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Procedure for Predicting Occurrence and Spacing of Thermal-Susceptibility Cracking in Flexible Pavements

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The inability of previous models to accurately predict transverse cracking in pavements in the southwestern United States has led to the laboratory validation of the concept of thermal susceptibility of unstabilized base-course material. Thermal susceptibility is the volumetric contraction of a granular base-course material when it is frozen. This contraction produces cracking in the base course that is highly dependent on the environment in the general area. This paper presents the results of a study that attempted to quantify this mechanism and to predict crack spacings and the rate of crack appearance. The procedure used involves the combination of linear viscoelasticity and linear viscoelastic fracture mechanics. Crack spacings in the base course are calculated by using the results of a finite-element study of the frozen properties of the base course. The effect of these cracks (i.e., the rate at which they propagate reflection cracks through the asphalt surface layer) is determined by using a fracture mechanics approach. Intensity factors are calculated for the viscoelastic thermal stress in the asphalt caused by a temperature cycle and for the stress caused by the deformation of a crack in the base course caused by a freeze. The integration of these distributions in the Paris equation for crack growth gives the number of cycles to failure. These calculations were assembled into a computer model that uses daily climatic data and appropriate material properties to calculate the damage caused by daily temperature cycles. The behavior of asphalt and of sulfur asphalt are contrasted when placed over several base-course materials in two different environments, Abilene and Amarillo, Texas, to illustrate the effects of material-property variation and environmental influence. This model represents an initial theoretical approach to the problem of combining the effects on flexible pavements of environment and traffic to more accurately predict performance. Implications concerning reflection cracking can be drawn directly from the analysis of the effect of thermal susceptibility of the base course on the rate of reflection crack appearance.

To the driving public, cracked pavements are merely uncomfortable and, at worst, may become an irritation. To the engineer, however, the presence of cracking indicates that severe problems are present that will be accelerated by the presence of the cracks. Loss of load-transfer ability, weakening of subgrade stability, debonding, and accelerated rutting are common results seen after cracking is first noticed.

Throughout the southwestern United States, the most common form of cracking that is first visible is typically the transverse crack. This form of deterioration has, in the past, been associated primarily with low temperatures and, as a result, most of the research has concentrated on the fracture susceptibility of asphalt concrete under extremely low temperatures (1, 2, 3), which has not been very accurate for the Southwest. Subsequent studies have incorporated the concept of thermal fatigue and have increased the accuracy for predictions in the Southwest (1).

Recent studies of environmental effects on pavements in the west Texas area, however, have conclusively shown that there is a previously unconsidered environmental mechanism acting (4, 5, 6). This mechanism, thermal susceptibility, involves the contraction of an unstabilized granular base course when its temperature drops below freezing. The magnitude of this contraction is related to the environment (7) and material type and is an order of magnitude larger than that of asphalt concrete.

The deformation, or volume change, in the unstabilized granular base course is caused by particle reorientation in the clay-sized material (6). The reorientation is produced by the drying effect that results from the freezing of the water held in the larger voids. Previous studies have shown this deformation to occur in stabilized materials (7), but there its effect is greatly reduced because the stabilized material experiences shrinkage cracking during curing and drying. The cessation of activity below -6.7°C (20°F) is a result of the activity being confined to the clay minerals (8).

This paper presents the results of a study that examined the effect of thermal-susceptibility deformation of the base course on the rate of propagation of a crack through the asphalt concrete surface and included the effect of daily temperature cycles. The study also included the development of a procedure to predict crack spacing that is based on the principles of fracture mechanics and the material properties of the substances studied. The result is a computer model that allows the study of crack appearance under general conditions for any area. The development of this model is explained in the following sections, and calculations for two cities in Texas are presented.

FRACTURE MECHANICS

When a stress field is applied to a material that has a crack or small flaws, these cracks will produce stress singularities near the tips. By using linear elastic theory, researchers have recently approached the problem of developing mathematical formulations to make practical application of the concepts involved in fracture mechanics. Attention has been focused primarily on this stress field near the tip of the crack, which has the form $[1(r)^{1/2}]$ for both linear-elastic and linear-viscoelastic materials. The magnitude of this stress is the stress-intensity factor (K_I).

