Specific Energy of Damage as Fracture Criterion for Asphaltic Pavements

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The concept of the specific energy of damage as a fracture criterion for asphaltic pavements is discussed. The theoretical and experimental aspects on which the specific energy of damage can be evaluated are outlined. These are the modified crack layer methodology and a simple fatigue crack propagation testing program. To demonstrate the validity of the proposed concept, four case studies are presented. These include the effects of additive loading, processing conditions, stress levels, and testing temperature on the fracture resistance of various asphaltic pavements. It was found that the specific energy of damage (γ') is capable of discriminating the subtle effects introduced by polymer additives as well as their loading percentages. It was also found that γ' reflects the increase in the fracture resistance of an asphalt mixture because it was enhanced by the dynamic/static compaction method. The value of γ' was found to be independent of stress level and testing temperature. The current findings attest to the fact that γ' can be viewed as a material parameter reflecting the fracture toughness of a material. On this basis a logical connection can be constructed among the chemical structure, processing conditions, as well as in-service conditions (stress level and temperature), and a long-term performance-related parameter, namely, the γ' of the mixture.

Traditionally, two main approaches have been used in the study of fatigue crack propagation, namely, a phenomenological approach and a fracture mechanics-based approach. The phenomenological or S-N approach to the fatigue lifetime of a pavement is based on the endurance concept that uses Wohler's technique (*1*), in which the number of cycles to failure is correlated with the applied stress or strain through empirical constants. Because of its simplicity this approach has been widely adopted (*2–5*); however, it carries severe limitations. It does not discriminate between crack initiation and propagation, and its constants are simply regression constants without physical meaning. In addition, even homogeneous materials exhibit an order of magnitude scatter in their fatigue lifetimes (*6,7*), so it is not reasonable to model a heterogeneous material such as pavement in such a manner. A good review of this approach has recently been given (*8*).

Fracture parameters such as the stress intensity factor K, based on linear elastic fracture mechanics theories, and the energy release rate J, based on elastic-plastic theory, have also been used as correlative tools in empirical formulas based on Paris and Erdogan's (*9*) power law equation to describe fatigue crack propagation (FCP) in various materials. This fracture mechanics-based approach carries its own difficulties, as outlined previously (*8*). Schapery (*10–12*) proposed a theory in an attempt to relate the constants obtained from the Paris and Erdogan (*9*) equation to some physical and mechanical properties of materials displaying viscoelastic responses. This theory has been examined by various researchers, for example, Majidzadeh et al. (*13*), Germann and Lytton (*14*), and Little et al. (*15*), on asphalt concrete mixtures. It appears from the literature that there are conflicting reports on the general applicability of Schapery's theory to characterizing various asphalt concrete mixtures to FCP.

The concept of a crack as an ideal cut with associated surface energy has led to the development of linear elastic fracture mechanics theories to evaluate the fracture resistance of brittle materials. Modern viscoelastic and viscoplastic materials challenge the adequacies of these theories for characterizing their fracture behaviors. Guided by the deformation theory of plasticity, which is essentially nonlinear elastic theory, Rice (*16*) extended Eshelby's (*17*) contour integrals, which are path independent by virtue of the energy conservation theorem, and formulated the energy release rate for materials displaying elastic-plastic responses. The path-independent J-integral proposed by Rice (*16*) was viewed by Begley and Landes (*18*) as a measure of the crack tip elastic-plastic field and can be evaluated from the load displacement curve associated with crack extension during monotonic loading. Little et al. (*15*) have modified the J-integral analysis to include unloading effects. They suggested that their modified analysis, namely J^*, is suitable for comparative analysis of the energy release rate among various asphalt binders.

Exploration of the combo-viscoplastic fundamental properties of asphaltic pavements demands a focused and innovative study of their micro- and macromechanical phenomena relevant to their long-term performances. These phenomena encompass deformation processes induced by the applied mechanical forces accelerated by environmental challenges. In this regard relevant micro- and macromechanical phenomena in pavement would involve localized irreversible deformation processes, for example, microcracking of the binder and binder-aggregate interface. Interfacial microcracking in the meantime relates to yet another fundamental phenomenon, that is, adhesion of the binder to the aggregate surfaces. It is also essential to recognize that micromechanical processes in the mixture are controlled to a great extent by the viscoelastic character of the asphalt, which in turn is influenced by the state of stress or strain, the processing conditions, and aging. Hence, it is fundamentally important to study the dependency of the viscoelastic character of the systems considered, particularly on design parameters such as stress level and aging (exposed to increased temperature).

