EVALUATION OF THE FATIGUE PERFORMANCE OF AGED BITUMENS USING THE ESSENTIAL WORK OF FRACTURE METHOD

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ABSTRACT

It is well known that the aging process of bitumens differs based on their origin and composition. Due to a combination of traffic loading and life cycle aging, changes may occur in the bitumen properties and its fatigue resistance. The Essential Work of Fracture (EWF) method is a specific energy-based testing approach that has been successfully used for the fracture characterization of semi-ductile or ductile materials. The method identifies the essential work necessary for ductile fracture (we) and provides a way of measuring the strain tolerance of bitumens in the form of Critical Tip Opening Displacement (CTOD). Previous studies showed that the CTOD of the traditional laboratory aged bitumens and asphalts correlates well with fatigue performance in Accelerated Loading Facility (ALF) lanes at the Turner-Fairbank Highway Research Center (TFHRC). Dynamic shear testing of the bitumens extracted from in-situ ALF aged asphalts have indicated that bitumens suffer an embrittlement process that is usually more severe than that determined through traditional laboratory aging methods. This paper discusses the CTOD test results for the laboratory and in-situ aged bitumens used in the TFHRC ALF lanes and their relation with in service performance.

Keywords: aged bitumens, fatigue performance, non-linear fracture mechanics, Essential Work of Fracture, Critical Tip Opening Displacement, Accelerated Loading Facility

1. INTRODUCTION

There have been many efforts in the research community over the past decade to develop parameters capable of providing an accurate evaluation of fatigue performance in pavement materials. After the Superpave™ implementation in the United States in the early nineties, a significant amount of research has focused on refining the bitumen laboratory aging procedures and also on improving the high, intermediate, and low temperature performance grading evaluation. This interest has been triggered mainly by the advances in bitumen additives and materials testing methods. As bitumen modification technologies have evolved, the intermediate temperature performance parameter, loss modulus (i.e., G*sinδ), has been criticized for failing to accurately predict and control pavement fatigue performance [1-3].

While most fatigue experiments are time consuming and empirical by nature, the Essential Work of Fracture (EWF) method provides a fundamental approach that measures the total energy of ductile fracture for a set of several notched samples under tensile stress. The EWF testing method has been used for more than 30 years for the ductile failure characterization of metals, polymers, and various composites [4]. The underlying principle of the method assumes the existence of flaws that can act as stress concentrators in the materials under investigation. Air voids, fine aggregate particles, distinct phases of various additives or simply cracks that appear during the life cycle of the material due to exposure to the elements and traffic can act as stress concentrators in asphalt materials. Under typical tensile stress conditions, these flaws determine the appearance of micro and macro cracks that start to propagate. In addition, ductile materials exhibit various degrees of plastic deformation around the fracture zone that continues up to the moment of material separation (failure). The energy consumed for plastic deformation around the fracture zone has a “screening” effect in the process of energy transfer to the tip of the crack [4].The method determines the specific essential (w_e) and specific plastic (w_p) works of fracture, and calculates the Critical Tip Opening Displacement (CTOD) for the failure process. The CTOD represents the strain tolerance of a material in the presence of an opening crack in the ductile state. This study uses the term “failure” instead of “fracture” unless “fracture” is specifically required by the original EWF method terminology. Failure is a broader term that could include fracture and also something as slow as fatigue. The non-linear, fracture mechanics approach described in this paper proved to be a reliable tool for ranking the fatigue performance of bituminous and asphalt materials [5, 6]. This study will present and discuss the EWF and dynamic shear test results for bitumens of different levels of aging (field and laboratory) and their relation with in service fatigue performance. The results indicate that the CTOD of the bitumen (calculated by the EWF method) may be considered as a viable candidate for bitumen and asphalt fatigue performance.