These cracks, or flaws, will grow at a rate that is dependent on K_I. In an elastic material, the critical value of K_I (K_{Io}) represents the limit of stable crack propagation. If the value of K_I by a thermal loading is larger than K_{Io}, failure will occur and the crack will propagate instantaneously to the surface of the pavement. In the case of low-temperature cracking of asphalt concrete where temperatures are at or below the glass transition point, the material will behave elastically and the concept of a K_I-value must be considered. For thermal fatigue, however, the temperatures of interest are at or above the glass transition point, and the material behaves as a viscoelastic material. There is no K-value for a viscoelastic material, and it need not be considered in a thermal-fatigue analysis (9); propagation will be a continuous process without catastrophic failure until extremely low temperatures occur. Paris (10, 11) first suggested that for fatigue-crack propagation in metal, the crack growth rate was almost exclusively dependent on the change in K_I during each cycle (ΔK) (i.e., the amplitude of K) and only secondarily dependent on the mean stress and frequency. He proposed the following equation to describe the crack growth rate:

$$(dc/dN) = A(\Delta K)^n \tag{1}$$

where

c = crack length,
N = number of cycles, and
A and n = material constants obtained from experimental tests.

Recent data collected at Ohio State University (12, 13, 14, 15) from tests on sand asphalt beams and slabs resting on elastic foundations indicate that the crack-propagation process in an asphalt mixture can be predicted by using this power law relationship. The prediction of total fatigue life (N_f) can then be obtained by integrating Equation 1 to obtain the number of cycles to failure:

$$N_f = \int_{C_0}^{C_f} [1/A(\Delta K)^n]\, dc \tag{2}$$

where C_0 and C_f are the initial and final crack size respectively within the asphalt concrete. Once the material constants (A and n) have been found, a prediction of fatigue-crack propagation can be made if the history of the loading sequence, the crack length, and the boundary conditions are known. The previous studies of fracture in asphalt concrete do not, however, provide a means of predicting the values of A and n or of their variation with loading and environment, which are usually obtained as a result of the fatigue or fracture testing when the results are known.

Recently, Schapery (9, 16, 17) has developed a completely general theory of crack growth in viscoelastic media by using the power law relationship $D(t) = D_0 + D_1t^n$. The result allows prediction of the response of a viscoelastic medium by using the results of elastic solutions for the K-values and also shows the relation of A and n to the material properties and the input parameters.

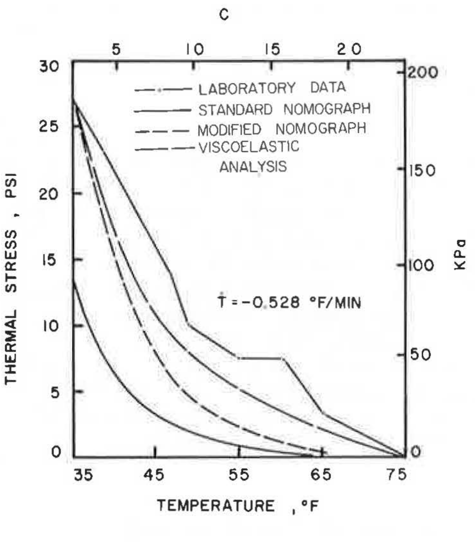
The remaining quantity needed to calculate crack-propagation rates is the value of ΔK produced by each thermal load (temperature cycle). Although analytical solutions have been obtained, the geometrical considerations are limited (18, 19, 20). The finite-element method is generally used because of its ability to handle very general geometries, a variety of loading conditions, and a range of material properties. The problem with the finite-element approach has been the large computation time that results from the use of the very fine element mesh configurations required to obtain acceptable accuracy near the crack tip.

A new crack-tip element that uses the complex-variable technique and the hybrid-element concept has been formulated by Tong, Pian, and Lasry (21). When combined with a conventional finite-element code, this technique allows the proper consideration of the stress intensity at the crack tip and also produces an extremely efficient computer code (22).

During a thermal cycle, K_I reaches a maximum when the temperature reaches a minimum. For this analysis, it is assumed that the crack will undergo instantaneous, stable propagation when the pavement reaches its daily minimum temperature (or maximum K_I). Therefore, the calculated maximum value of K_I (K_{max}) is used in the calculation procedure to obtain the rate of crack propagation.

The rate of crack propagation is greatly influenced by the stress field that is applied to the crack tip. The two stress fields considered here are the viscoelastic thermal stress and the stress produced by thermal-susceptibility deformation in the base course. Both of these stresses are greatly influenced by the viscoelastic behavior of the asphalt concrete, which produces varying tensile stresses and moduli throughout the day, depending on the temperature and its rate of change. Both will influence any elastic analysis done to obtain stress-intensity factors. Thus, it is necessary to have the most accurate stress values that are possible to input into the finite-element procedure.

