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Using the Fracture Energy Index Concept to Characterize the HMA Cracking Resistance Potential under Monotonic Crack Testing

Abu N. M. Faruk[1], Xiaodi Hu[2+], Yuly Lopez[3], and Lubinda F. Walubita[1]

Abstract: In this study, the concept of the Fracture Energy (FE) Index was explored as a fracture parameter to characterize and quantify the cracking resistance potential of hot-mix asphalt (HMA) mixes subjected to monotonic loading in the laboratory. Mathematically, the FE Index was defined as a parametric ratio of the total FE to the HMA tensile strength and tensile strain at peak failure load per unit crack length. The concept was put into practice by testing commonly used Texas HMA mixes, with cracking resistance potential ranging from poor to good, under the Overlay Tester -monotonic loading setup (OT_M) along with two other more commonly used monotonic loading tests, namely: the Indirect Tensile Test (IDT) and the Semi-Circular Bending Test (SCB). Corresponding results indicated that the FE Index has promising potential to be used as a fracture parameter to discriminate and rank the cracking resistance potential of HMA mixes in the laboratory. As expected of monotonic loading crack tests, variability was within acceptable tolerances, except for the SCB that exhibited high variability, particularly at higher asphalt-binder contents. The FE Index also exhibited sensitivity to HMA mix-design variables such as the asphalt-binder content, particulalry for the OT_M and IDT tests. Overall, the OT_M and the IDT tests exhibited supperiority over the SCB test and would readily serve as surrogate crack tests for routine HMA mix-design and screening in the laboratory. For room temperature testing at 25°C, the SCB test appeared to be better suited for low asphalt-binder content mixes.

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***Key words**: Cracking; Fracture energy index; Hot mix asphalt (HMA); IDT; Monotonic loading; Overlay tester; SCB.*

Introduction

Presently, one of the prevalent distresses on hot-mix asphalt (HMA) pavements is cracking. Various factors including poor mix-designs, poor construction practices, high traffic loading, and climatic changes contribute to this distress [1]. In Texas (USA), this distress is further exacerbated by the shift to stiffer asphalt-binders and use of by-products such as RAP (reclaimed asphalt pavement), shingles, etc., that often tend to improve the rutting resistance properties of HMA mixes at the expense of cracking susceptibility [2]. In the current design approaches, an empirical relationship is used to predict the cracking resistance of HMA from conventional engineering material properties such as the elastic modulus and tensile strength [3, 4]. In order to significantly improve pavement designs, the mechanisms behind the initiation and propagation of cracks in HMA must be better understood. The use of fracture mechanics and the development of valid fracture tests are arguably indispensable steps in the evolution of performance-based pavement designs [5, 6].

Several laboratory test procedures to evaluate the fracture response and cracking resistance potential of HMA mixes are presently in practice. The Disc-Shaped Compact Tension Test (DSCTT), Semicircular Bending Test (SCB), the Indirect-tension Test (IDT), and the Direct-tension Test (DT) are some of the most commonly used crack tests operating in a monotonic loading mode [7, 8]. In Texas, however, the Overlay Tester (OT) is the most commonly used HMA cracking test in a repeated (dynamic) loading mode. While, the number of cycles to failure in the OT test remains to be a good indicator of a HMA mix's cracking life in the field, the high variability in the OT test results introduces some degree of reliability issues. These authors in their recent works [8] have attempted to explore few other HMA crack tests in the repeated loading mode, namely, Repeated IDT (R-IDT) and Repeated SCB (R-SCB), and have concluded that the high result variability is somewhat inherent when the HMA crack tests are ran in repeated (dynamic) loading mode.

Therefore, the next logical step towards establishing a reliable and practical HMA laboratory cracking test is exploring some monotonic loading tests. Indeed, in a recent study, these authors have successfully explored the OT test setup in a monotonic loading mode to characterize the fracture properties and cracking resistance potential of HMA mixes in the laboratory through measurement of the tensile strength, tensile strain at peak failure load, modulus/stiffness, and fracture energy (FE) [9,10]. The fracture energy was defined as the work required to produce a crack of unit surface area, where, the work required for fracturing the sample was represented by the area under the load versus displacement curve. However, while variability in the test results was generally low with coefficient of variation (COV) values less than 30% [2], the calculated fracture parameters failed to exhibit satisfactory discriminatory potential for screening and differentiating mixes in terms of their laboratory cracking resistance potential. Thus, this continuation study focused on developing a fracture parameter with the potential to characterize and differentiate the cracking resistance potential of HMA mixes in the laboratory, namely the FE Index.

The FE Index – Concepts and Definitions

[1] Roads, Materials, and Pavement Engineering, Texas A&M Transportation Institute (TTI), College Station, TX 77843, USA.
[2] Wuhan Institute of Technology, Wuhan, China.
[3] Corasfaltos, Bucaramanga, Colombia.
[+] Corresponding Author: E-mail huxiaodi625@hotmail.com
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The FE Index is defined as a mathematical parameter that combines three other HMA fracture parameters, namely, the fracture energy (G_f), the HMA tensile strength (σ_t), and tensile strain at peak load (ε_t). The general mathematical definition of the FE Index is presented in the following expression:

$$FE \quad Index = \frac{G_f}{l_{cr}\sigma_t}\varepsilon_t = \frac{G_f}{l_{cr}E_t} \tag{1}$$

where, l_{cr} is the length traversed by the crack and E_t is the HMA tensile modulus or stiffness. The complex interaction of these three parameters ensures that the complete loading history of the HMA specimen (complete load-displacement response) is taken into account in the resulting parameter (FE Index) and, at the same time, it is able to effectively capture the fracture potential of the mix being tested. Mathematically and as expressed in Eq. (1), the FE Index is simply a parametric ratio of the total FE to the HMA tensile strength and tensile strain at peak failure load per unit crack length.