2. ALF EXPERIMENT AND THE FULL SCALE FATIGUE PERFORMANCE EVALUATION

The Federal Highway Administration (FHWA) initiated a major experiment to assess new fatigue and rutting specification methods using the Accelerated Loading Facility (ALF) at Turner Fairbank Highway Research Center (TFHRC). The experiment was designed to generate rapid loading of full-scale pavement sections. The fatigue findings of the ALF experiment provides accelerated field performance data that may be used to further validate the EWF method. The experimental site was located in McLean, Virginia, where the moderate climate of the region is representative for a large section of the continental United States. Details of the construction parameters of the testing lanes and fatigue evaluation results can be found in previous publications [7, 8]. A total of 12 lanes were tested in the ALF and they were all constructed with a 12.5 mm Hot Mix Asphalt (HMA) design. Aggregate source, gradation, and air void contents were maintained within close tolerances for the entire experiment. The only variable among the pavement materials in the testing lanes was the bitumen modification procedure and thus the bitumen quality. Seven lanes were each 100 mm thick while the remaining five had a thickness of 150 mm. For this study, only five lanes (lanes L2 through L6) were evaluated for two reasons: 1) the fatigue resistance of the 150 mm thick lanes was superior to that of the thinner lanes, required excessively long loading periods, and the results of fatigue experiments on those lanes did not provide acceptable validation data (fatigue performance became affected by oxidative aging variability over the extended experimental time) and 2) both lanes L1 and L7 had a high degree of fatigue resistance to accelerating loading and the nature of their respective composites (neither Arizona crumb rubber contained in lane L1 or 0.3% polyester (PET) fiber contained in lane L7 is soluble) made it impossible to conduct a complete and meaningful extraction. Reference [5] provides further details of the laboratory testing difficulties for fiber modified bitumen from lane 7. Table 1 provides a summary of the pertinent data for the materials used for the 2002 TFHRC ALF experiment used in this study.

Table 1: Pertinent properties for the 2002 TFHRC ALF experiment materials.

Material (Lane)	Lane	Continuous PG, ºC	G*sinδ at 25ºC, MPa
Control (L2)	2	72-23	5.33
Air Blown (L3)	3	74-28	3.58
SBS (L4)	4	74-28	1.44
CRTB (L5)	5	79-28	2.11
RET (L6)	6	74-31	1.16

Note: SBS = styrene-butadiene-styrene linear triblock copolymer; CRTB = crumb rubber as blended according to a terminal process and RET = reactive ethylene terpolymer.

The width of each testing lane was divided into two experimental sites named S3 and S4. The right sides of each lane (sites S3) were subjected to an accelerating loading after an average of about two years of natural weather exposure (natural aging). The left sides of each lane (sites S4) were exposed for about five years to natural aging after which they were subjected to an accelerated aging process for a total of 8 weeks. During this accelerated aging period, the temperature of the sites was maintained at 74°C using the radiant heaters on the ALF testing machines. The fatigue loading experiments for the S4 sites were initiated following the accelerated aging. Figure 1 presents the final fatigue testing results for lanes L2 through L6.

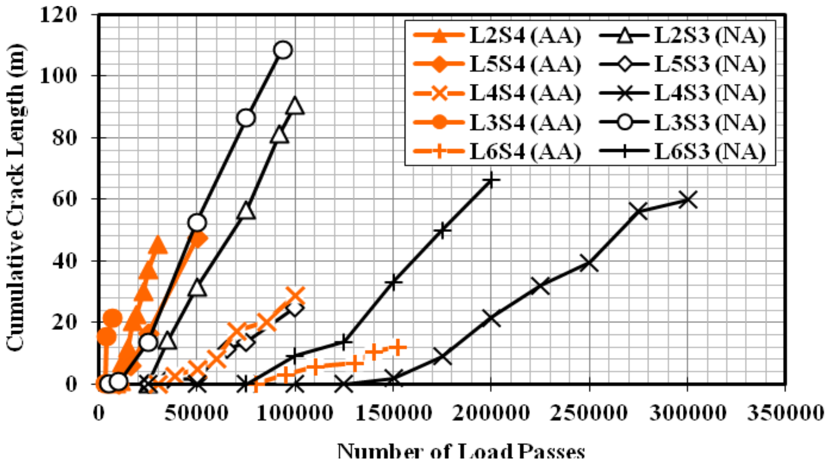
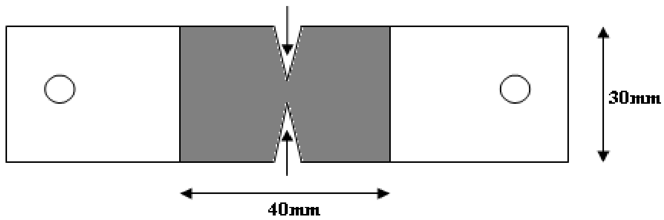


Figure 1: Cumulative crack length versus number of loading passes in the ALF experiment (testing conditions, 19°C & 16,600lbs); NA = Natural Aged; AA = Accelerated Aged.

Based on the number of load passes at 20m of crack length for all the lanes at the end of the experiment, the fatigue ranking for natural aged S3 sites is L4>L6>L5>L2>L3 while for the accelerated aged (S4) sites the ranking is L6>L4>L5>L2>L3. The only difference between the S3 and S4 rankings is the switch between the two top performers, L4 and L6. The top performer in loading experiments after natural exposure, lane L4, became the second best in ranking after the accelerated aging. The rankings are the same irrespective of the reference parameter used (crack length or amount of area cracked) [7, 8]. The ranked fatigue performances of the selected test lanes provide a basis to correlate the laboratory determined CTOD of the bitumens with the accelerated field performance.

