FED and more importantly, an excellent correlation was observed between IC FED and mixture FED of these mixtures. In conclusion, the ICDT test can be used to determine the IC FED, which provides valuable insights regarding the effect of IC characteristics on mixture FED.

Keywords: interstitial component; fracture energy density; digital image correlation; finite element analysis; damage tolerance; failure strain

1 1. INTRODUCTION

2 1.1 Background

3 Load-induced fatigue cracking at intermediate temperatures is a major asphalt pavement distress
4 mode. Cracks typically originate and propagate through binder film not aggregate grains and thus,
5 fatigue resistance of asphalt binder significantly impacts fatigue performance of asphalt mixtures
6 (1). The parameter $G^*\sin(\delta)$ in the current Superpave specification has been used to describe
7 the binder's contribution to mixture fatigue damage resistance. However, the effectiveness of this
8 parameter is questionable primarily because its testing procedure does not introduce sufficient
9 damage into the specimen (2). Several advanced binder cracking tests have been developed during
10 the last decade, including the linear amplitude sweep (LAS) test, the double edge notched tension
11 (DENT) test and the binder fracture energy (BFE) test. The LAS test consists of cyclic loading
12 with loading amplitudes that are systematically increased to accelerate damage. LAS testing
13 procedure includes a frequency sweep to obtain an undamaged material response and an amplitude
14 sweep to evaluate damage evolution (3-4). The DENT test is essentially a ductility test but with
15 two notches of controlled depth placed in the center of the specimen (5). This test can be performed
16 to obtain the essential work of fracture as a measure of the fatigue and crack resistance behavior
17 of asphalt binders. The BFE test is a direct tension test with an optimized specimen geometry that
18 ensures accurate measurement of stress and strain on the fracture surface, which in turn ensures
19 accurate fracture energy density (FED) calculation (6-7). Each of the three tests now has an
20 AASHTO provisional standard to characterize the fatigue damage tolerance, resistance to ductile
21 failure, and fracture tolerance of asphalt binders (8-10), respectively. Studies have also shown that
22 binder relaxation properties, captured by the R-value from relaxation spectra, correlate with
23 cracking performance of asphalt mixtures (11-13). Rheological parameters such as the Viscous to
24 Elastic Transition (VET) temperature and the complex modulus at the VET temperature (G^*_{VET})
25 have also been successfully employed to characterize changes in properties of asphalt binder at
26 different levels of age hardening and/or distress level (cracked or uncracked sites) (14-15).

27 Mixture cracking performance is also governed by factors that binder tests alone cannot account
28 for, such as binder content and aggregate structure. Testing mixtures directly currently appears to
29 be the only way to assess the effect of these factors on mixture cracking performance. Several
30 mixture cracking tests are now available, including the Texas Overlay test (16-17), the semi-
31 circular bending test (18), the Superpave indirect tension test (19-20), the bending beam fatigue
32 test (21-22), the simplified viscoelastic continuum damage fatigue test (23-24), the disk-shaped
33 compact tension test (25), the dog-done direct tension (DBDT) test (26), and the direct tension test
34 (27-28). In the U.S., many of these tests have been evaluated in the NCHRP 9-57 project, but there
35 was no consensus on the selection of an ideal cracking test for routine use (29). Outside of the
36 U.S., the RILEM committees TC 101 and TC 152 performed the first interlaboratory tests on
37 mixture fatigue and identified the needs for understanding and modeling the complex phenomena
38 appearing during fatigue of bituminous mixtures (30). In response, the RILEM committee TC 182
39 conducted a follow-up interlaboratory campaign that evaluated eleven mixture tests (five general
40 fatigue test specimen geometries) and different models using damage theory (31). Results
41 indicated that the classical fatigue analysis had great limitation, but the damage approach appeared
42 to be a rational option to characterize mixture fatigue (31-32). The European Union now has
43 standardized the bending test on prismatic shaped specimens to evaluate the crack initiation of
44 asphalt mixtures (33) and the semi-circular bending test to evaluate the crack propagation (34).

1 1.2 Research motivation

2 Literature indicates that binder tests alone cannot provide a complete assessment of mixture
3 cracking performance, and although promising, these commonly used mixture tests are also known
4 to be complex and labor-intensive. Therefore, there is a need for a simpler test that can be used to
5 obtain properties relevant to mixture cracking performance. It is well-documented that
6 performance of an asphalt mixture is closely related to its aggregate structure (35-36). Mixture
7 aggregate structure can be expressed by separating the gradation into two major components:
8 dominant aggregate size range (DASR) and interstitial component (IC) (37-38). DASR defines the
9 size range of interactive coarse aggregate that forms the primary structural network of aggregate
10 and provides mixture resistance to shear. IC is made up of fine aggregates, binder and air voids
11 within the interstitial volume that bonds the coarse aggregate structure together, resisting primarily
12 tension and, to a lesser extent, shear (38).

13 IC is primarily responsible for the mixture tensile properties and thereby strongly affects mixture
14 cracking performance. IC coarseness affects the distribution of asphalt binder and the air void
15 structure within the interstitial volume (39-40). Generally, finer IC gradations result in aggregates
16 in closer proximity to each other, and hence, more thinly distributed asphalt binder, and smaller,
17 less interconnected air voids, which lead to stiffer and more brittle mixtures. Conversely, coarser
18 IC gradations result in more sparsely distributed aggregates, thus, more coarsely distributed asphalt
19 binder, and larger, more interconnected air voids, which lead to less stiff and less brittle mixtures
20 (39-40). Therefore, it would be of great benefit to identify or develop a test that requires small
21 quantity of materials and short period of time for testing and data analysis to determine the fracture
22 energy density (FED) of the mixture IC portion, which is a component that logically appears to be
23 strongly related to the mixture FED. This would add value in terms of optimizing mixture design,
24 ranking mixture performance and eventually predicting mixture fracture properties and
25 performance without the need of testing mixtures.