Figure 1. Comparison of prediction schemes for viscoelastic thermal stresses.



STRESS PREDICTIONS

Viscoelastic Thermal Stresses

The most accurate scheme developed for prediction of viscoelastic thermal stress was presented in a Joint Army-Navy-Air-Force publication (23) and first applied to asphalt concrete by Chang, Lytton, and Carpenter (22). In Figure 1 (22) the viscoelastic thermal-stress data of Monismith and others (24) and of Shahin and McCullough (1) are compared to actual laboratory data for asphalt concrete beams (24) and the stresses predicted by using the effective-modulus viscoelastic scheme discussed here. This comparison clearly shows the scheme used here to be the most accurate for the situation examined.

The input data necessary to predict the viscoelastic thermal stresses include the following:

1. The isothermal creep compliance and the associated shift functions, D_o, D_1, and a_t;
2. The coefficient of thermal expansion;
3. The rate of temperature drop and the minimum temperature; and
4. Poisson's ratio.

Thermal-Susceptibility Stresses

In a restrained, intact layer such as a base course before it cracks, contraction caused by the freezing temperature will produce a tensile stress that is the same everywhere along the length of the pavement. Because thermal susceptibility is initiated only when the base course freezes, all material properties for the base course will relate to the frozen condition. Because of the inhomogeneity of paving materials, there will be areas of property variation that cause stress concentration or stress relief, and cracking will initiate at the areas of stress concentration. As it is impossible to predict the number or severity of these anomalies, certain simplifying assumptions must be made in lieu of any stochastic procedure.

When a base course in a pavement structure has a preexisting crack spacing of L, the tensile stress in the base course will be a maximum at the center of the span, because of the restraint provided by the asphalt surface and subgrade layers. If the magnitude of this stress at the midspan exceeds K_{Ic} for the frozen base material, which behaves elastically, the base course will crack. The tensile strength of the base course is a very rough approximation of the point at which fracture will initiate and is used here because no data are available for critical stress-intensity factors in frozen base course material. In this analysis, when the tensile stress at midspan exceeds the tensile strength, the base course will fracture and this crack will deform under the effects of thermal susceptibility.

The factors producing the tensile stress at midspan are:

1. E_B (the frozen Young's modulus of the base),
2. L (the original crack spacing),
3. ΔT (the drop in temperature below freezing that initiates the thermal-susceptibility activity), and
4. α_B (the freeze coefficient of the base course).

By using the results of finite-element calculations, a regression equation was formulated to predict the midspan tensile stress by varying the above properties. The equation is as follows:

$$\sigma_{TENSILE} = (5.616 \times 10^{-3})(E_B)(\alpha_B)^{0.7886}(\Delta T)^{1.4506}[-1.868 + 22.899 \text{ LOG}(3.281\,L)]^{0.68596} \quad (3)$$

(This equation was developed for use with U.S. customary units only; values in Figure 6 are not given in SI units.) Whenever a combination of these parameters produces a tensile stress greater than the tensile strength, the base course will crack, producing a resulting crack spacing of L/2.

Figure 2 is a plot of Equation 3 and shows the existing crack spacing (L), for which a given freezing temperature (ΔT) will cause the base course to crack at a spacing of L/2 for various levels of base-course tensile strength. The larger the value of ΔT, the higher the stress, and the smaller the crack spacing that will develop as a result of the freeze. Because thermal susceptibility ceases at -6.7°C (8), there can be no smaller crack spacing than that which occurs at ΔT = -6.7°C.

It is evident from the figure that a very small freezing temperature could produce cracking at a very large spacing when L is already long. Because of the unpredictable occurrence of the inhomogeneities, the first crack spacing that occurs cannot be predicted. This inaccuracy is compounded by the fact that the curve is nearly asymptotic at crack spacings greater than 55 m (180 ft). The most easily predicted spacing is the minimum spacing for a ΔT of -6.7°C. For simplicity, the initial crack spacing is assumed to be a multiple of this minimum spacing.

