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Reflection Cracking Models: Review and Laboratory Evaluation of Engineering Fabrics

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A review of recent theoretical models for analyzing reflection cracking in pavements is presented. Four models are applicable to asphalt overlays of jointed-concrete pavements, and one model deals with asphalt overlays of existing flexible pavements. Both mechanistic and phenomenological models are reviewed, together with a critique of each model's shortcomings. A two-dimensional finite-element analysis of flexible overlay stress for jointed-concrete slabs subjected to seasonal and daily temperature changes is presented. The analysis shows that, contrary to some existing models, curling temperature gradients (cold or slab surface relative to bottom) produce joint openings that induce only tension stress in the overlay. A technique is presented for equating daily (curling) thermal loads to seasonal thermal loads in terms of equivalent maximum overlay stress. The finite-element analysis suggests that a reflection cracking model must consider the ratio of loading and temperature dependency of the asphalt overlay modulus in any stress calculation. Laboratory testing is currently being conducted to verify reflection cracking models and assess performance of geotextiles and stress-absorbing membrane interlayer systems to reduce cracking.

Reflection cracking is the cracking of a resurface or overlay above underlying cracks or joints. It occurs in overlays of both flexible and rigid pavements and is a major cause of distress; it includes spalling, surface water infiltration to underlying layers, and a general reduction in structural stiffness. Reflective cracks require continued future maintenance for crack sealing and patching and thus are a significant expense item.

Reflection cracking is not a new engineering problem. Since the early 1950s many different materials, methods, and techniques have been tried to prevent or at least delay reflection cracking. Most of these efforts have been for an asphalt concrete (AC) overlay on existing portland cement concrete (PCC) slab applications, where existing cracks or joints are usually reflected through the overlay within a year (1). Early research recognized that the probable cause of reflection cracking was movement of some form in the underlying pavement at existing cracks and joints. This movement can result from both traffic- and environment-induced forces, and includes differential vertical movement, thermal- or moisture-induced expansion, contraction, or distortion (curling) at underlying joints and cracks.

Because the overlay is bonded to the existing pavement, movement at underlying joints or cracks induces stresses in the overlay. Sufficiently high stresses can cause fracture or cracking of the overlay. If the induced stresses do not exceed the yield strength of the overlay material, cracking could still develop as the result of cyclic load applications that produce fatigue fracture of the AC. Bond breakers, cushions, rubber-asphalt stress-absorbing membrane interlayers (SAMIs), fabrics, and stronger overlays modify the existing pavement and are among the methods that have been used in an attempt to mitigate the reflection cracking problem.

The literature indicates that reflection cracking studies and field experiment projects to date have generally been of an empirical nature, with little control or identification of the parameters known to affect cracking. Characterizing the existing pavement in terms of joint width, load transfer, crack spacing, crack and joint opening under known temperatures, and deflection under load are usually not part of such studies. Obviously, certain crack-prevention treatments are sensitive to some of these factors, as demonstrated in numerous field studies.

Figure 1. Bending of overlay by joint vertical movement.

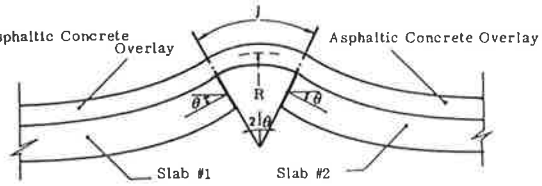
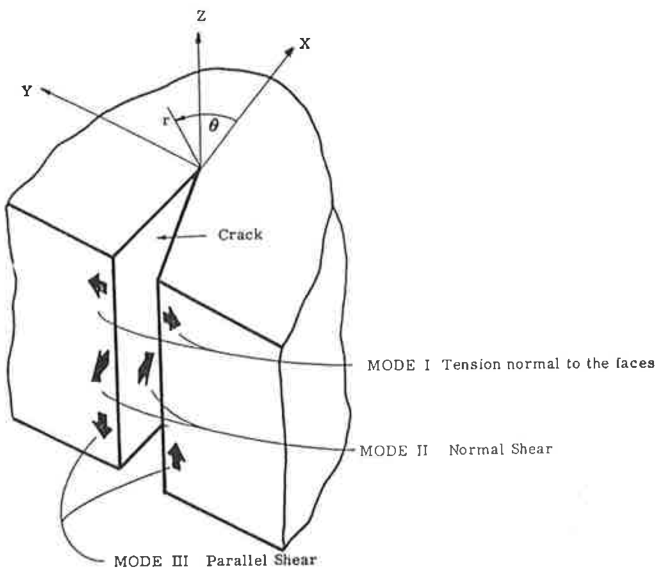


Figure 2. Modes of crack deformation.