This paper outlines an innovative approach for characterizing the micromechanical phenomena resulting from fatigue cracking in terms of the specific energy of damage concept. In this approach crack propagation and its associated damage are considered irreversible processes, and hence, the general framework of the thermodynamics of irreversible processes is employed for modeling the FCP phenomenon. The specific energy of damage,

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which is proposed as a candidate material parameter characteristic of asphaltic pavements' resistance to crack propagation (fracture toughness), is the energy required to transfer a unit volume of a material from the undamaged to the damaged state. The experimental and analytical procedures required to extract the specific energy of damage for various asphaltic pavements are discussed. Case studies demonstrating the consistency of the specific energy of damage concept for characterizing the resistance of asphaltic pavements to fatigue crack propagation are presented. The effect of chemical structure, processing conditions, stress levels, and environmental temperatures on the FCP resistances of different asphaltic pavements are studied in terms of the specific energy of damage concept.

SPECIFIC ENERGY OF DAMAGE CONCEPT

The development of fatigue crack-resistant asphaltic pavements necessitates the thorough understanding of the combo-viscoplastic behavior of the binders (asphalt) and the additives (modifiers), which have been shown to be the major constituents influencing asphaltic pavements' crack resistance. Recently, the modified crack layer (MCL) approach has been proposed (*19*). The capability of this approach for discriminating the subtle effects introduced by different chemical structures and processing conditions in asphaltic mixtures has been demonstrated (*20–22*). The MCL model essentially addresses the difficulties encountered in the general applicability of the crack layer model (*23,24*). These difficulties are the identification and quantification of damaged species associated with FCP in materials.

The MCL model has been expressed as

$$T\dot{S} = (J^* - \gamma' a)\dot{a} + \dot{D} \qquad (1)$$

where

T = "ambient" temperature,
$\dot{S}$ = rate of change of the entropy of the system of the crack and the surrounding damage,
γ' = specific energy of damage,
a = crack length,
$\dot{a}$ = crack speed (see Equation 2),
$\dot{D}$ = rate of energy dissipation on material transformation associated with active zone evolution.

At minimum entropy the term $T\dot{S}$ = 0 and Equation 1 can be written as

$$\dot{a} = \frac{\dot{D}}{(\gamma' a - J^*)} \qquad (2)$$

where $\dot{a}$ is the crack speed, which can be expressed as da/dN for cyclic fatigue, with N being the number of cycles.

The energy release rate J^* can be evaluated experimentally. For stress control fatigue

$$J^* = \frac{1}{B}\left(\frac{\partial P}{\partial a}\right) \qquad (3)$$

where P is the potential energy (area above the unloading curve) at each crack length a, and B is the specimen thickness. Under strain control fatigue, J can be used instead of J^*, and it is expressed as

$$J = -\frac{1}{B}\left(\frac{\partial U}{\partial a}\right) \qquad (4)$$

where U is the strain energy (area under the loading curve at the corresponding crack length a).

It has been shown (*19,20*) that the cyclic rate of energy dissipation $\dot{D}$ associated with stress control loading can be expressed as

$$\dot{D} = \beta' \frac{dW_i}{dN} = \beta' \dot{W}_i \qquad (5)$$

where β' is the coefficient of energy dissipation, and the quantity $\dot{W}_i$ is the change in work expended on damage formation and history-dependent viscous dissipative processes within the active zone of the propagating crack. It was also shown (*22*) that

$$\dot{W}_i = \frac{1}{B}(H_i - H_o) \qquad (6)$$

where H_i is the area of hysteresis loop at any crack length, and H_o is the area of the hysteresis loop before crack initiation.

Substituting Equation 5 into Equation 2 and rearranging gives

$$\left(\frac{J^*}{a}\right) = \gamma' - \beta' \left[\frac{\dot{W}_i}{\left(\frac{da}{dN}\right)a}\right] \qquad (7)$$

The quantities J^*, da/dN, $\dot{W}_i$, and a can be measured during fatigue crack propagation experiments as reported previously (*20–22*). It was shown that if the quantities between brackets in Equation 7 are plotted in the *x-y* domain a straight line is obtained, which attests to the fact that the theory is in accord with the experimental results. This will directly give the value of γ', which is the intercept of the straight line.

It should be emphasized that establishing the γ' criteria is based on measuring more fundamental parameters related to the fracture behavior of materials than any other FCP laws. These are the change in work $\dot{W}_i$ expended on damage formation and history-dependent viscous dissipation processes, the volumetric amount of damage, which is taken as a linear function of the crack length, the conventional crack speed, and the energy release rate J^*. This makes the specific energy concept a sound alternative for characterizing various asphaltic mixtures to FCP.

CASE STUDIES

Relationships Between Structure and γ'

In this section the γ' concept is used to discriminate the subtle effect introduced by varying the polymeric additive loading in two asphaltic mixtures. The γ', characteristic of the fracture toughness of the mixtures, and their dissipative character, β', have been extracted on the basis of FCP experiments by making use of Equation 7. Relationships between γ' and the additive loading (percentage of polymer in the asphalt) have been constructed. Two asphalt cement modifiers that belong to the general group of thermoplastic polymers have been studied. These modifiers are SBS Kraton® D4463 (thermoplastic rubber and styrenic block copolymer) and Elvax (ethylene vinyl acetate).