Because cracking is most likely to occur at midspan, each crack spacing will be one-half of the preceding crack spacing, as illustrated in Figure 3. This divides the crack spacing curve into distinct intervals that require that a definite freezing temperature (ΔT) be reached before the base course will crack further. When a ΔT of -3.4°C (26°F) occurs in Figure 3, the spacing of L = 13.2 m (43.2 ft) will crack, producing a resultant crack spacing of 6.6 m (21.6 ft). A new crack spacing will not occur until the temperature drops to -3.8°C (25°F) in the base. When this occurs, the spacing of L = 6.6 m (21.6 ft) will experience an excessive tensile stress, causing a resultant crack spacing of 3.3 m (10.8 ft) to begin. Any freezing temperature that does not reach -3.8°C will not produce a new crack spacing, but will propagate the existing cracks in the base course further into the asphalt concrete, as the base course continues to deform under the subsequent freeze-thaw cycles. This deformation produces a stress in the asphalt that will be controlled by its modulus. A study of the finite-element calculations conducted to obtain Equation 3 (22) showed that, after fracture, 60 percent of the stress in the base course transferred into the asphalt concrete as a result of the deformations. This is the stress used to obtain the K_I-values for thermal susceptibility. The magnitude of the stress is directly related to ΔT and L.

STRESS-INTENSITY FACTORS

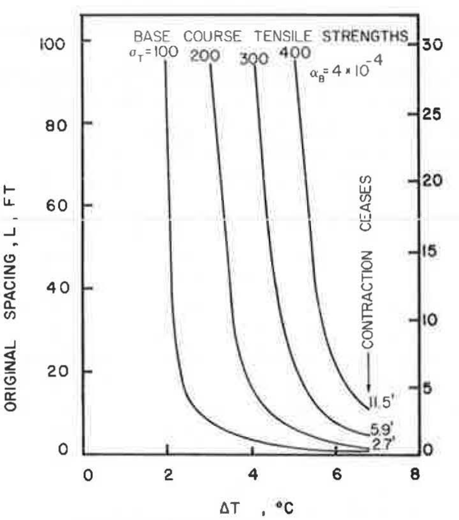
Viscoelastic Thermal Stress

The distribution of K-values for viscoelastic thermal stress has been calculated in a previous study of thermal stress effect on reflection cracking (22). An average stress distribution for western Texas produced the K-value versus crack length curves given in Figure 4 (22). The larger stress occurs at the surface, as indicated by the higher value of K_I. For this analysis, only one pavement thickness is investigated, 3.8 cm (1.5 in).

Thermal-Susceptibility Stresses

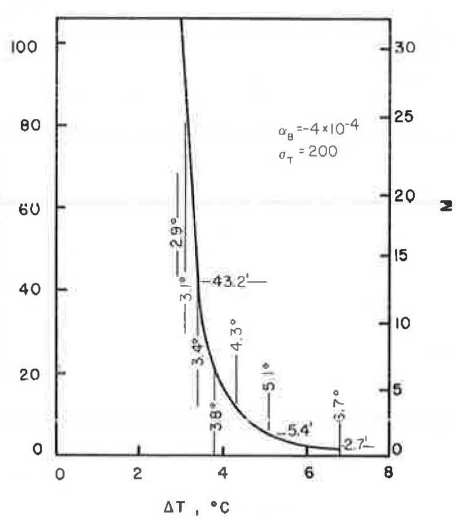
The base course produces a tensile stress in the asphalt concrete layer when the base course cracks under a low temperature. Temperature cycling of the base course below freezing will produce cyclic deformation of the crack and produce a stress in the asphalt concrete with each cycle. This activity is identical to the process of reflection cracking in an overlay over a cracked or jointed pavement. The stress produced by the thermal-susceptibility deformation will be greatest nearest to the crack. This is shown in Figure 5. The curves are differentiated by the magnitude of the tensile stress predicted by Equation 3. The stress, rather than the deformation, is used in this analysis because the stresses

Figure 2. Crack spacing as a function of temperature drop in base course that will cause existing crack spacing to crack at midspan.



Note: t°C = (t°F - 32)/1.8.

Figure 3. Crack spacings as multiples of minimum spacing and temperature drop necessary to cause this spacing.



Note: t°C = (t°F - 32)/1.8.

Figure 4. Variation of K_I with crack length that is caused by average thermal-stress cycle.