Past research, however, has not established quantitative relations between these factors and the success or failure of preventative techniques.

EVALUATION OF EXISTING REFLECTION CRACKING MODELS

Within the past decade several theoretical (mathematical) models have been developed to analyze and predict the occurrence of reflection cracking. All of these models consider the same mechanisms noted above (e.g., reflection cracking is caused by differential horizontal or vertical movements in the underlying layer). The models differ in the methods used to predict the magnitude of underlying layer movements, the magnitude of stresses induced in the overlay by such movements, and the response of the overlay to stress state (sudden facture versus fatigue fracture). Currently existing models are summarized in the following sections, and evaluations of each model's limitations are presented.

Ultimate Strength Model--Ohio State University

The ultimate strength model developed at Ohio State University (OSU) (2) is a nomograph procedure for predicting AC overlay stresses on joints or cracks that result from thermal-induced movements in underlying PCC slabs. Separate stress analyses are performed for horizontal slab movements (i.e., due to seasonal changes in average slab temperature) and vertical slab movements that occur due to slab curling (i.e., the temperature state where the top of the PCC slab is colder than the bottom).

Horizontal movement of the PCC slab (d) for a change in slab temperature [T(°F)] is calculated by using an average value (f) for the friction coefficient, which is similar to calculations for determining temperature reinforcement in jointed reinforced-concrete pavements. Most importantly, this model neglects the resistance to joint movement provided by the uncracked overlay that is bonded by a tack coat to the underlying slab. The OSU model assumes that this resistance is small and that thin overlays do not affect joint movement due to temperature change. Inputs to a finite-element model to determine overlay stresses are the joint dimension, the thickness and modulus of elasticity of the overlay, and the slabs.

The effect of vertical movements on the overlay due to slab curling is also based on the premise that thin overlays do not significantly affect the curling of slabs. Thus the restraint against curling of the slabs provided by the uncracked overlay is again neglected. This important assumption permits the curved shapes of slabs to be predicted by using a computer simulation (PLATES program) of the Westergaard solution for temperature differentials between the top and bottom of the slab. Curling-induced overlay stresses are estimated on the assumption that the overlay takes the slope shown in Figure 1 (2).

For a joint width (j) and edge slopes (θ) calculated from the PLATES program (radians), the radius of curvature in the overlay can be estimated from

$$R = j/2\theta \quad (1)$$

In turn, overlay stresses can be calculated from

$$\sigma_{ov} = E_{ov}h_{ov}/j \quad (2)$$

where E_{ov} is the overlay stiffness, and h_{ov} is the overlay thickness.

Equation 2 is derived from the basic strength of materials for pure bending, i.e., $\epsilon(u) = u/R$, where $\epsilon(u)$ is the axial strain distance from the neutral axis, and R is the radius of curvature. Because Equation 2 is derived from pure bending, symmetric bending of the overlay, where there is tension at the top and compression at the bottom, is implied.

The OSU ultimate strength model presents an easy nomograph procedure for determining overlay stresses from thermal movements of underlying PCC slabs. However, the accuracy of the stress computation is suspect due to the following factors:

1. Restraint imposed by the uncracked overlay against slab movements (horizontal and curling) is not considered. Thus the calculated force in the overlay at the time of cracking is probably incorrect.
2. Overlay stresses due to horizontal joint movement appear low and should be validated by additional finite-element investigation.
3. The tack-coat bonding-stress values are also low and should be established by a laboratory investigation that considers temperature, tack-coat type and amount, and roughness of the PCC slab.
4. The Westergaard analysis used to predict slab curling neglects the weight of the slab and overlay, which would reduce the curl.
5. The simplistic analysis of overlay stresses due to curling should be verified by finite-element analysis. The fact that curling introduces a horizontal joint opening is neglected by the analyses. This horizontal movement could be significant and change the stress state considerably.
6. The model is incapable of assessing effects of crack-prevention measures on stresses in the overlay.
7. The model does not make recommendations for

selecting design parameters such as temperature change, curling, AC modulus, and AC strength.