26 **2. OBJECTIVES**

27 The main objective of this study was to determine the fracture energy density (FED) of the
28 interstitial component of asphalt mixtures at intermediate temperature (10°C). Detailed objectives
29 were as follows:

- 30 • Present the interstitial component direct tension (ICDT) test derived from the DBDT test,
31 including the specimen geometry, specimen composition, compaction method, testing
32 protocols and data interpretation procedure.
- 33 • Evaluate two methods of strain determination, i.e., a digital image correlation (DIC) system
34 and a predictive equation of strain derived from finite element analysis (FEA), to obtain
35 local strain for determination of IC FED.
- 36 • Determine the relevance and accuracy of the FED obtained from the ICDT tests by
37 comparing the IC FED to the corresponding mixture FED.

1 **3. SCOPE**

2 This study adopted eight mixtures whose mixture design and mixture FED results were available
3 from a previous study (39). Experimental factors included two aggregate types (Georgia granite
4 and Florida oolitic limestone), one asphalt binder (PG 67-22 unmodified binder), one DASR and
5 four IC gradations for each aggregate type. ICDT tests were conducted on the IC portion of these
6 eight mixtures to obtain the corresponding IC fracture properties, specifically IC FED. The
7 emphasis was to determine whether the effect of IC coarseness on mixture FED can be captured
8 by performing the ICDT tests. Note that FED describes the damage tolerance before fracture
9 occurs and therefore, it should only be regarded as a fracture limit and not as a complete
10 characterization of cracking performance, which involves both crack initiation and propagation.

11 **3.1 Mixture Gradation**

12 Two mixtures commonly used in Florida, one with Georgia granite and one with Florida oolitic
13 limestone, were selected as base mixtures. Identification of DASR range for both mixtures was
14 conducted by means of particle interaction analysis, which requires the relative proportion of
15 particles from two contiguous sieve sizes to be within 70/30 to form an interactive network (34).
16 The granite mixture had a DASR range of 9.5 to 1.18 mm whereas the DASR of limestone mixture
17 was broader (from 12.5 to 1.18 mm) (Supplement Figure 1). Consequently, both mixtures had the
18 same IC range, which includes aggregates passing the 1.18 mm sieve.

19 To isolate the IC and its effects on mixture properties and performance, the coarse
20 aggregate structure of the two base mixtures was kept constant and only their IC gradations were
21 changed. This resulted in a total of eight mixtures. IC coarseness for both granite and limestone
22 mixtures increased from IC 1 to IC 4 with IC 3 being the reference mixture (Supplement Figures
23 2 and 3). All mixtures were fine dense-graded and were designed following the Superpave system
24 with 12.5 mm NMAAS gradations and traffic level C, which corresponds to 3-10 million Equivalent
25 Single Axle Loads over 20 years.

26 **3.2 Mixture Parameters**

27 Table 1 lists the volumetric information of the eight mixture designs. Mixtures with coarser IC
28 required more asphalt content, resulting in higher voids in mineral aggregate (VMA) and voids
29 filled with asphalt (VFA) values. Table 1 also summarized the mixture FED of the eight mixtures
30 after short-term oven aging (STOA), which were determined by performing the Superpave indirect
31 tensile (IDT) strength test. Fracture energy density (FED), which is defined as the energy per unit
32 volume required to initiate fracture, is one of the most important failure limits of asphalt mixtures
33 (20-21). Mixtures with a coarser IC gradation yielded greater FED, which indicates greater damage
34 tolerance before fracture occurs. A potential explanation for this trend is that coarser IC gradation
35 resulted in more coarsely distributed asphalt binder, and larger, more interconnected air voids,
36 which lead to less stiff and less brittle mixtures with higher FED (39-40).

1 Table 1. Volumetric parameters for granite and limestone mixtures

Mixture		Air voids (V _a , %)	Total asphalt binder (P _b , %)	VMA (%)	VFA (%)	FED (kJ/m ³)
Georgia granite	IC 1	4.0	4.5	12.9	69.0	3.4
	IC 2	4.0	4.8	14.9	73.2	4.3
	IC 3	4.0	5.4	14.9	73.2	7.5
	IC 4	4.0	5.8	15.5	74.2	7.2
Florida limestone	IC 1	4.0	5.7	11.4	65.0	2.2
	IC 2	4.0	5.9	12.3	67.5	2.1
	IC 3	4.0	6.0	12.2	67.3	3.1
	IC 4	4.0	6.9	13.9	71.3	3.9