Gradation requirements corresponding to Ohio Department of Transportation (ODOT) specification item 403 (*25*) were adopted in the preparation of all specimens with the two additives. An optimum AC-5 asphalt cement content of 8 percent was used, as evaluated from maximum stability and unit weight. Additive loadings of 6, 10, and 15 percent were used for each polymer. The bulk polymer was first heated to the compaction temperature of 160°C (320°F) and was then blended with the asphalt cement with a high-speed electric mixer until a uniform blend was achieved. Beams measuring 381 mm long × 50.8 mm thick × 88.9 mm deep (15 × 2 × 3.5 in.) were prepared from the modified asphalt mixtures containing 8 percent asphalt by weight with a unit weight of 149 pcf by the following procedure. The aggregate, modified asphalt cement and the mold were preheated to 160°C (320°F) before blending and compaction. Beams were compacted by sustaining a 13.79-MPa (2,000-lb/in^2) pressure through a steel plate for 1 min in agreement with ASTM 3202-83. Beams were allowed to cool off in the compaction mold and were usually tested 7 days after preparation and conditioning. Conditioning consisted of subjecting each beam to a constant temperature of 60°C (140°F) for 1 day.

Fatigue tests were conducted at a constant frequency of 0.5 Hz under load control from zero to a constant maximum load of 289 N (65 lb). Each cycle consisted of a 0.2-sec load duration with a 2-sec rest period. Tests were conducted at room temperature [21.1°C (70°F)]. An initial notch of 6.35 mm (0.25 in.) was placed in each specimen with a saw before testing. Three specimens were tested at each set of conditions, and the average value of γ' was obtained.

The relationships between the values of γ' obtained from Equation 7 and the percentage of additive (chemical structure) are given in Figure 1 for both the Kraton and Elvax modified asphalt mixtures. It is seen from Figure 1 that γ' has an optimum value at about 10 percent Elvax loading, whereas there is no optimum value for the Kraton-based mixtures. The value of γ' increases with the increase in the Kraton loading within the range of percent Kraton tested.

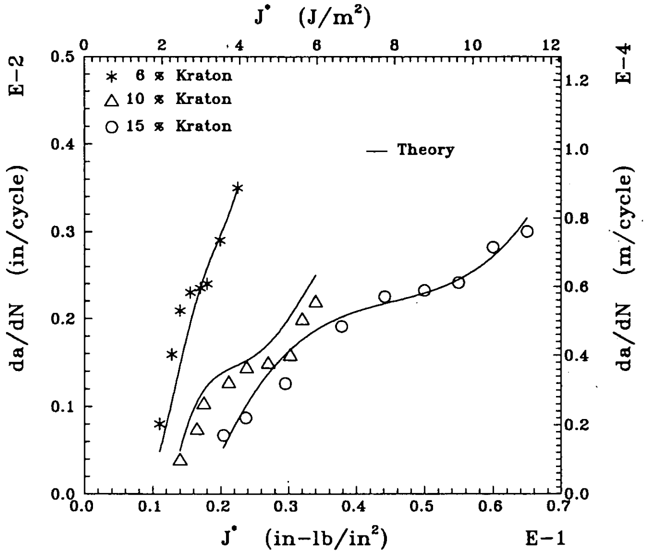

FIGURE 2 Theoretically predicted FCP speed on the basis of MCL model (together with experimental data) for modified AC-5 asphalt concrete mixtures with different Kraton loadings.

To demonstrate the relationship between γ' and the fracture toughness of the material, final results of FCP experiments for the Kraton-modified AC-5 with different loadings are discussed here. In Figure 2 the theoretically predicted FCP speed on the basis of the values of γ' and β', obtained from the modified crack layer model together with the experimental data, are shown. It is evident that the mixture with 15 percent additive, which has the highest γ', is the most resistant to FCP. This is easily established by comparing the value of J^* for the different mixtures at any constant crack speed. The higher the value of J^* the more resistant the material is to FCP.

The dissipative character, β', of each polymer-modified mixture was also extracted by using Equation 7. The relationships between the values of β' and the additive loadings for both Kraton- and Elvax-modified AC-5 asphalt mixtures are shown in Figure 3. It is evident from Figure 3 that the β'–percent additive relationship takes an opposing trend to the γ'–percent additive relationship for both the Kraton and Elvax asphalt mixtures. Such findings

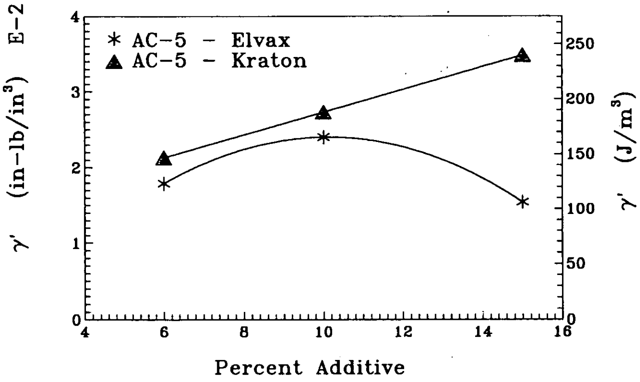

FIGURE 1 Relationship between γ' and percent additive loading.

