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Using fracture energy to characterize the hot mix asphalt cracking resistance based on the direct-tensile test

Uso de la energía de fractura para caracterizar la resistencia al agrietamiento de mezclas asfálticas a partir del ensayo de tensión directa

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Abstract

Cracking is currently one of the most common distresses in hot mix asphalt (HMA) pavements, often costing the highway agencies million of dollars in maintenance and rehabilitation activities. Laboratory characterization of HMA cracking resistance thus constitutes a fundamental step in mix-design and analysis to ensure adequate field performance in terms of this distress. This study assesses the suitability of analyzing the HMA cracking resistance using fracture parameters determined based on the direct tension test, which include the fracture energy. Corresponding results suggest that the fracture energy and the proposed fracture energy indices has promising potential to be used as fracture parameters to discriminate the cracking resistance potential of HMA mixes in the laboratory. More research is recommended to further refining this concept and relate to field cracking resistance data.

---------- *Keywords:* Hot mix asphalt (HMA), cracking resistance, direct tensile test, tensile strength, fracture energy

Resumen

El agrietamiento, en particular aquel asociado a carga, es actualmente una de las patologías más comunes en mezclas asfálticas de pavimentación, y a menudo cuesta millones de dólares a las agencias viales en actividades de

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mantenimiento y rehabilitación. Por tanto, la caracterización en laboratorio de las mezclas asfálticas constituye un paso fundamental en el diseño de mezcla y su análisis para asegurar adecuado desempeño en campo en términos de esta patología. Este estudio evalúa la posibilidad de analizar la resistencia al agrietamiento de mezclas asfálticas con base en parámetros de fractura determinados a partir del ensayo de tensión directa, los cuales incluyen la energía de fractura. Los resultados correspondientes sugieren que la energía de fractura y los índices de energía de fractura propuestos tienen potencial para ser usados como parámetros de fractura para discriminar la resistencia potencial al agrietamiento de mezclas asfálticas en laboratorio. Se recomienda investigación adicional para refinar estos conceptos y establecer relaciones con datos de resistencia al agrietamiento en campo.

---------- *Palabras clave:* Mezcla asfáltica en caliente, resistencia al agrietamiento, ensayo de tensión directa, resistencia a tensión, energía de fractura.

Introduction

Cracking is one of the major structural distresses prevalent in today's hot-mix asphalt (HMA) pavements. Ensuring adequate mix-cracking resistance is one way to minimize this distress. However, mix cracking resistance, which can be defined as the measure of HMA's ability to withstand fracture damage, is a complex function of several variables including HMA mix-design characteristics, traffic, pavement structure, and the environment [1]. All these factors need to be discretely taken into account when quantifying and modeling the fracture properties and cracking resistance potential of HMA mixes. Figure 1 shows an example of cracking on the HMA pavement surface manifesting as alligator cracks (i.e., resembling the skin of an alligator).

Proper laboratory characterization of the HMA fracture properties and screening for cracking resistance potential thus constitutes a fundamental and integral component of HMA design and analysis to ensure adequate field performance. However, most existing laboratory crack test methods are empirical in nature, laborious, lengthy, and do not often characterize the fundamental HMA fracture properties that are directly related to cracking performance. Most often, such empirical test methods not only fail to produce cracking resistant HMA mixes, but are also impractical for routine mix-design applications.

Figure 1 Example of fatigue cracking occurring on the HMA pavement

The repeated loading flexural bending beam fatigue test, for instance, is ideal for scientific or research purposes, but it is not readily applicable for industry-routine purposes or daily mix-design screenings due to the complexity nature of the sample preparation process and lengthy test time [2]. The monotonic loading indirect tension (IDT) test on the other hand, is too empirical and its loading configuration does not directly induce tension that is critical for HMA fracture damage and cracking propagation [3]. Furthermore, some of the test methods such as the flexural and diametral fatigue are reported to be associated with high variability in the test results and poor repeatability. Ghuzlan and Carpenter [4] reported, for instance, high variability in the test parameters computed based on the flexural fatigue test.