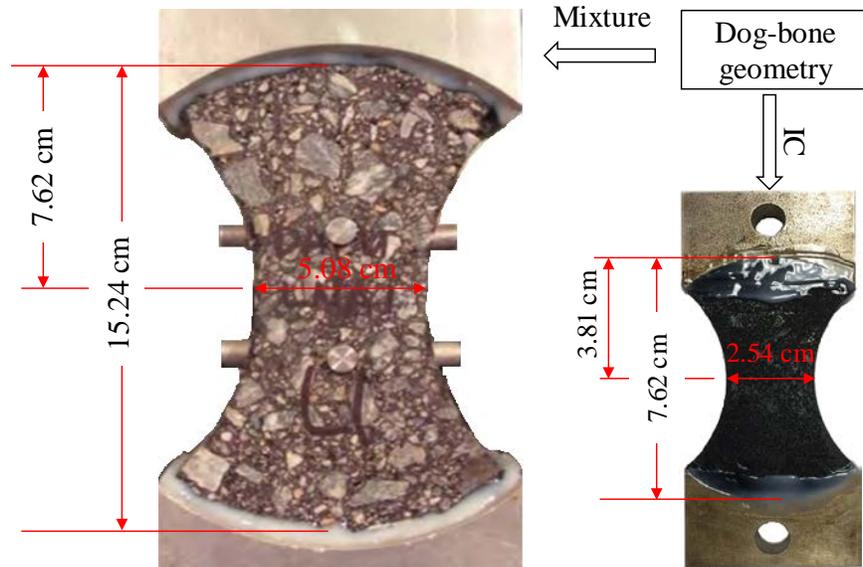
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3 **4. INTERSTITIAL COMPONENT DIRECT TENSION TEST**

4 The ICDT test was miniaturized from the DBDT test, which was developed by Koh et al. (2009)
 5 (26) to obtain fracture properties of asphalt mixtures. Significant modification was required to
 6 adapt the DBDT concept so the resulting ICDT test would be applicable for testing interstitial
 7 component. This included scaling down the specimen geometry, determining specimen
 8 composition, developing compaction method, and identifying appropriate data collection system
 9 and associated data analysis method.

10 **4.1 Specimen geometry**

11 As shown in Figure 1, the geometry of ICDT specimen simulated that of the dog-bone direct
 12 tension test developed by Koh et al. (2009) (26). A scale factor of 0.5 was used for all dimensions,
 13 except that the thickness of the DBDT specimen was 5.08 cm whereas the ICDT specimen was
 14 1.27 cm. The dog-bone geometry had high stress concentration in the middle of the specimen
 15 where stress was approximately 40% greater than that near the ends. Moreover, it introduced non-
 16 uniform stress state in middle of the specimen with the tensile stress at the outer edges about 30%
 17 greater than at its center. This resulted in a unique advantage that the failure plane was known a
 18 priori, so that stress and strain could be measured directly on the failure plane, ensuring consistent
 19 determination of FED (41).



1
2 Figure 1. Dog-bone geometry for mixture and IC specimens

3 4.2 Specimen composition

4 The composition of IC component should reflect the relative volume of effective binder and IC
 5 aggregates in mixtures. The effective binder refers to the binder that is not absorbed by the DASR
 6 aggregates and the IC aggregates are aggregates that are finer than the DASR range as determined
 7 by the DASR-IC model. Therefore, the weight ratio of aggregates to total binder of the IC
 8 specimen is the same as the weight ratio of IC aggregates to effective binder of the corresponding
 9 mixture. Table 2 summarizes the composition of the eight mixtures and their IC
 10 specimens. Mixtures of the same aggregate type had the same weight of DASR and IC aggregates but different
 11 effective binder content and weight ratio of IC aggregates to effective binder. Consequently, the
 12 IC specimens of different mixture type had different compositions of aggregate and total binder.

1 Table 2. Compositions for mixture specimens and corresponding ICDT specimens

Mixture and IC specimen compositions		Mixture Superpave gyratory compacted pill				ICDT specimen		
		DASR aggregate (g)	IC aggregate (g)	Effective binder (g)	IC aggregate to effective binder	Aggregate (g)	Total binder (g)	Aggregate to total binder
Granite mixtures	IC 1	3069	1431	174	8.2	66.0	8.0	8.2
	IC 2			213	6.7	63.2	9.4	6.7
	IC 3			219	6.5	62.2	9.5	6.5
	IC 4			229	6.2	61.1	9.8	6.2
Limestone mixtures	IC 1	3015	1485	162	9.2	61.2	6.7	9.2
	IC 2			182	8.2	59.9	7.3	8.2
	IC 3			182	8.2	59.8	7.3	8.2
	IC 4			222	6.7	56.9	8.5	6.7

2 Knowing the volume of the ICDT specimen (32cm³), the weight ratio of IC aggregates to effective
 3 binder of the mixture to be evaluated, and the bulk specific gravity values of aggregates and binder,
 4 the weights of aggregates and total binder of the corresponding ICDT specimen can be determined
 5 by using Equations 1 and 2. Then, the weight of aggregates was further broken up in accordance
 6 with the IC gradation of the mixture to prepare the batching sheet for ICDT specimens.

$$\frac{W_A}{W_B} = C \quad (1)$$

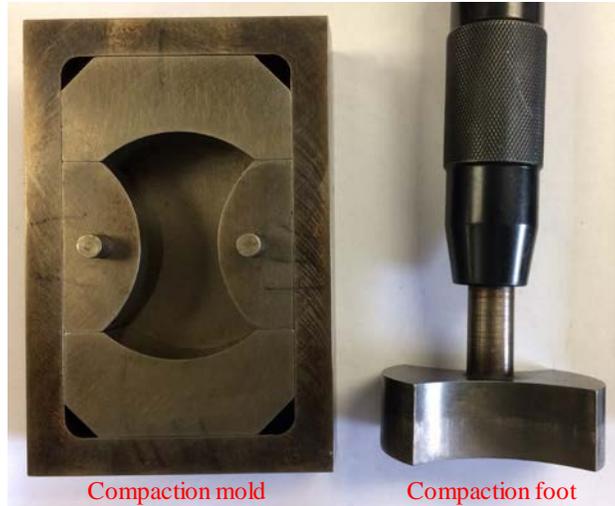
7 Where, W_A and W_B are weights of aggregate and binder of the ICDT specimen,
 8 respectively; C is the weight ratio of IC aggregates to effective binder of the mixture.

$$\frac{W_A}{G_{se}} + \frac{W_B}{G_b} = V_{ICDT} \quad (2)$$

9 Where, G_{se} is the effective specific gravity of IC aggregates; G_b is the specific gravity of
 10 asphalt binder; V_{ICDT} is the volume of ICDT specimen which is 32cm³.