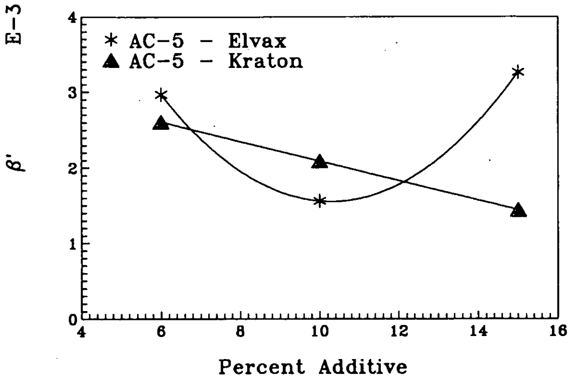

FIGURE 3 Relationship between β' and percent additive loading.

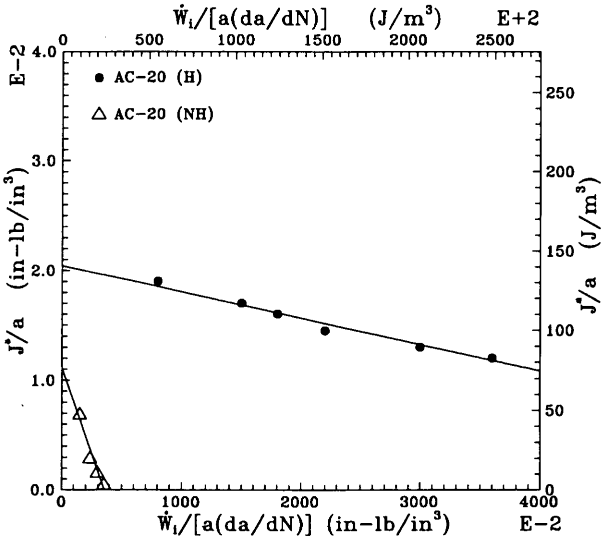

FIGURE 4 FCP behaviors of dynamically/statically (*H*) and statically (*NH*) compacted AC-20 asphalt concrete mixtures plotted in form of MCL model to obtain γ' and β'.

indicate that a higher value of γ' and lower value of β' can be associated with a tougher mixture.

Regarding the effect of additive loading, it was found that the fracture resistance of the Kraton-modified AC-5 mixture as reflected by γ' increases with the increase in the additive loading. Within the range of Kraton percentages tested (6 to 15 percent) it appears that both the polystyrene end blocks and butadiene rubbery midblocks are working together to improve the fracture toughness γ' of the Kraton-modified asphalt mixtures. On the other hand the Elvax-modified AC-5 asphalt concrete mixture showed a maximum fracture resistance at 10 percent additive loading. This can be attributed to the competing effects of the softer ethylene phase and the harder vinyl acetate phase in the Elvax modifier.

Thus, establishing structure-γ' relationships can serve an important role in asphalt mixture design. Such relationships can guide the development of asphalt mixtures with superior resistance to crack propagation (fracture toughness) and assessment of the lifetimes of these mixtures in service.

Relationships Between Processing Conditions and γ'

The effect of processing conditions on γ' was studied by changing the method of compaction of the beams. Beams made from an AC-20 mixture were compacted statically and with a static-dynamic combination method. An optimum asphalt content of 8 percent by weight, as determined from maximum stability and unit weight analysis, was used along with gradation requirements according to ODOT item 403 (*25*). The same procedure described previously was used to compact the statically compacted beams. The air void content for the conventionally compacted specimens was 1.3 percent.

The equipment required for the dynamic-static compaction includes a modified Marshall compaction hammer with a 44.48-N (10-lb) weight and an 0.457-m (18-in.) drop. The compaction face was modified to accept a 152.4 by 50.8 mm (6 × 2 in.) rectangular plate instead of the usual 98.4 mm ($3\frac{7}{8}$-in.)-diameter circular tamping base. The base of the compaction hammer was also preheated by using a bath of boiling water as a convenient method. The heated mold placed on a compaction pedestal was filled with the heated asphalt-aggregate mixture to about half of the depth of the mold. The layer was compacted at three positions by applying 10 blows at each position. The remaining heated asphalt-aggregate mixture was added to the mold as in the first stage, and another series of 30 blows was applied. Following the dynamic compaction procedure, the beam was subjected to a pressure of 13.79 MPa (2,000 lb/in^2) in a hydraulic press for 1 min. The compacted beam was then allowed to cool off in the mold before it was removed, and it was usually tested 7 days after preparation and curing. Curing was the same as that for the conventionally compacted specimens. The air void content was about 1.24 percent.