In terms of the physical attributes and mechanical response behavior of the HMA, the FE Index is conceptualized as an indicative parameter that provides a quantification of the HMA mechanical response in terms of the fracture energy required for complete cracking of an HMA specimen over a given thickness relative to the HMA tensile modulus (stiffness). Or in other words, it is a parametric ratio that provides a physical and mechanical quantification of the fracture energy required to crack a specimen (of a unit thickness or length) as a function of the HMA tensile modulus (stiffness). Based on these definitions, a higher FE Index in magnitude would desirably indicate a better HMA mix in terms of resistance to fracture damage and cracking; and vice versa for lower FE Index values. Thus, lower FE Index values would be undesirable as far as the HMA resistance to fracture damage and cracking is concerned.

Study Objectives and Scope of Work

Using the monotonic loading OT (denoted as OT_M) test along with the more commonly used monotonic loading IDT and the SCB crack tests, the technical objectives of this study were as follows:

- Explore the potential of the FE Index as a means to characterize and differentiate the fracture damage and cracking resistance potential of HMA mixes in the laboratory.
- Evaluate the sensitivity of the FE Index to HMA mix-design variables such as changes in the asphalt-binder content (AC).
- Compare the monotonic loading tests (OT_M, IDT, and SCB) based on the FE Index parameter and overall laboratory test experience.
- Compare and relate the monotonic loading OT_M test to its repeated OT counterpart.

To achieve these objectives, the research methodology incorporated development of the analysis models for calculating the fracture parameters from the three monotonic test data followed by extensive laboratory testing of various Texas HMA mixes to measure their fracture properties. MS Excel and Matlab [11] routine software were then used to compute the related fracture parameters including the HMA tensile strength, tensile strain, modulus (stiffness), FE, and FE Index.

In terms of the paper structure, an overview of the three aforementioned monotonic loading tests including the derived models for calculating the FE Index are discussed in the subsequent sections, followed by the experimental design plan. Results of the FE Index computations are then presented and analyzed, followed by a comparison of the three test methods. The paper then concludes with a summary of key findings and recommendations.

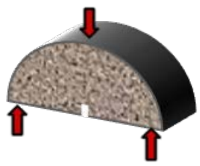
Crack Test Methods and Analysis Models

Three monotonic crack tests, namely the OT_M, the IDT, and the SCB were comparatively evaluated and are summarized in Table 1 including the loading input parameters, test conditions, and references to previous documented research.

The Monotonic OT (OTM) Test

The Overlay Tester (OT) is a simple performance test traditionally used for characterizing the reflective cracking resistance potential of HMA mixes in the laboratory under repeated

Table 1. HMA Fatigue Cracking Tests in Monotonic Loading Mode.

	OT_M	IDT	SCB
Sample			
Dimensions	150mm L × 75mm W × 37.5mm T	150mm ϕ×62.5mm T	150mm ϕ× 75mm H × 62.5mm T (6.25mm Notch)
Test Parameters	3.125mm/min, Tensile Loading @25°C	50 mm/min, Compressive Loading @25°C	1.25 mm/min, Compressive Loading @25°C
Test Time Per Specimen	≤ 10 Minutes	≤ 10 Minutes	≤ 10 Minutes
Output Data	Tensile Strength (σ_t), Strain at Peak Load (ε_t), Tensile Modulus (E_t), FE (G_f), & FE Index		
References	[8]	[2, 10-12]	[2, 10]

Legend: L = length; W = width; T = thickness, H = height; ϕ = diameter

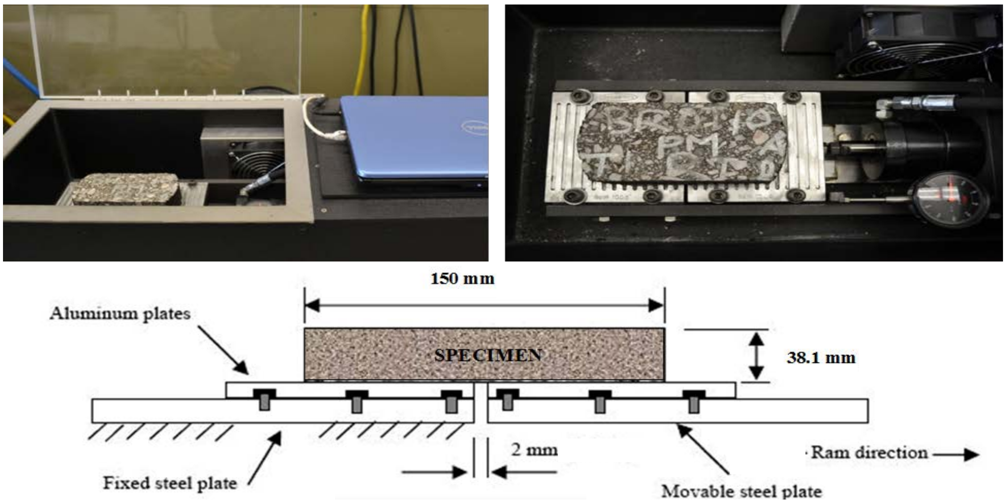


Fig. 1. OT Setup for Monotonic Loading Testing.

