Validation of the Essential Work of Fracture Approach to Fatigue Grading of Asphalt Binders

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ABSTRACT

This paper considers the essential work of fracture approach to asphalt binder grading for fatigue performance. Earlier published test results (Andriescu et al., Journal of the Transportation Research Board, No. 1875, 2004, pp. 1-8 and Andriescu et al., Proceedings of the Canadian Technical Asphalt Association, Vol. 49, 2004, pp. 93-122), are further analysed and subsequently validated with fatigue cracking data from the US Federal Highway Administration's pavement testing facility (FHWA PTF), which has recently become available.

Samples were tested in double-edge-notched tension (DENT) while the ligament length was varied. Duplicate measurements were generally found to be highly reproducible. Shapes of the load versus displacement records were found to be self-similar for all ligament lengths yet distinctly different between binders. The specific total work of fracture was plotted versus the ligament length to provide nearly straight lines. These observations validate the essential work of fracture approach to asphalt binder testing.

The analysis of the DENT test results provides: (1) the essential work of fracture, w_e, a measure of the work done in the

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fracture process zone, (2) the plastic work of fracture, βw_p, associated with energy absorbing processes away from the process zone, (3) the net section stress, σ_n, which provides an approximation for the tensile yield stress, σ_{ty}, and (4) the critical crack tip opening displacement, δ_t (= w_e/σ_{ty}), all in ductile failure.

Binder parameters were compared with cracking rates in the respective lanes of the FHWA PTF. Only the δ_t property was able to correctly rank performance and provide a high correlation with cracking distress for all five PTF sections studied. A system containing fibres, showed surprisingly high essential and plastic works of fracture compared to other materials that were evaluated. This ability for damage delocalisation may well explain the fact that the corresponding PTF lane shows almost no cracking to date.

Given the fact that δ_t is a proven fracture mechanics based parameter that provides a measure of strain tolerance in the presence of cracks in the brittle-to-ductile and ductile states, it deserves further investigation for fatigue ranking of asphalt binders. Eventually the authors envision the need for a comprehensive specification that includes limits on binder and perhaps mixture w_e, w_p, and δ_t in the ductile state.

INTRODUCTION

This paper documents and discusses the validation of a new fatigue grading approach for straight and modified asphalt binders. Although a number of publications have recently proposed various ways of obtaining parameters that are purported to be useful for the ranking of asphalt binders in fatigue, a consensus on which method is most desirable has yet to be found. An ideal test should provide an accurate, simple and reproducible property that is able to consistently rank performance in well-controlled trials and in practice.

Fatigue cracking is a major form of distress in asphalt pavements in both Canada and the United States. Potentially this is also the most costly form of distress. Once appropriate high- and low-temperature grades are selected, moisture damage is addressed through the use of appropriate antistripping agents for a particular binder, and ravelling is controlled through regular preventative maintenance, it is almost inevitable that in the end a pavement will fail due to some form of fatigue distress.

The large amount of resources that are currently spent on fatigue research shows that this is a problem that is considered to be important by many. The authors have embarked on an effort to better control the phenomenon through the development of a more fundamental testing method. It is believed that the essential work of fracture approach to grading shows promise and that it will be able to sort the good from the not so good materials.

This effort is supported in Canada through the Ministry of Transportation of Ontario, which has recently drafted a test method, LS-299 (draft) - Asphalt Cement Grading for Fracture Performance using Double-Edge-Notched Tension Procedure (*1*), which will hopefully soon be used more widely to get a better handle on load-induced cracking in northern pavements. In the United States the Federal Highway Administration (FHWA) is in active pursuit of better tests and hence has constructed a number of new lanes in its pavement testing facility (PTF) dedicated to the study of fatigue. The object of this paper is to validate the essential work of fracture approach with the recently obtained FHWA PTF data.

BACKGROUND

Fatigue Failure in Asphalt Pavements

Binder, mastic and aggregates preferably exhibit plastic flow and reorient themselves without opening cracks at high temperatures. The behaviour of binder/mastic at very low temperatures is to become very stiff yet brittle. Pavements preferentially crack across the lanes not due to structural inadequacy under traffic, but due to a build up of tensile thermal stresses that can exceed the strength of the material. The distress known as fatigue failure is manifested by significant surface cracks induced over extensive traffic repetitions at moderate temperatures that are typically in the 15ºC to 30ºC range. This type of failure includes both ductile and brittle processes. Fatigue cracks are believed to either initiate at the bottom or top of the asphalt layer then propagate upwards or downwards, respectively. However, the way in which fatigue manifests itself does depend somewhat on the geographical location.

In southerly climates, the surface layer of the asphalt pavement can often become very hard and brittle due to oxidation and volatilisation. In the end stage of a pavement's life this could lead to alligator-type cracks, which has historically been recognized as the primary symptom of fatigue. The photograph in Figure 1 provides an illustration of this distress pattern.

Figure 1. Late Stage Alligator Type Fatigue Cracks

In northerly climates, fatigue plays a role that is less well documented and understood. It has been reported that pavements with thicker structures show less transverse cracking (*2*). Also, lanes with less traffic show fewer transverse cracks (*3*). Alligator type cracking is rare in northern regions, which may be due to the usually rapid appearance of transverse cracks. Such cracks reduce a significant amount of repetitive thermal stress and hence slow the progression of wheelpath fatigue. Generally lower traffic levels in northern regions must also play a role. In very old northern pavements, a final disintegration of the structure can be associated with load induced cracking.

Recent reports further indicate that in relatively new pavements in both southerly and northerly regions, premature wheelpath cracking is not uncommon (*2, 4*). Such cracking is often associated with paving equipment-induced segregation during construction and is influenced by high thermal stresses and heavy vehicle loading (*2, 4*). This top-down cracking distress is currently being studied under NCHRP project 1-42A. Fracture properties of both the binder and mixture are thought to play an important role in preventing this type of failure (*2, 6*).

Conventional Binder Tests

There is an abundance of test methods that have been proposed over the years to predict fracture performance in service from simple and sometimes not so simple binder tests in the laboratory. Those that are most commonly used in North America include the elastic recovery, toughness/tenacity, ductility, and force ductility tests (for instance, see (*7-10*)). They were all developed long ago, are relatively simple to perform, give fairly reproducible results, yet for the most part they are empirical in nature. Their relationship to what actually happens in the pavement during and just before crack formation is unclear.

The various properties that are measured are likely of little use since the different processes of elastic, viscous, and plastic deformation, as well as crack initiation and propagation are confounded. The energy associated with the actual formation of the crack, which is likely one of the more important properties for fatigue, is combined with the viscous and plastic energy absorbed in the entire sample, which is likely of much lesser importance for what is generally a more localised failure in the asphalt mixture under severe loading conditions in service.

For example, if a force-ductility test were to be done on a wide range of binder materials with two different sample dimensions or geometries, then the relative rankings will likely change depending on the binders being studied, which is characteristic of a test that determines an *engineering property*. For grading purposes it is generally much preferable to measure a *material property* that is independent of specimen size and geometry and that is closely related to the actual fatigue fracture events as they occur in the asphalt pavement. Material properties are those that do not depend on specimen size and geometry and hence are ideal for performance ranking.

The elastic recovery test has likely originated from the observation that it is readily able to set apart elastomer-modified binders from straight run and other non-polymer modified materials. The test appears to be completely empirical and provides simply a measure of the presence of elastomers. As such it is still unclear what if any relation there is between the presence of elastomer and performance in the field. Binders with a high elastic recovery may not always perform in a desirable fashion.

Despite these concerns there are still a large number of user agencies that specify many of the conventional test methods for acceptance purposes. This fact likely stems from their use of large, historical databases that show some relation between the measured binder properties and performance.