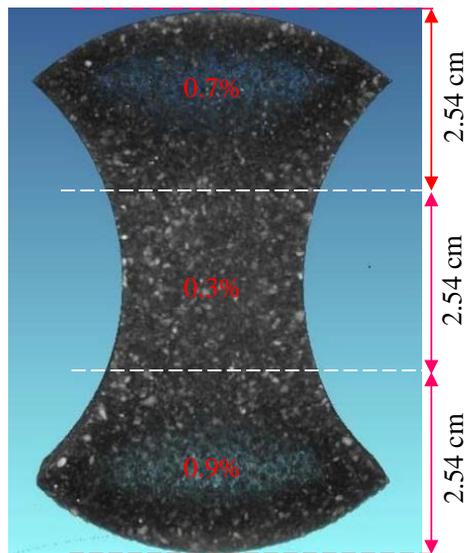
11 4.3 Specimen compaction

12 Loose IC mix was STOA conditioned and compacted in a stainless-steel mold using a specially
 13 designed compaction head, as shown in Figure 2. ICDT specimens were compacted to zero percent
 14 air voids because air void content and distribution (e.g., interconnected, isolated, small or large) is
 15 a mixture level factor that cannot be properly replicated or assessed by testing IC alone. ICDT
 16 specimens should be compacted to a target thickness of 1.27 cm (0.5 inch), which is the key
 17 parameter to control during compaction to obtain zero air voids.



1
2 Figure 2. ICDT specimen compaction mold and steel foot

3 Two ICDT specimens were randomly selected for evaluation of the compaction effect. The ICDT
4 specimen was evenly cut into three parts, on which weight and volume measurements were
5 performed to determine their air void content. The portions close to the two heads had an average
6 air void content of 0.8%, while the middle section had a near zero percent air void content of 0.3%.
7 Results of density measurement were confirmed by using X-ray computed tomography. Figure 3
8 shows some air voids appeared to concentrate near the two heads, but no air voids were observed
9 in the middle section where fracture occurs, and FED is determined. Even though air voids were
10 slightly higher near the heads, fracture occurred through the middle of all specimens tested.



11
12 Figure 3. Distribution of air voids within the ICDT specimen determined by X-ray CT and
13 measured air voids content of two heads and the middle section

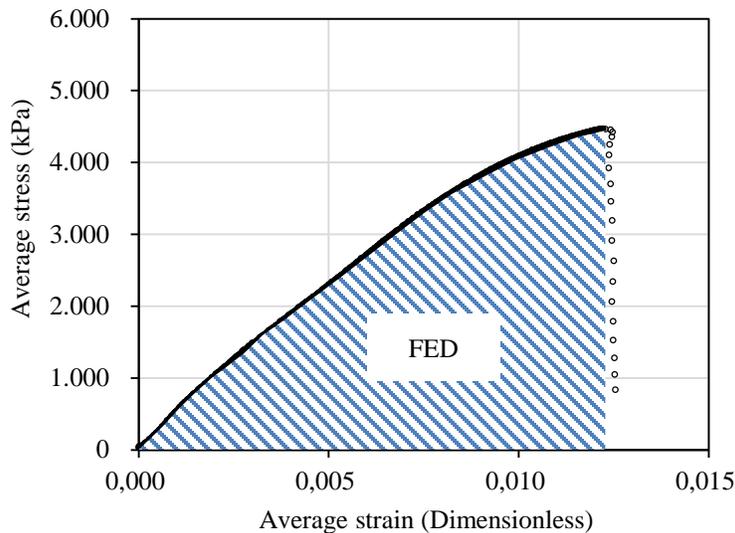
1 4.4 Testing protocol

2 For each mixture type, six replicates with a thickness of 12.7 ± 0.25 mm were prepared for testing.
3 Epoxy was used to bond the specimen to the loading heads. To increase the effectiveness of
4 bonding, sandpaper was used to remove the asphalt film from the top and bottom heads of the
5 specimen. In addition, the loading heads were v-grooved to enhance bonding strength between the
6 epoxy and loading head by increasing contact surface area.

7 ICDDT specimens were placed in an experimental chamber set to 10°C for 2 hours before testing.
8 The same temperature chamber was used for both conditioning and testing. The specimen was
9 oriented vertically and aligned with the loading frame by matching the cavities of the two heads
10 with two pins on loading frame. ICDDT tests were performed at 10°C at a displacement rate of 50.8
11 mm/min, which were the same testing conditions used for the Superpave IDT strength test to
12 determine the mixture FED.