In Figure 4 the average results from three beams tested by each of the two processing methods are shown in the form of Equation 7. As can be seen the data from each set of the processing conditions form very good straight lines. The average values of γ' and β' for each mixture are shown in Table 1. It is observed from Table 1 that the average value of γ' for the dynamically and statically compacted AC-20 (*H*) mixture is about 1.8 times greater than that for the statically compacted AC-20 (*NH*) mixture, whereas the average value of β' for the statically compacted AC-20 mixture is about 13 times greater than the average value for the dynamically and statically compacted AC-20 (*H*) mixture. A larger value of γ' indicates that more energy is required to cause a unit volume to change from undamaged to damaged material, whereas a higher value of β' reflects the larger percentage of energy expended on dissipative processes and damage growth within the active zone. These two observations indicate that the dynamically and statically compacted AC-20 (*H*) mixture is more resistant to crack propagation than the statically compacted AC-20 (*NH*) one. This finding is in accord with the fatigue lifetime of each mixture. The dynamically and statically compacted specimens have an average fatigue lifetime of 14,000 cycles, whereas the statically compacted specimens have an average lifetime of 2,500 cycles. Thus, γ' has demonstrated its capability of reflecting the increase in the fracture toughness of the mixture, as enhanced by the dynamic-static compaction method.

TABLE 1 Average γ' and β' for AC-20 Mixtures

Mixture	γ' (J/m^3)	β'
AC-20 Stat/Dyn	141 ± 20	$2.40 \pm 0.15 \times 10^{-4}$
AC-20 Stat	77 ± 15	$3.14 \pm 0.20 \times 10^{-3}$

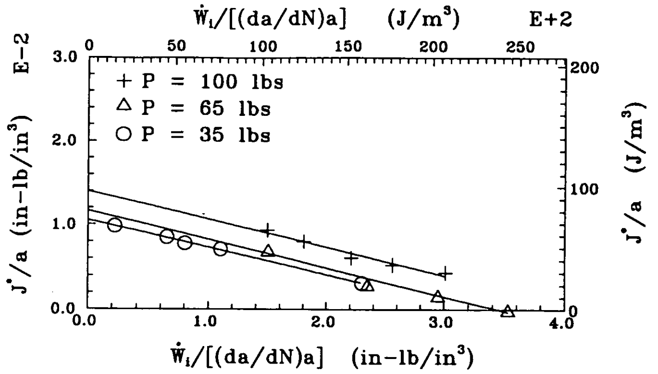

FIGURE 5 FCP behavior of AC-20 asphalt concrete mixture tested at three different maximum stress levels plotted in form of MCL model to obtain γ' and β'.

Relationships Between Stress Level and γ'

In this section the dependence of γ', as extracted from the MCL model, on the level of stress during fatigue loading is examined. The study was designed to verify the invariant nature of γ', which is proposed as a material parameter characteristic of the asphalt concrete mixture's resistance to crack propagation. The consistency of β' is also to be assessed in view of the level of loading or stress.

An AC-20 asphalt concrete mixture was prepared for the study by using gradation requirements corresponding to ODOT specification item 403 (*25*). An optimum asphalt cement content of 8 percent was used, as evaluated from maximum stability and unit weight. The beams were prepared by the same methods described in the previous section for the structure-γ' relationship. Four point flexural FCP tests were performed on three geometrically identical notched beams at three levels of stress. Tests were conducted in a laboratory environment at room temperature [21°C (70°F)] by using an invert haversine waveform. The load application period was 0.2 sec; this was followed by a 2-sec rest period between repeated loads. The notch depth was 6.35 mm (0.25 in.). Maximum loads of 444.8, 289, and 155.7 N (100, 65, and 35 lb) were used with continuous cycle load applications from zero to the maximum load. These levels correspond to approximately 29, 19, and 10 percent of the ultimate bending stress, respectively. All other experimental conditions were kept constant.

The average results for the three tested specimens at each stress level are plotted, on the basis of the MCL model, in Figure 5. It is evident from Figure 5 that the experimental points for all of the specimens at different stress levels make a good straight line, in which γ' is the intercept and β' is the slope. The average values of γ' and β' on the basis of three identical specimens at each stress level are given in Table 2.

In Figure 6 the experimental data are plotted, with the straight line based on the average values of γ' and β'. It can be seen that the average line represents the data at the different stress levels reasonably well. Bearing in mind the severe heterogeneity of the asphalt concrete mixture, the variations in γ' and β' can be tolerated and it is probably safe to conclude that the values of γ' and β' are independent of the stress level.

The consistency of γ' can be understood by examining Equation 7 and assuming that the term $\dot{W}_i/(da/dN)a$ is equal to 0 to obtain γ' at the intercept. It can be seen that γ' is dependent on the ratio J^*/a. As can be seen in Figure 6 this ratio, which is simply the slope of the curves, is almost constant at any given crack length for the three stress levels shown, and hence, γ' is independent of stress level. By a similar analysis, now assuming that the terms J^*/a and γ' are constant, it can be seen that β' is dependent on the ratio $\dot{W}_i/(da/dN)a$. It has been observed that both $\dot{W}_i$ and (da/dN) increase with the increased stress level, and it appears that they have increased proportionally since β' has remained constant.