loading (tension) mode at 25°C [12]. It is an electro-hydraulic system that applies direct tension load to HMA specimens [13]. The setup used for the OT monotonic loading test is the same as that for the standard repeated OT test except for the ram direction, which is unidirectional in the case of the monotonic loading OT testing. For easy identification, the following abbreviations, "OT_R" and "OT_M" shall be used to denote the "Repeated (dynamic)" and "Monotonic" loading OT tests, respectively. The OT_M schematic layout and specimen set-up are illustrated in Fig. 1.

The Indirect Tension (IDT) Test

The typical IDT setup requires a servo-hydraulic closed-loop testing machine capable of axial compression [2, 14]. As shown in Table 1, the specimen is typically loaded diametrically in compression and this indirectly induces horizontal tensile stresses in the middle zone of the specimen that ultimately causes cracking [15, 16]. For the evaluation of the tensile properties of the HMA mixes, the permanent deformation at the loading points is undesirable [14]. Therefore, the compressive load is often distributed using loading strips that are curved at the interface to fit the radius of curvature of the IDT specimen.

The Semi-circular Bending (SCB) Test

As illustrated in Table 1, the SCB specimen is a half disk that is loaded in compression using a three-point flexural apparatus to induce tension at the bottom center zone of the specimen [2, 14]. Crack initiation and subsequent propagation was centrally localized through a 6.25 mm (0.25 inches) notch at the base of the specimen. The same equipment that is used with the IDT can be used for SCB testing.

Although not accounted for in this study, and as will be discussed in the subsequent text, it is necessary to note that permanent deformation at the points of loading in both the IDT and SCB tests may undesirably occur at test temperatures such as 25°C (77°F) or higher; leading to a possible composition of both compressive and tensile failure modes in the specimen with multiple cracks. However, the temperature used for all these tests (25°C as indicated in Table 1 was chosen for consistency with the Texas specifications [12]. This temperature also facilitates for industry use, since 25°C is considered "room" temperature.

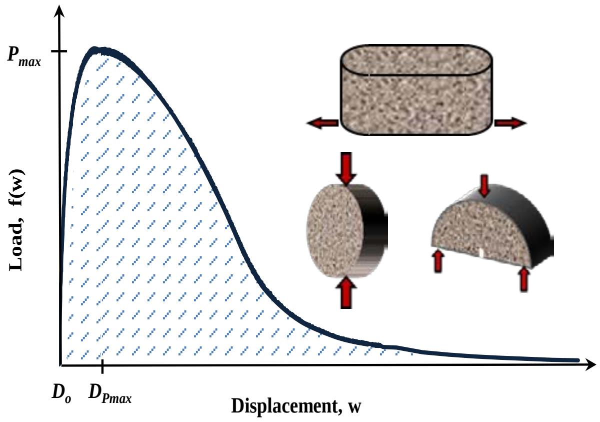


Fig. 2. Load-Displacement Response Curve: Monotonic Testing.

Data Analysis Models

The output from all the three monotonic tests is the load-displacement response curve (Fig. 2), which is used to calculate various HMA fracture parameters. Table 2 lists the evaluated fracture parameters and their respective generalized analysis models [2-17].

However, these generalized models vary slightly depending on the test type. For example, the exact analytical models used for HMA tensile strength for the IDT and the SCB tests are:

$$\sigma_{IDT} = \frac{2P_{max}}{\pi t D} \tag{2}$$

$$\sigma_{SCB} = 4.263\frac{P_{max}}{tD} \tag{3}$$

where, t and D are the thickness and the diameter of the specimen respectively. And P_{max} is the axial peak load, as indicated in Fig. 2.

Table 2. Generalized Data Analysis Models for the HMA Crack Tests.

#	Fracture Parameter	Notation	Unit	Analytical Model
1	HMA Tensile Strength	σ_t	MPa	$\sigma_t = \frac{Peak\ Load}{Cross\ Section\ Area} = \frac{P_{max}}{A}$
2	HMA Tensile Strain at Peak Failure Load – Ductility Potential	ε_t	(mm/mm)	$\varepsilon_t = \frac{Disp.@\ pick\ load}{Initial\ disp.@\ zero\ load}$
3	HMA Tensile Modulus – Stiffness in Tension	E_t	MPa	$E_t = \frac{HMA\ tensile\ strength}{Tensile\ strain} = \frac{\sigma_t}{\varepsilon_t}$
4	Fracture Energy (FE)	G_f	J/m^2	$G_f = \frac{Work}{Area\ of\ cracked\ section} = \frac{1}{A}\int f(x)dx$
5	Fracture Energy Index	FE Index	None	$FE\ Index = \frac{G_f}{l_{cr}\sigma_t}\varepsilon_t$