13 4.5 Data interpretation procedure

14 Time, load magnitude, and load-head displacement, was measured using the material testing
15 system (MTS) acquisition software at an adjusted rate of 2048 points per second (the test generally
16 takes less than 2 seconds to complete). Load was transformed into average stress in the central
17 cross-sectional area of the specimen by dividing force by the area of fracture plane, which is equal
18 to 3.23 cm^2 (0.5 in^2). Average strain was determined by using either a digital image correlation
19 (DIC) system or a predictive equation established between displacement and average strain using
20 finite element analysis (FEA). The DIC system is believed to provide the most accurate local strain
21 measurement; however, considering the cost and added complexity of the associated equipment, it
22 was of great interest to determine whether the predictive equation could be used as a surrogate.
23 FED is defined as the area under the stress-strain curve until the stress peak (Figure 4).

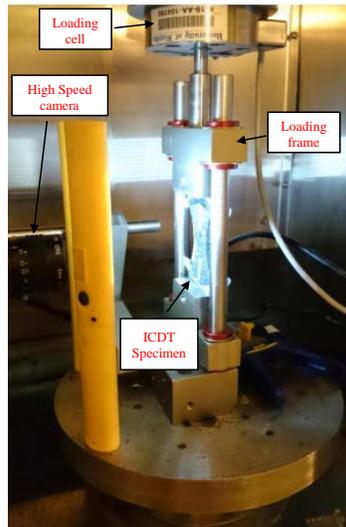


24

25 Figure 4. Determination of IC fracture energy density

1 4.5.1 Strain determination using digital image correlation (DIC)

2 The DIC system was adopted as a non-contact measurement tool to investigate the strain
3 distribution and the instant of fracture of the ICDT specimens. Crack initiation and propagation
4 was visualized by plotting the strain development in a color scale. Once the location and instant of
5 fracture was determined, the system was used to obtain the strain values on the failure plane to
6 determine the IC FED. The DIC system has two main components: a high-speed camera to acquire
7 a sequence of images of the specimen surface during loading and an imaging process software to
8 obtain data of interest (in this case, the local displacement and corresponding strain) (42). Figure
9 5 illustrates the ICDT test setup with a high-speed camera in front of an ICDT specimen been
10 placed on the loading frame inside the environmental chamber.



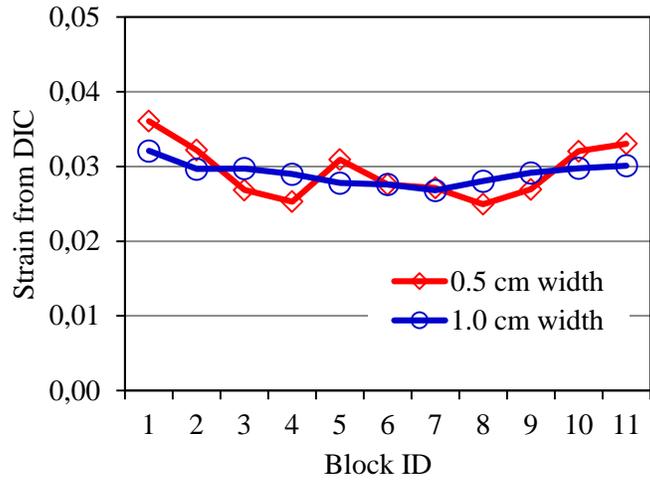
11
12 Figure 5. ICDT test setup

13 The basic principle of DIC is the tracking of the same points (or pixels) between two or more
14 consecutive images. The specimen surface facing the camera was treated using white paint to
15 create a well-contrasted and homogeneous randomly oriented texture. In this case, white paint was
16 sprayed on either the front or the back surface of a ICDT specimen. The grey values of a deformed
17 image (slave image) are statistically compared to an un-deformed image (master image). This step
18 can determine the displacement of any feature location relative to its original position and estimate
19 the corresponding strain by using a technique called area-based matching. Details regarding the
20 DIC system can be found in work by Romeo (42).

21 There are three main steps associated with the analysis of images for determination of strain on
22 the fracture plane (Supplement Figure 4). Step 1 is the selection of the region of interest (ROI),
23 which is then meshed regularly (e.g., 10×10) in horizontal and vertical directions. Displacement
24 used to determine the strain is computed as the difference of the feature location between each
25 image frame in sequence and the reference (which is fixed). The length of the ROI was fixed to be
26 2 cm to avoid edge effects. Step 2 is the identification of the instant of fracture within the ROI
27 based on strain data in a color scale, which uses red to represent 0 strain and black to represent
28 strain of 0.1. This scale of 0 (red) to 0.1 (black) was calibrated so that the instant of fracture can
29 be represented by the color of light blue/blue, making it easy to identify. Step 3 is the selection of
30 a secondary region of interest (SROI) from which strain on the failure plane can be obtained.

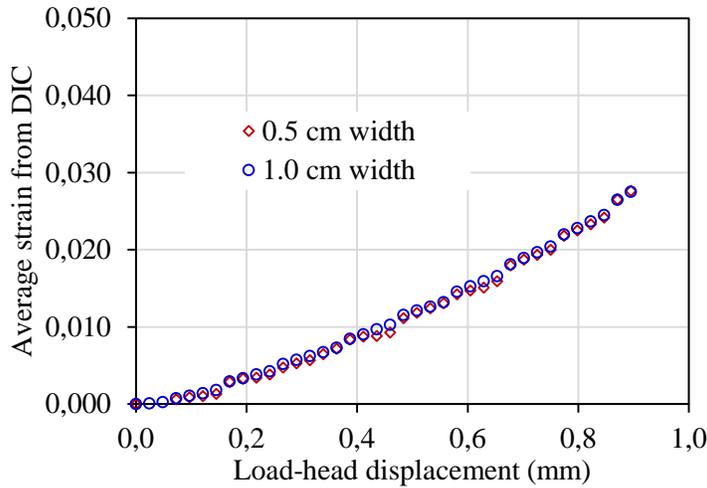
1 Output data from the DIC are the average tensile strain and the time of the instant fracture, which
2 was used to identify the load at fracture by matching with the MTS time.