Ultimate Strength Model--Austin Research Engineers

Austin Research Engineers (ARE) developed a procedure for reflection crack stress or strain analysis that considers two different failure modes (3). The first is an opening mode [Figure 2 (4)], which is due to horizontal movements of the underlying PCC slab that result from seasonal temperature reduction. Joints or cracks without steel reinforcement, or cracks with steel reinforcement [such as a continuously reinforced-concrete pavement (CRCP)], can be analyzed for horizontal movement. The second mode is a shearing mode (Figure 2) that results from differential deflection across the joint or crack as the traffic load moves across the discontinuity.

In developing the model, a number of assumptions were made, including (a) the materials are elastic in response, (b) temperature variations are uniformly distributed in the existing concrete slab (no curling), (c) concrete movement is continuous with slab length, and (d) movement is uniform with depth in a particular layer.

The ARE ultimate strength model has been computerized in a program called RFLCR to minimize difficulties in using the model. It is the most versatile procedure currently available because it can consider slab or overlay reinforcement, bond breakers, and granular cushions (shear failure analysis only). However, the simplifications in the model that permit strain calculations without the use of analytical computations for stress distribution have not been validated. This is the primary problem with the ARE model. Although force magnitudes may be reasonable, the assumed simplistic distribution of stresses within the overlay for both open and shear failure modes is suspect because no concentration of stresses at the joint tip are considered. Other, less significant problems with the ARE model include the following:

1. Characterization of the existing pavement by joint opening measurements over a certain temperature range cannot necessarily be extrapolated to a different design temperature range. For example, restraint exhibited between 70° and 50°F may not identify the restraint between 70° and 20°F.
2. The assumed value for bonding stress between the overlay and slab is important in the analysis because it establishes the gage length over which the overlay force at the joint is distributed. The suggested values need to be validated experimentally.
3. The concept that a bond breaker reduces overlay strain by merely increasing gage length for force transfer should be validated by analytical investigations of stress distribution.
4. Load transfer is determined from preoverlay measurements, and no adjustment is made for the effect of the overlay, which may be an important consideration. Also, load transfer is probably load and temperature dependent.
5. The temperature for determining dynamic modulus in the shear model is not specified, but according to the model a high temperature would be critical because larger strains would result. However, the allowable strain is likely to be temperature dependent.

Fracture Mechanics Model--OSU

Fracture mechanics has been used to develop a reflection cracking propagation model for asphalt overlays on PCC slabs (4,5). The model considers only traffic-induced fatigue cracking that results from differential deflection at slab joints or cracks.

The first step in applying fracture mechanics principles was to identify the fracture mode(s) associated with crack initiation and extension (Figure 2). A finite-element stress analysis of full-scale pavements predicted that the asphaltic overlay would be in compression, thus leading to the conclusion that the opening mode (mode 1) type fracture does not occur. The computer analysis also predicted significant relative vertical displacement (mode 2) between the two concrete slabs when loaded at the edge of the load over the center of the crack position. These conclusions led to the hypothesis that load-induced reflection cracking is the result of general or mixed-mode fracture of the bituminous material that occurs under the simultaneous interaction of $-K_1$ (negative σ_x), K_2, and K_3. Laboratory testing of two- and three-dimensional model overlay pavements supported this hypothesis.

Sih's theory of fracture (6), which is based on the field strength of the local strain-energy density, was used to analyze mixed-mode crack propagation. The two fundamental hypotheses of crack extension in Sih's theory are

1. The crack will spread in the direction of maximum potential energy density or minimum strain-energy density, and
2. The critical intensity (S_{cr}) of this potential field governs the onset of rapid or brittle crack propagation.

In those cases where a fracture is not a rapid unstable process [i.e., the stress-intensity factor under an applied load condition does not exceed the critical stress-intensity factor, or the strain-energy-density factor (S_{min}) is less than the critical value (S_{cr})], slow, stable fatigue crack growth is presumed. Typically, crack growth laws relate the rate of change of crack length to the stress level or stress-intensity factor, such as

$$dc/dN = A(\Delta K)^n \quad (3)$$

For mixed-mode fracture, the OSU model uses the crack growth law in terms of the strain-energy-density factor along the direction of fracture (S_{min}):

$$dc/dN = B(\Delta S_{min})^n \quad (4)$$

The fatigue life, or number of load applications to produce a crack through the overlay, is given by

$$N_f = \int_{c_o}^{c_\alpha} [1/B(\Delta S_{min})^n]\, dc \quad (5)$$

where c_o is the initial starter flow, and c_f is the crack length at which the overlay is considered failed (either the thickness or the length at which the critical $S_{min} = S_{cr}$ is reached, whichever is less). S_{cr}, B, and n are material constants derived from fatigue tests on asphaltic-concrete beams.