3. ESSENTIAL WORK OF FRACTURE METHOD AND CRITICAL TIP OPENING DISPLACEMENT

Details of the EWF theory and calculations can be found in previous publications [4-6]. Hence, only the most important aspects are reviewed here. The EWF method most frequently utilizes the Double-Edge-Notched-Tensile (DENT) geometry and samples are tested at a monotonic rate to failure. In essence, the method replicates the ductile failure in tension of a material and determines the fundamental parameters that control the process. A diagram of the DENT sample is presented in Figure 2. Single arrows indicate ligament position.



Note: Ligament lengths, L = 5, 10 and 15mm; Thickness, B = 6.5mm.

Figure 2: DENT sample design.

The computer controlled testing instrument records the force versus displacement until failure for samples having 3 different ligament lengths (5 mm, 10 mm, and 15 mm). Sample testing is done in duplicates and measurements are usually highly reproducible. Figure 3 shows representative force-displacement data for the DENT test on extracted Control bitumen (L2) tested in duplicates.

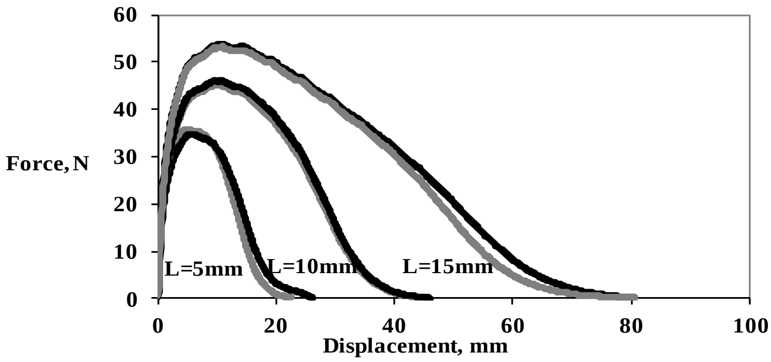
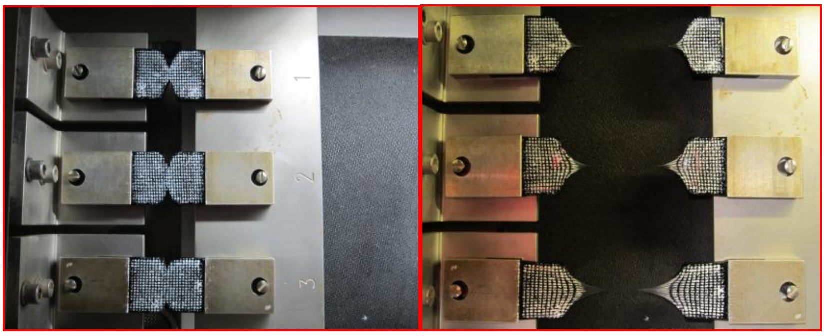


Figure 3: Typical raw data of a set of six DENT tests (replicates for 3 ligament lengths).

The area under the force-displacement curves represents the total energy to fracture (W_t). Based on the technical committee 4 of the European Structural Integrity Society recommendations, Mai et al. (2001) have pointed out that certain experimental conditions must be met in order to have a valid test result [4]. These involve the similarity of the force-displacement curves for various ligament lengths (i.e., they need to have the same appearance), and the existence of a fully yielded ligament at peak load. Our test data showed good reproducibility for all materials and conditions for a valid test were consistently observed. Figure 4 provides images for a set of DENT specimens (a) just prior to testing and (b) after failure. A white grid was painted on each sample to reveal the extent and the shape of the plastic failure zones around the ligament area.



(a) **(b)**

Figure 4: Pictures of a set of DENT samples (3 samples with different ligament lengths) (a) before and (b) after the complete failure.

After carefully observing the fracture processes in numerous ductile materials, Cotterell and Reddel [9] were the first to propose that the total work of fracture for a DENT specimen is composed of two additive energies:

(1) "the essential work performed in the end region" of the notches (W_e), associated with the generation of new surfaces; and
(2) "the non-essential work performed in the screening plastic region" surrounding the ligament zone (W_p).