3 To evaluate the strain distribution along the fracture plane, the SROI was further divided into
4 eleven columns (same length) and corresponding strain data at fracture of each column was
5 collected. Figure 6 indicates that the strain distribution along the fracture surface is nonlinear, with
6 the largest strain at the edges and the lowest strain value at middle of the specimen. The effect of
7 the SROI width on the accuracy of the determined strain was investigated. Figure 6 also shows an
8 SROI width of 0.5 cm resulted in a similar strain distribution on the failure plane as an SROI width
9 of 1.0 cm. Although the larger SROI yielded a smoother strain distribution, the average strain
10 across the fracture surface was almost identical for the two SROI widths (i.e., 0.0293 and 0.0290).



11
12 Figure 6. Strain distribution on the fracture surface of a ICDT specimen

13 Figure 7 reveals a nonlinear correlation between the load-head displacement and average strain.
14 This nonlinearity may be attributed to the induced and re-distributed damage within the specimen
15 throughout the testing process. Of note, both SROI widths (1.0 and 0.5 cm) yielded almost identical
16 correlation between the load-head displacement and average strain values. Thus, the SROI
17 dimension of 1.0 cm in width and 2.0 cm in length was used throughout the analysis of DIC data.



18
19 Figure 7. Correlation between average strain and load-head displacement

1 4.5.2 Strain determination using finite element analysis (FEA)

2 A previous effort was made to develop a predictive equation for the ICDT test to obtain average
3 local strain based on load-head displacement using the FEA method (43). Due to specimen
4 symmetry, it was only necessary to simulate 1/4 of the specimen with appropriate boundary
5 conditions. The model assumed a linear elastic material with stiffness of 1 MPa and Poisson’s ratio
6 of 0.45. The strain field was independent of stiffness and was only affected by the displacement
7 level. The correlation between load-head displacement and average strain on the failure plane (i.e.,
8 middle plane) was expressed by Equation 3.

$$y = 0.0199x \tag{3}$$

9 where, y is the average strain (dimensionless) of the failure plane and x is the load-head
10 displacement (mm).

11 Results based on the FEA analysis (i.e., average strain, tensile strength and the resulting FED
12 values) were compared to DIC results to determine whether the predictive equation can be used as
13 an alternative to the DIC system.

14 **5. RESULTS AND DISCUSSION**

15 5.1 Repeatability of the ICDT test

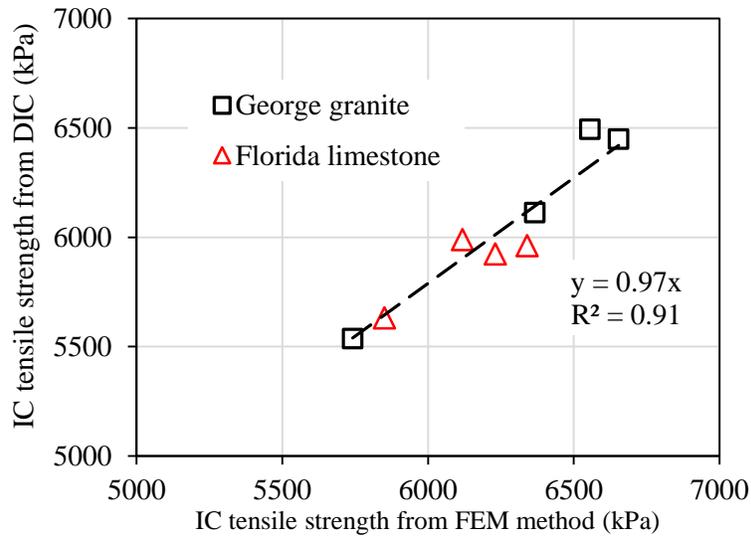
16 An analysis of variance was conducted to evaluate the repeatability of the ICDT tests. Due to the
17 limited number of replicates, a normalization technique was employed. For example, FED of six
18 replicates of a IC type was averaged, and then FED of the individual IC specimen was normalized
19 to that average. This resulted in a population of 48 composed of 8 IC types and 6 replicates per
20 type. Table 3 presents the coefficient of variance (COV), which is the standard deviation divided
21 by the average of the population, determined for normalized tensile strength, failure strain and
22 FED. The DIC method resulted in greater variance in failure strain and FED than the FEA method.
23 This was expected because the DIC method more accurately captured the instant of fracture.
24 Tensile strength was less variable than failure strain and FED and the difference in COV of the
25 tensile strength between the DIC and FEA methods was negligible. Note that the COV of IC FED
26 was within the range reported for the single edge notch bending test (i.e., 3-28%) and the semi-
27 circular bending beam test (15-34%) (44-45).