One of the recent test methods investigated by Walubita et al. [5] that exhibited potential as a surrogate cracking test is the direct tension (DT) test. Under this initial DT test protocol, the HMA fracture properties and cracking resistance potential were quantified in terms of the tensile strength and tensile strain at the peak failure load. As presented in this paper, this continuation study evaluated the potential of using the specific fracture energy (or fracture energy) from DT testing as an additional parameter to characterize the fracture properties and cracking resistance potential of HMA mixes. Specifically, the paper addresses the following objectives:

1) Use the DT test data to compute the subsequently indicated fracture parameters to quantify and characterize the HMA cracking resistance potential:
    - Uniaxial direct tensile strength (or tensile strength)
    - Ductility potential measured in terms of the tensile strain at the peak failure load
    - Elastic tensile stiffness (or tensile modulus)
    - Fracture energy, and
    - Fracture energy indices
2) Evaluate the applicability of the fracture energy along with the aforementioned fracture parameters for discriminating and comparative ranking of HMA mixes in terms of the laboratory cracking resistance potential.
3) Explore the potential of using the fracture energy index concept to characterize and discriminate the laboratory cracking resistance potential of HMA mixes.

In terms of the paper layout, following this introduction is a description of the DT test protocol, analysis models for computing the fracture parameters, and the experimental design plan. Results are then presented and analyzed followed by a section of conclusions and recommendations.

The direct-tension (DT) test protocol

For this study, the DT test parameters consisted of a continuous axial tensile loading at a displacement rate of 1.27 mm/min, which was recommended in previous research [5]. For the displacement-loading rate of 1.27 mm/min, the DT test duration was at most 5 minutes. Figure 2 shows the laboratory test set-up and the corresponding loading configuration.

The DT test was conducted at 20 °C with a minimum temperature pre-conditioning time of 2 hours. This temperature was monitored via a thermocouple probe attached inside a dummy HMA specimen also placed in the same environmental-temperature chamber as the test specimens. As shown in the figure 2, the DT test specimens were cylindrically shaped with final dimensions of 50 mm radius by 150 mm in height.

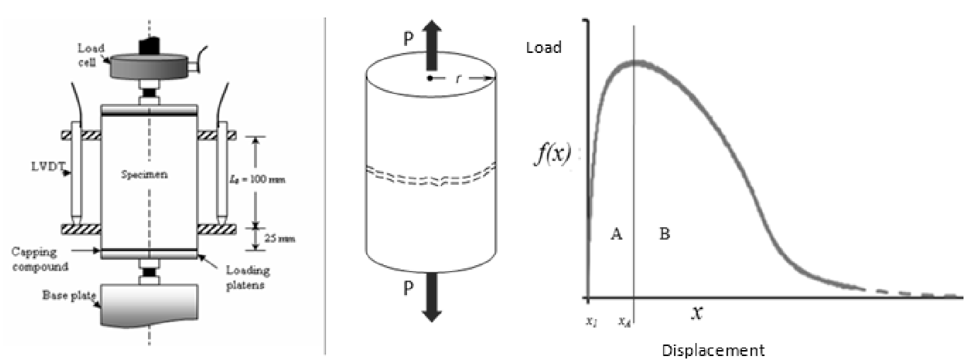

Figure 2 Direct tension (DT) test set-up and loading configuration

Analysis models for computing the fracture parameters

Based on the DT test output data, the HMA tensile strength (σ_t) in MPa, tensile strain at the peak failure load (ε_f) in mm/mm, tensile modulus (E_t) in MPa, and fracture energy ($G_{f(DT)}$) in J/m^2 were calculated using Equations 1 to 4, respectively.

$$\sigma_t = \frac{P_{\max}}{\pi r^2} \tag{1}$$

$$\varepsilon_f = \frac{\Delta L}{L_0} \tag{2}$$

$$E_t = \frac{\sigma_t}{\varepsilon_f} \tag{3}$$

$$G_{f(DT)} = \frac{1}{\pi r^2}\int_{x_1}^{x_2} f(x)\,dx \tag{4}$$

were P_{max} is the maximum tensile load at failure (i.e., break) (kN), r is the specimen radius (mm), ΔL is the maximum elongation at P_{max} (mm), and L_0 is the initial centre to centre distance between the linear variable displacement transducers (LVDTs) (mm), which was 100 mm in this study (figure 2).