Binder and Mixture Loss Moduli

In response to the mainly empirical nature of the conventional test methods, researchers funded under the Strategic Highway Research Program (SHRP) developed the dynamic shear rheometer for the accurate measurement of the binder loss modulus, $G^*\sin\delta$ (*11*). They argued that the amount of energy dissipated in a binder under sinusoidal loading conditions should accurately correlate to the amount of damage in the sample, and therefore be a measure of fatigue susceptibility. Their arguments largely followed those first made some 20 years earlier by Quedeville (*12*) and van Dijk (*13, 14*), who studied the dissipated energy (DE) concept in binders and mixtures.

Validation for the binder loss modulus limits, as proposed by the SHRP researchers, was obtained from the testing of materials used in the Zaca-Wigmore pavement trial (*11*). These tests suggested that an upper limit of 5.0 MPa on the binder loss modulus, at 10 rad/s, would largely prevent the occurrence of fatigue cracking in the pavement.

The use of the binder loss modulus as a fatigue grading parameter has now been refuted and deemed “counterproductive for many typical pavements” (*15, p. 666*). Others have concluded that the parameter shows no correlation with performance in accelerated loading tests, that it “falls in a zone that is fairly insensitive” (*16, p. 225; 17, p. 146*), and that it “does not correlate adequately with field performance” (*18, p. 604*). These conclusions could be inferred from a close inspection of the original Zaca-Wigmore data for which several binders that produced widely different fatigue severity in the pavement had loss moduli close to the limiting 5.0 MPa (*11*).

The researchers who originally came up with using the binder loss modulus have recently proposed to hold on to it until a better test method becomes available (*19*). It is the authors’ hope that others will gain more experience with (and confidence in) the essential work of fracture test method so that one day it may be able to replace the loss modulus for performance grading in fatigue.

Work under the SHRP mixture program validated the findings of van Dijk (*14*), that the initial mixture loss modulus, $S_o\sin\delta$, correlated well with the fatigue life in controlled strain, with lower mixture loss moduli giving higher fatigue lives (*20*). However, the same researchers also found that the DE concept was unable to provide a unique relationship between cycles to failure, N_f, and the cumulative dissipated energy to failure, W_N. The SHRP mixture team came to the conclusion that "relationships are different for different mixes and are affected by both test temperature and mode of testing" (*20*).

Despite this observation, it is evident from the early work of van Dijk (*13, 14*), Chomton and Valayer (*21*), Monismith et al. (*20*), and more recently Roque et al. (*6*), and Daniel et al. (*22*), that the use of $S_o\sin\delta$ for fatigue grading appears to have more merit than the use of the binder loss modulus, $G^*\sin\delta$. In the case of mixtures, it may be that a larger portion of the total work input causes damage rather than viscous and plastic flow. As such, the $S_o\sin\delta$ should correlate better with field data than the $G^*\sin\delta$, for which the contributions are likely totally confounded. Additional insights into this issue are provided in a recent paper by Uzan et al. (*23*), which will be discussed in the following section on fracture energy in asphalt research.

It is the authors' opinion that the problems with the binder loss modulus, $G^*\sin\delta$, and to a lesser extent with the mixture loss modulus, $S_o\sin\delta$, as fatigue grading parameters, are largely similar to those discussed for the conventional test methods. $G^*\sin\delta$ is a rheological property in the low strain regime that measures the total energy loss (in the low strain regime), in between two parallel plates in a rheometer. As such, it probably has little relation to the way in which a binder fails in an asphalt mixture. The actual failure processes in the pavement likely occur around stress concentrations (notches, voids), involve only small amounts of energy dissipation in the linear viscoelastic regime, involve a much larger amount of viscous energy dissipation in the high strain regime, some of which is associated with damage while much of it is not, and involves only a small degree of plastic deformation away from the fracture process zone. The inability of the dynamic shear rheometer to separate the energies and different phases of the fatigue process in the binder is an inherent drawback of the approach.

It is hoped that the issue of what parameter to use for performance grading will become clearer if the energies are considered individually. Furthermore, it would be beneficial if most of this can eventually be done with a simple, accurate, and reproducible binder or mastic test rather than with more involved mixture tests. The authors recognize, however, that binder tests will never be able to predict differences due to gradation, binder content, interfacial effects, exudation (oil absorption), and other mixture variables.

Fracture Energy in Asphalt Research

The proposal to use fracture energy parameters for performance grading has a long history in asphalt research (for instance, see (*23*-*30*)). For a review of the subject prior to 1997 the reader is referred to Ioannides (*26*), while for a more recent review reference is made to Uzan et al. (*23*), some relevant aspects of which are summarized herein.

Early work on the application of fracture mechanics focused on the use of fracture toughness, K_{Ic}, and energy, G_{Ic} (or J_{Ic}), which were considered as potentially useful properties for relating laboratory results to field performance (*27*-*30*).

Irwin (*24*) made the following comments: “fatigue characterizations in terms of fracture energy are as good or better than stress or strain fatigue characterizations”, “the fracture energy fatigue curves were sloped more steeply with respect to the abscissa, making fracture energy a slightly more discriminating failure criterion.” Since then, numerous other researchers have investigated the use of fracture properties to study failure in asphalt mixtures (e.g., see (*23, 26*)). However, because of difficulties, which, as reviewed by Ioannides, mainly relate to the possible formation of large damage zones (producing non-linear effects), and due to specimen-size effects, it was argued that this approach is unlikely to become successful for design purposes.

Largely in response to these problems, research groups in the US and Europe have recently started to investigate the fatigue process from more mechanistic and fundamental perspectives.

Some of these efforts involve new ideas while others repeat the work of years past.

Daniel et al. (*22*) comments that the DE approach, as first developed by van Dijk (*14*), Chomton and Valayer (*21*), Monismith and coworkers (*20*), and more recently by Roque and coworkers (*6*), appears to provide identical results to the viscoeleastic continuum damage (VECD) approach as first promoted by Kim and coworkers (*31*). However, both methods are still not able to provide a complete assessment of the fatigue process. Reports that “the VECD approach had difficulty ranking the two gradations according to the field performance”, “because only the damage growth characteristics were evaluated”, and “the DE approach was shown to be valid for uniaxial tension testing, but did not provide conclusive results for the Westrack mixtures”, suggest that both methods are still lacking in their ability to accurately predict the fatigue process (*22*). A recent study by Lundstrom and Isacsson (*32*) also questions the use of monotonic tests to describe asphalt fatigue behaviour and points out a certain degree of empiricism in the VECD approach to fatigue grading.

In contrast to these observations, it is interesting to note the conclusion in a recent paper by Wen and Kim (*33*) on the development of a simple performance test for fatigue. The authors found that “fracture energy at 20°C is proven to be an excellent indicator of the resistance of mixtures to fatigue cracking” in a validation study for which they used a limited number of mixtures.

Hence, considering these recent and past statements, beginning with the work of Quedeville (*12*), van Dijk (*13, 14*), Irwin (*24*) and others, on fracture energy, we have proposed that the fracture toughness of the binder will provide an improved indicator for fatigue cracking (*34, 35*). However, the question that still remains to be answered is what methods are best used to measure this and other fracture mechanics-based properties in a binder, mastic and mixture?

The main drawback of the current models and test methods for asphalt mixtures at ambient temperatures is that they have not separated the effective energies implicated in: (1) elastic deformation; (2) viscous and plastic deformation away from the crack zone; and (3) essential work performed in the process zone to produce the new surfaces, in a straightforward manner (e.g., see Uzan et al. (*23*)). It is unclear at this moment which parts are critical for performance prediction. Wen and Kim (*33*) argue that the elastic part of the energy is important whereas Roque et al. (*6*) subtracts the elastic part from the area under the stress-strain curve to focus on the dissipated strain energy. However, Wen and Kim (*33*) make the observation that "both strain energy and damage energy are highly correlated to the amount of fatigue". Uzan et al. (*23*) suggests that the viscoelastic energy associated with damage, as obtained by subtracting the dissipated viscoelastic energy from the total viscoelastic energy, is the most pertinent property for fatigue. Our work on the essential work of fracture test is able to simplify the issue considerably, hence a short description of the basic ideas are included hereafter.