The authors of the EWF theory also noticed that W_e is proportional to the new surface areas created, while W_p is proportional to the volume of the plastic zone around the fracture zone. Because the ligament length, L, is the major factor that determines the extent of plastic deformation, the volume dependence of the plastic work of fracture can be written as the product between the surface of the ligament zone multiplied by the ligament length and by a proportionality factor β. As a result, the expression of the total work of fracture, W_t, can be written as:

$$W_t = W_e + W_p = LBw_e + \beta L^2 Bw_p, \quad (1)$$

Where B is the thickness of the material, and w_e and w_p are the corresponding specific fracture energy terms for W_e and W_p.

The β factor is a constant for a given material which is bitumen in our study. Rewriting equation (1) in specific terms, provides a relationship for the total specific work of fracture (w_t) being equal to the specific essential work of fracture (w_e) plus the product between the ligament length (L) and the scaled, specific plastic energy term (βw_p).

$$w_t = w_e + \beta w_p L \quad (2)$$

According to the equation (2), a plot of the total specific work of fracture (w_t) versus the ligament length (L) must result in a straight line, with the intercept being the specific essential work of fracture (w_e) and the slope providing the specific plastic work of fracture multiplied by β. If needed, β can be evaluated from a photographic image of a sample during the failure process or it can simply be carried over as a constant in future analyses [4, 5]. Equation (2) allows the graphical determination of the energies involved in the fracture process. Based on ASTM 813-89

[10], the findings of the technical committee 4 of the European Structural Integrity Society [11], and many others (Mai et al. 2001 [4], Luna et al 2003 [12]), fracture is said to be under plane strain conditions, and w_e and βw_p can be considered material properties when the thickness of the sample (6.5 mm) is about the same size of the ligaments involved in the test design. The essential work of fracture can be considered an expression for the fracture toughness of ductile materials that have similar resistance to plastic deformation. It is not clear which term (w_e or βw_p) is most critical to assure good fatigue performance, but both terms likely have to be large in order for a material to perform well [5].

The EWF method also allows for the calculation of a strain tolerance in the form of Critical Tip Opening Displacement (CTOD), essentially the strain tolerance of the material under severe tensile constraint in the presence of a notch. As pointed out by Cotterel and Reddel in 1977 [9] and Hashemi and O'Brien in 1993 [13] and by many others, the CTOD can be considered as an alternative "material property" and it represents the ultimate elongation necessary to initiate the crack propagation. Cotterel and Reddel (1977) observed that for small ligaments, "the screening plastic zone vanishes" and they approximated the value of the specific essential work of fracture as:

$$w_e = \delta \text{ x } \sigma_{ty} \quad (3)$$

Where δ represents the critical tip opening displacement and σ_{ty} represents the yield stress in tension [9].

Equation (3) suggests that the steps to determine the CTOD involve: 1) the experimental determination of the specific essential work of fracture and 2) the evaluation of the yield stress in tension for the material being tested. Previous studies showed that the degree of constraint in the ligaments of bitumens tested in tension (the net section stress at peak loads) is increasing with a decrease in ligament length [5]. As a result, the value of the net section stress at peak load for the samples with the smallest ligament lengths (5 mm in our studies), represent a good evaluation for the yield stress in tension (σ_{ty}) for the material tested. In the DENT design, the smallest ligament length (5mm) is roughly the same size as the samples thickness (6.5mm), rendering it probably the best testing geometry available for plane strain testing conditions (equal material boundary conditions) and the evaluation of yield stress in tension [5, 6]. Based on equation (3), CTOD can be calculated as the ratio between the specific essential work of fracture (w_e) and the net section stress at peak load for the smallest ligament length. The specific essential work of fracture (w_e) is determined as the result of the intercept of the linear regression line of the plot of specific total work of fracture (w_t) versus ligament length, while the value of the net section stress at the peak load for the smallest ligament (5mm) is simply recorded during the tests.

4. RECOVERED BITUMEN TESTING RESULTS

To obtain original asphalt materials, both S3 and S4 sites of lanes L2 through L6 were cored once the fatigue loading experiments were finished. Asphalt cores were carefully washed and left to dry overnight. A total of 4 cores were taken from each lane and site. A water cooled circular saw was used to cut slices of one inch thickness from both the top and bottom portion of each core. The top slices originating from the same lane and site were combined for the extraction of the bitumen. The extraction was performed according to AASHTO standard T 319-07 procedures [14]. The solvent of choice was a blend of 85% toluene and 15% ethanol. From about 4 kg of asphalt approximately 200 g of bitumen were extracted. Similarly, the bottom slices from all cylinders originating from the same sites were combined to yield enough extracted bitumen for rheological and EWF testing. Extractions from the top and bottom of the cored mix provide a good indication on how ductile failure properties vary between surface and bottom of the pavement, while the average of the failure parameters between the top and bottom parts should provide a good evaluation of the overall performance of that pavement. The amount of bitumen extracted was sufficient to perform DENT and dynamic shear testing. All the testing was replicated to ensure the accuracy of the testing results. DENT testing conditions were 25°C and 100 mm/min. These conditions were chosen for convenience and to compare the DENT test results for the ALF bitumens with those reported in an earlier publication [5]. The results for extracted bitumens from the top one inch and bottom one inch materials from all investigated sites are presented in Table 2.