The OSU fracture mechanics model is not a complete method for predicting the occurrence of reflection cracking. An analytical method for computing stress-intensity factors and S_{min} (such as in the finite-element model) must be combined with a program that calculates fatigue life in an incremental fashion by using the growth law given in Equation 4. A nomograph procedure could be developed from this model, which would be similar to the nomograph procedure developed by Majidzadeh and others (7) for fracture mechanics predictions of load-associated fatigue cracking in flexible pavements. Thus further development of the OSU fracture mechanics model is necessary before it could be implemented by pavement engineers.

Fracture Mechanics Model--Texas Transportation Institute

The Texas Transportation Institute (TTI) fracture mechanics model also uses fracture mechanics crack-propagation theory to predict cracking. Only mode 1 fracture and, therefore, the K_1 stress-intensity factor induced by horizontal thermal movements of the underlying layer are considered. However, rather than the simple crack growth law given in Equation 3, the TTI model uses Schapery's theory on crack growth in viscoelastic materials to develop the following growth law (8):

$$dc/dN = Bt\ (\Delta K)^{2(1+1/m)} \tag{6}$$

where

$$B_t = (\pi/6\sigma\ m^2 I_1^2)\ [(1-\nu^2)D_2/2\Gamma]^{1/m}\ [\int_0^{\Delta t} W(t)^{2(1+1/m)} dt] \tag{7}$$

where

- ν = Poisson's ratio,
- σ_m = maximum tension strength the AC mixture can sustain,
- I_1 = dimensionless integral between 0 and 2,
- Δ_t = period of the load cycle,
- $W(t)$ = wave shape of stress-intensity factor,
- m = slope of straight-line portion of tension creep compliance curve for the AC binder,
- D_2 = intercept of straight line with log t = 0 on creep compliance curve, and
- Γ = fracture energy density (force times displacement) to produce a unit area of crack surface.

The TTI model is also not a complete procedure for predicting the occurrence of reflection cracking. It is a technique for obtaining crack growth laws without having to perform fatigue tests. Fatigue life is then obtained by integrating Equation 6 from the limits of c_o to c_f, which is similar to Equation 5 in the OSU fracture mechanics model. The limitations of the OSU fracture mechanics model are applicable to the TTI model.

Phenomenological Model

Resource International, Inc. (RII) developed a phenomenological model for crack prediction in overlaid flexible pavements that are reinforced by placement of engineering fabrics on the existing surface before placement of the overlay. The model considers only traffic load stresses in predicting the fatigue life of the overlaid pavement, and it has been used in the design of the RII computer program.

This model was established after extensive laboratory testing that established the relation between the fatigue life of reinforced and normal or unreinforced AC beams. All fatigue tests were beams on elastic foundations that were tested at a constant load at 70°F. The performance factor of the fabric in enhancing fatigue or delaying reflective cracking is called the fabric effectiveness factor (FEF), i.e.,

$$FEF = N_f\ \text{reinforced}/N_f\ \text{unreinforced} \tag{8}$$

where FEF is the ratio of fatigue lives obtained from the beam tests. The range of FEF is generally between 4 and 8, depending on stress level, placement depth within the beam, and fabric type.

The FEF function is expressed as

$$FEF = a_1\ (\epsilon_h)^{a_2} \cdot GEO \tag{9}$$

where

- a_1, a_2 = constants, depending on fabric type;
- ϵ_h = horizontal strain at the bottom of the existing asphalt-bound layer (in./in.); and
- GEO = geometry factor that considers depth of fabric placement relative to neutral axis depth.

The fatigue life of the pavement in the design computer program (HWYPAV) is

$$N_f = N_{f_u}'\ (FEF) \tag{10}$$

where N_{f_u}' is a strain-dependent distress function for AC developed from AASHO Road Test data.

Cracking of the existing pavement is accounted for by reducing the elastic modulus of this layer. HWYPAV uses the elastic multilayer program ELSYM5 to calculate pavement strains.

