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Fatigue characteristics of modified asphalt binders using fracture mechanics

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ABSTRACT

This paper presents a new criterion to estimate fatigue characteristics of modified asphalt binders based on fracture mechanics theory. A finite element analysis using the FRANC2D software was carried out to establish the relationship between the crack length propagation and the stress intensity factor of the specimen tested in the Dynamic Shear Rheometer. The experimental results showed that temperature rise reduces two fracture parameters: crack growth rate at failure (da/dN) and stress intensity factor (ΔK). da/dN and ΔK showed high capacity of explaining the fatigue characteristics of modified asphalt binders. Modifiers may improve mechanical damage resistance of the asphalt binder.

1. Introduction

Fatigue cracking in asphalt pavements has been considered an object of study for several authors and research agencies in an attempt to solve the problem of premature mechanical deterioration of pavements [1]. The main motivation for studying fatigue in asphalt binders concerns the resistance of asphalt mixtures to fatigue cracking, which is consistently explained by the resistance of the asphalt binder to the action of cyclic loading [1,2]. An alternative to overcome this problem and improve the pavement service life is the addition of modifiers to the pure asphalt binder. There are evidences that this type of addition increases the fatigue resistance of the base binder and, consequently, improves the performance of pavements [3–5].

Several researchers have made efforts to understand the fatigue behavior of asphalt binders [6–10]. As a consequence of these studies, some proposals have emerged to establish criteria to indicate the fatigue resistance of asphalt binders [6–10]. For instance, the Superpave specification for asphalt binders limits the maximum value of $G^{*}\sin\delta$ parameter at the intermediate temperature of the performance grade on the PAV aging condition to control fatigue cracking. Several studies have indicated that the adoption of this parameter to control fatigue cracking is not appropriate to characterize the fatigue behavior of asphalt binders used in paving [2,3,7,10–12]. Some authors have suggested that this parameter must be suppressed from the Superpave specification [11].

The time sweep test was one of the first test proposals to minimize the limitations of the fatigue parameter of the Superpave specification [6]. This test is based on the definition of fatigue damage as a function of material mechanical degradation

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Nomenclature

G^*	shear complex modulus
δ	phase angle
da/dN_c	critical crack growth rate
N	number of cycles
a	crack length
a_f	crack length at failure
K	stress intensity factor
K_{I}	stress intensity factor in mode I
K_{II}	stress intensity factor in mode II
N_{p20}	number of cycles of crack propagation
ΔK_c	critical stress intensity factor range

Abbreviations

LAS	linear amplitude sweep
AC	asphalt cement
EVA	ethylene vinyl acetate
PE	polyethylene
SBS	styrene butadiene styrene
PPA	polyphosphoric acid
VECD	viscoelastic continuum damage
DSR	dynamic shear rheometer
RTFOT	rolling thin-film oven test

due to repeated loads. The test procedure performed in the dynamic shear rheometer (DSR) consists of applying cyclic loads in oscillatory regime at a constant strain or stress and at a fixed frequency. The test provides a reasonable analysis of the fatigue behavior of the material, but it can take too long.

In 2010, the linear amplitude sweep (LAS) test [12] was proposed as an attempt to replace the time sweep test and overcome the problem of time duration. The LAS test has maintained some characteristics of the time sweep procedure, e.g., the application of reversal cyclic loadings and the fixtures used in the DSR. The difference lies on the loading scheme, once progressive increments of strains are applied in order to accelerate the damage.

The analysis of the data obtained from the LAS test proposed by Johnson [12] uses the theory of viscoelastic continuum damage (VECD), which has been used extensively to model the fatigue behavior of asphalt mixtures. This analysis provides an estimate of the fatigue life at any strain amplitude by means of a single test of short duration. In this approach, the material suffers mechanical degradation over cycles but the specimen is assumed into the hypothesis of continuity, i.e., the object completely fills the space it occupies. The damage criterion is associated with the change in the loss modulus ($G^*\sin\delta$) [12].

In 2012, Hintz [13] hypothesizes that the fatigue process creates geometry changes in the specimen due to macrocracking rather than changes in viscoelastic properties. This author proposed another criterion for estimating the damage tolerance based on fracture mechanics. The failure criterion is the parameter a_f, that is, the minimum point of the curve generated by the relationship between da/dN (crack growth rate) and the parameter "a" (the crack length). This parameter corresponds to the point before a rapid increase in the crack growth rate is observed [13].

The problem with the a_f parameter is that this criterion does not account for the load and strain level associated with the failure crack length. Moreover, in a study presented by [14] on a set of modified asphalt binders, the fatigue failure "a_f" was not clearly observed for the AC + Rubber and the AC + EVA. Such author [14] proposed an alternative analysis based on the dissipated energy ratio and the observation of oscillatory variables of the test.

To overcome these problems and provide a failure criterion to establish a relationship between load/strain and fatigue failure, this paper presents a new analysis method of the LAS test based on fracture mechanics. A numerical model using finite elements (FE) was created to represent the specimen on the DSR and to determine the stress intensity factors using the Franc2D software. Comparisons between numerical and experimental results of the LAS test were performed and good agreement was observed.

1.1. Background

Fracture mechanics has played an important role in predicting the lifetime of materials which are subjected to time-dependent crack growth, as observed in the fatigue processes. The crack growth due to fatigue has been studied over the last 60 years and this approach has been used, mainly, to describe the failure of metals and aircraft components [15,16].