Essential Work of Fracture and Critical Crack Tip Opening Displacement

Aside from the divergent opinions expressed in the recent literature, the authors are of the opinion that mixture tests are time consuming and the correspondence with the real fatigue life is still fragile at best. To address some of these difficulties, we have started to investigate an exceedingly simple method for the determination of material properties that are either independent of, or have a predictable dependency on, specimen size and geometry and which are involved in ductile failure of the binder and mixture (*34, 35*). We determine the specific essential work of fracture, w_e, the specific plastic work of fracture, βw_p, and the critical crack tip opening displacement, δ_t, which can be both failure and fatigue resistance criteria, in double-edge-notched tension (DENT).

From the net section stress in a DENT specimen, σ_n, we are able to get an approximation of the tensile yield stress of the binder, σ_{ty}, under a certain degree of constraint. This yield stress allows us to calculate the critical crack tip opening displacement, $\delta_t = w_e/\sigma_{ty}$, which is likely the most desirable property for fatigue performance grading since it provides a measure of strain tolerance in the brittle-to-ductile and ductile regimes in the presence of sharp cracks. To our knowledge, the essential work of fracture approach has received no attention in the asphalt literature until our first publications on this subject in 2004 (*34, 35*). However, it has been successfully used for quite some time to describe fracture in polymers, metals, and a host of composite materials (*36*).

A proposal to use the crack opening parameter, δ_t (m), for grading of asphalt binders in terms of their low temperature performance was recently made by Roy and Hesp (*37*), although the authors measured it indirectly as the ratio of the brittle state fracture energy, G_{Ic} (J), to compressive yield stress, σ_{cy} (N.m^{-2}):

$$\delta_t = G_{Ic}/\sigma_{cy} \qquad [1]$$

The compressive yield stress was used as a substitute for the tensile yield stress since the latter is inaccessible at low temperatures due to brittle failure. The binder δ_t's so obtained were compared to mixture test results for which there appeared to be a strong correlation (*37*). Current efforts at low temperatures are focussed on a more direct measurement of δ_t through the crack mouth opening displacement in a compact tension (CT) test on a small binder specimen (*38*).

For ductile failure, our two previous publications provide a detailed overview of the background to the essential work of fracture method as well as a significant amount of binder and mixture test results (*34, 35*), only the most essential details of which are reproduced herein.

In essence, the fracture analysis as first adopted by Cotterell and Reddel in 1977 (*39*) and further developed by Mai and coworkers (*36*), assumes that the total energy consumed in a constant rate of loading test on a DENT sample is partitioned into two parts, the essential part, W_e (J), associated with the formation of the fracture surfaces, and the plastic part, W_p (J), associated with energy absorbing processes away from the fracture process zone:

$$W_t = W_e + W_p \qquad [2]$$

These energy terms are additive and associated with different parts of the specimen. The ingenious insight provided by Cotterell and Reddel (*38*) is that the essential part of the work is surface related and the plastic part is volume related:

$$W_e = w_e \times LB\text{, and} \qquad [3]$$

$$W_p = w_p \times \beta L^2 B \qquad [4]$$

where,

w_e is the specific essential work of fracture ($J.m^{-2}$),
w_p is the specific plastic work of fracture ($J.m^{-3}$),
L is the ligament length in the DENT specimen (m),
B is the specimen thickness (m), and
β is a geometry factor to account for the shape of the plastic zone around the ligament (*34-36*).

Hence, the specific total work of fracture, $w_t = W_t/LB$, readily accessible from the DENT test, can be written as the sum of the specific essential, w_e, and specific plastic work of fracture, w_p, as follows:

$$w_t = W_t/LB = w_e + \beta w_p L \qquad [5]$$

This relationship provides the basis for the partitioning of the essential and plastic works of fracture. The geometry factor, β, depends on the shape of the plastic zone and can be assigned a value from a photographic analysis of the plastic zone or, alternatively, it can be carried along as a constant in any further analysis, provided the force versus displacement records are all of the same shape (i.e., self-similar).

Considering equation 5, it is obvious that if the theory is valid, that a plot of the specific total work of fracture, w_t, versus the ligament length, L, should provide a straight line with intercept w_e and slope βw_p. The essential work of fracture is likely a very important parameter for fatigue grading since it is solely related to the damage process. However, it is believed that the plastic work is also of importance and may explain differences in performance for binders with equal essential works of fracture. Further research with carefully designed pavement trials should try to resolve to what extent and under which circumstances plastic works of fracture are important.

Once the essential work of fracture is determined, the net section yield stress in a small ligament, σ_n, can be used to determine the crack tip opening displacement according to,

$$\delta_t = w_e/\sigma_n \qquad [6]$$

where,

δ_t is the critical crack tip opening displacement (m), and
σ_n is the net section stress, used here as a surrogate for the tensile yield stress ($N.m^{-2}$).

The crack tip opening displacement at failure is a parameter that has been successfully used for the design of structures against failure in the ductile-to-brittle and ductile states. It was first developed in the metals field by Wells in 1962 (*40*) and has since been used extensively by others (for instance, see (*41-44*)). It is believed that the yield stress is of significant importance and that it is likely able to explain differences in performance for binders of equal works of fracture. Eventually an asphalt binder or mastic specification is envisioned that sets limits on w_e, w_p, δ_t, and some measure of rate susceptibility for these in the ductile state.

EXPERIMENTAL

Materials

The materials in this study were obtained in sufficient quantities from various suppliers of modified asphalts. A detailed description of the binder properties is provided in Table 1.

Procedures

Binder Testing

The binder properties as listed in Table 1 were determined on rolling thin film oven (RTFO) and pressure aging vessel (PAV) aged residues using equipment at the Turner-Fairbank Highway Research Center in McLean, Virginia.

The essential work of fracture tests on asphalt binders and mixtures were conducted on an MTS Sintech 2/G test frame at Queen's University in Kingston, Ontario. The procedure for binder testing is now described in a new Ontario test method, LS-299 (draft) - Asphalt Cement Grading for Fracture Performance using Double-Edge-Notched Tension Procedure while additional details can be found in earlier publications (*1*).

TABLE 1. Pertinent Properties of PTF Binders

Binder	Modification Type	Grade, ºC	G*sinδ, kPa	$T_{G^*\sin\delta = 5\ \mathrm{MPa}}$, ºC
L2	Control	72-23	5326	25.4
L3	AB	74-28	3577	22.6
L4	SBS	72-31	1443	17.1
L5	CR-TB	79-28	2110	21.3
L6	RET	74-31	1160	14.3
L7 †	FIBS	-	-	-

† Rheological properties for the fibre-modified binder were not determined due to the particulate nature of the additive. However, the base asphalt in L7 was from the same source and grade as L2. AB = Air Blown; SBS = styrene-butadiene-styrene linear triblock copolymer; CR-TB = crumb rubber as blended according to a terminal process; RET = reactive ethylene terpolymer; and FIBS = 6.5-mm long, recycled poly(ethylene terephthalate) (PET) fibres.

In brief, samples were poured with the aid of silicone moulds in between aluminium end pieces. The end pieces were grooved in order to allow binder to form large contact areas for shear transfer of the load, which prevented failure at the aluminium inserts for all but the toughest binders. The specimens were all effectively 40 mm long, 30 mm wide, and 6.5 mm thick. Notch depths varied from 5 to 25 mm with corresponding ligament lengths from 25 to 5 mm. The notch angle was kept constant at 30º. A schematic of the specimen dimensions as well as a photograph of a failed specimen are provided in Figure 2.