The work (fracture energy) required to fracture the specimen is represented by the area under the load versus displacement curve (figure 2). Mathematically and as illustrated by Equation 4, the total fracture energy is the area enclosed within the integral limits x_1 and x_2. For this study, the fracture energy was only computed up to the point of peak failure, which is part A in figure 2. Corresponding calculations were conducted using the Matlab [6] software. Fracture energy for part B was not computed because the DT tests were terminated at the instance of 50% drop in the peak failure load.

In addition, the concept of fracture energy index was introduced, where the fracture energy ($G_{f(DT)}$) is divided by the HMA tensile strength (FE_σ *Index*) and tensile modulus (FE_E *Index*), respectively; see Equations 5 and 6.

$$FE_\sigma\ Index = \frac{G_{f(DT)}}{\sigma_t} \tag{5}$$

$$FE_E\ Index = \frac{G_{f(DT)}}{E_t} \tag{6}$$

Experimental design plan

The experimental design plan incorporated various mixes of historically known good and poor cracking resistance performance in the field [7]. In total, up to ten HMA mixes with different mix designs were evaluated and are listed in table 1.

Table 1 HMA Mix-Design Characteristics

#	*Mix Type*	*Binder + Aggregate*	*Gradation*	*Field Cracking Resistance Potential*
1	Type B_01	4.5% PG 64-22 + Limestone	Coarse (22.4 mm NMAS)	Poor (rarely designed for cracking resistance)
2	Type B_02	4.5% PG 64-22 + Limestone	Coarse (22.4 mm NMAS)	Poor (rarely designed for cracking resistance)
3	Smoothseal_Type B	8.9% PG 76-22S + Gravel/Limestone	Fine (9.5 mm NMAS)	Good

#	Mix Type	Binder + Aggregate	Gradation	Field Cracking Resistance Potential
4	Type C	4.7% PG 70-22 + Igneous	Dense (16 mm NMAS)	Moderate
5	Type D_01	5.6% PG 76-22 + Igneous	Dense (12.5 mm NMAS)	Moderate
6	Type D_02	4.8% PG 70-22 + Limestone	Dense (12.5 mm NMAS)	Moderate
7	Type D_03	5.3% PG 76-22 + Igneous	Dense (12.5 mm NMAS)	Moderate
8	Type F_CR	6.8% PG 64-22 + Granite + 7% Crumb Rubber	Fine (9.5 mm NMAS)	Good
9	PFC	5.9% PG 76-22 + Igneous	Open (19 mm NMAS)	Moderate to poor (not designed for cracking resistance)
10	Superpave	5.9% PG 70-22S + Gravel + 1.5% Lime	Dense (12.5 mm NMAS)	Moderate

Note: NMAS = nominal maximum aggregate size

Note that all the mixes in Table 1 were designed in the laboratory based on the Texas gyratory compactor method [8, 10], except the PFC (permeable friction course) that was designed using the Superpave gyratory compactor [8, 9]. The field cracking resistance potential in column 5 of Table 1 were assigned based on previous research findings and actual field experience with the mixes in Texas, USA [5, 7]. DT test specimens (50 mm radius by 150 mm in height) fabricated from these mixes (table 1) in the laboratory were gyratory molded to a target total air void content of 7 ± 0.5% for the fine-, dense-, and coarse-graded mixes tested and 20 ± 1% for the PFC mixes [8]. These DT specimens are typically cored from 75 mm in radius samples of higher height (i.e., height > 150 mm) to improve the homogeneity of the air voids distribution [11, 12].