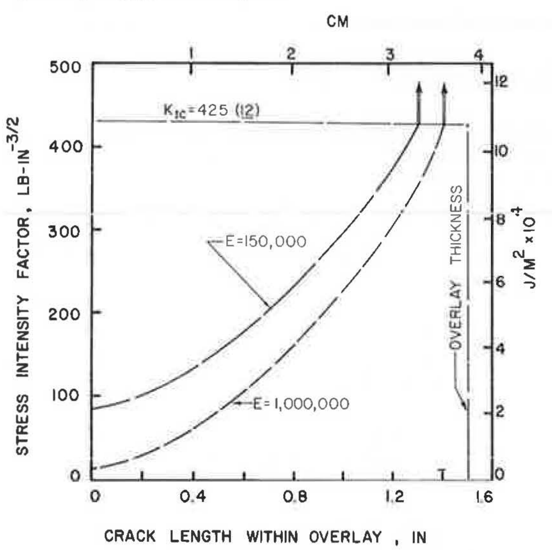
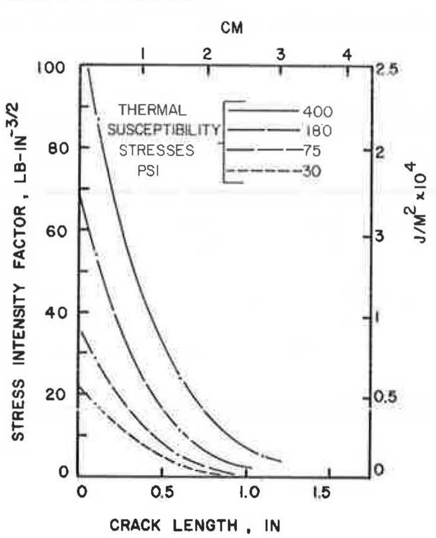


Figure 5. Variation of K_I with crack length that is caused by thermal-susceptibility-induced stress from base course.



are known and directly related to the deformations that produce the stresses.

PREDICTING NUMBER OF TEMPERATURE CYCLES TO CAUSE FAILURE

The pavement to be analyzed for thermal susceptibility cracking is a newly constructed flexible pavement as shown in Figure 6. Each layer is characterized by the material properties indicated, and a plane strain condition is assumed for crack propagation (9).

Thermal Stresses

The number of cycles to failure (defined as the cycles for complete crack propagation) is obtained from the integration of Equation 2 and the proper distribution of K_I-values. Numerical integration of the K_I-values was done by using Simpson's rule. The results are shown in Figure 7 (22), which also shows the effect that changing the material properties (A and n) will have on the pavement life. The values of $A = 1 \times 10^{-12}$ and $n = 5$ were chosen for the complete analysis because they represent midrange values predicted by both experiment and theory (9, 15).

Figure 6. Cross section of pavement analyzed for thermal-susceptibility cracking.

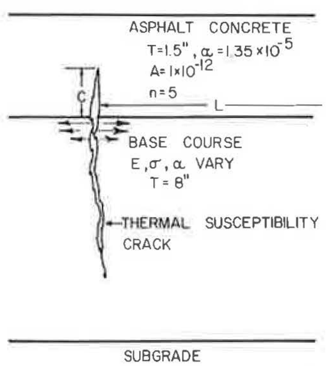
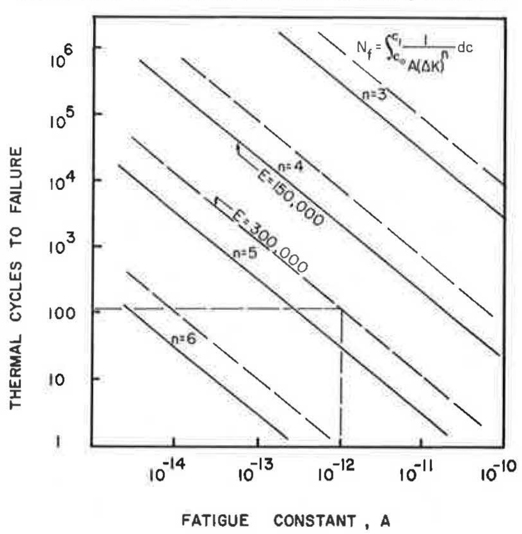


Figure 7. Life of pavement surface subjected to average thermal cycle as function of A and n fracture parameters.



Note: Indicated life is 100 cycles.