The essential work of fracture for the fibre-modified material was determined with a larger specimen dimension in order to accommodate the fibres. Samples were cooled overnight at room temperature and subsequently tested in a screw-driven MTS Sintech 2/G load frame at 25ºC and a crosshead displacement rate of 100 mm/min.

The rate of 100 mm/min was chosen since it assures results within a reasonable amount of time. The test temperature of 25ºC was chosen for convenience. However, tests have been conducted on other binders at rates ranging from a low of 0.1 mm/min to a high of 3,000 mm/min and at temperatures from –12ºC to +36ºC.

These experiments revealed that the essential work of fracture ranking for most binders does not change in any major way from what is given by the ranking at 25ºC and 100 mm/min. Some hard binders become brittle at higher speeds while softer materials retain their ductility at even the fastest speed obtainable (Andriescu, Unpublished Work, 2005).

The specific total works of fracture, determined for samples with varying ligament lengths, was determined from the area under the force versus displacement curve and the ligament cross sectional area, $w_t = W_t/LB$. The specific total works of fracture were plotted according to equation 5 and linear regression analysis provided the specific essential and plastic works of fracture, w_e ($kJ.m^{-2}$) and βw_p ($MJ.m^{-3}$), respectively.

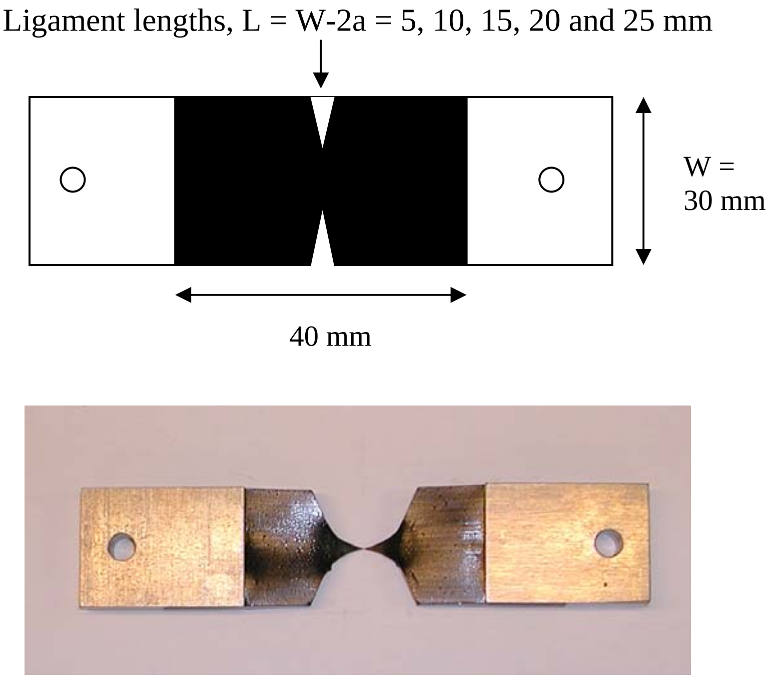

Figure 2. Schematic of Double-Edge-Notched Specimen and Photograph of Failed Specimen

Federal Highway Administration Accelerated Loading Facility

The FHWA's Pavement Test Facility (FHWA PTF) is designed to cost effectively induce representative full-scale pavement distresses through the application of actual tire loads to a representative pavement section. The FHWA PTF consists of two accelerated loading machines (ALF), to simulate traffic at controlled loading and pavement temperatures, and 3420 m^2 (0.83 acres) of grounds that provides space for 12 pavement test lanes. A photograph of both ALF machines and a close-up of a loading wheel are provided in Figures 3.

Figure 3. Federal Highway Administration's Pavement Testing Facility Showing Both Accelerated Loading Machines and Close-Up of Super-Single Loading Wheel Tire

The PTF has been operated in a series of experiments with the current 12-lane configuration since 1993; in that year, the 12-lane area was worked to provide a 660-mm (26-in.) pavement structure (dense-graded, crushed aggregate base and hot mix asphalt over a uniformly prepared, AASHTO A-4 subgrade soil.

Each pavement test lane in the current FHWA PTF experiment, the seventh at the PTF, is 4 m (13 ft) wide and 50 m (165 ft) long. Each lane provides four sites for ALF tests, two in the north half, two in the south. During the 2002 construction of the current test lanes, existing hot-mix asphalt (HMA), ultra thin whitetopping, and 50 to 100 mm (2 to 4 in.) of the crushed aggregate base were removed. The top of the remaining base was scarified and re-compacted and 100 mm of the same size crushed aggregate was added and compacted. Finally, 100 or 150 mm of HMA were added, as appropriate, to restore the full 660-mm base plus HMA structure.

The area immediately south of the PTF test lanes is the primary parking lot for the FHWA's Turner-Fairbank Highway Research Center (TFHRC). Because the lot was in need of rehabilitation at the time of the PTF lane reconstruction, the researchers and the TFHRC facility staff decided to repave it with 50- and 75-mm thick HMA overlays. The overlays served as control strips for each of the PTF test lanes; they were used to determine the appropriate rolling pattern to achieve the target density, to calibrate the contractor's nuclear density gauge, and to allow laboratory testing of the mixture's binder content, aggregate gradation, maximum specific gravity, and volumetrics. Density and thickness were checked on small rectangular blocks sawed from the pavement. Construction quality was greatly enhanced by this strategy, as the paving contractor was using most of the modified asphalt binders for the first time, and the construction specifications, especially for density and thickness, were tighter than for normal construction. Lanes 1 through 7 were constructed with 100 mm (4 in.) of HMA (over 560 mm [22 in.] of aggregate base), and Lanes 8 through 12 with 150 mm (6 in.) of HMA (over 510 mm [20 in.] of aggregate base). The primary variable in the test lanes is the asphalt binder, with the aggregate and mixture properties kept as constant as possible across the lanes. Table 1 lists the binders used in Lanes 2 through 7.

The binder for Lane 1 contained crumb rubber prepared according to the Arizona wet process. Since the binder content and mix design were adjusted accordingly, the materials were not evaluated for this study.

Loading Conditions, Strain and Rut Depth Measurements

The pavement sections were loaded at various temperatures and load levels. However, this paper only considers data obtained for six of the seven 100-mm thick sections at 19ºC and 16,600 lbs load since other experiments are still ongoing. The wheel loading speed was 18 km/h (11.5 mph) and sections were loaded in one direction only.

Strain gauges used in this study were H-bar type, embedded asphalt strain gauges and were fabricated by Construction Technology Laboratory (CTL) of Columbia, Maryland. A total of 60 strain gauges were installed in the 12 lanes of pavement.

Rutting measurements were obtained by recording the elevation changes between the initial elevations (before loading) and the elevations at different loading passes through the devices of rod and level. There are eight elevation recording locations at the centerline of loading at both the pavement surface and the top of the base course. The difference of rut depth between the surface and the top of the base course is the rutting in the HMA layer.

Crack Mapping

Manual crack mapping at the site was done at various intervals during the loading. The pavement was moistened to visually highlight cracks and transparent plastic sheets were placed over top to trace the outline. The cumulative crack length and the percent cracked area were determined. Both of the quantifications of the fatigue cracking on the site rank the performance of each mixture the same. At the time, crack width and severity was not incorporated, however, the ranking is still the same by the number of cycles to surface initiation. Thus, either cycles to surface initiation or cycles to a cumulative crack length may be used for comparisons to binder and mixture test parameters.