The RII model has the following limitations:

1. Because the model is phenomenological, the mechanics of crack propagation and crack arrest are not identified.
2. FEF values need to be investigated to determine if they are temperature or scale dependent. FEF values were established from small beam tests and may differ from those under full-scale conditions.

DEVELOPMENT OF A LABORATORY MODEL

Simulation of reflective cracking of rigid pavement overlays requires modeling of both thermal and traffic loading conditions. As previously noted, thermal stresses result from both seasonal and daily changes in slab temperature. Thermal loading can be represented by the superposition of two different thermal conditions:

1. Uniform change (ΔT) in slab temperature, which represents seasonal changes in average slab temperature that occur over long time periods, and
2. Pure curling, which represents the daily or short time period temperature variation within the slab. [Pure curling means that the average slab temperature has not changed; however, the top of the slab is colder than the bottom, and the temperature is assumed to be linearly related to slab depth. The curling gradient (CG) is given in degrees Fahrenheit per inch of slab depth.]

A representation of thermal loading by using the above definitions is shown in Figure 3. The reference temperature (T_R) is the zero-stress temperature for the overlay. Slab temperatures less than T_R will transfer stresses to the overlay. The expected monthly average slab temperature and curling gradient for overlaid concrete slabs in Ohio are shown in Figure 4 (2). This figure is based on a computer prediction of pavement temperature developed from field temperature measurements on several pavements in central Ohio (2). Slab thickness varied from 8 to 10 in., and asphalt overlay thickness varied from 2.5 to 5.0 in. for the Ohio study pavements. Figure 4 estimates thermal load magnitudes. Expected CG varied from 0.5°F/in. in spring and fall to about 1.0°F/in. in winter. Mean slab temperature changes by about 40°F from summer to winter, dropping at a rate of about 8°F/month

Figure 3. Example of PCC slab thermal loading.

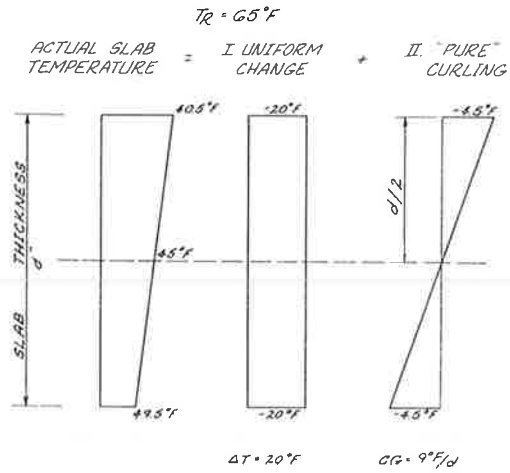


Figure 4. Expected seasonal pavement and CG temperature.

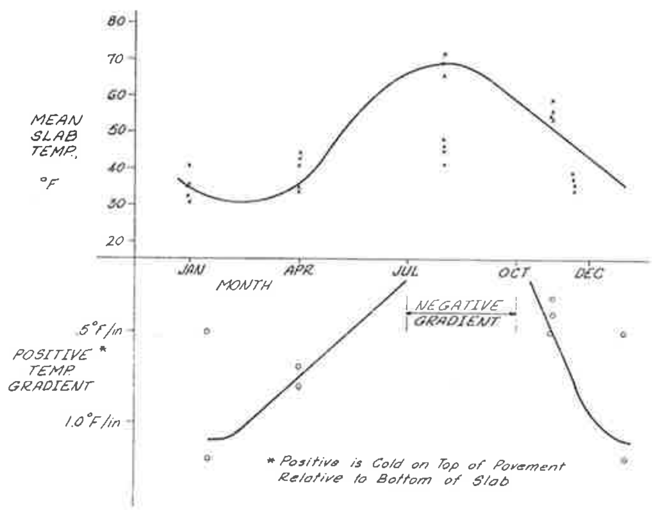
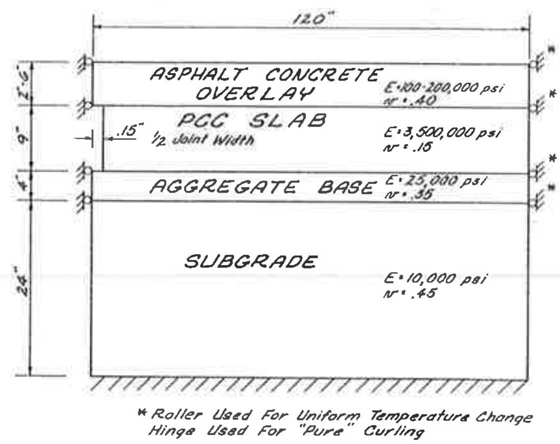


Figure 5. Schematic of two-dimensional finite-element model.



during the fall. This range of thermal loading parameters should be simulated in laboratory testing.