Although most research works in fatigue have been addressed on fatigue of metals, mechanical degradation processes due to cyclic loading is a problem in almost all structural systems and asphalt binders are not invulnerable to this phenomenon.

The cyclic load makes that a finite number of polymer chains be broken as cracks advance. In polymers, for instance, chain scission and hysteresis heating are the two main mechanisms that control the fatigue process. In brittle materials, crack growth occurs by chain scission and the crack tip yielding often has a minor effect. On viscoelastic materials, the region surrounding the crack tip may be influenced by local effects and viscous flow [17].

Regarding asphalt binders, stiffness is highly influenced by temperature. At intermediate temperatures, asphalt binders are more rigid and elastic than at high temperatures. The results of a research study conducted by the Strategic Highway Research Program (SHRP) [18] defined the temperatures of the typical rheological behavior of asphalt binders before and after aging in the field in relation to the main pavement distress modes. As a result of this investigation, the prevailing failure mode at the temperature zone of 0–40 °C is fatigue damage [19].

Several studies have applied linear elastic fracture mechanics (LEFM) to mechanical model of asphalt binders, especially at low temperatures [20–24]. Other authors [24,25] have also performed analyses using three theories: LEFM, Elastic Plastic Fracture Mechanics (EPFM), and Time Dependent Fracture Mechanics (TDFM) at lower service temperatures. Recently, other studies have applied the fracture mechanics approaches to study the mechanical behavior of asphalt binders at low temperatures on Beam Bending Rheometer [26] and Direct Tensile Test (DTT) [27]. Most of these studies used fracture mechanics theory considering permanent load regime and few of them have used oscillatory load regime in torsion, assuming cyclic repeated loads to analyze the mechanism of fatigue degradation in asphalt binders.

Even though LEFM theories are less accurate with the increase of the inelastic region at the crack tip, these inaccuracies may be neglected when the material is subjected to stress far less that the yield stress. Furthermore, the accelerated scheme of loading may induce rapid crack growth, which makes mechanical nonlinearities that arise from fracture process zone be disregards [12]. Corrections in the presence of high plasticity on the crack tip may be applied to the LEFM, but this approach can have a reasonable accuracy for purposes of comparison and ranking of materials.

1.2. Fatigue based on fracture mechanics approach

Fracture mechanics is an accurate theory for crack growth model due to fatigue [28,29]. In the 1960s, Paris and Erdogan [29], showed the application of fracture mechanics to fatigue problems. The Paris law for fatigue processes establishes that there is a relationship between the crack growth rate (da/dN) and parameters or functions dependent on the stress intensity factor (k). It is expressed as follows:

$$\frac{da}{dN} = f(\Delta k) \tag{1}$$

Problems of fatigue crack growth for several materials can be accurately addressed by estimating the stress intensity factor values and their relationship to the crack length. The estimation of the parameter k allows a proper evaluation of the stress field in the crack tip, thus determining the energetic state of the crack [30].

2. Materials and methods

2.1. Asphalt binders and testing

To prepare the modified asphalt binders, the following materials were used: (a) a 50/70-penetration-grade base asphalt binder supplied by the Replan–Petrobras refinery (Paulinia, Sao Paulo, Brazil) and graded as PG 64-xx; (b) UB-160C low-density polyethylene (PE); (c) Innovalt® E200 polyphosphoric acid (PPA); (d) crumb rubber with 100% of the particles passing on a #30 sieve; (e) HM 728 ethylene vinyl acetate (EVA); (f) D1101 SBS copolymer and (g) 4170 Elvaloy terpolymer.

The formulations were prepared using a Fisatom 722D low-shear mixer and a Silverson L4R high-shear mixer. Table 1 shows the modifier contents and the processing conditions. The modifier contents were selected in order to reach the same high-temperature performance grade for all the formulations – PG 76-xx – according to the new version of the Superpave specification (AASHTO M320-09, Table 3). The LAS tests were performed on a DSR model AR-2000ex.

Table 1
Modifier contents and processing variables.

Formulation	Formulations (% by mass)			Processing variables			
	Binder (AC)	PE	PPA	Shear level	Speed (rpm)	Temperature (°C)	Time (min)
Base binder	100.0	–	–	–	–	–	–
AC + PE	94.0	6.0	–	Low	440	150	120
AC + PPA	98.0	–	1.2	Low	300	130	30
AC + Rubber	86.0	14.0	–	High	4,000	190	90
AC + EVA	92.0	8.0	–	Low	300	180	120
AC + SBS	95.5	4.5	–	High	4,000	180	120
AC + Elvaloy + PPA	98.4	1.3	0.3	Low	300	190	120[a]

[a] The polyphosphoric acid was added to the AC + Elvaloy after 60 min of mixing time.

Table 2
Complex shear modulus and phase angle for the testing conditions.