RESULTS AND DISCUSSION OF RESULTS

Asphalt Binder Test Results

For the sake of completeness, the binder test results as presented in our earlier papers are briefly reviewed in Figures 4-6. Some raw data are presented in Figure 4, which presents the duplicate force versus displacement records for a series of DENT specimens with notch depths ranging from 5 to 25 mm in 5 mm increments. The results show that the test method can be highly reproducible and that the tests for different ligament lengths are self-similar. This confirms that all specimens went through the same sequence of stretching, yielding, and tearing, which is a requirement for a valid essential work of fracture test. The full ligament section has to yield before the necking/tearing process finishes the sample since otherwise the analysis according to equation 5, assuming full-ligament yielding, would be invalid.

The essential work of fracture analysis for all five regular (i.e., non-fibre modified) binders is presented in Figure 5 while the essential and plastic works of fracture are presented in Figure 6 (*34, 35*).

The data in Figure 5 show that the energy analysis according to equation 5 appears to be valid, yielding nearly straight lines for all binders tested (r^2 from 0.92 to 0.99), which again confirms that the testing approach is sound.

Second, the essential and plastic works of fracture vary by significant amounts between binders. For instance, binders used in Lanes 4 and 5 show differences in essential works of fracture of as high as 2.5-fold, which can be considered very significant in light of the good reproducibility of the test method.

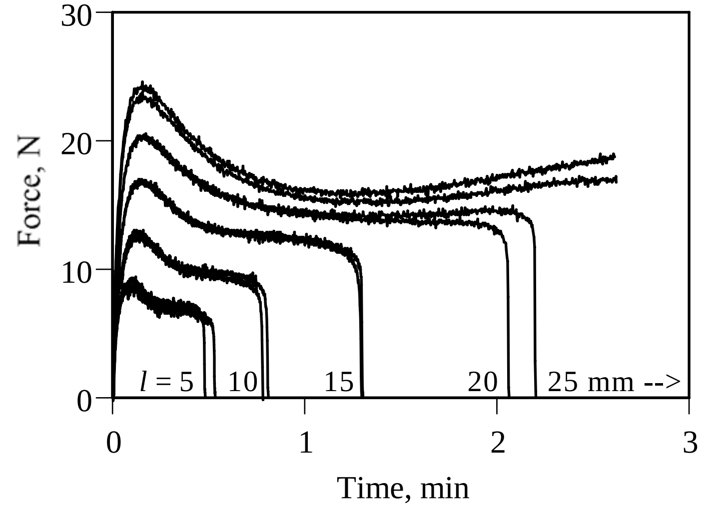

Figure 4. Representative Force-Displacement Data for the Double-Edge-Notched Tension Test on Binder L6 (*34*) (Note: The 25-mm ligament length samples failed to break before the maximum crosshead displacement was reached.)

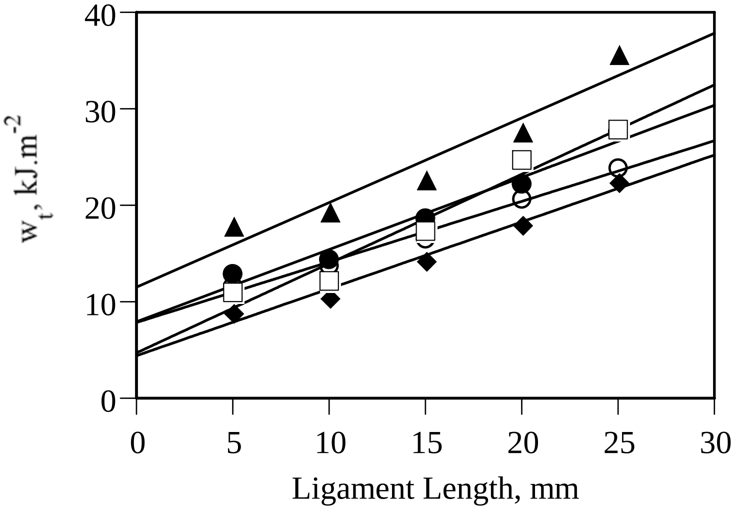

Figure 5. Essential Work of Fracture Analysis According to Equation 5 for the Five Regular PTF Binders (*34*) (● = L2; ○= L3; ▲= L4; ♦ = L5; and □ = L6)

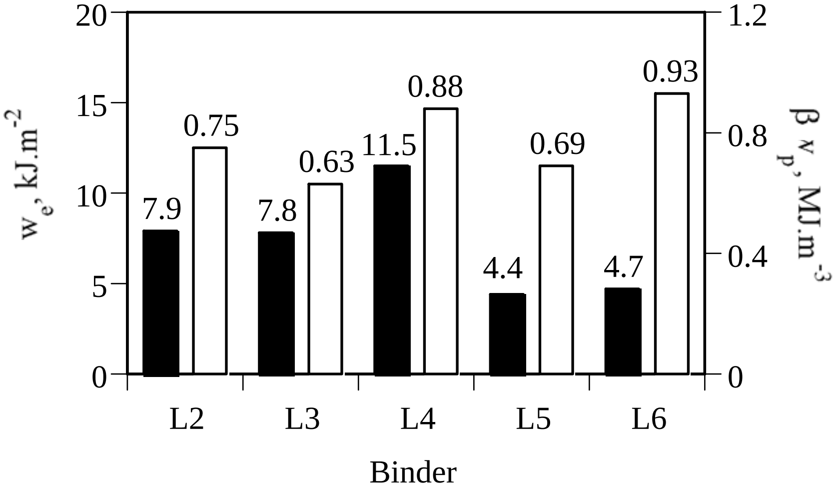

Figure 6. Essential and Plastic Works of Fracture for the Five Regular PTF Binders (*34*)

The DENT test for the fibre-modified binder was conducted in an attempt to obtain data for comparison. The test was initially conducted on unaged control binder, modified with 2 percent by weight of 6.4-mm long fibres. The loading rate was set at 30 mm/min and the temperature was 25ºC. The testing conditions and specimen dimensions were modified to accommodate the fibres. Specimen thickness was 12.4 mm, length was 25 mm, and width was 40 mm while ligament lengths varied from 10 mm to 30 mm.

The results as presented in Figure 7 are somewhat unusual in that the analysis according to equation 5 yielded an essential work of fracture of 55 kJ.m^{-2}, nearly five times higher than the next competitor L4. However, the graph also presented a negative slope of –1.0 MJ.m^{-3}, which would violate one of the basic assumptions of the essential work of fracture analysis that the plastic work increases with the square of the ligament length.

There are likely two factors that can explain these seemingly anomalous results. First, the fibres will orient themselves to some extent in the necking and tearing process. Once this happens the material will gain strength (i.e., increase its yield strength) and the specific total work of fracture will increase faster than the scaling of the energies would indicate, hence a negative slope can occur.

However, experiments on other unaged and very soft binders and mixtures, which did not contain any fibres, have given similar negative slopes. Therefore, an alternate explanation of the negative slope can come from the fact that the smaller ligament lengths reach the yield point faster than the longer ligament lengths (*45*). For harder, aged binders this effect is totally overshadowed with the increase in plastic work at higher ligaments. However, for softer, unaged materials, the lower time to yield for small ligaments could perhaps lead to a significant enough increase in the yield stress, and hence the plastic work of fracture, to produce a negative slope such as the one shown in Figure 7. This experiment illustrates one of the potential problems with the testing approach and the issue of negative slopes deserves further investigation. Nevertheless, the essential work of fracture obtained from Figure 7 appears to still have value in that it here again reflects the work required to produce the fracture surface.