To manufacture and subject full-scale pavement models to actual thermal loads as experienced in the field is not economically feasible in the laboratory. Thus model pavements are used that have external forces applied to produce joint movements equal to those of full-scale pavements under field thermal loading. Uniform or seasonal reductions in slab temperature are simulated by applying horizontal tensile forces to the PCC slabs to produce joint openings similar to those of full-scale pavements. Traffic forces are simulated by applying dynamic vertical loads to the model pavements, with the model supported on elastic foundation, which is similar to previous OSU studies (5,7).

The most difficult simulation is curling of the PCC slab. Recent studies at the University of California and the Portland Cement Association were not successful in inducing temperature curling of model PCC slabs. Thermal gradients are difficult to establish in the laboratory, and the gradients necessary to curl model slabs of short length have to be large in order to produce the same curled shape as full-scale slabs because the curling deformation is directly proportional to slab length squared (L^2).

A theoretical investigation of curling in full-scale slabs was conducted because of the difficulties in modeling curling and the shortcomings of the OSU ultimate strength model in predicting the significance of overlay stresses that result from slab curling. The purpose of this investigation was to determine the overlay stresses produced by curling and to determine if curling could be equated to uniform temperature change: Does curling produce horizontal joint openings and, if so, could these stresses be equated to joint openings that result from a uniform temperature change (ΔT)?

A two-dimensional finite-element analysis that used the SAP IV program of the full-scale pavement shown in Figure 5 was conducted. As shown in Figure 5, only asphalt overlay modulus and overlay thickness were varied in these analyses. The slab length was 20 ft in all cases. Two separate thermal loading conditions were analyzed: a uniform reduction (ΔT) of 30°F in slab temperature, and a pure CG of 0.5°F/in. Overlay stresses and joint openings were found to be linearly related to ΔT and CG for constant overlay thickness and modulus. Both full friction (no slip) and no friction (slip) between the PCC slab and aggregate base were investigated. Full friction reduced overlay maximum stress by less than 6 percent for a uniform temperature change and 4 percent for curling when compared with the no-friction condition. Full bond was assumed between asphalt overlay and PCC slab in all cases.

Computed stresses in the overlay at the center of the joint as a function of depth (Z) are shown in Figures 6-8. In all cases, for both curling load and uniform temperature change, maximum stress occurs at the bottom of the overlay. The stress distributions are similar for the uniform temperature change and curling loading conditions. The similarities occur throughout the range of overlay thickness and overlay modulus investigated. (Note that a ΔT of 3°F was used to plot Figures 7 and 8b simply to provide stresses of closer magnitude to those of the curling load. Recall that stress is linearly related to ΔT.) Figures 6 and 8a show that, for curling load, the overlay stress at the joint in the horizontal (X) direction is in a tensile state throughout overlay depth and rapidly increases in magnitude below 0.6 times the overlay thickness.

The computed shear stress at the overlay-slab interface is shown in Figure 9. Again, the stress distributions are similar for the two loading conditions. These shear stresses would have to exceed the tack-coat bonding stress to cause slippage between the two layers. The maximum shear stresses are greater than the 6- to 10-psi bonding stress

Figure 6. Overlay stress for curling load.

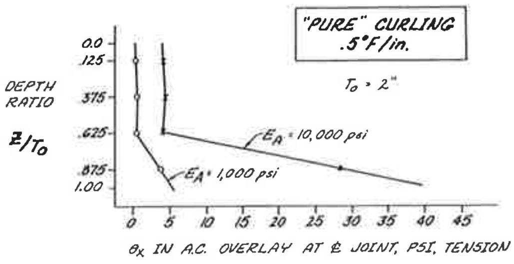


Figure 7. Overlay stress for uniform temperature.

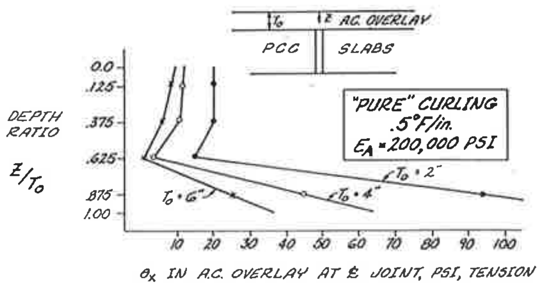


Figure 8. Overlay stress versus modulus.