28 Table 3. Coefficient of variation of IC fracture properties

Property	Coefficient of variance (%)	
	FEA	DIC
Failure strain (ϵ_f)	11.8	16.2
Tensile strength (S_t)	5.8	5.8
Fracture energy density (FED)	12.9	16.7

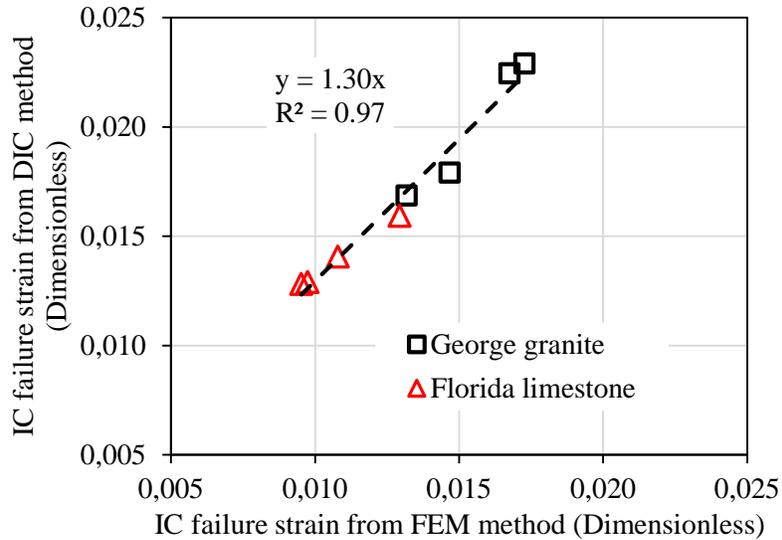
1 5.2 Evaluation of data interpretation methods

2 IC fracture properties (i.e., tensile strength, failure strain and FED) obtained from the DIC method
3 were compared to those obtained from the FEA approach. Figure 8 plots the IC tensile strength on
4 average for eight mixtures and it shows that the tensile strength values determined by the DIC and
5 FEM were strongly correlated. The DIC method, which was believed to more accurately capture
6 the instant of fracture, yielded relatively lower tensile strength than the FEA, indicating the instant
7 of fracture occurred slightly before the stress reaching the peak on the FEA stress-strain curve.



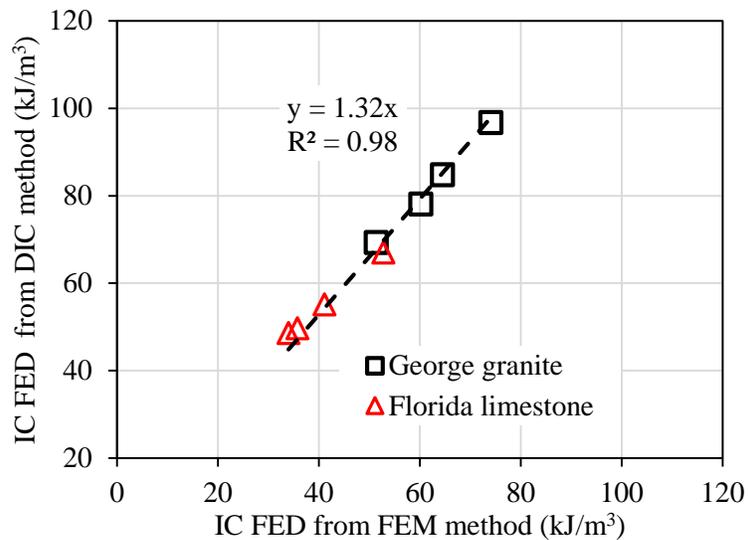
8
9 Figure 8. IC tensile strength as determined using the FEA method and the DIC method

10 As shown in Figure 9, there appeared to be an excellent correlation in failure strain between the
11 DIC and FEA methods. The DIC method yielded greater failure strain values than the FEA method,
12 which was expected because the DIC method more accurately determined the strain on the failure
13 plane whereas the FEA results were obtained from an analysis on non-damaged specimen.
14 Importantly, the DIC strain was consistently 30% greater than the FEA strain of the mixtures
15 evaluated, which allows for estimation of DIC strain based on FEA strain.



1
2 Figure 9. IC failure strain as determined using the FEA method and the DIC method

3 As a result, IC FED values as determined using the DIC method were strongly correlated (i.e.,
4 approximately 32% greater) with those from the FEA method (Figure 10). Although the FEA
5 method yielded lower IC FED values than the DIC method, the underestimation (or the ratio
6 between two strain values) appeared to be consistent for the eight IC types. Therefore, it seems
7 feasible to use the prediction equation of strain from the FEA as a surrogate to the DIC system for
8 determination of IC FED.