Formulation	25 °C		35 °C	
	G^* (Pa)	δ (degrees)	G^* (Pa)	δ (degrees)
AC base binder	1.12E+07	49.5	2.13E+06	61.5
AC + PE	1.49E+07	43.2	4.22E+06	49.5
AC + PPA	1.24E+07	43.6	2.91E+06	51.1
AC + Rubber	7.19E+06	46.8	1.30E+06	55.7
AC + EVA	8.64E+06	44.8	1.90E+06	47.7
AC + SBS	1.26E+07	44.3	2.58E+06	55.3
AC + Elvaloy + PPA	1.03E+07	48.1	1.73E+06	59.7

The LAS test uses the parallel plate geometry of 8 mm in diameter and 2 mm in gap. The procedure recently standardized by AASTHO TP 101-14 consists of applying a reverse cyclic loading in two stages: (a) a frequency sweep with the application of a constant strain of 0.1% and frequencies ranging from 0.2 to 30 Hz; and (b) a linear amplitude sweep with linear strain increments from 0.1% to 30% in a time interval of 300 s and a constant frequency of 10 Hz. The tests were conducted at 25 and 35 °C on short-term aged samples (RTFOT, ASTM D2872-04 [31]). Table 2 provides information about the stiffness (G^*) and elasticity (phase angle) of the materials for the testing conditions at frequency of 10 Hz. These results were obtained in the frequency sweep step of the LAS test.

2.2. Applying fracture mechanics using a finite element model in FRANC 2D

To evaluate the stress field at the crack tip, the determination of the stress intensity factors k is required. It was obtained by finite element model simulations of the specimen in the DSR and by applying the principles of fracture mechanics using the FRANC2D software. The software was developed by the Cornel University and utilizes a two-dimensional finite element approach to simulate curvilinear crack propagation in planar (plane stress, plane strain, and axisymmetric) structures. This is a free computational code available on internet.

To create the numerical model, FRANC2D was used considering a section of a specimen (Fig. 1). The element was modeled as a planar axisymmetric element representative of the specimen. Ten divisions in the vertical axis and twenty divisions in the horizontal axis were created to generate the mesh. This was created using the automatic option. The stress distribution used on the numerical model is assumed to be a parabolic shape. Such stress distribution was assumed based on the theoretical approach presented by [32] in order to account for the progressive increment of stresses in the specimen.

The theory used to determine the direction of crack growth was the Maximum Circumferential Theory, as well as the critical fracture load applied in the model. This theory states that the crack moves towards the maximum circumferential stress surrounding the crack tip when a critical value of the stress is reached [33]. The stress intensity factors are calculated using the J-integral, which is a integral along a curve independent of the path for integration [34]. The J-integral is defined by:

$$J = \int_{\Gamma} \left(W dy - T \cdot \frac{\partial u}{\partial x} ds \right) \tag{2}$$

where Γ is a curve surrounding the crack tip, T is the traction vector defined to the outward normal along Γ, $T_i = \sigma_{ij} n_j$, u is the displacement vector, and ds is an element of the arc along Γ. The crack propagation is obtained automatically by FRANC2D software without user interaction. At each crack length increment, the software constructs a finite element mesh, calculates the stress intensity factors, calculates the direction of propagation of the crack, deletes the finite elements along the crack, updates the figure geometry and reconfigures the FE mesh. The stress intensity factor is calculated for each crack increment.

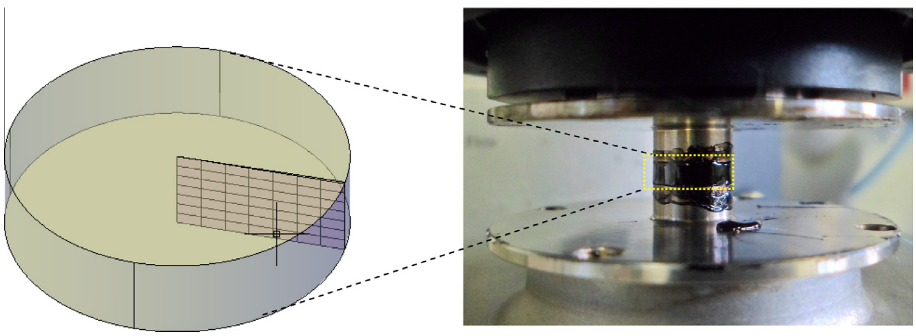


Fig. 1. Schematic specimen in the LAS test.

3. Results and discussion

3.1. Numerical modeling in franc 2D

The energy stored in the material around the crack tip is a function of the crack length, applied load and geometry. The energy state on the structure can be expressed, in global form, using the equivalent factor stress intensity K_{eq} (Eq. (3)). This variable is a combination of stress intensity factors for fracture modes I and II [34], where θ_p is the direction angle of crack propagation

$$K_{Eq} = K_I \cos^3\left(\frac{\theta_p}{2}\right) - 3K_{II}\cos^2\frac{\theta_p}{2}\sin\left(\frac{\theta_p}{2}\right)\sin\left(\frac{\theta_p}{2}\right) \tag{3}$$

Fig. 2 shows the results of the crack propagation of the finite element model in the FRANC2D software. The results of the finite element model showed that the stress intensity factor in mode I (K_I) is always much higher than the factor in mode II (K_{II}). Consequently, the energy available to the crack growth can be expressed purely in this case by K_I. It can be verified that the crack growth path obtained in finite element models follows the path observed in the DSR test, i.e., a circumferential crack growing from outside to inside of the specimen [13]. Fig. 3(b) shows a photo in which one observes a circumferential crack on a specimen of after torsion fatigue.