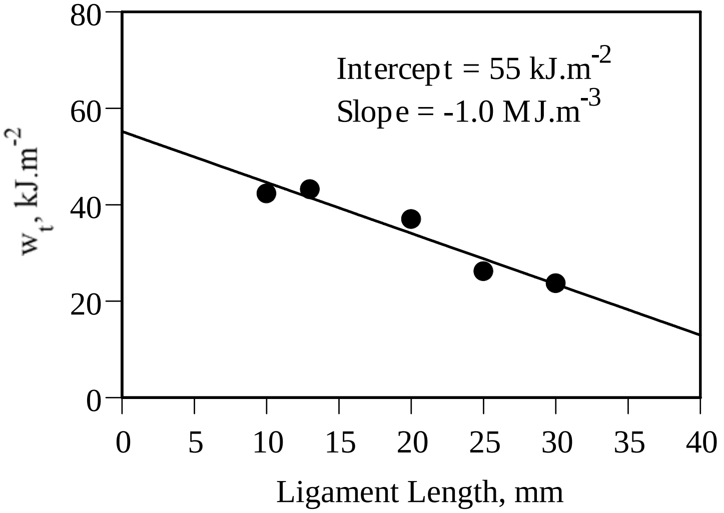

Figure 7. Essential Work of Fracture Analysis According to Equation 5 for the Fibre-Modified PTF Binder

Subsequent to the tests on the unaged binder containing 2 percent fibres, a number of PAV-aged samples containing 6 percent fibres (the same as the composition that was used in Lane

7) were tested at the same conditions as for the other binders. These tests were considerably more difficult and produced unreliable results. Hence, until a better test geometry is developed for testing very tough materials, the fracture properties measured for the fibre system will not be considered in any correlations. However, it is fair to say that it was one of the toughest materials tested and that this likely explains its superior performance.

The critical crack tip opening displacements obtained according to equation 6, assuming that the net sections stress for the smallest ligament provides a reasonable approximation for the tensile yield stress, are given in Figure 8. A detailed discussion of these results will be given in the section on fatigue performance ranking. However, it is clear from the data that there is a wide range of δ_t properties for these six systems. The fibre-modified material clearly shows superior performance, which appears to be reflected in the results obtained from the ALF experiment.

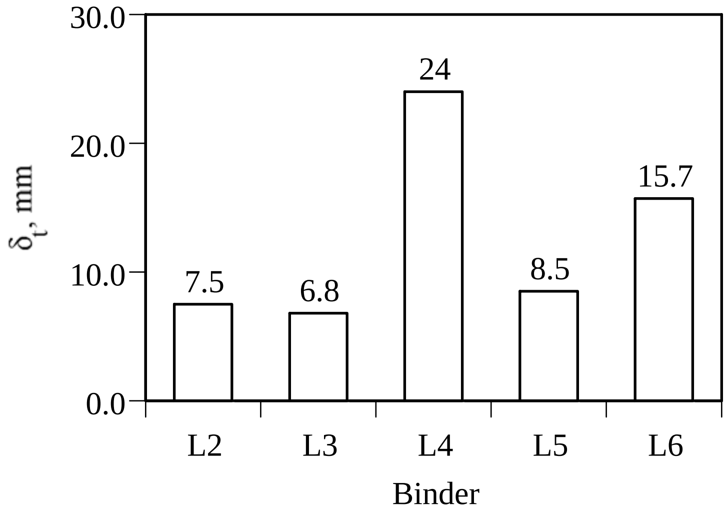

Figure 8. Critical Crack Tip Opening Displacement for Five Binders at 25°C and 100 mm/min Rate of Loading

A final issue investigated for the regular binders was how the net section stress varies with the ligament length. The data from Figure 9, as presented in our earlier paper, suggests that the various binders were in varying degrees of plane-strain condition. If these tests would all have been in the plane-stress mode then the net section stress would have been approximately equal to 1.15 times the tensile yield stress, according to Hill's plastic yield criterion (*46*), irrespective of the ligament length.

The stresses for the binders in Lane 2 (Control) and Lane 3 (Air Blown) are significantly higher at lower ligament lengths than what they are at higher ligament lengths, and this is reflected in their relatively low δ_t values of Figure 8.

The curves in Figure 9 can be fit with high precision to a power law, of which the constants reflect a measure of the strain rate susceptibility of the materials:

$$\sigma_n = a\,H\,L^{-m} \qquad [7]$$

The results for this analysis are provided in Table 2. It shows that the fit is excellent with correlation coefficients all surpassing 0.95.

The data show that binders L2 and L3 have a generally higher net section stress but relatively similar rate susceptibility compared to L5 and L6. Binder L4, the SBS-modified binder, appears to be the only material with significantly higher strain rate susceptibility. If and how these findings can be used for future performance grading deserves further attention.

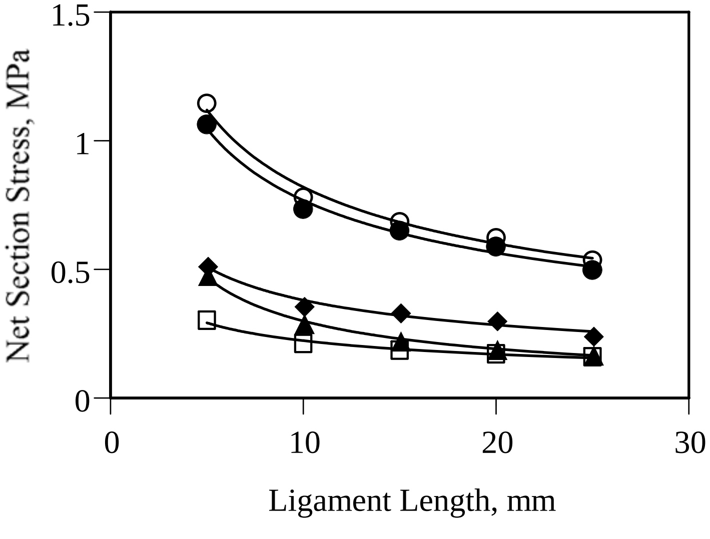

Figure 9. Power Law Fit to Net Section Stress Data (● = L2; ○= L3; ▲= L4; ♦ = L5; and □ = L6)

TABLE 2. Power Law and Correlation Coefficients for Net Section Stress Data

Binder	Modification Type	a	m	r^2
L2	Control	2.14	0.446	0.985
L3	AB	2.31	0.449	0.986
L4	SBS	1.33	0.647	0.996
L5	CR-TB	1.01	0.422	0.957
L6	RET	0.54	0.390	0.979

Rutting Observations

Before the fatigue correlations are considered it is worthwhile to say a few words about the rutting observations for the various lanes in the facility.

Since it is virtually impossible to generate fatigue cracks in a relatively new pavement structure without causing ruts, the two distress mechanisms are likely coupled. Rutting causes plastic deformation and during the final stages of this process cracks open up, which can be considered as part of the fatigue process. Conversely, fatigue cracks can open up and this in turn can accelerate the permanent deformation in the pavement structure. As mentioned earlier, the fatigue fracture process can occur in the absence of rutting but this is only likely to happen due to other aggravating conditions, such as thermal stresses and/or surface hardening of the binder (*2*, *4*). The rut data for Lanes 2-7 are presented in Figure 10. The symbols indicate the points at which the first visual surface cracks appeared.

The data is interesting is several respects. The permanent deformation ranking appears to be almost the same as the fatigue onset (and severity) rankings for Lanes 3 through 7, with Lane 2, containing the unmodified binder, being the exception. Further, there appears to be an increase in the rate of permanent deformation for Lane 2 (Control) and Lane 3 (Air Blown) after surface cracks became visible. However, this increase is only moderately significant and hence it can be concluded that the two mechanisms are coupled, yet not very strongly. Finally, the fibre-modified Lane 7 shows a rate of rutting that is significantly lower than what is observed in the other five lanes. This beneficial effect deserves further investigation and is the subject of current investigations in our laboratories.