Table 2: CTOD values for the extracted bitumen from top one inch and bottom one inch of lanes L2 through L6 (site S3 and site S4 of each lane).

L2 S3 Top, mm	L2 S4 Top, mm	L3 S3 Top, mm	L3 S4 Top, mm	L4 S3 Top, mm	L4 S4 Top, mm	L5 S3 Top, mm	L5 S4 Top, mm	L6 S3 Top, mm	L6 S4 Top, mm
7.7	6.6	8.2	6.5	11.8	6.9	9.9	7.2	12.8	9.0
L2 S3 Bottom, mm	**L2 S4 Bottom, mm**	**L3 S3 Bottom, mm**	**L3 S4 Bottom, mm**	**L4 S3 Bottom, mm**	**L4 S4 Bottom, mm**	**L5 S3 Bottom, mm**	**L5 S4 Bottom, mm**	**L6 S3 Bottom, mm**	**L6 S4 Bottom, mm**
14.4	11.8	9.2	10.0	37.4	33.4	16.6	17.6	20.1	20.3

5. LABORATORY AGED BITUMEN TESTING RESULTS

In a separate experiment, enough quantities of all 5 bitumens used in lanes L2 through L6 were aged in the Rolling Thin Film Oven (RTFO) test, followed by a Pressure Aging Vessel (PAV) procedure. Previous studies performed at TFHRC showed that the RTFO followed by PAV aging yielded material equivalent in rheological properties with the one extracted from the top one half inch of a real pavement after 2-3 years of exposure to natural aging [8]. The laboratory PAV-aged bitumens were tested in DENT at various temperatures and various testing speed rates. CTOD was determined for all 5 bitumens in each situation. The purpose of this experiment was to acquire information about CTOD values determined under various testing conditions and to generate ductile failure master curves. Testing temperatures of 13°C, 19°C, and 25°C were explored because it was expected that most of the fatigue life of the pavements is to be consumed within this interval. To make the ductile failure tests possible for all the 3 temperatures, the speed rate range started at 2.5 mm/min. A total of 5 testing speed rates were used (2.5, 5, 10, 20, and 40 mm/min) for each testing temperature. Ductile failure tests results are presented in Table 3.

Table 3: CTOD values of PAV-aged bitumen as a function of temperature and loading rate. No result (-) signifies brittle failure, excessive softness, or just invalid test results.

Lane #	Lane 2 Control, CTOD, mm			Lane 3 AirBlown, CTOD, mm			Lane 4 SBS, CTOD, mm			Lane 5 CRTB, CTOD, mm			Lane 6 RET, CTOD, mm		
Temperature / Speed Rate	**13°C**	**19°C**	**25°C**	**13°C**	**19°C**	**25°C**	**13°C**	**19°C**	**25°C**	**13°C**	**19°C**	**25°C**	**13°C**	**19°C**	**25°C**
2.5mm/min	10.9	15.0	21.2	9.2	13.7	15.4	35.1	68.3	-	11.4	15.4	-	24.2	-	50.1
5mm/min	11.0	13.5	17.9	8.4	11.0	13.4	27.4	53.6	-	11.0	14.6	18.5	-	36.3	47.8
10mm/min	9.7	10.5	15.8	6.8	10.3	13.1	21.4	50.6	76.7	10.5	12.8	17.7	18.5	35.2	35.7
20mm/min	-	9.5	15.0	6.7	-	11.1	-	45.8	68.3	-	12.3	17.2	17.5	32.5	28.5
40mm/min	-	9.4	14.2	-	-	11.0	-	34.1	59.2	-	11.9	14.7	-	21.1	27.3

Based on the data from Table 3, the ductile failure master curve was generated for each of the 5 bitumens tested. Figure 5 represents an example of the ductile failure master curve for the PAV-aged bitumen of lane L2.