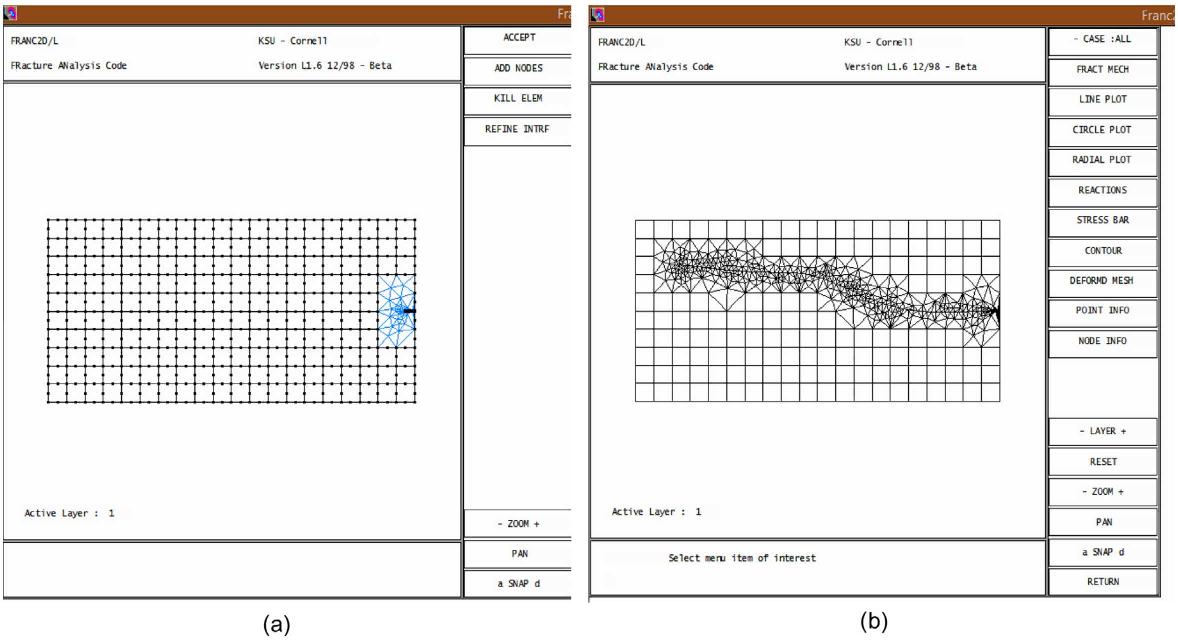


Fig. 2. Finite element models in the FRANC2D software: (a) initial finite element mesh. (b) Predicted crack growth after a propagation of the initial crack.

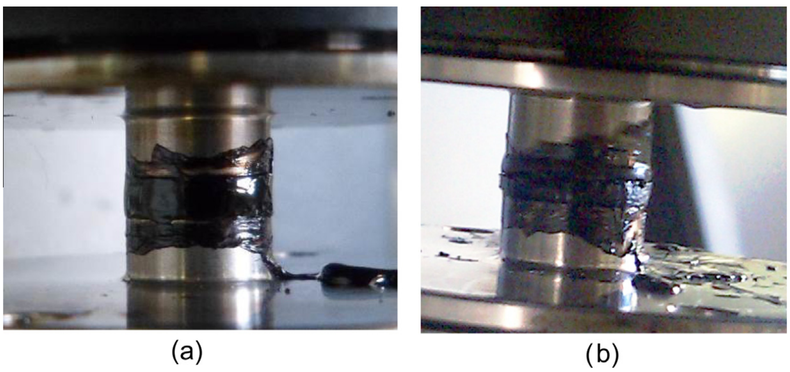


Fig. 3. Specimen of asphalt binder in torsion fatigue (a) before test, and (b) after test.

3.2. Experimental results of fatigue behavior based on fracture mechanics on the LAS test

The picture presented in Fig. 4(a) shows the crack pattern of the fracture surface specimen of 0.47 carbon steel in reversed torsion fatigue of notched cylindrical specimens [35]. Murakami et al. [35] indicates that in torsional fatigue, the crack grows according to the mode I fracture and the surface shows the so-called *factory-roof* morphology. This fact was observed in the present study as well.

Fig. 4(b) presents a photo of the fracture surface of the AC + PE after the LAS test at 35 °C. Table 2 provides information about this, and it shows the high levels of stiffness and elasticity of the AC + PE at 35 °C (G^* = 4.22E+06 and δ = 49.5°). The direction and shape of the cracks of the other asphalt binders were similar to the pattern observed for the AC + PE, and also followed the material behavior described by other authors [35,13]. Such fact suggests that, at least in some extent, the mode I fracture is the major mode of propagation of cracks in the torsion fatigue test on the DSR.

Based on the observations previously mentioned, the stress intensity factor K_I was calculated considering the solution of the fundamental problem of Griffith [17]. This problem can be written as follows:

$$K_I = \sigma \cdot \sqrt{\pi \cdot a} \tag{4}$$

Eq. (4) was applied to the LAS test in which direct oscillatory measurements of stresses and strains at each cycle were performed. In the last expression, σ corresponds to the oscillatory stress and a is the crack length which is calculated as a function of the change in the torque applied during the test. The variable "a" is calculated as follows [13]:

$$a = 4 - 4^* \left(\frac{T_0/\varphi_0}{T_i/\varphi_i} \right)^{0.25} \tag{5}$$

where T_0 and φ_0 are the initial torque and displacement, respectively. T_i and φ_i are the corresponding torque and displacement values in cycle i, respectively.