Analysis of stress-controlled FCP experiments on the basis of the MCL theory revealed that the parameters controlling the fracture process, namely, γ' and β', appear to be independent of the stress level of fatigue loading.

Relationships Between Temperature and γ'

In this section the effect of temperature on the fracture and fatigue behaviors of Kraton-modified AC-5 asphalt concrete mixture is studied. Specimens were tested at three temperatures [1.67, 21.1, and 29.4°C (35, 70, and 85°F)]. The stress level and all other experimental conditions were kept constant as described in the section on the structure-γ' relationship. The Kraton loading was 6 percent by weight of the 8 percent asphalt cement binder. Beams were again prepared in the same manner as described previously in the section on the structure-γ' relationship.

The results for typical specimens tested at the three temperatures (1.67, 21.1, and 29.4°C) are plotted, on the basis of the MCL theory, in Figures 7, 8, and 9, respectively. It is evident from Figures 7 to 9 that the experimental points in each case make a good straight line in which γ' is the intercept and β' is the slope. The relationship between γ' and temperature is given in Figure

TABLE 2 Average γ' and β' for AC-20 Mixture Tested at Three Different Maximum Stress Levels

Maximum Load (N)	Percent Ultimate Bending Stress	γ' (J/m³)	β' E-3
444.8 (100 lbs)	29%	96.6	3.33
289.1 (65 lbs)	19%	77.6	3.18
155.7 (35 lbs)	10%	72.8	3.22
average values		82.3	3.24

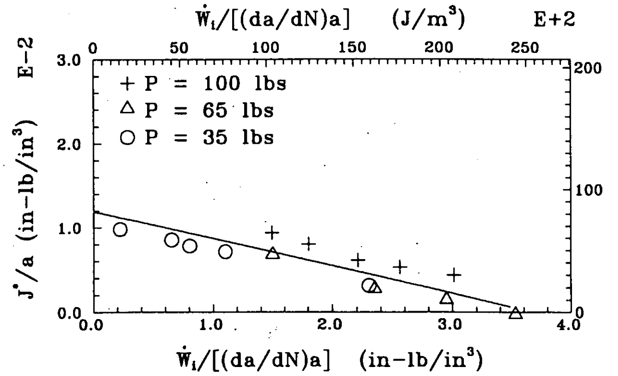

FIGURE 6 FCP data for AC-20 asphalt concrete mixture tested at three different maximum stress levels plotted in form of MCL theory along with the straight line representing average values of γ' and β'.

10. As seen from Figure 10, the value of γ' is almost independent of temperature. Thus, it is safe to conclude that γ' is a material constant that reflects the material's resistance to crack propagation because it has been found to be independent of testing conditions (stress level and temperature).

On the other hand, the value of β', which reflects the dissipative character of the material, depends strongly on temperature. This was not the case for the stress level tests described previously. There is a sharp increase in β' as the test temperature increases from 1.67 to 21.1°C (35 to 70°F). At temperatures greater than 21.1°C (70°F), β' appears to have less dependency on temperature. The consistency of γ' with temperature and the increase in β' with temperature have been reported independently (*26*) during fatigue crack propagation studies on PEEK. This lends support to the proposed approach by verifying it independently on other materials.

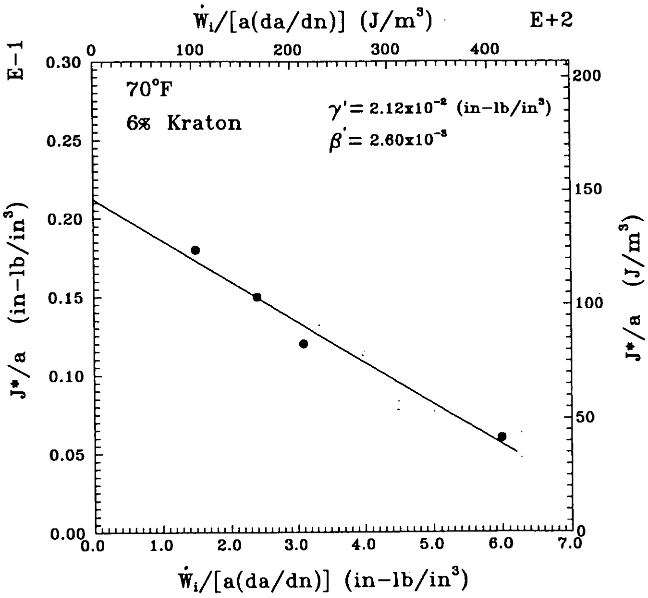

FIGURE 8 FCP behavior of 6 percent Kraton-modified AC-5 asphalt concrete mixture tested at 70°F plotted in form of MCL model to obtain γ' and β'.