Legend: l_{cr} = Length traversed by crack

Experimental Design Plan – Materials and HMA Mixes

Commonly used Texas mix types, namely: Type B, Type D, and CAM (Crack Attenuating Mixture), with different mix-design characteristics, were evaluated and are listed in Table 3. For each mix, three replicate specimens were tested per test type per AC level. However, the Type D2 mix was exclusively used for the AC sensitivity testing. Therefore, samples for this HMA mix (Type D2) were laboratory mixed and molded from raw materials while varying the AC content from 4.5% up to 5.5%. As can be noted from Table 3, the Type B, Type D1, and CAM samples (in contrast to the Type D2) were all molded from "plant-mix materials" that were hauled directly from the construction site. All the specimens were molded to a target density of 93±1% as specified by TxDOT standards [18].

Note that the comments in the last column of Table 3 are based on the crack resistance performance of the mixes from previous repeated loading OT tests (OT_R) and historical field performance observations [2, 8, 12, 19]. However, this categorization should not be taken as a standard but was merely used as a reference guide for this study based on previous research and field performance observations [2, 8, 19]. For consistency with the standard OT_R test (Texas spec Tex-248-F) and as shown in Table 1, all the tests discussed in this paper were conducted at a room temperature of 25°C [12].

Laboratory Test Results and Analyses

The laboratory test results at 25°C are presented and analyzed in this section including test method comparisons and sensitivity to AC variations. However, it should be noted that these laboratory results pertain only to the HMA mixes and the laboratory test conditions defined in this study. Therefore, the overall findings and conclusions may not be exhaustive.

OT_M, IDT, and SCB Test Results

Fig. 3 presents the load-displacement response curves and shows a fairly similar response trend for the three mixes in each of the three test methods. The CAM, usually known for being a softer and more crack resistant mix, have the most ductile response curves with low peak loads, whereas, the Type B mix shows much more brittle response behavior [2]. The Type D1 is clearly a better mix than Type B both in terms of higher peak loads and ductility potential.

From the computed HMA fracture parameters in Table 4 and Fig. 4, it is clear that the FE Index is the most reflective of the mixes' perceived laboratory cracking resistance performance. Both the tensile strength (function of the peak load) and the strain (function of displacement at the peak load) only take the load increment portion of the load-displacement response curve into account. On the other hand, the fracture energy (function of the area under the load-displacement curve), though considers the complete loading history of the specimen, fails to effectively capture the mixes' behavior due to the compensating effects of increasing and decreasing areas under the response curves [9]. This is most evident in case of the SCB fracture energy values for the Type D1 and CAM mixes. While the two FE values are practically similar (G_f = 285 and 280 J/m^2, respectively), it is evident from Fig. 3(c) that their response curves are completely different. The FE Index, on the other hand, effectively combines these three fracture parameters to capture the complete loading history of the specimen so that it can show a better reflection of the expected cracking performance of the mix. This is also clearly presented in Fig. 4, where the FE Index exhibits a distinctive increasing trend from the poor Type B mix to the more crack-resistant CAM mix (see Table 3).

Based on the COV values in Table 4, the IDT is the most repeatable test followed by the OT_M and the SCB, respectively. Also, in most of the cases, the COV values are within the 30% limit. The computed parametric values also seem to be reasonable and are consistent with some literature publications. The IDT tensile strength values for instance, fall within the Texas specified range of 0.6~1.4 MPa (85~200 psi) [18]. As reported by Huang et al. [15] and Walubita et al. [2], the SCB tensile strength values are typically about 1.5 to 2.0 times higher the corresponding IDT values.

Discrimination and Screening of HMA Mixes

Fig. 4 provided an assessment of the potential of the fracture parameters to differentiate the crack resistance potential of the mixes, which is a crucial aspect of the HMA mix-design process. To