Fig. 5 shows the normalized values of K versus a based on the numerical results from the Franc2D software and the experimental results in the DSR. In the first part of the curves (up to a certain value of the parameter a), a proportional increase in the K values with increasing a values is observed. For higher a values, the material behavior can be described by minor changes in the parameter K up to the maximum point. The normalized intensity factor decreases after this point. This decrease in the k values indicates changes in the stress state of the material originated by the rapid crack propagation. It is therefore suggested that failure by fatigue in the specimen can be observed in the maximum point of the curve K versus a.

Fig. 5 shows that numerical results of FE model in FRANC2D and the experimental results present similar shape and good agreement. The AC base binder and the AC + SBS showed the best agreement. The AC + EVA, the AC + CRubber and the AC + PPA at 35 °C showed the major differences between numerical and experimental results. However, these differences are minor when the values are closer to the failure.

As previously described, the fatigue phenomenon is commonly modeled using the number of cycles and the crack length increment, which are connected by the stress intensity factor range, ΔK. Thus, a criterion to determine the fatigue failure of asphalt binders on the LAS test may be the point of the curve da/dN versus ΔK in which an abrupt behavior change is observed. This approach seems reasonable because at this point the stress intensity factor and the rate of crack propagation change suddenly due to the collapse of the specimen.

Fig. 6 shows the curves da/dN versus ΔK. The numerical data obtained in the LAS test and reported elsewhere [14] indicate that failure by fatigue is not clearly observed for the AC + Rubber and the AC + EVA based on the a_f criterion. However,

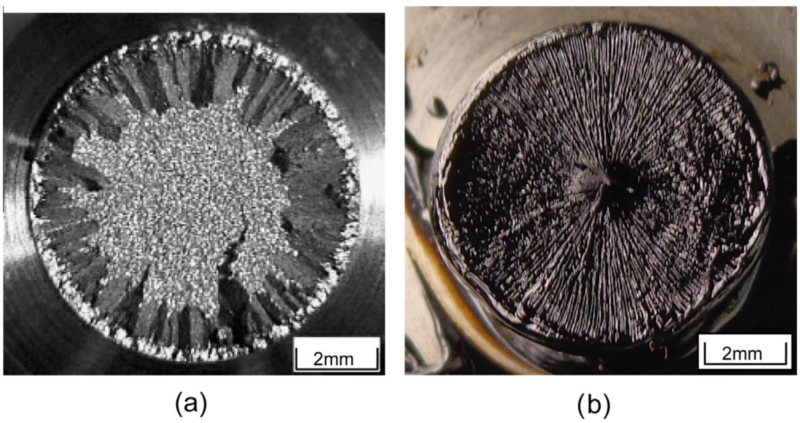
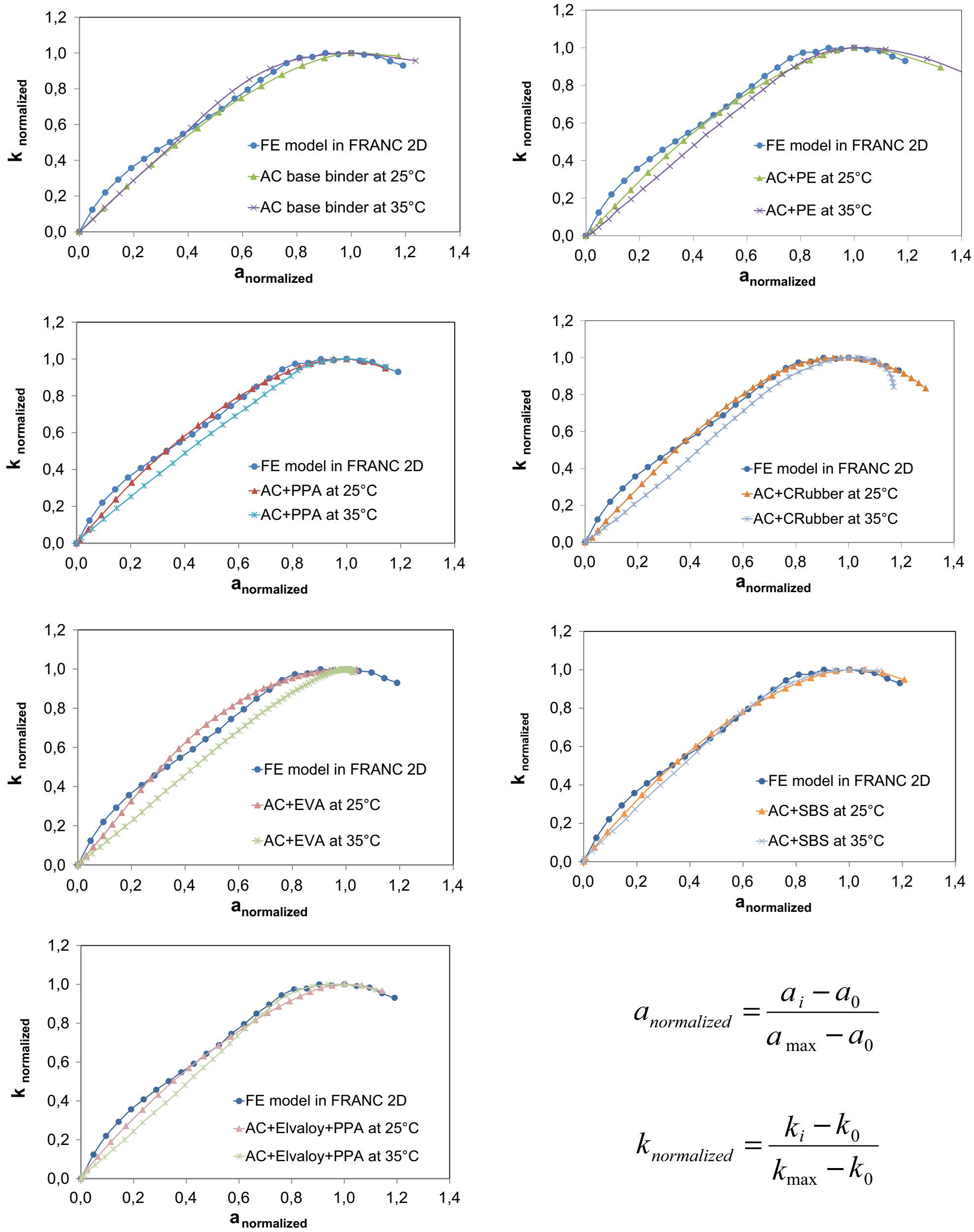