Thermal Susceptibility

The K_I-value versus crack length curves in Figure 5 could be integrated separately and added to the results shown in Figure 7 to give the thermal stresses. The K_Is for both stresses can be directly superimposed, however, because they are both opening-mode values. The resulting distribution is shown in Figure 8. When the curves in this figure are integrated to obtain the number of cycles to failure, the data presented in Figure 9 result. These curves show that thermal susceptibility stresses in the base course reduce the number of temperature cycles necessary to propagate the crack in the base course through a 3.8-cm-thick asphalt concrete surface. In a real pavement, the temperature cycles occur randomly, which requires the use of Miner's hypothesis of linear cumulative damage (9). This application is a direct consequence of the visco-elastic theory when A, n, and ΔK are constant, which will be true for each cycle. For the temperature ranges investigated here, no significant variation in A and n has been reported.

The results shown in Figure 9 have been combined into an equation that can be used as the damage equation in the computer code. The equation is as follows:

Figure 8. Variation of K_I with crack length that results from combined action of average thermal-cycle and thermal-susceptibility stresses.

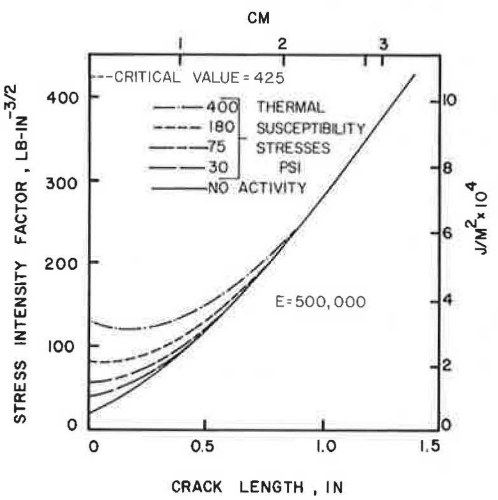
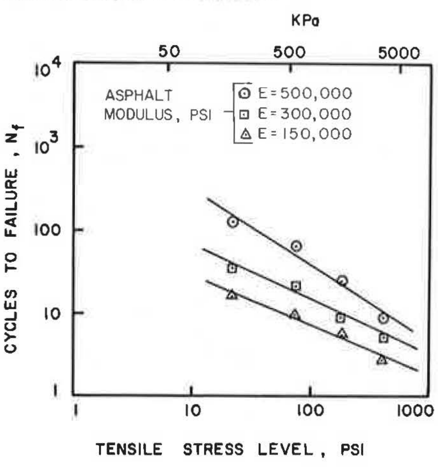


Figure 9. Life of pavement surface subjected to combined K_Is as function of thermal-susceptibility stress developed in base course.



$$N_f = A(\sigma)^B \quad (r^2 = 0.98) \qquad (4)$$

where

σ = 60 percent of stress predicted by using Equation 3 as causing the K_I used to determine N_F,
A = antilog [1.5176 + 4.4127 × $10^{-6}(E_A)$], and
E_A = effective modulus of asphalt concrete.

The reciprocal of Equation 4 represents the damage caused by a specific temperature cycle. When this value sums to 1.0, the crack has propagated to the surface of the asphalt concrete layer. This damage equation forms the basis of the crack prediction code, which uses easily obtained stress predictions to calculate the damage for each temperature cycle.

PREDICTING CRACKING IN PAVEMENT EXPOSED TO ENVIRONMENT

To predict the in-service behavior of a pavement, it is necessary to first have temperature data for the pavement. Hourly pavement temperatures are calculated by using Barber's equation (25) as modified by Shahin and McCullough (1). This procedure uses daily climatic data that can be obtained from the National Oceanic and Atmospheric Administration on computer tapes. Temperatures are calculated at the top surface, midpoint, and bottom of the asphalt surface for every hour. If the temperature at the top of the base course does not drop below freezing, there is no thermal-susceptibility damage, but thermal-fatigue damage may occur. If the average temperature of the surface course drops appreciably, damage caused by the average viscoelastic thermal stress can be accumulated.