Results and analyses

This section presents results and analyses of the mixes studied in terms of the HMA tensile strength, tensile strain at the peak failure load, and tensile modulus. In addition, a second subsection discusses the results obtained in terms of fracture energy and fracture energy indices.

Tensile strength, tensile strain at the peak failure load, and tensile modulus

Figure 3 shows the stress-strain curves registered for the mixes evaluated in the DT test up to the tensile strain at the peak failure stress. These stress-strain curves provide an overall idea of the diversity of mix responses obtained for the mixes evaluated, which should be related to the mix cracking resistance. Differences in the stress-strain response were observed between the fine-graded mixes (i.e., Smoothseal_Type B and Type F_CR) and the coarse- and dense-graded mixes (i.e., Type B, Type C, Type D, and Superpave). The fine-graded mixes—typically exhibiting good field cracking resistance potential; see table 1—were characterized by the lower tensile stress and the higher tensile strain values, whereas the coarse- and dense-graded mixes—typically exhibiting moderate and poor field cracking resistance potential; see table 1—developed the opposite spectrum of stress and strain values. An intermediate stress response and the smallest tensile strain at the peak failure load were obtained for the open-graded PFC mix, which is not typically designed for cracking resistance [5].

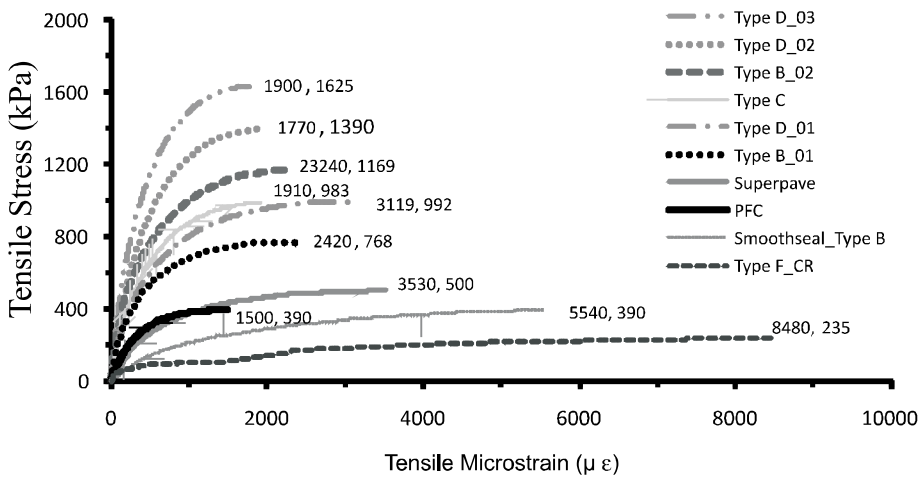

Figure 3 Stress-strain response curves

Figure 4 shows the tensile strain at the peak failure load values and figure 5 shows the tensile strength values computed based on the DT test data. As suggested in previous research [5], this tensile strain was adopted as an index of ductility potential (or potential to elongate, under tensile stress, prior to breakage) for the HMA. Thus, high values of the tensile strain at the peak failure load are associated with desirable ductile mixes. Previous research [5] also reported a threshold value of 3000 $\mu\varepsilon$ to define a pass-fail criterion allowing discrimination of cracking resistant and not cracking resistant HMA mixes (i.e., $\varepsilon_f \geq 3000\ \mu\varepsilon$ is associated with cracking resistant HMA mixes) in the laboratory. The same criterion was adapted in this study to differentiate the cracking HMA response. In addition, the tensile strength was adapted as an index of ultimate load capacity for the HMA.