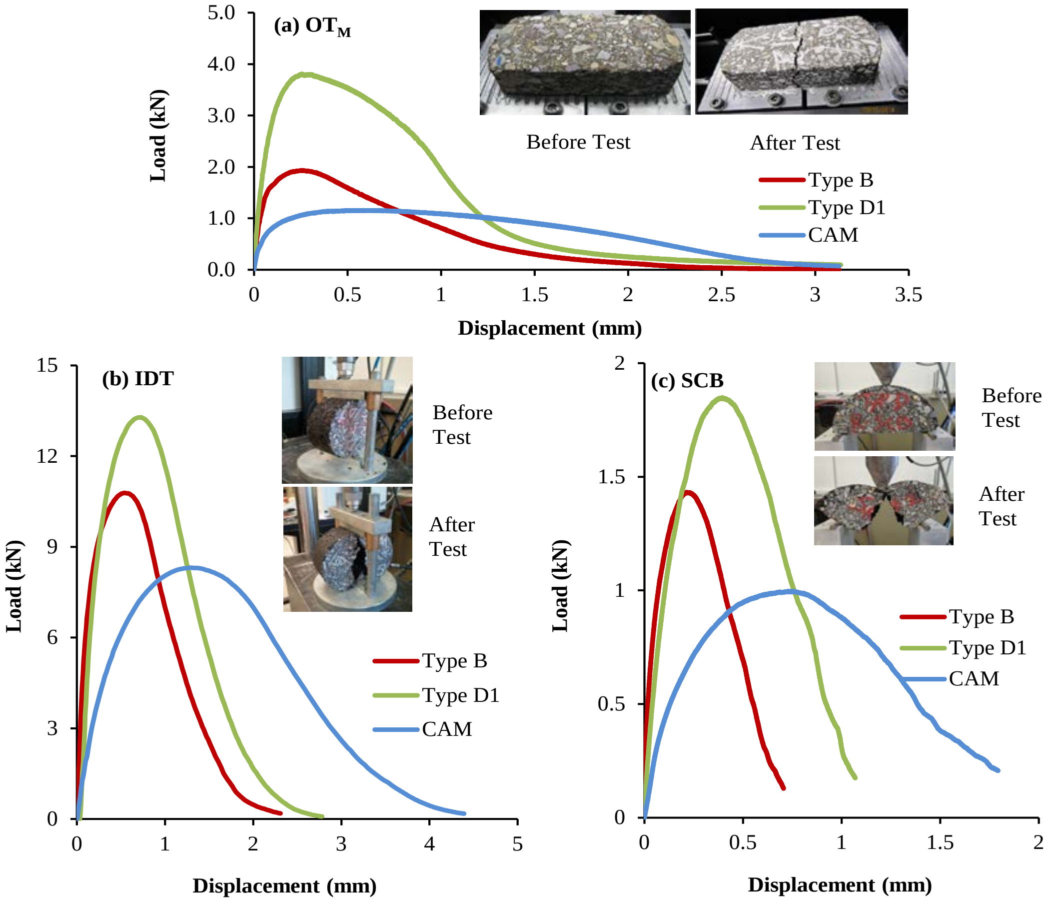


Fig. 3. Monotonic Loading Tests: Load-Displacement Response Curves: (a) OT$_M$, (b) IDT, and (c) SCB.

Table 3. HMA Mixes and Mix Design Characteristics.

#	HMA Mix	Aggregate Gradation	Mix-Design Characteristics	Used in Highway	Sample Type	Comment
1	Type B	Coarse-graded (19 mm NMAS)	4.6% PG 64-22 + Limestone + 30% RAP	IH 35	Plant Mix	Marginal
2	Type D1	Fine-graded (9.5 mm NMAS)	5.1% PG 64-22 + Quartzite + 20% RAP	US 59	Plant Mix	Good
3	Type D2	Fine-graded (9.5 mm NMAS)	4.5 - 5.5% PG 70-22 + Limestone	-	Lab Molded from Raw Materials	Good
4	CAM	Fine-graded (9.5 mm NMAS)	7.0% PG 64-22 + Igneous/Limestone	SH 121	Plant Mix	Very good

Legend: NAMS = Nominal maximum aggregate size

Table 4. Summary of Results: OT$_M$, IDT, and SCB at 25°C.

Test	Mix Type	Fracture Energy, G_f (J/m^2)		Tensile Strength, σ_t (MPa)		Strain, ε_t (mm/mm)		*FE Index*	
		Avg	COV	Avg	COV	Avg	COV	Avg	COV
OT$_M$	Type B	640	*20.6%*	0.683	*8.7%*	0.1423	*29.3%*	3.68	*28.8%*
	Type D1	1475	*14.9%*	1.331	*7.9%*	0.1510	*8.4%*	5.44	*17.0%*
	CAM	786	*13.6%*	0.400	*7.4%*	0.2995	*30.9%*	15.32	***34.0%***
IDT	Type B	136	*2.3%*	0.710	*3.8%*	0.0149	*9.9%*	1.88	*11.8%*
	Type D1	193	*8.1%*	0.876	*3.7%*	0.0190	*19.4%*	2.76	*24.4%*
	CAM	226	*5.2%*	0.547	*2.0%*	0.0340	*4.1%*	9.21	*10.0%*
SCB	Type B	145	*26.4%*	1.400	*18.6%*	0.0062	*13.3%*	0.92	*24.7%*
	Type D1	285	*30.4%*	1.826	*24.1%*	0.0108	*23.9%*	2.46	***40.9%***
	CAM	280	*7.7%*	1.013	*4.4%*	0.0188	*30.6%*	7.63	***38.9%***

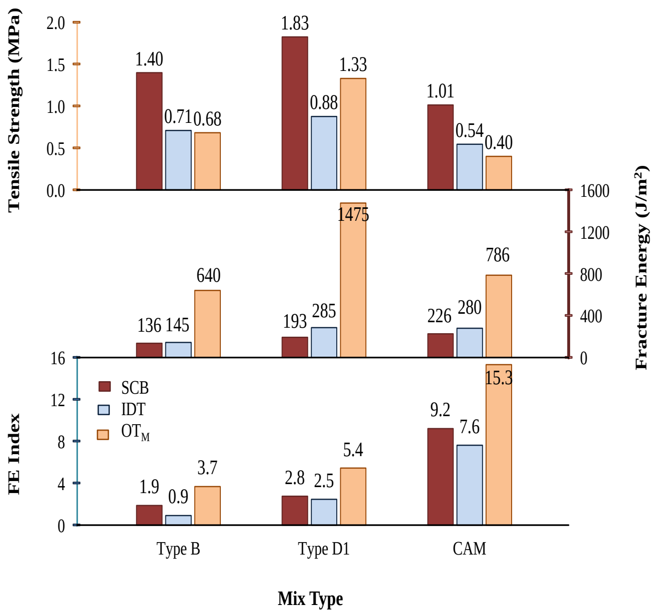


Fig. 4. Summary of Results: OT_M, IDT, and SCB at 25°C.

further investigate the ability of the fracture parameters to screen mixes, two approaches were used: the discriminatory ratio (DR) concept and Tukey's HSD statistical analysis. The results of these analyses are presented in Table 5.