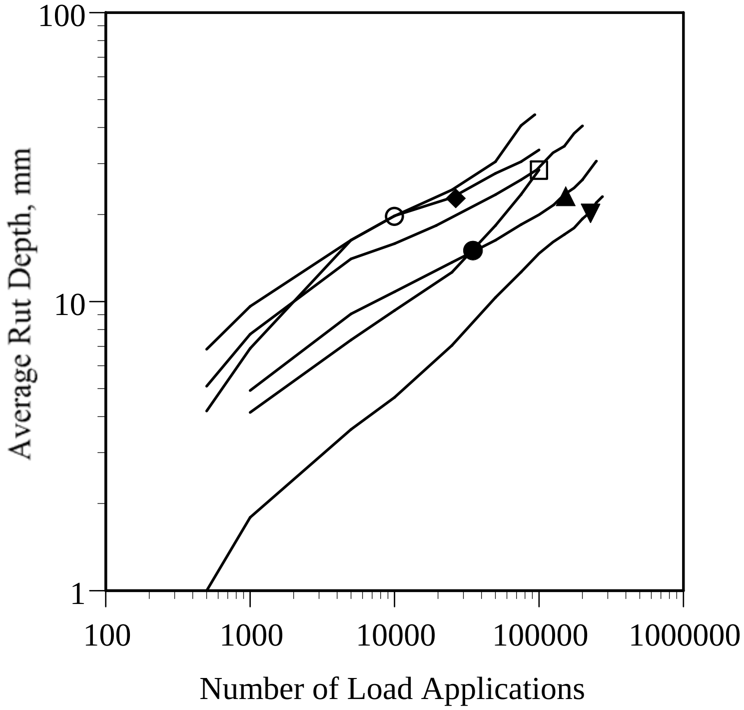

Figure 10. Rutting Data for Six PTF Lanes
(Note: Symbols indicate first visible onset of surface cracks.)
(● = L2; ○= L3; ▲= L4; ♦ = L5; □ = L6; and ▼ = L7)

Fatigue Cracking Observations

Figure 11 provides a series of photographs of three of the six test lanes while the cumulative crack length data are presented in Figure 12 as a function of load applications.

Both the photographs and the cumulative cracking data show that there are clear differences in performance. The cracking rates for Lanes 2-7 are distinctly different and since all other variables are more or less the same this suggests that these differences in fatigue distress are largely due to some variation in the binders' ability to withstand repetitive loading.

FIGURE. 11 Representative Photographs of Three PTF Lanes [Left] Lane 2 (Control) after 100,000 loadings; [Middle] Lane 4 (SBS) after 300,000 loadings; and [Right] Lane 5 (CR-TB) after 100,000 loadings.

The results also show that the fatigue and rutting rankings are different. Lane 2 made with the relatively hard control binder ranks much better in rutting than in fatigue. However, the fibre-modified lane here also outperforms all others given that at 275,000 loadings it had only reached about 9 m of visible fatigue cracks. Insight into why these differences are so big is obtained by considering the various binder properties that were measured. This analysis is discussed in the next section on fatigue performance ranking.

Fatigue Performance Ranking

The ranking of the different PTF lanes for their fatigue fracture performance is as follows: L7 (fibres) > L4 (SBS) > L6 (RET) > L5 (CR-TB) > L2 (Control) > L3 (Air Blown). In this study, the average cracking rate, up to a 20 m total crack length, is used as a performance measure. However, it should be stated that any other measure of cracking severity, would render similar conclusions. Figures 13-15 provides the correlations between various binder properties as discussed in this paper and the average cracking rates in Lanes 2 through 6. Lane 7 was omitted from the analysis since neither the loss modulus nor essential work of fracture tests were conducted with sufficient confidence to render usable data.

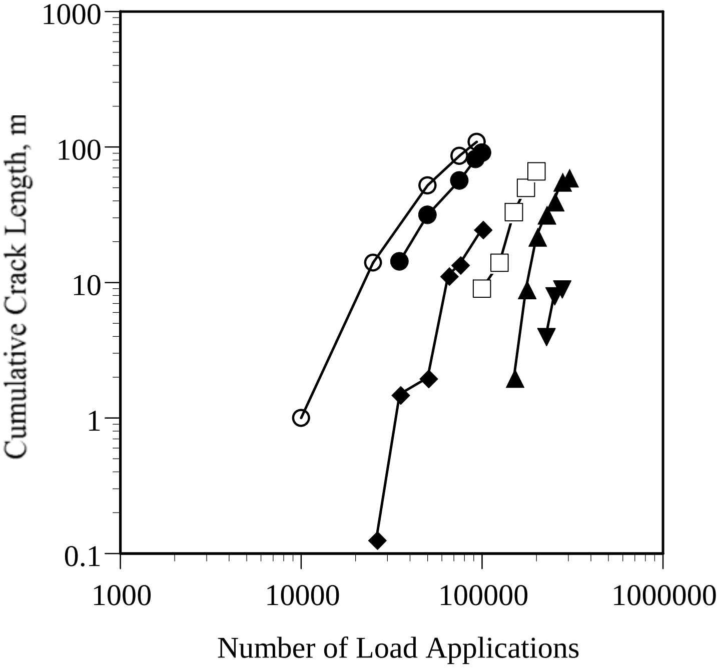

Figure 12. Fatigue Cracking Data for Six PTF Lanes
(● = L2; ○= L3; ▲= L4; ♦ = L5; □ = L6; and ▼ = L7)

The results in Figures 13-15 are given on double-logarithmic scales for the sake of being able to provide straight-line correlations. However, it is more instructive to look at differences on a linear scale in order to come to some kind of comparison to which it is possible to relate.

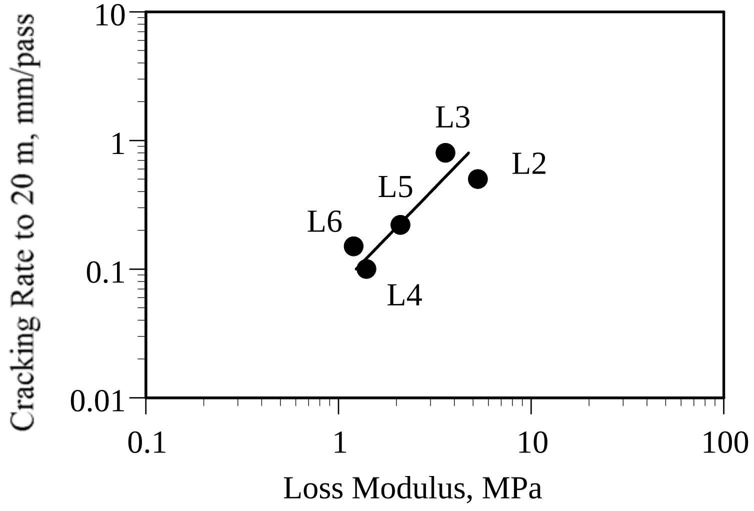

Figure 13. Correlation Between Fatigue Cracking Rates and Binder Loss Moduli ($r^2 = 0.78$)