CONCLUDING REMARKS

γ' is proposed as a material parameter characteristic of an asphalt mixture's resistance to crack propagation (fracture toughness). It is based on a constitutive equation, the MCL model, which is derived from the thermodynamics of irreversible processes. The validity of the approach was demonstrated through several case studies. It discriminated the subtle effects introduced by different loadings of two polymer modifiers, namely, Elvax and Kraton, to

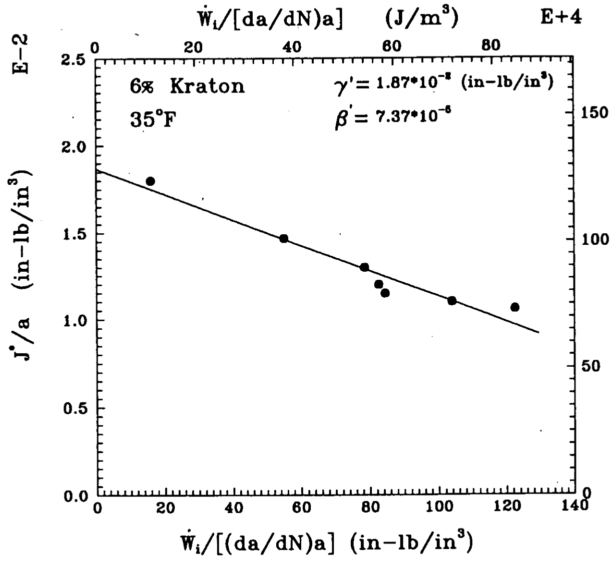

FIGURE 7 FCP behavior of 6 percent Kraton-modified AC-5 asphalt concrete mixture tested at 35°F plotted in form of MCL model to obtain γ' and β'.

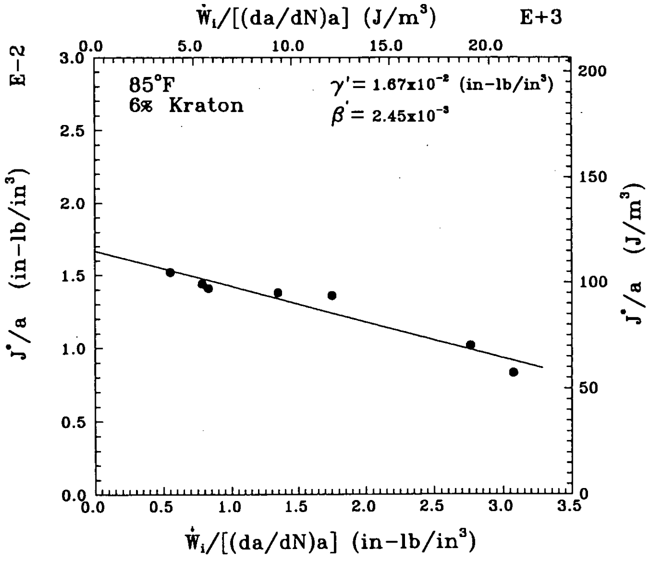

FIGURE 9 FCP behavior of 6 percent Kraton-modified AC-5 asphalt concrete mixture tested at 85°F plotted in form of MCL model to obtain γ' and β'.

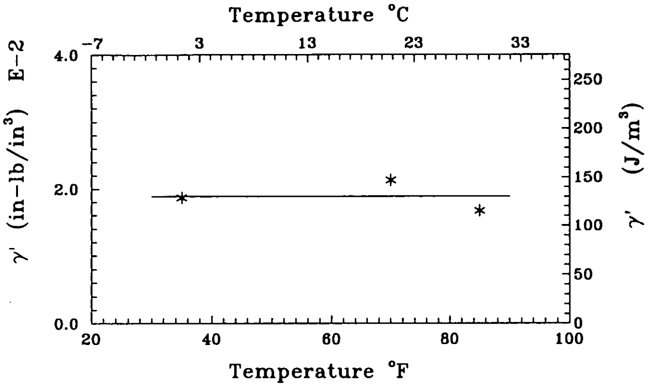

FIGURE 10 Relationship between γ′ and temperature for 6 percent Kraton-modified AC-5 asphalt concrete mixture.

an AC-5 asphalt concrete mixture. The validity of the approach was further tested by studying the effects of processing conditions on the value of γ′. Again γ′ successfully reflected the superior toughness of an AC-20 mixture that had been subjected to both dynamic and static compaction to that of an AC-20 mixture that had only been statically compacted. The usefulness of γ′ as a material parameter was shown with studies on the effects of both maximum stress level during fatigue testing and testing temperature. In both cases the specific energy of damage was found to be consistent, showing very little change over the range of stress levels and temperatures considered. On this basis it is safe to conclude that γ′ can be viewed as a material constant that reflects changes in material composition and processing but that has little dependency on testing conditions.