The discriminatory ratio (DR) is an arithmetic ratio of two corresponding parametric values (e.g. G_f, σ_t, and FE Index) comparing a good mix with a relatively poor mix. The larger the DR in magnitude, the greater the difference between the mixes and the more effective the fracture parameter is in discriminating mixes. Based on the DR values computed in Table 5, it is evident that the FE Indices provide a superior degree of discrimination between good and poor lab crack resistant mixes than the other two facture parameters. Also, among the three test methods, the FE Index calculated from the SCB tests have the highest DR values.

Analysis of variance (ANOVA) and Tukey's Honestly Significant Differences (HSD) multiple comparison procedure at a 95% confidence level (CL) were used to statistically investigate the potential of the test parameters' ability to differentiate the crack resistance potential of the HMA mixes. For these statistical analyses, the degree of freedom (DoF) for the ANOVA was dictated by the number of groups (HMA mix Types) analyzed (3 in all cases) and the number of specimens tested (also 3 in all cases). Therefore, for all ANOVA analyses, the between group DoF would be 2 and the within group DoF would be 6.

The interpretation of the ANOVA results in Table 5 is as follows: for a particular test method, the mixes having parametric values that are statistically not significantly different are listed in the same group (e.g. A, B or C). A mix categorized in Group A has higher numerical values than a mix listed in Group B for the same parameter whereas, a mix in Group B would have higher numerical values than a mix in Group C and the difference in their numeric values are statistically significant. For example, the CAM mix has the highest FE Index value for the OT_M test (Table 4) and hence, is categorized in Group A, whereas, the Type B and Type D1 falls in the same group (Group B), which indicates that the difference in their FE Index values is statistically insignificant.

Following the results in Table 5, it is observed that the Tukey's HSD statistical analysis mostly fail to show any clear discrimination among Type D1 and Type B mix types. However, one needs to take into consideration that, while comparing two mixes based on a certain parametric value, the Tukey's HSD method of statistical analysis takes their respective result variability into account. Therefore, any fracture parameter that has high degree of result variability (high COV) is less likely to show any statistical discrimination among mixes. Indeed, the high COV values associated with the SCB-FE Indices (Table 4) explain why despite having a relatively high discriminatory ratio of 2.67, the mixes Type B and D are listed in the same Group B based on the Tukey's HSD analysis (Table 5). However, it should be noted that only three mixes were evaluated and as such, additional testing with more mixes is recommended to substantiate these findings.

Sensitivity to Changes in the Asphalt-Binder Content (AC)

A Type D mix (Mix Designation: Type D2) (PG 70-22 + Limestone) with three different AC levels (4.5, 5.0, and 5.5%) was utilized to assess the sensitivity of the three tests to HMA mix-design variables such as AC variations. The computed facture parameters and statistical categorization (ANOVA & Tukey's HSD) are presented in Fig. 5 and Table 6, respectively. The interpretation of the statistical categorization is same as that for the Table 5 discussed in the preceding section except that in this case, the existence of a third statistical group is noticed (4.5% AC level for OT_M and IDT). This signifies that for the OT_M and the IDT tests, each of the three tested AC levels have FE Indices that are (statistically) significantly different from one another with their numerical values increasing with increasing asphalt-binder contents.

Table 5. Screening of HMA Mixes Based on Discriminatory Ratios and Statistical Analysis.

Analysis Type	Mix Type	Fracture Energy, G_f			Tensile Strength, σ_t			FE Index		
		OT_M	IDT	SCB	OT_M	IDT	SCB	OT_M	IDT	SCB
Discriminatory Ratio	CAM /Type B	1.23	1.66	1.93	0.59	0.77	0.72	4.16	4.90	8.29
	CAM /Type D1	0.53	1.17	0.98	0.30	0.62	0.55	2.82	3.34	3.10
	Type D1 /Type B	2.30	1.42	1.97	1.95	1.23	1.31	1.48	1.47	2.67
Statistical @ 95% Confidence Level (ANOVA & Tukey's HSD)	Type B	B	B	A	B	A	A	B	B	B
	Type D1	A	B	A	A	A	A	B	B	B
	CAM	B	A	A	B	B	B	A	A	A