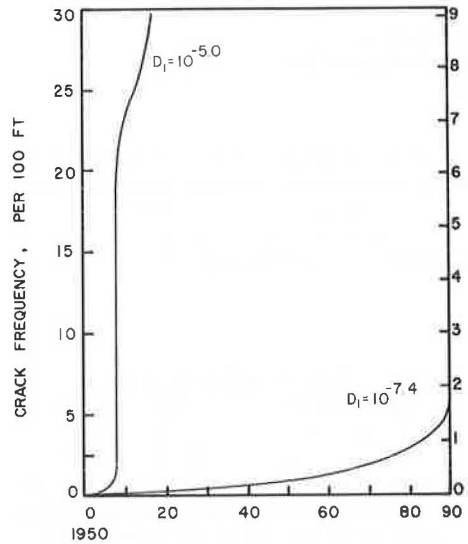
If the temperature at the top of the base course falls below freezing, several calculations are made. First, the temperature is checked to see what crack spacing it will produce, as shown in Figure 3. If the temperature is low enough to produce a new crack spacing, the base is cracked and the stress in the asphalt is calculated based on the new spacing. The damage equation (i.e., Equation 4) is used to calculate the damage that each existing crack in the base course produces in the asphalt concrete as a result of this cycle. If the temperature drop is not low enough to produce a new spacing, Equation 4 is used with the existing crack spacing to obtain a damage value for each existing crack for that temperature cycle.

The damage value for each cycle is added to a storage register that represents a particular crack spacing. No damage can be accumulated for a specific spacing until the temperature has at least once fallen low enough to produce that crack spacing in the base course. At this time, damage will begin accumulating for that spacing.

To illustrate the behavior of different materials when exposed to the environment, asphalt concrete and sulfur asphalt concrete were examined in two different environments when placed over different base courses. Figure 10 shows the influence of changing the stiffness of the asphalt layer in an Abilene, Texas, environment. The larger the value of the negative exponent (i.e., D_I), the stiffer the material.

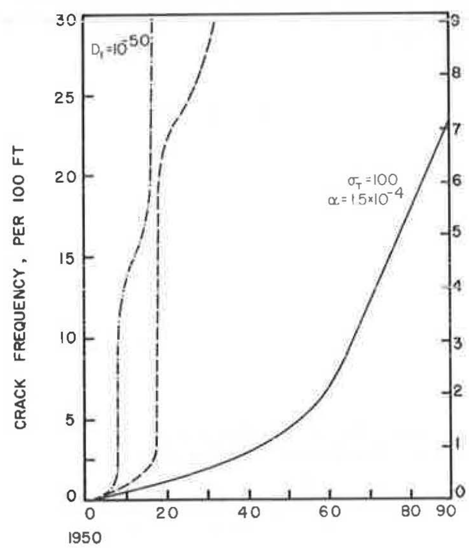
A sulfur asphalt will be stiffer and have a lower slope to the log creep-compliance curve. The behavior of a sulfur asphalt in Abilene is shown in Figure 11. There is a marked increase in the time for a given crack spacing to occur for the sulfur asphalt. The influence of the base course is also illustrated; decreasing the tensile strength and freeze coefficient reduces the amount of cracking at a given time after construction.

Figure 10. Crack-frequency predictions for Abilene, Texas, illustrating effect of varying compliance or stiffness of asphalt concrete.



Note: n = 0.5, σ_T = 17.20 MPa (250 lbf/in²), and α_B = 3.5 x 10^{-4}.

Figure 11. Crack-frequency predictions for Abilene, Texas, illustrating effect of using sulfur asphalt.

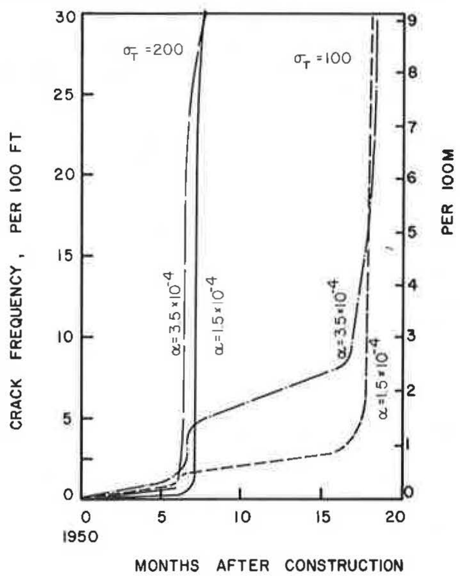


Note: n = 0.25, D_I = $10^{-5.77}$, σ_T = 17.20 MPa (250 lbf/in²), and α_B = 3.5 x 10^{-4}, unless otherwise indicated.

For the sulfur asphalt, a D_I-value of 10^{-70} completely eliminated cracking. This value is obtainable for a sulfur asphalt, but probably not for a normal asphalt concrete, at the reference temperature of the creep curves used here.