Fig. 4. Fracture surface of cracked specimen: (a) 0.47 carbon steel in torsion fatigue of notched cylindrical specimens [34], and (b) AC + PE asphalt binder at 35 °C in torsion fatigue on DSR.



$$a_{normalized} = \frac{a_i - a_0}{a_{\max} - a_0}$$

$$k_{normalized} = \frac{k_i - k_0}{k_{\max} - k_0}$$

Fig. 5. Comparison of the relationships between K versus a obtained from the finite element model and actual data from the DSR.

the failure of these samples can be recognized with the application of the suggested criterion, namely, the AC + Rubber (Fig. 6 (a) and (b)) and the AC + EVA (Fig. 6(c) and (d)). Table 3 shows the minimal points of the curves da/dN versus ΔK (ΔK_c). These results were obtained from two replicates for each of the eight asphalt binders in the LAS test. It can be seen that the results have good repeatability, since the variations are all lower than 16.2%.

The AC + EVA and the AC + Rubber describe crack growth rates lower (Table 3) than the other materials. Interestingly, the tendencies observed in Fig. 6 for the AC + EVA and the AC + CRubber show that apparently these materials do not exhibit growth rate after failure and in the case of the AC + EVA the tendency is to decrease the crack growth rate. Based on these observations, one can verify that the mechanical fatigue behavior can be divided into two phases. The first phase in which the mechanical damage is caused by crack growth due to fatigue and the second phase where material fracture occurs. In the first phase, the crack grows steadily under the application of load cycles. In the second phase, the crack grows unsteadily and