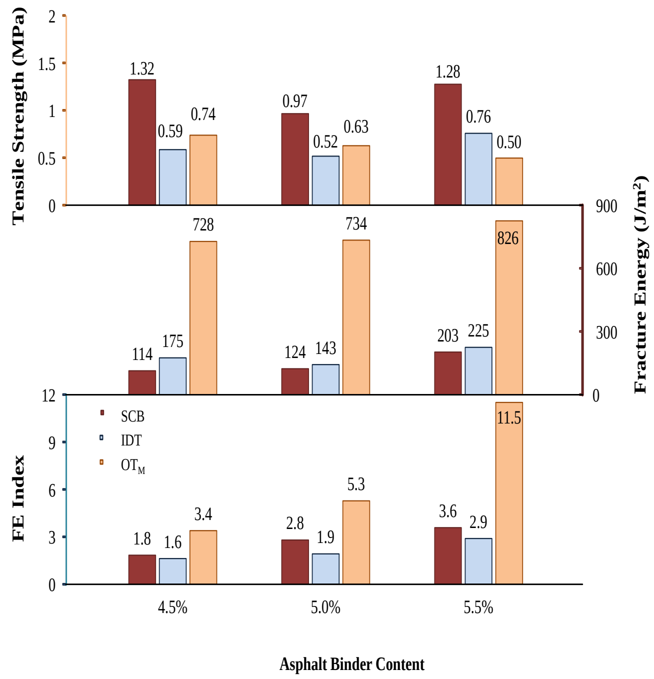


Fig. 5. Sensitivity to Change in Asphalt Binder Content (AC) at 25°C.

Table 6. FE Index with Changing AC Levels for Type D2 Mix at 25°C.

AC	FE Index			Statistical Categorization @ 95% Confidence Level (ANOVA & Tukey's HSD)		
	OT_M	IDT	SCB	OT_M	IDT	SCB
4.5% (COV)=	3.40 *(3.4%)*	1.84 *(1.2%)*	1.63 *(24.0%)*	C	C	A
5.0% (COV)=	5.28 *(4.2%)*	2.81 *(4.6%)*	1.93 *(33.5%)*	B	B	A
5.5% (COV)=	11.51 *(10.2%)*	3.59 *(10.7%)*	2.90 *(42.4%)*	A	A	A

* *Coefficient of Variation (COV) in bold-italic*

Fig. 6. Issues with the SCB Test at High AC Levels: Development of Multiple Crack Paths in 5.5% AC HMA Specimens.

The results in Fig. 5 clearly show the superior sensitivity of the FE Index over the FE and tensile strength in terms of capturing the effects of AC variations. Particularly, the FE Indices calculated from the OT_M test seem to be the most sensitive to AC changes. The FE Indices from the IDT and SCB tests are fairly similar in magnitude and reflects on the two tests' respective abilities to discriminate mixes with varying AC levels as shown in the statistical analysis in Table 6. Whereas, both OT_M and IDT are successful in determining the statistical difference in the FE Index values at different AC levels, the SCB test results lists all three AC level results in the same statistical group. That is the SCB is unable to show any statistical difference amongst the 4.5, 5.0, and 5.5% AC contents at 25 °C. It is also noted from Table 6 that the SCB test results become highly variable (high COV values) at high AC levels. As evident in Fig. 6, the SCB specimens with high AC level (i.e., 5.0 and 5.5%) experience growth of multiple crack paths that jeopardize the authenticity of the test results and at the same time increase the variability in the test results (see Table 6). It is believed that the unique specimen geometry and loading configuration of the SCB test (Figs. 2 and 6) leads to potential crack failures at the points of loading at higher AC levels (softer mixes) and contributes to the formation of multiple crack paths; which is undesirable. Thus, it is safe to assume that at room temperature, i.e., 25°C, this test (SCB) is better suitable for testing of low AC mixes. In fact, most literature suggests conducting the SCB test at temperatures lower than the room temperature, i.e., below 25°C [14, 20].

Just like Table 4, the high variability of the SCB test results at 25°C is again clearly evident in Table 6, with some COV values exceeding 30%. By contrast, both the OT_M and IDT exhibits acceptable repeatability with COV values significantly lower than 30%.

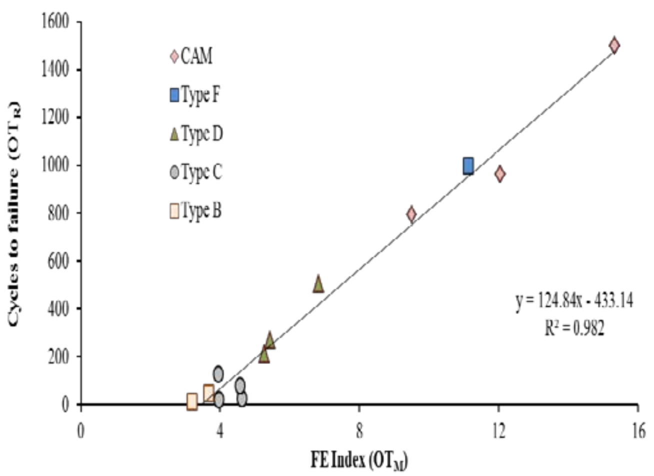


Fig. 7. Relationship between OT_R Cycles and OT_M FE Index at 25°C.

Comparison of Test Methods

Table 7 provides a subjective comparison of the three crack test methods based solely on the HMA mixes evaluated in this study and on the authors' laboratory experience with these crack test methods at 25°C.