The effect of the climatic region is illustrated in Figure 12, which shows the behavior of an asphalt pavement in Amarillo, Texas, a more severe environment. The pavement cracks in slightly less time than a similar pavement in Abilene. The data in Figure 12 show that the tensile strength of the base course has more effect than the freeze coefficient of the base course in determining crack appearance. The lower the tensile strength of the base course, the lower the amount of cracking.

Figure 12. Crack-frequency predictions for Amarillo, Texas, illustrating effect of tensile strength of base course.



Note: n = 0.5 and D_1 = $10^{-6.4}$

CONCLUSIONS AND RECOMMENDATIONS

Several significant factors are presented and developed in this paper. First, a thermal-susceptibility mechanism, previously validated and related to the environment, is shown to possess the damage potential to crack a base course at regular intervals and propagate these cracks through the asphalt concrete. Second, a theory of viscoelastic fracture mechanics is applied to a pavement system to predict environmentally induced transverse cracking. This theory has accurately predicted fatigue-load damage in asphalt concrete and can reasonably be expected to apply to environmental loadings. Finally, an improved method for calculating viscoelastic thermal stresses was incorporated into a routine that uses daily climatic data to calculate stresses and stiffness levels in asphalt concrete. These values are important in calculating the stress intensity factors, which are the major factors affecting the rate of crack propagation.

The combination of these three considerations provides a mechanistic procedure for studying the effect of temperature on a flexible pavement system. A broad range of environments can be studied; the input parameters for the climate are available for every portion of the United States. The values used here can be considered reasonable for common pavement sections in the southwestern United States. Actual properties for a frozen base course, determined in the laboratory, are used to predict the crack spacing and the occurrence of the cracks. The variation of performance with changes in the properties shows how critical the proper consideration of these properties is. To date, there has not been an in-depth study of the expected variations in A, n, and D_1 with temperature or with changes in the mix properties of the asphalt concrete, although these can be estimated from previous studies. The frozen properties of base courses have been obtained for only one or two base-course materials. An in-depth study of these properties is essential before more precise calculations of the expected crack spacings and rate of crack appearance can be conducted. The procedure developed here is directly applicable to the study of reflection cracking in overlays resulting from both traffic and environment. This represents the next stage in the development of this predictive procedure and may be a most promising application of fracture mechanics for the design and analysis of overlays.

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Evaluation of Increased Truck Size and Mass on Pavement Life and Design Thickness

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The results are presented of an analytical study that evaluated the effects of increased vehicle size and mass on pavement life and thickness. The techniques are applicable primarily to relatively new or reconstructed pavements; however, an approach is also presented that shows how they can be used to evaluate the effect on pavements that have been in service for several years. An increase in legal single-axle loads from 80 to 110 kN [18 000 to 24 000 lbf/in^2 (18 to 24 kips)] or in tandem-axle loads from 140 to 200 kN [32 000 to 44 000 lbf/in^2 (32 to 44 kips)], could result in a loss of pavement life of up to 80 percent if applied to the existing system. The incremental thickness for new construction or reconstruction associated with the heavier trucks would require a maximum of 65 mm (2.5 in) of surfacing material. Truck configuration can also substantially affect the number of equivalent 80-kN axle loadings. The incremental thickness for new or reconstructed pavements associated with the different truck configurations can amount to approximately 40 mm (1.5 in) of surfacing material.

With the changing and growing demands on today's technology, there has arisen the need to evaluate the impact of increasing the sizes and masses of vehicles. The U.S. transportation system must be responsive to any change in vehicle dimensions. An evaluation of the effects of changed vehicle sizes on the highway system requires an analysis of the effect of increased vehicle loads on pavement performance.

The objective of this paper is to evaluate, by using analytical techniques, the effects of increased vehicle loads on pavement life and pavement thickness. The techniques developed apply to relatively new or reconstructed pavements. Additional work is under way to evaluate the effects of increased loads on pavements that have been in service for several years.

The axle loadings used are within the range forecast in the U.S. government 1980 goals report (1); i.e., single-axle loads of up to 115 kN (26 kips) and tandem-axle loads of up to 200 kN (44 kips). Results of this study are in three forms:

1. An estimate of the reduction in life of existing pavements if no change in current maintenance practices occurs,
2. An estimate of the additional pavement thickness that will be required to maintain the level of service under present legal loads, and
3. An evaluation of the relative pavement damage