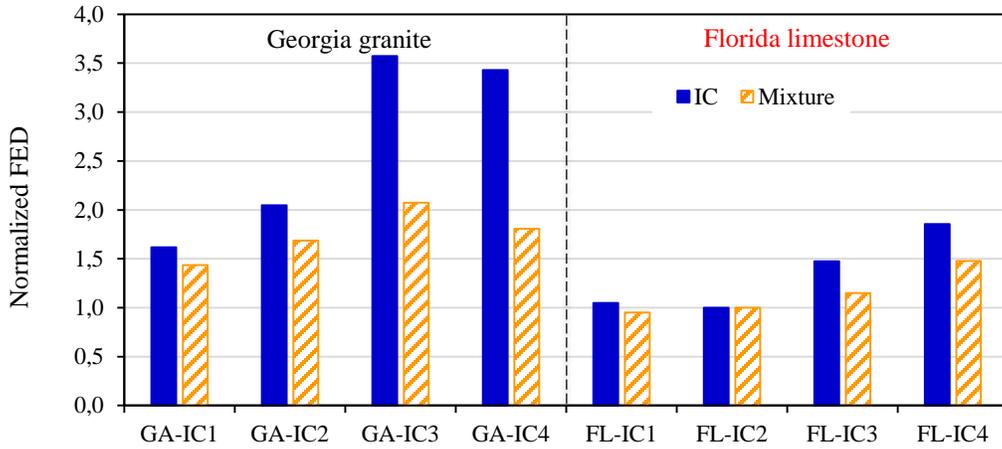


9
10 Figure 10. IC FED as determined using the FEA method and the DIC method

11 5.3 Analysis of correlations between IC FED and mixture FED

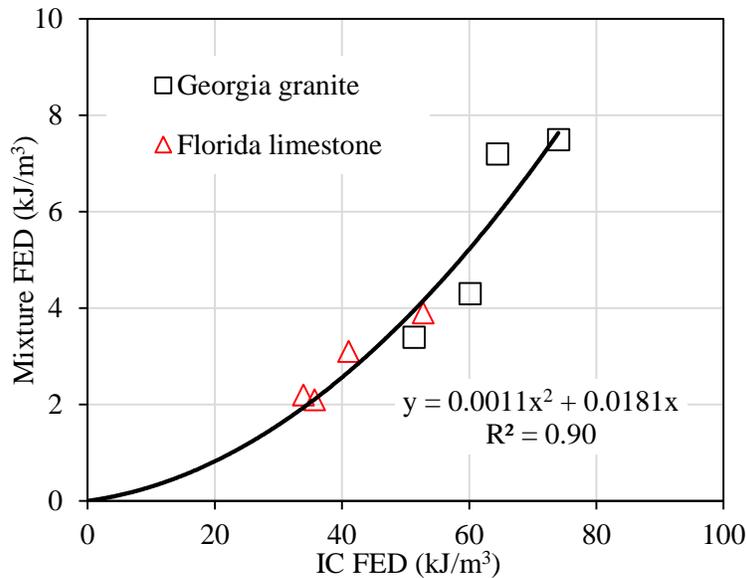
12 A qualitative evaluation of the correlation between IC FED and mixture FED was conducted by
13 normalizing them with respect to the lowest values obtained from FL-IC2. As shown in Figure 11,
14 IC FED distinguished between these mixtures, which had the same coarse aggregate structure but

1 different composition of IC component. Moreover, IC FED ranked these mixtures in the same
 2 order as mixture FED, which substantiates the dominant effect of IC on mixture performance and
 3 validates the sensitivity of the newly developed ICDT test to changes in IC composition.



4
 5 Figure 11. Normalized IC and mixture FED with respect to that of FL-IC2

6 A quantitative evaluation of the correlation between IC FED and mixture FED was conducted by
 7 plotting them against each other. As shown in Figure 12, the IC FED and mixture FED results of
 8 the eight mixtures were highly correlated so that the use of a second-order polynomial function
 9 with intercept forced to zero satisfactorily fitted these values with the coefficient of determination
 10 being 0.90. It is evident that mixture FED is strongly related to IC FED in a positive manner. Figure
 11 12 also reveals that mixture FED increased more rapidly than IC FED as the IC coarseness
 12 increased. This may be attributed to the effect of air void content and distribution, which is a
 13 mixture level factor that cannot be properly replicated or assessed with the ICDT test.



14
 15 Figure 12. Correlation between IC FED and mixture FED

1 **6. FINDINGS AND CONCLUSIONS**

2 This study employed the ICDT test, which was derived from the DBDT test originally developed
3 for asphalt mixtures, to obtain IC FED at intermediate temperature (10°C). Two methods of strain
4 determination were evaluated including a DIC system and a predictive equation based on FEA
5 analysis. ICDT tests were performed on the IC portion of two sets of four mixtures, whose mixture
6 FED results were available from a previous study. It was of great interest to determine whether IC
7 FED adequately reflects the effect of IC characteristics on mixture FED. Findings are summarized
8 as follows.

- 9 • Specimen preparation procedures proposed in this study resulted in ICDT specimens with
10 designed geometry, composition and desired air void content.
- 11 • DIC method revealed that local strain nonlinearly distributed on fracture plane with the
12 largest strain obtained from the edge and lowest value from the middle of the specimen.
- 13 • DIC method indicated that the average strain exponentially increases with increased load-
14 head displacement, possibly due to the accumulation of damage.
- 15 • The ICDT test was found to be repeatable as indicated by the COV of IC fracture properties.
16 DIC method yielded slightly higher COV of failure strain and IC FED than FEA method.
- 17 • DIC method resulted in greater IC failure strain and FED values than those based on the
18 FEA predictive equation. More importantly, there appeared to be a constant ratio between
19 DIC strain to FEA strain, as well as between DIC FED and FEA FED.
- 20 • IC FED distinguished between eight mixtures and ranked them in the same order as mixture
21 FED. More importantly, an excellent correlation was identified between IC FED and
22 mixture FED results, supporting the relevance and accuracy of IC FED.

23 Overall, the ICDT test suitably determines the FED of mixture IC portion, which provides valuable
24 insight regarding the effect of IC characteristics on resulting mixture FED. Moreover, the FEA
25 predictive model can be adopted as a surrogate to the DIC system to obtain the IC failure strain.
26 The second-order polynomial function that was used to fit the IC and mixture FED is only valid
27 for the mixtures evaluated in this study. Future work is needed to account for mixture factors (e.g.,
28 air voids and coarse aggregate structure), along with IC FED to predict mixture FED. Additional
29 work is also necessary to obtain properties associated with resistance to crack propagation for a
30 more complete assessment of cracking performance at intermediate temperatures.

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1

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