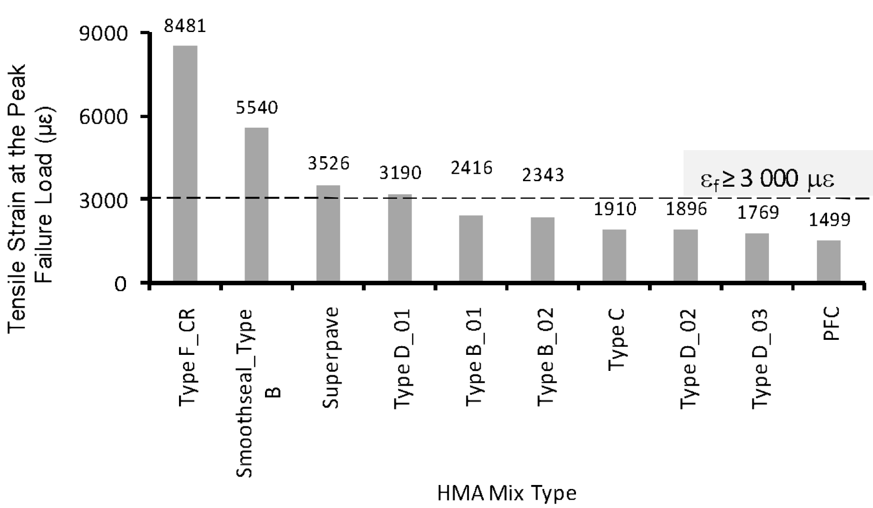

Figure 4 Tensile strain at peak failure load

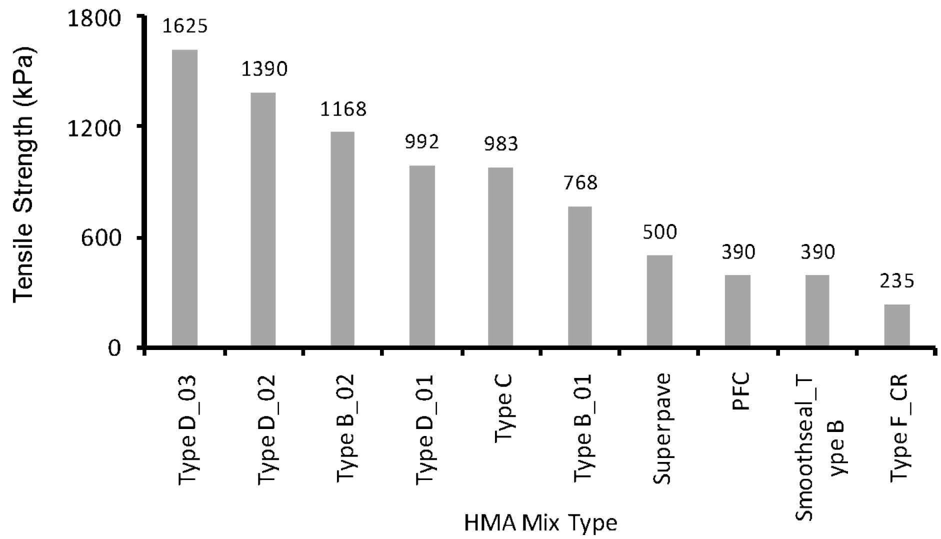

Figure 5 Tensile strength values

Based on the data shown in the figure 4 and the aforementioned threshold value of tensile strain at the peak failure load (i.e., 3000 με), the mixes exhibiting adequate ductility—and, therefore, expected adequate laboratory cracking resistance—correspond to: Type F_CR, Smoothseal_Type B, Superpave, and Type D_01. This initial screening of mix cracking resistance is consistent with table 1 in terms of the field cracking resistance potential. As theoretically expected, the PFC mix is the least cracking resistant in terms of the ductility criterion. In general, PFC mixes are rarely designed for cracking-resistance purposes [13]; their primary functions include provision of surface drainage, minimizing splash effects particularly during rainy seasons, and provision of skid resistance characteristics [13, 14].