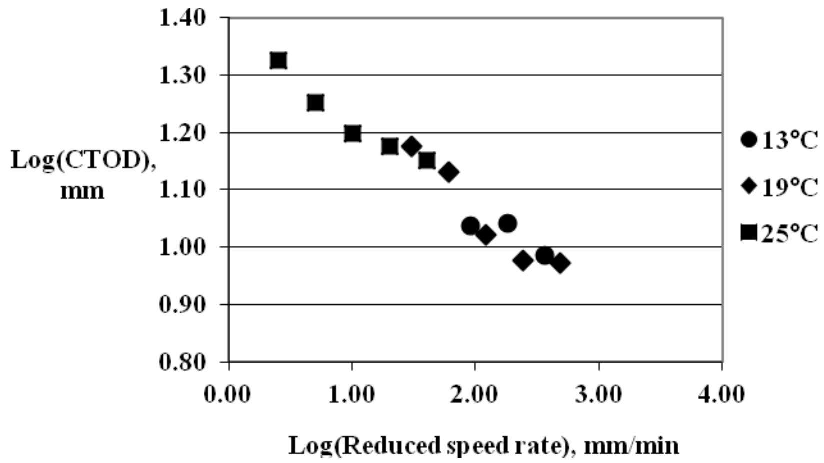


Figure 5: Ductile failure master curve for the PAV-aged bitumen of lane L2.

The log of the CTOD values obtained for 13°C and 19°C experiments were shifted to the right on the log(reduced speed rate) axis toward the log(CTOD) values determined at 25°C. The shifting of log(CTOD) values were optimized and the failure shift factors (mm/min) for each bitumen determined.

The laboratory PAV-aged bitumens were tested at the same temperatures using a Dynamic Shear Rheometer (DSR). The rheological master curve for the log(loss modulus) (i.e., log(G*sinδ)) was generated by testing in dynamic shear all 5 laboratory PAV-aged bitumens (of lanes L2 through L6) at 5 frequencies (2.5, 5, 10, 20 and 40 radians per second), 3 temperatures (13°C, 19°C and 25°C) and at a strain of 2%. The testing strain of 2% was chosen to ensure that the bitumens are within the linear viscoelastic region. Testing frequency started at 2.5 radians per second and was doubled with each increase, similarly with the testing speed rates in the ductile failure experiment. Loss modulus (G*sinδ) values were recorded in all the combinations of (previously) described testing conditions for all 5 bitumens and dynamic shear master curves were generated. The shifting of the log(G*sinδ) values on the log(reduced frequency) axis were optimized and the dynamic shear shift factors (rad/s) for each bitumen determined. Figure 7 represents an example of the dynamic shear master curve obtained for the PAV-aged bitumen of lane L2.

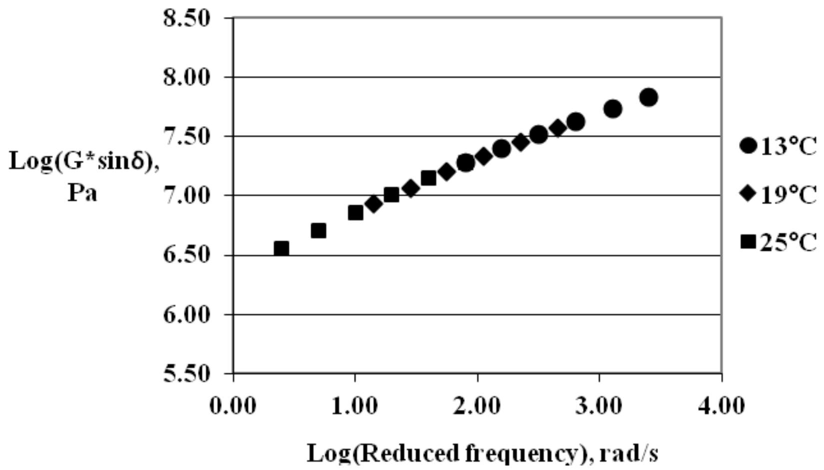


Figure 6: Dynamic shear master curve for the PAV-aged bitumen of lane L2.

Table 4 presents the shift factors that were determined based on the described master curve generation for the 5 laboratory aged bitumens (lanes L2 through L6) in ductile failure and dynamic shear. The contrast between the two sets of shift factors indicates the differences in time temperature superposition principle between ductile failure and dynamic shear tests. Master curves and shift factors are usually used to determine material parameters that are not easily accessible to experimental conditions.

Table 4: Shift factors in ductile failure (*) versus dynamic shear for the PAV-aged bitumens (lanes L2-L6).