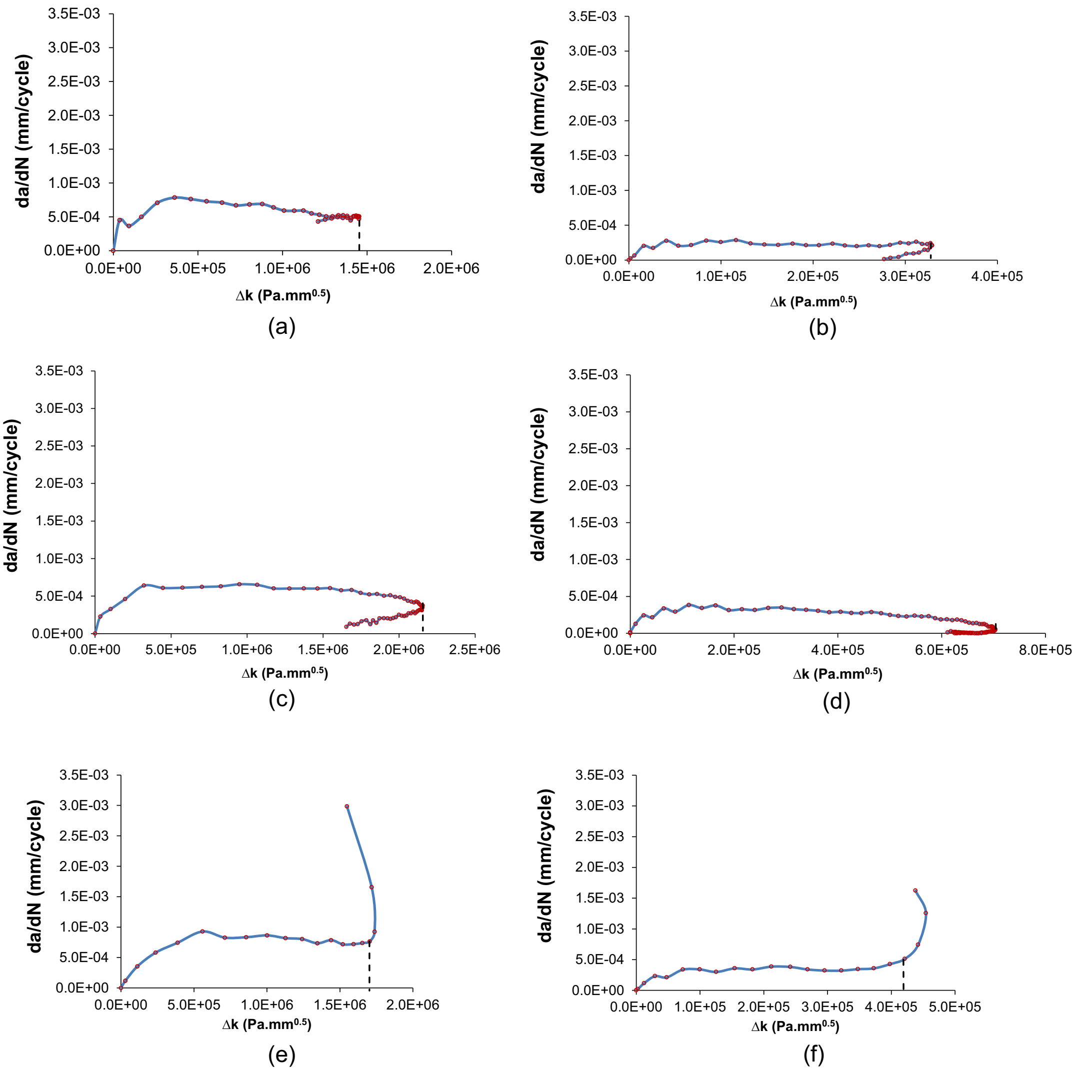


Fig. 6. Curve da/dN versus ΔK. (a) AC + CRubber at 25 °C, (b) AC + CRubber at 35 °C, (c) AC + EVA at 25 °C, (d) AC + EVA at 35 °C, (e) AC base binder at 25 °C, and (f) AC base binder at 35 °C.

the material fracture is observed. In the region of fracture, the crack grows unstably and the mechanical behavior is either linear or non-linear (cohesive), according to the composition of the asphalt binder.

The fatigue behavior can be modeled by the LEFM up to the point ΔK_c, according to Fig. 6. The material shows a fracture behavior after ΔK_c, and this behavior is characterized by a considerably smaller region (in terms of number of cycles) than the fatigue one. The behavior on fracture depends on the asphalt binder type. For the AC base binder (Fig. 6(e) and (f)), the fracture modeled by the LEFM seems to maintain a rapid and unstable crack growth, whereas the AC + EVA and the AC + Rubber (Fig. 6(a)–(d)) presents a softening mechanical behavior in the fracture phase that might indicate a cohesive mechanical behavior. Such behavior indicates that these materials may have a superior fatigue resistance by exhibiting some residual resistance even after failure.

3.3. Validation of the experimental results and discussion

Fig. 7 presents the validation of the new proposed criterion with the time sweep test results using the N_{p20} failure criteria based on the dissipate energy concept [5]. The time sweep test was performed in the controlled strain mode at 10% strain and 10 rad/s, at 25 °C and 35 °C. Normally, two replicates were run for each binder. If results varied by more than 15%, a third replicate was run [6,36].

Table 3
Results of LAS test using fatigue approach based on fracture mechanics.

Formulation	Replicate 1		Replicate 2		%Var.[a]	
	da/dN_c (mm/cycle)	ΔK_c[b] (Pa $mm^{0.5}$)	da/dN_c (mm/cycle)	ΔK_c[b] (PA $mm^{0.5}$)	da/dN_c	ΔK_c
Results at 25 °C						
AC base binder	9.24E−04	1.74E+06	8.81E−04	1.94E+06	4.7	10.8
AC + PE	6.75E−04	2.38E+06	7.12E−04	2.52E+06	5.3	5.6
AC + PPA	7.53E−04	2.00E+06	7.65E−04	2.04E+06	1.6	2.2
AC + CRubber	5.06E−04	1.45E+06	5.34E−04	1.59E+06	5.3	9.1
AC + EVA	3.73E−04	2.16E+06	3.32E−04	2.05E+06	11.6	4.9
AC + SBS	6.81E−04	2.10E+06	7.46E−04	1.94E+06	9.1	7.9
AC + Elvaloy + PPA	5.76E−04	1.95E+06	5.68E−04	1.79E+06	1.3	8.6
Results at 35 °C						
AC base binder	3.58E−04	3.73E+05	3.98E−04	4.20E+05	10.7	12.0
AC + PE	5.00E−04	9.58E+05	4.34E−04	9.53E+05	14.3	0.6
AC + PPA	2.91E−04	6.74E+05	3.43E−04	6.01E+05	16.2	11.4
AC + CRubber	1.80E−04	3.40E+05	2.10E−04	3.29E+05	15.8	3.4
AC + EVA	1.38E−04	7.03E+05	1.31E−04	6.91E+05	5.8	1.7
AC + SBS	4.83E−04	5.55E+05	4.27E−04	5.87E+05	12.4	5.4
AC + Elvaloy + PPA	2.11E−04	4.22E+05	2.39E−04	3.93E+05	12.4	7.2

[a] Percentage of variation calculated in relation to the average.
[b] $\Delta k_c = k_i - k_{i-1}$.