Comparison of the field cracking resistance potential ranking indicated in table 1 and the data shown in figures 1 and 5 suggests that the cracking resistant mixes are characterized by the lower tensile strength values. However, caution should be exercised bearing in mind that higher total air voids contents can also lead to lower tensile strength values. Substantial differences were observed in terms of the tensile strength values for the ten mixes analyzed. For example, values of 235, 390, and 390 kPa, respectively, were reported for the Type F_CR, Smoothseal_Type B, and PFC mixes, while the Type D_03, Type D_02, and Type B_02 reported values of 1625, 1390, and 1168 kPa, respectively. As indicated in the table 1, the second group of mixes is characterized by the moderate to poor cracking resistance in the field. In other words, high values of ultimate load capacity are not necessarily an indication of high cracking resistance potential. In addition, the ranking of HMA mixes obtained based on the tensile strength values is not consistent with table 1 in terms of both the mix-design characteristics and field cracking resistance potential. Therefore, additional fracture parameters, as discussed in the subsequent section, were proposed to differentiate and rank the HMA mixes.

Figure 6 shows the tensile modulus values for the mixes evaluated. This parameter was adapted as a representation of the HMA mix stiffness. High values of the tensile modulus are, therefore, related to high stiffness in the HMA mixes.

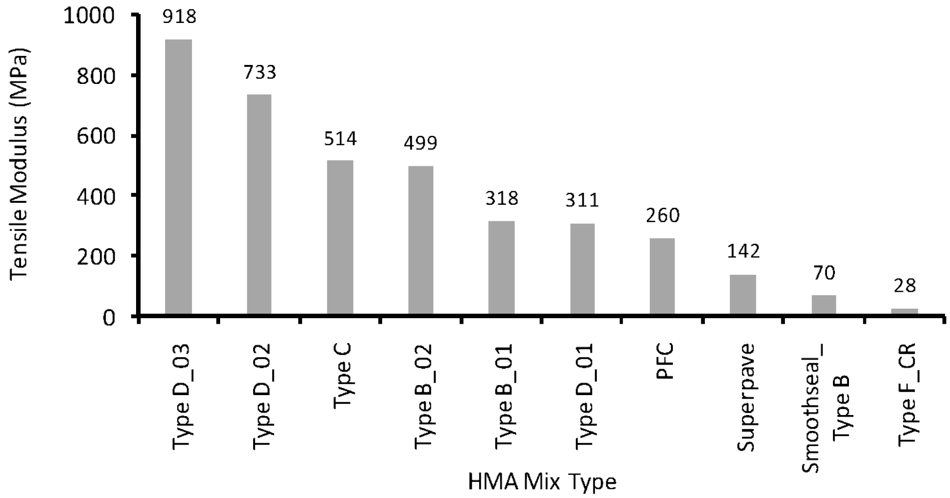

Figure 6 Tensile modulus values

As shown in figure 6, substantial differences were also observed in the tensile modulus values obtained for the mixes evaluated. Higher stiffness values were obtained for the Type D, Type B, and Type C mixes, while lower stiffness values corresponded to the PFC, Superpave, Smoothseal_Type B, and Type F_CR, respectively. The differences in the internal structure of the dense-graded mixes and PFC mixes can explain the intermediate stress-strain response of the PFC mix. As compared to the stone-on-stone contact and cohesion provided by the mastic in the dense-graded HMA, the PFC mix basically relies on the stone-on-stone contact obtained in the coarse aggregate fraction—while the fine aggregate fraction partially fills the air voids of the coarse aggregate skeleton—to develop its stiffness.

As previously discussed for the tensile strength, the ranking of HMA mixes based on the tensile modulus is not consistent with table 1 in terms of field cracking resistance potential. This conclusion provided additional evidence to explore both the fracture energy and fracture energy indices, which are presented in the subsequent text.