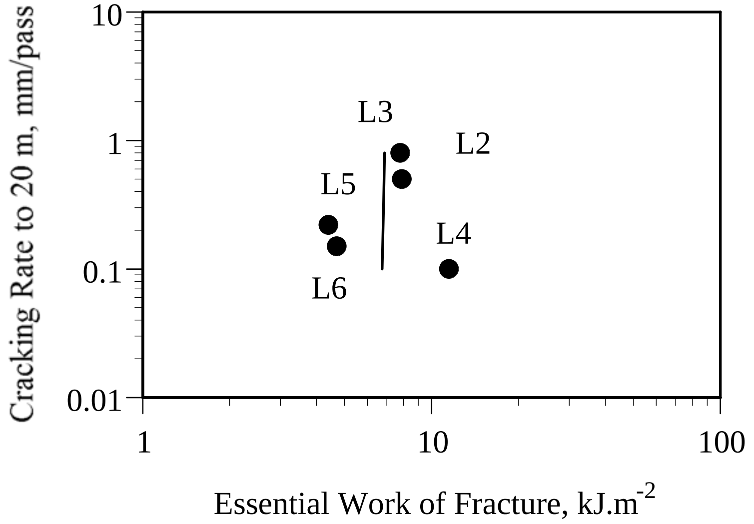

Figure 14. Correlation Between Fatigue Cracking Rates and Essential Works of Fracture ($r^2 = 0.36$)

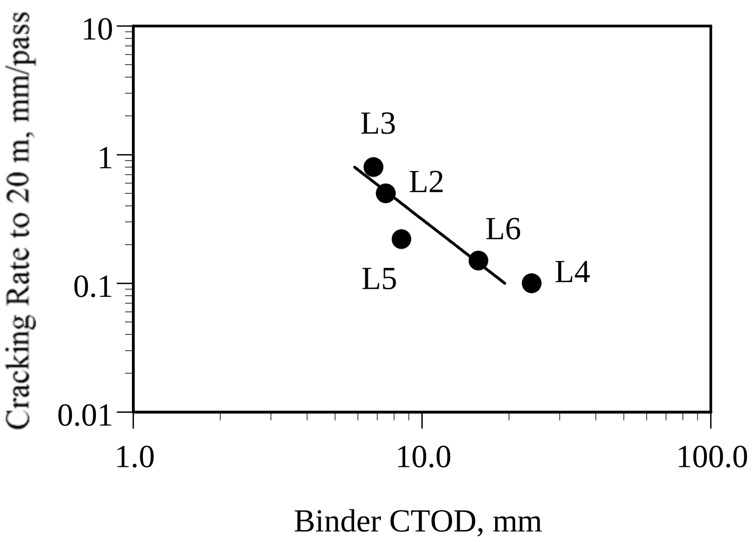

Figure 15. Correlation Between Fatigue Cracking Rates and Critical Crack Tip Opening Displacements ($r^2 = 0.83$)

The G*sinδ property is unable to rank the performances of L6 compared to L4 and of L3 compared to L2. Binder L4 had a 25 percent higher G*sinδ than L6 and hence should have performed worse. However, L4 had only about 20 m of fatigue cracks at 200,000 wheel passes while L6 had 66 m, the reverse of what the loss modulus predicted. Binder L3 has a 50 percent lower G*sinδ than L2 and hence should perform better. However, L3 had about 52 m of cracks at 50,000 passes while L2 had 31.5 m, again the reverse of what the loss modulus predicted.

For the essential work of fracture the correlation is even worse than for the loss modulus and similar arguments could be made in terms of relative rankings. Although it may be noted that the best performing binder L7 had a very high essential work of fracture.

Figure 15 shows that the critical crack opening displacement, δ_t, is able to do better at performance prediction compared to the other properties. The δ_t property not only ranks the binders correctly, it does so with a fairly high degree of accuracy. Given the somewhat arbitrary test temperature, rate of loading, and aging protocol that was used to obtain the δ_t in this study, as well as the minor variations in asphalt thickness and voids contents in the PTF lanes, there may be some degree of coincidence to this good correlation.

Nevertheless, δ_t is a fracture mechanics-based property that provides a measure of strain tolerance in the brittle-to-ductile and ductile regimes and therefore the high correlation may not be all that coincidental. The authors are pleased with these preliminary results and hope that others will start to use the test method in additional validation studies that are required to obtain evidence for the hypothesis that this is in fact a superior fatigue grading approach.

Pavement Response Variations

The differences in pavement response will eventually have to be included in any pavement model that is going to correctly predict fatigue performance. Initial, longitudinal, peak pavement strains were measured and were found to vary by as much as a factor of two (*47*). Lanes 2, 3 and 7 all reached about 500-620 microstrain right underneath the wheel at 19ºC, 18 km/h (11 mph), and 62 kN load. In contrast, Lanes 4, 5 and 6 reached anywhere from 860 to 1080 microstrain under the same conditions. The transverse strains were even more divergent with Lanes 2, 3, and 7 reaching anywhere from 500 to 690 microstrain and Lanes 4 through 6 reaching anywhere from 980 to 1520 (*47*). Some of these differences may have been due to minor variations in construction variables such as lift thickness, voids and binder contents.

It is unclear what effect if any this variable has had on the fatigue response of the sections. These were *initial* strains only and hence the lower toughness binders would have quickly lost stiffness and therefore may have also lost their possible advantage from the initial low strain. Conversely, the lower stiffness sections may have been penalized to some extent by the fact that they were compared to higher stiffness sections. The fibre-modified section (Lane 7) shows that for superior fatigue resistance it is probably best to use a high stiffness binder (i.e., low deflection), coupled with a high toughness or crack opening displacement (which is apparently most readily obtained with fibres).

Pavements are usually designed according to the stiffness requirements imposed by the base and subgrade. Once these are known then the design engineer decides to use one, two, or perhaps more lifts of asphalt of a given thickness. It is not often known exactly how stiff the pavement structure will be under a given traffic loading and therefore it may be difficult to predict the fatigue characteristics in advance. Nevertheless, the results obtained in this study appear to provide a good fit between the crack tip opening displacement and the observed cracking severity and hence the developed test method is a promising candidate for further validation studies leading to a performance-based specification for binders, mastics, and/or mixtures.

CONCLUSIONS

Given the review of the literature and the results presented in this paper, the following conclusions are provided:

- The loss modulus, $G^*\sin\delta$, which is currently the standard parameter for fatigue grading of asphalt binders, provides only a crude measure of performance and is not able to correctly rank the PTF materials. This conclusion agrees with the findings of others.
- The only parameter that correctly ranks, and provides a good correlation with, cracking severity for all materials investigated in this study is the crack tip opening displacement, δ_t.
- Binders with approximately equal works of fracture but with different yield stresses will show differences in fatigue, with the lower yield stress material outperforming the higher yield stress material. Hence, binder (and mixture) fracture energy alone is likely only going to be able to rank materials with similar yield stresses.
- Since crack tip opening displacement, δ_t, provides a measure of strain tolerance in the presence of sharp cracks in the ductile-to-brittle and fully ductile states, it provides an ideal parameter to grade asphalt binders, mastics, and mixtures for fatigue distress.

FURTHER WORK

It would be worthwhile to further investigate the essential work of fracture approach to asphalt grading with an eye on the development of an improved asphalt binder and/or mastic specification for fatigue. Large-scale field trials with carefully chosen binders may be needed to assess the effectiveness of the critical crack tip opening displacement property as a fatigue grading parameter.

The Ministry of Transportation of Ontario has embarked on an effort to build such trials. In 2003 the first 3.5 km pavement trial, containing seven different binders of all similar grades, was constructed just north of Timmins, Ontario, while two additional trials are in the planning stages. It is expected that the combined 22 test sections will be able to add validation for the proposed binder test. However, such large-scale trials are often difficult to control in that minor variations in the subgrade, lift thickness, voids and binder contents can quickly make the findings challenging to interpret. Hence, it is hoped that additional experiments such as the one discussed in this paper can be conducted to provide a final answer to the question of what test method is best used for fatigue performance grading and whether such method needs to be done on binders, mastics, and/or mixtures.

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DISCLAIMER

None of the sponsoring agencies necessarily concurs with, endorses, or has adopted the findings, conclusions or recommendations either inferred or expressly stated in subject data developed in this study.

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