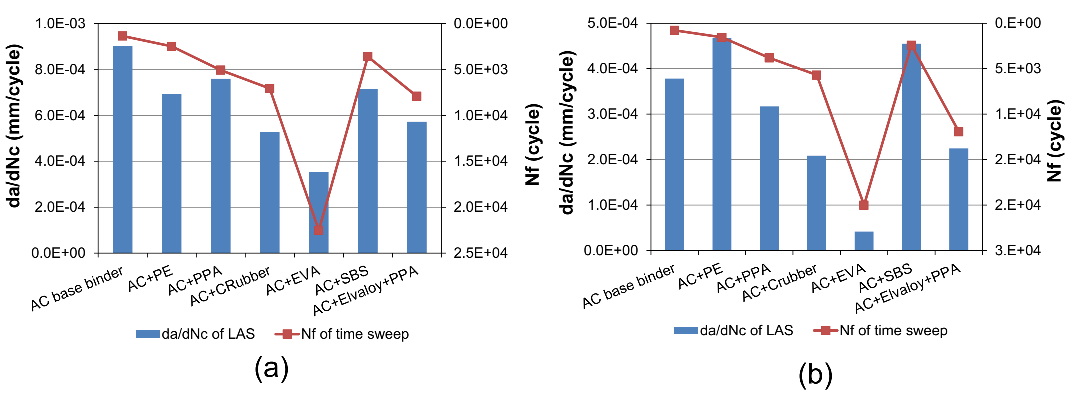


Fig. 7. Comparison of the failure results between the LAS test and the time sweep test at: (a) 25 °C and (b) 35 °C.

The comparison of the results of LAS test and the time sweep showed similar tendencies with slight discrepancy in the fatigue behavior. These discrepancies can be attributed to differences in load mode and frequencies on the LAS and the time sweep test, i.e., the LAS test is an accelerated test with incremental strain whereas the time sweep test is performed at a constant strain.

Fig. 8 shows the results of the average of two replicate of the LAS test at 25 and 35 °C using the proposed criteria. Low crack growth rates (da/dN_c) indicate that the material is more tolerant to fatigue damage. On the other hand, higher critical stress intensity factors (ΔK_c) may indicate that the material has a higher energy storage capacity. Therefore, it resists to higher stress levels. According to this rationality, materials with better behavior to fatigue should have high values ΔK_c (higher toughness) and lower values of da/dN_c (lower crack growth rate).

It is important to mention that all modified asphalt binders had crack propagation rates lower than the base asphalt binder in the tests performed at 25 °C. At 35 °C, the AC + PE and the AC + SBS had crack propagation rates higher than the base asphalt binder, whereas the AC + PE showed the highest toughness to fracture by fatigue. The AC + EVA exhibited the best fatigue behavior at both temperatures, showing the highest toughness to fatigue and the lowest crack growth rates. The results showed that the temperature rise produces a decrease into the fracture toughness by fatigue and at the same time, the crack growth rate is reduced. This implies that temperature rise may decrease the speed of crack propagation. On the other hand, the stress intensity factors also reduce and, consequently, the capacity of the pavement to support heavy traffic loading may also be reduced.

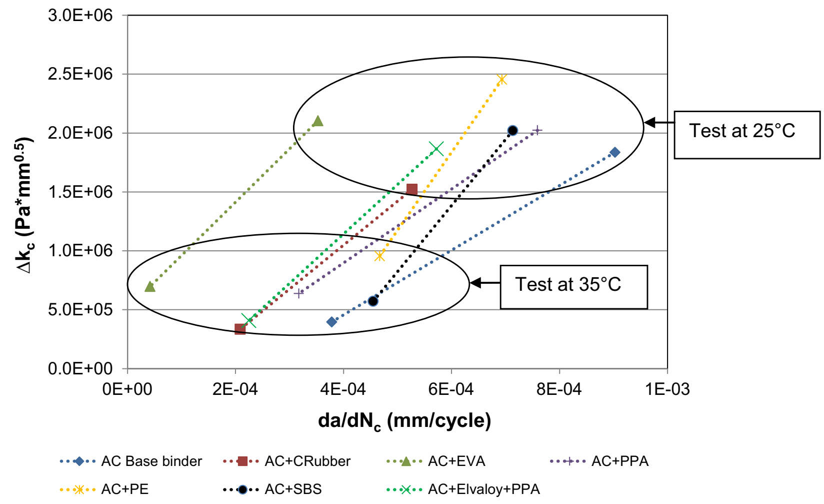


Fig. 8. Curve da/dN_c versus Δk_c for the asphalt binders on LAS test.

4. Conclusions

This paper presented an alternative criterion for fatigue characterization of asphalt binders in the Dynamic Shear Rheometer (DSR) based on fracture mechanics. A numerical FE analysis framework was used to investigate the crack propagation characteristics of specimens of modified asphalt binders using the LAS tests. Numerical results were compared to experimental results and good agreement was observed. These results were validated with the results of the time sweep test.

The following conclusions were achieved with respect to the outcomes of the asphalt binders studied:

- The achievements of the present study provide a practical criterion that may be suitable for ranking the fatigue resistance of asphalt binder in the LAS test. Two parameters were applied to estimate the fatigue characteristics of asphalt binders: (i) crack growth rate at failure and (ii) toughness to fracture by fatigue.
- The temperature rise reduces the crack growth rate at failure and also the toughness to fracture by fatigue.
- Addition of modifiers is a good alternative to increase the fatigue resistance of the asphalt binders; the AC + EVA showed the best fatigue behavior on the LAS test at 25 and 35 °C; the AC base binder showed the worst fatigue behavior on the LAS test at 25 °C and the AC + SBS the worst fatigue behavior at 35 °C.

This new approach to analyze the results of the LAS test has the following advantages: to determine with good precision the fatigue failure in materials in which the a_f parameter is not enough to determine the failure point; to relate the stress intensity factor to the crack growth rate; to provide information about toughness and crack growth rates related to the fatigue process in asphalt binders with an accurate criterion and to compare the fatigue behavior of different materials under similar load or strain conditions.

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