Fracture energy and fracture energy indices

Results from the computation of fracture energy (Equation 4) and fracture energy indices (Equations 5 and 6) based on the DT test data are summarized in table 2. Higher values of fracture energy are theoretically desired, since they are associated with more ability to absorb mechanical energy in the mix during the loading process up to the failure condition. In addition and based on equations 5 and 6, the higher the fracture energy index in magnitude, the greater the cracking resistance potential of the mix. In the table 2, the mixes were ranked in a decreasing order of the magnitude of the fracture energy indices. A similar ranking was obtained for both indices, i.e., FE_σ and FE_E. In addition, table 3 presents the ranking of the HMA mixes evaluated from maximum to minimum value of each parameter indicated in the table. Specific values to arrive to this ranking correspond to the data presented in figures 3 to 6.

Table 2 Listing of Computed Fracture Parameters

Rank #	***HMA Mix***	σ_t ***(kPa)***	ε_f ***(με)***	E_t ***(MPa)***	$G_{f\,(DT)}$ ***(J/m²)***	FE_σ ***Index***	FE_E ***Index***
1	Type F_CR	235	8481	28	53	0.23	1.89
2	Smoothseal_Type B	390	5540	70	55	0.14	0.79
3	Superpave	500	3526	142	52	0.10	0.37
4	Type D_01	992	3190	311	102	0.10	0.33
5	Type B_01	768	2416	318	61	0.08	0.19
6	Type B_02	1168	2343	499	82	0.07	0.16
7	Type D_02	1390	1896	733	72	0.05	0.10
8	Type C	983	1910	514	52	0.05	0.10
9	Type D_03	1625	1769	918	81	0.05	0.09
10	PFC	390	1499	260	17	0.04	0.07

Table 3 HMA Mix Ranking Based on Direct Tension (DT) Test Results

Rank#	ε_f	σ_t	E_t	$G_{f\,(DT)}$
1	Type F_CR	Type D_03	Type D_03	Type D_01
2	Smoothseal_Type B	Type D_02	Type D_02	Type B_02
3	Superpave	Type B_02	Type C	Type D_03
4	Type D_01	Type D_01	Type B_02	Type D_02
5	Type B_01	Type C	Type B_01	Type B_01
6	Type B_02	Type B_01	Type D_01	Smoothseal_Type B
7	Type C	Superpave	PFC	Type F_CR
8	Type D_02	PFC	Superpave	Superpave
9	Type D_03	Smoothseal_Type B	Smoothseal_Type B	Type C
10	PFC	Type F_CR	Type F_CR	PFC

As noted in the table 3 and with the exception of the tensile strain, the fracture parameters—including the fracture energy—were not able to effectively and consistently discriminate the cracking resistance potential of the different HMA mixes evaluated or provide a ranking that is consistent with the historically observed field performance. However, looking at their magnitudes, both of the fracture energy indices shown in table 2 exhibited a ranking of the HMA mixes that is consistent with the mix-design characteristics listed in table 1 and field performance expectation of these mixes [4, 7].

Both indices show the Type F_CR and Smoothseal_Type B as the most superior in terms of the laboratory cracking resistance potential. As observed in table 1, these mixes have the highest amount of asphalt-binder content, and are traditionally designed to offer crack resistance properties in HMA pavement structures. These mixes are predominantly used as surfacing layers or overlay mixes to mitigate reflective cracking [7]. In addition, crumb rubber is typically incorporated to improve the mix's cracking resistance properties and hence, the superior ranking of the Type F_CR mix [7]. As theoretically expected, the PFC mix is the least cracking resistant in terms of the fracture energy indices; partly because of the high total air voids content and the fact that this mix is rarely designed for cracking resistance functions.