Temperature, °C	Lane 2	Lane 3	Lane 4	Lane 5	Lane 6
13°C	1.6*/1.5	1.9*/1.5	2.5*/1.5	2.3*/1.5	0.9*/1.5
19°C	1.1*/0.8	0.7*/0.8	1.0*/0.8	1.5*/0.8	0.3*/0.8
25°C	0*/0	0*/0	0*/0	0*/0	0*/0

6. DISCUSSIONS

Previous investigations found that the ranking based on the strain tolerance (CTOD values) of the laboratory-aged (PAV) bitumens is identical with the ranking in terms of fatigue performance for lanes L2 through L6 [5].

In general, bitumen aging speed rates present relatively significant variations between laboratory and in situ situations. As a consequence, the DENT and dynamic shear investigations of the bitumens extracted from original ALF asphalts is a possible better approach for validation of any performance test method than the one that uses tests performed only on laboratory-aged materials. The result of the EWF tests performed on extracted materials from the naturally aged pavements showed that the ranking based on average bitumen strain tolerance (average CTOD between top and bottom values for the extracted bitumens) is identical with the ranking of fatigue performance for lanes L2 through L6. Average loss modulus values (between top and bottom extracted bitumens) and loss modulus values for laboratory aged bitumens are not reflecting the ALF lanes ranking performance. Table 5 presents a summary of fatigue performance ranking for natural aged lanes versus the CTOD and the respective loss modulus values for PAV-aged and natural aged (recovered) bitumens.

Table 5: Fatigue performance ranking for natural aged lanes versus the CTOD and loss modulus values for PAV-aged and natural aged (recovered) bitumens.

ALF Lanes Ranking (best on top)	PAV Aged Bitumen CTOD, mm	Natural Aged Bitumen CTOD, mm	PAV Aged Bitumen G*sinδ, MPa	Natural Aged Bitumen G*sinδ, MPa
L4 (SBS)	24.0	24.6	1.44	3.45
L6 (RET)	15.7	16.5	1.16	4.73
L5 (CRTB)	8.5	13.3	2.11	2.41
L2 (Control)	7.5	11.1	5.33	6.25
L3 (Air Blown)	6.8	8.7	3.58	4.57

The average CTOD values for the recovered, natural aged bitumens from site S3 for each lane appears to do a better job in discriminating the performance between various pavements used in the ALF experiment at TFHRC. The differences between average CTOD values for natural aged bitumens are more significant and they reflect better the ranking for fatigue performance of the lanes. These findings suggest that the bitumen's CTOD may be used for the control of fatigue cracking and that a lower limit on CTOD may be used in a fatigue specification. A simple DENT test, using a relatively small quantity of aged bitumen appears to be able to rank materials based on performance, eventually allowing user agencies to save significant amounts of resources by selecting the appropriate materials for a given paving contract.

DENT tests performed on extracted bitumens indicated that the accelerated pavement aging process of 8 weeks lead to a general decrease in the average CTOD values. Table 2 offers excellent details about the variation in CTOD values with aging on the top compared with the bottom of the pavements. Bitumen aging speeds may present relatively significant variations between natural aging and accelerating aging situations and is reasonable to expect that the fatigue ranking for accelerated aged pavements may change. Site 4 of the lanes L2 through L6 underwent a two speed aging process making difficult to discriminate which factors might have influence the final performance most: natural or accelerated aging steps.

A significant drop can be observed for the average CTOD values between top and bottom for bitumens extracted from lane L4 before and after the accelerating aging process. For this lane, the drop in the average CTOD was about 4.4mm while for all others the decrease in CTOD average between top and bottom was less than 2mm.

Another important observation is that the relative high strain tolerance of polymer-modified bitumens is almost entirely lost at the top layer by the action of weathering and this process was found to be rather catastrophic after accelerated aging. The CTOD value for the naturally aged bitumen extracted from the top layer of lane L4 has decreased by almost a factor of two after accelerated aging. Actual CTOD decrease was from 11.8 mm to just 6.9 mm. The strain tolerance decrease with accelerating aging in the surface layer of lane L4 is the highest among all the materials investigated. The CTOD value of the top layer extracted bitumen of the accelerated aged lane L4 (6.9 mm) became about the same as the top layers extracted bitumens for poor performers of lanes L2, L3 and L5 respectively. The differences that exist with aging progression between top and bottom layers of the same pavement depend on bitumen modification and may indicate that the cracking pattern will change with time. From a blend of top-to-bottom and bottom-to-top cracking in natural (moderate) aging situations, the damage can be determined by a predominantly top-to-bottom cracking progression for advanced aged pavements. A limited investigation of the asphalt cylinders cores taken from the ALF pavements following advanced aging and loading indicated a statistical predominance of top-to-bottom cracking distress [8]. This subject deserves further study once more sophisticated non-destructive monitoring techniques for asphalt cracking become available. It is worth mentioning that an asphalt containing bitumen with good strain tolerance (high CTOD) will exhibit good overall fatigue performance as the average values of CTOD values between top and bottom layers are still relatively high. Figure 9 represents the CTOD decrease in the top inch of the ALF pavements after the accelerated aging process.