Based on Table 7 and the preceding results, the OT_M and the IDT tests seem to have several advantages over the SCB test and, therefore, are deemed more suitable for routine applications as HMA crack tests at 25°C. However, insufficient correlation to field data is still a cause for concern. As an initial step towards addressing this issue, the OT_M test was compared with the standard repeated

Table 7. Comparison of Test Methods at 25°C.

	OT_M	IDT	SCB
Sample Preparation	Easy	Simplest	Fair (Requires Notching)
Potential to Test Field Cores	Yes	Yes	Yes
Overall Test Simplicity	Very Simple	Very Simple	Simple
Test Time Per Specimen	≤ 10 Minutes		
Test Variability (COV ≤ 30%)	Very Repeatable	Very Repeatable	Variable
Mix Screening Ability	Good	Good	Good
Sensitivity to AC Variations	Very good	Good	Moderate
Correlation to Field Data	Needs Validation		
Practicality of Implementation	Yes	Yes	Fair

loading OT test (OT_R) that has a proven correlation with field performance data [2]. Several Texas mixes were tested in the OT_M test setup and the computed FE Index values were compared with their respective OT_R cycles to failure [8]. The test results at 25°C are presented in Fig. 7.

Evidently Fig. 7 shows a good linear correlation between the OT_R cycles to failure and the OT_M FE Indices at 25°C, reinforcing the promising potential of the OT_M test for routine HMA mix-design applications. Furthermore, analysis of the results in Fig. 7 leads to the establishment of a correlation model to estimate the OT_R cycles based on the results of the OT_M FE Index, as follows:

$$OT\ Cycles = A \times (FE\ Index) + B \quad (4)$$

where, the correlation coefficients *A* and *B* are determined using curve fitting techniques in Fig. 6. Note that the OT_M is a much shorter test (≤ 10 minutes) with the potential to test numerous HMA specimens in a day and is more repeatable with the potential to generate multiple data outputs compared to OT_R test [8]. Therefore, predicting the OT_R cycles from the OT_M FE Index will practically be preferred, particularly in an industrial setup or mass production setting. Additionally, this will also offer the users the option to use either the OT_R and/or OT_M test using the same equipment setup.

Summary and Recommendations

In this paper, the FE Index concept was explored and implemented in comparatively evaluating three HMA crack tests, namely the monotonic loading Overlay Tester (OT_M) test, the indirect tension (IDT) test, and the semi-circular bending (SCB) test at room temperature (i.e., 25°C). The objective was to develop a laboratory crack test in the monotonic loading mode that could be universally adopted as a simple test for routine HMA mix-design and mix screening. Results and key findings based on the laboratory crack-resistance characterization of the commonly used Texas mixes (at 25°C) include the following:

- Among the four HMA fracture parameters evaluated (i.e., σ_t, ε_t , FE, and FE Index), the FE Index is the most reflective of the cracking performance of a mix. This is due to the ability of the FE Index parameter to capture the mix's fracture response over the entire loading history. It also provided a superior degree of discrimination between good and poor crack resistant mixes than the other parameters based on the discriminatory ratio evaluation.
- In general, the monotonic loading crack tests were very repeatable with reasonably acceptable variability in the test results. However, high result variability was observed in case of the SCB test, with COV values greater than 30%. In particular, at high asphalt-binder content (AC) levels at 25°C, the SCB test becomes very problematic with formation of multiple crack paths and unrealistic result outputs, partly attributed to the specimen geometry and the loading configuration.
- The FE Index parameter exhibited superior sensitivity to changes in the HMA mix-design variables such as the AC variations, than the other fracture parameters evaluated. In particular, the FE Index calculated from OT_M test showed higher sensitivity to AC changes than the other tests. A statistical analysis of the FE Index parameters with varying AC levels confirmed this observation for the OT_M and the IDT tests. However, due to high degree of result variability, the SCB test results did not show significant sensitivity to AC changes at room temperature (25°C).
- An overall comparison of the three test methods at 25°C showed several advantages of the OT_M and IDT tests over the SCB test including ease of sample preparation, higher degree of repeatability, better mix screening ability, and better sensitivity to AC variations, thus making the OT_M and IDT more suitable for routine HMA mix-design applications as HMA crack tests.
- Although the evaluated monotonic tests yet lack sufficient field validation, the OT_M FE Index showed promising potential through its evident correlation with the repeated OT_R test results.

In consideration of the mixes and the test characteristics evaluated in this study, the OT_M and the IDT tests would be recommended for routine HMA mix-design applications and mix screening at room temperature (25°C); and should be explored further. However, due to its better sensitivity to AC changes and a promising potential to correlate with its repeated loading OT_R counterpart, the OT_M test would rank slightly ahead of the IDT test. Nonetheless, it should be noted that compared to the repeated loading crack tests, the monotonic loading single shot tests do not fully simulate the continuous opening and closing of cracks/joints or gradual propagation of cracking in the field. The monotonic loading configurations also do not incorporate the rest period or account for the HMA elastic recovery that occurs with the passage of traffic in the field. Considering these factors, along with the lack of sufficient field validation, the authors recommend use of these monotonic loading tests as supplementary tests to be routinely used in conjunction with other more established HMA crack tests such as the repeated loading OT test. However, more HMA mix testing is recommended including evaluating the crack test methods at lower test temperatures, i.e., below room temperature (i.e., less than 25°C), to further substantiate the results and findings of this study.

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