From these results, it can be concluded that the fracture energy indices provide a realistic discrimination and ranking of the HMA mixes studied. Further exploration of this concept with more HMA mixes as well as validation with field performance data should be considered in future studies. Between the two indices however, the FE_E index would be favored on the basis that it provides a more distinctive discrimination among the mixes. Another parameter to consider that provided a realistic ranking similar to the *FE* indices is the tensile strain at peak failure load; with a difference occurring only for the Type C and Type D_02 mixes. In fact, the FE_E index and tensile strain values exhibit an almost linear relationship with a coefficient of correlation of 0.983 (and R^2 equal to 0.966; see figure 7). Therefore, both of these fracture parameters can be used to discriminate and screen mixes in the laboratory.

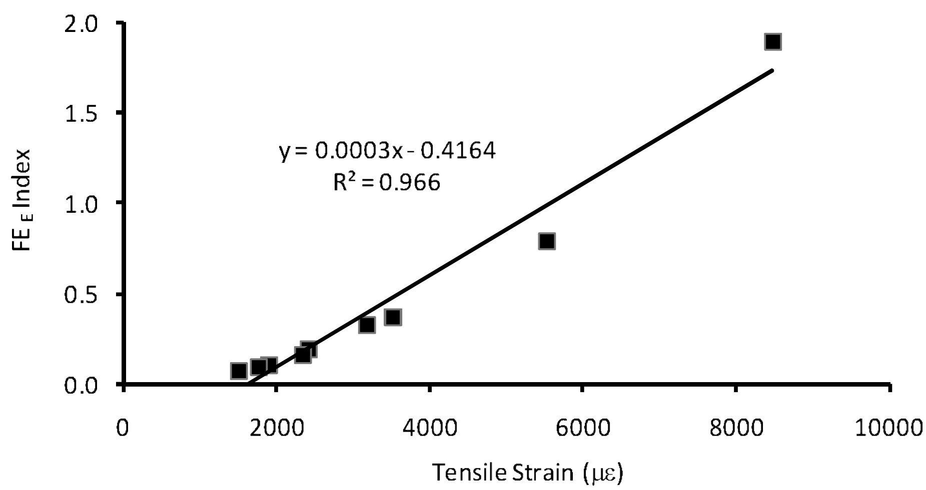

Figure 7 Relationship between FE_E index and tensile strain values

Conclusions and recommendations

This paper evaluated the suitability of analyzing the HMA cracking resistance using fracture parameters determined based on the direct tension (DT) test. The fracture parameters analyzed corresponded to the tensile strength, tensile strain at the peak failure load, tensile modulus, and fracture energy. In addition fracture energy indices were proposed and analyzed as alternative fracture parameters for differentiating and ranking HMA mixes in terms of the cracking resistance potential in the laboratory. Based on the results and analyses conducted, the following conclusions were drawn:

The fracture parameters, including the tensile strength, tensile modulus, and fracture energy, were not able to effectively and consistently discriminate the cracking resistance potential of the HMA mixes evaluated or provide a ranking that is consistent with the historically observed field performance. However, the ranking of the HMA fracture resistance based on the tensile strain at the peak failure load exhibited reasonable agreement with both the mix-design characteristic and the field cracking resistance potential of the mixes.

As an alternative, the ranking determined based on the fracture energy indices (computed from the tensile strength, tensile modulus, and fracture energy values) proved realistic agreement with both the mix-design characteristic and the field cracking resistance potential of the mixes. Therefore, computation of the fracture energy and corresponding indices proved to be useful for HMA ranking and mix design purposes. The inclusion of parameters related to the entire stress-strain response curve of the HMA for computation of the fracture energy indices is considered an advantage over the conventional fracture parameters (i.e., tensile strength, and tensile strain at the peak failure load).

Overall, recommendations are that the fracture energy indices, in particular the FE_E and the tensile strain at peak failure load exhibited great potential for routine application to differentiate and screen mixes in the laboratory. Thus, consideration should be given to incorporate these fracture parameters in the HMA mix-design processes.

Additional research should be conducted to further explore the fracture energy indices concept and validate the conclusions reported in this study based on field performance data of more HMA mixes. The same concept could also be applied to characterize the HMA response subjected to different conditioning processes (e.g., asphalt oxidative aging).

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