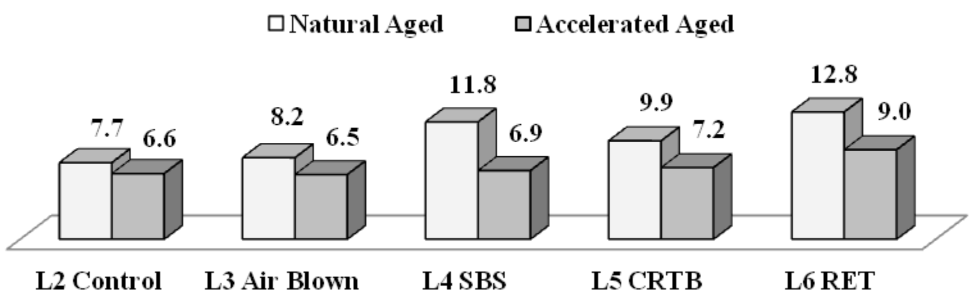


Figure 7: CTOD (mm) decrease in the top inch of the extracted bitumens after the accelerated aging process.

The predominance of top-to-bottom cracking with the progression of aging may be determined by the top-to-bottom gradient increase in bitumen failure properties (i.e. CTOD values). The steep drop in the CTOD values of extracted bitumens from the surface layer of lane L4 (SBS) following accelerated aging, may explain why the best performer is losing its top position in favor of lane L6 material. For lanes L2, L3, and L5, the CTOD values corresponding to the top and bottom (as well as the average between top and bottom) of extracted bitumens did not significantly change with aging and this explain why their performance ranking has not changed.

The larger availability of laboratory-aged materials allowed for an investigation on how the changes in temperature and testing speed rate influence the bitumen strain tolerance and to generate ductile failure and dynamic shear master curves. The data in Table 4 show that the dynamic shear shift factors are identical for all materials investigated while ductile failure shift factors vary to some degree. This indicates that there are fundamental differences between bitumen behavior in dynamic shear and in ductile failure. As a result, the dynamic shear shift factors cannot be used to predict ductile failure events and vice versa. Fatigue performance, as possible reflected by the ranking in the CTOD values of the laboratory aged bitumens remains the same despite wide changes in testing speed rate and at various temperatures for the limited case of five binders investigated.

7. SUMMARY AND CONCLUSIONS

The non-linear fracture mechanics theory (EWF) can be used to evaluate ductile failure properties of bitumen and asphalt. The method provides the specific essential work involved in the generation of new surfaces of material, the specific plastic work responsible for deformation away from the failure zone, and allows the calculation of CTOD. CTOD represents the tensile strain tolerance of the material in the presence of an opening crack. The method is highly reproducible and uses a relatively small quantity of material.

The ALF experiment provided an opportunity to validate the EWF testing method for both bitumens and asphalt pavements [6]. The strain tolerance ranking of bitumens for both laboratory-aged (PAV) and naturally-aged (extracted) materials is identical to the fatigue performance ranking of the TFHRC ALF lanes. As a result, CTOD may be considered as a viable candidate specification for asphalt fatigue performance.

The investigation of the CTOD values determined at various testing speed rates and various intermediate temperatures for all the tested bitumens did not find any changes in performance ranking. This observation may not be valid in the case of other groups of bitumens or for wider variations in testing conditions. The subject deserves further study as the optimum of which temperatures and testing speed rates are best to be used in laboratory fatigue evaluation is still under debate. Based on the data presented, higher testing temperatures and lower testing speed rates provide better discriminating results. Excessive plastic deformation may alter the fine discrimination between ductile failure energies, while less plastic deformation may lead to brittle failure. Bitumens which are softer or harder than the ones investigated may require an adjustment in test conditions since a balance between the optimum level of test temperature and speed rate would be desired (ductile failure is necessary to use the EWF approach).

Testing materials at various temperatures and speed rates is possible and provides the data for master curve generation. Time-temperature superposition can be investigated in ductile failure and the shift factors used in master curves generation can be determined. Ductile failure shift factors present a significant variation with the bitumen modification, while the dynamic shear shift factors does not change for any of the materials investigated. This suggests that ductile failure testing can capture variations in material behavior that remain undetected in conventional dynamic shear tests.

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