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REFERENCES

1. Wohler, A. *English Abstract in Engineering,* Vol. II, 1871, p. 199.
2. Monismith, C. L., K. E. Secor, and E. W. Blackmer. Asphalt Mixture Behavior in Repeated Flexure. *Proc., Association of Asphalt Paving Technology,* Vol. 30, 1961, p. 188.
3. Monismith, C. L., and J. A. Epps. *Asphalt Mixture Behavior in Repeated Flexure.* Report TE 69-6. University of California, Berkeley, 1969.
4. Pell, P. W., and I. F. Taylor. Asphalt Road Materials in Fatigue. *Proc., Association of Asphalt Paving Technology,* Vol. 37, 1969, pp. 423–458.
5. Pell, P. S. Fatigue Characteristics of Bitumen and Bituminous Mixes. *Proc., International Conference on the Structure and Design of Asphalt Pavements,* 1962, p. 310.
6. Clyton-Cave, J., R. J. Taylor, and E. Ineson. *Journal of Iron and Steel Instruments,* Vol. 180, 1955, p. 161.
7. McClintock, F. A. M., and A. S. Argon, eds. *Mechanical Behavior of Materials.* Addison Wesley, New York, 1966.
8. Rao Tangella, S. C. S., J. Craus, J. A. Deacon, and C. L. Monismith. *Summary Report on Fatigue Response of Asphalt Mixtures.* Report ASHRP-A/IR-90-011. National Research Council, Washington, D.C. 1990.
9. Paris, P., and F. Erdogan. *Journal of Basic Engineering,* in *Transactions of ASME,* Vol. 85, 1963, p. 528.
10. Schapery, R. A. A Theory of Crack Initiation and Growth in Viscoelastic Media. I. Theoretical Development. *International Journal of Fracture,* Vol. 11, 1975, pp. 141–159.
11. Schapery, R. A. A Theory of Crack Initiation and Growth in Viscoelastic Media. II. Approximate Methods of Analysis. *International Journal of Fracture,* Vol. 11, 1975, pp. 369–388.
12. Schapery, R. A. A Theory of Crack Initiation and Growth in Viscoelastic Media. III. Analysis of Continuous Growth. *International Journal of Fracture,* Vol. 11, 1975, pp. 549–562.
13. Majidzadeh, K., E. Kauffmann, and C. Saraf. *Analysis of Fatigue of Paving Mixtures from the Fracture Mechanics Viewpoint.* Report ASTM-STP 508. ASTM, Philadelphia, 1972, pp. 67–83.
14. Germann, P. F., and R. L. Lytton. Methodology for Predicting the Reflection Cracking Life of Asphalt Concrete Overlays. Report TT-2-8-75-207-5. Texas Transportation Institute, College Station, 1979.
15. Little, D. N., J. W. Button, et al. *Investigation of Asphalt Additives.* Report FHWA-R-D87/001. U.S. Department of Transportation, November 1986.
16. Rice, J. R. A Path Independent Integral and the Approximate Analysis of Strain Concentrations by Notches and Cracks. *Journal of Applied Mechanics,* Vol. 35, 1968, p. 379.
17. Eshelby, J. D. *Solid State Physics,* Vol. 3, 1956, pp. 79–144.
18. Begley, J. A., and J. D. Landes. *The J-Integral as a Fracture Criterion.* ASTM STP 514. ASTM, Philadelphia, 1972, p. 1.
19. Aglan, H. Evaluation of the Crack Layer Theory Employing a Linear Damage Evolution Approach. *International Journal of Damage Mechanics,* Vol. 2, 1993, pp. 53–72.
20. Aglan, H., I. Shehata, L. Figueroa, and A. Othman. Structure-Fracture Toughness Relationships of Asphalt Concrete Mixtures. In *Transportation Research Record 1353,* TRB, National Research Council, Washington, D.C., 1992, pp. 24–30.
21. Aglan, H., and J. L. Figueroa. A Damage Evolution Approach to Fatigue Cracking in Asphalt Concrete Mixtures. *Journal of Engineering Mechanics,* Vol. 119, 1993, pp. 1243–1259.
22. Aglan, H. Polymeric Additives and Their Role in Asphaltic Pavements. Part I. Effect of Additive Type on the Fracture and Fatigue Behavior. *Journal of Elastomers and Plastics,* Vol. 25, 1993, pp. 307–321.
23. Chudnovsky, A. Crack Layer Theory. In *10th U.S. Conference on Applied Mechanics* (J. P. Lamb, ed.). ASME, Houston, 1986, p. 97.
24. Aglan, H., A. Chudnovsky, et al. Crack Layer Analysis of Fatigue Crack Propagation in Rubber Compounds. *International Journal of Fracture,* Vol. 44, 1990, p. 167.
25. Department of Transportation Specification. *Construction and Materials Specifications.* Ohio Department of Transportation, Columbus, January 1989, p. 112.
26. Brillhart, M., and J. Botsis. Fatigue Fracture Behavior of PEEK. *Proc. Society of Plastics Engineering Annual Technical Conference,* 1992, pp. 136–139.

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