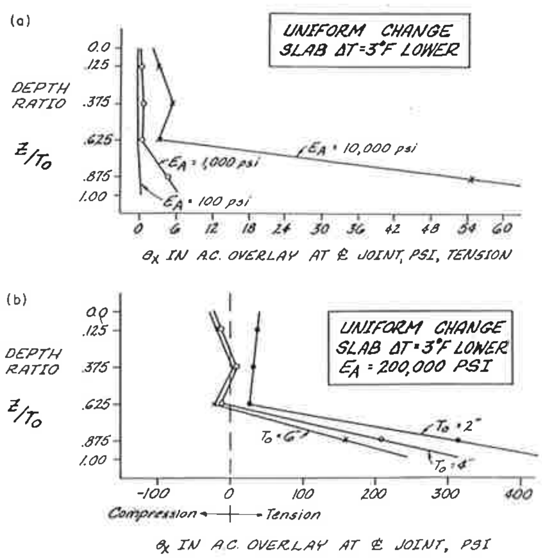


Figure 9. Overlay stress versus distance from joint.

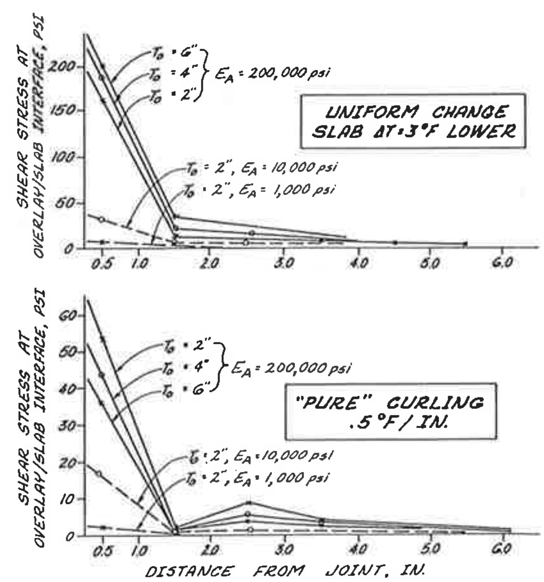
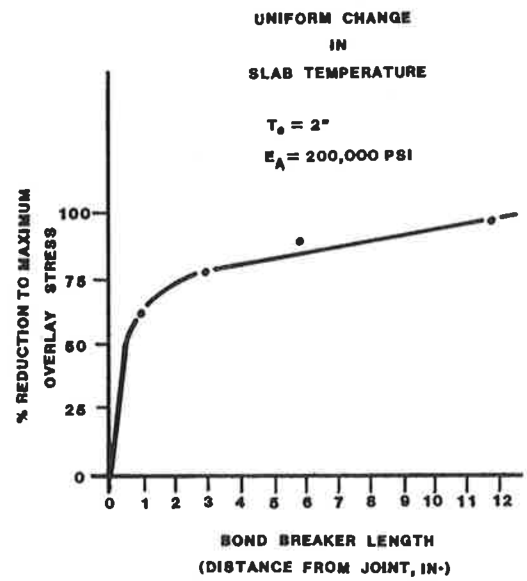


Figure 10. Overlay stress versus bond-breaker length.



suggested by Majidzadeh and Suckarieh (2), but are generally less than those given by ARE (3).

The effect of breaking the bond, either by slippage or by the introduction of a bond breaker on maximum overlay stress is shown in Figure 10. A dramatic reduction in stress is predicted for bond-breaker lengths as short as 1 in. The data in Figure 10 indicate that the ARE model, which uses the bond-breaker length to increase the gage length for the overlay stress calculation, probably underestimates the stress reduction by a significant amount. Bond between overlay and slab will be an important parameter in laboratory testing. The data in Figure 10 indicate that improper bonding near the joint can significantly affect test results.

The high sensitivity of overlay stress to overlay stiffness is clearly illustrated in Figure 11. As noted earlier, the ARE model suggests that creep modulus (Ec) be used for stress calculations. However, Ec is both temperature and loading time dependent. Figure 12 presents this dependency for a typical dense-graded AC with Ec calculated by the Heukelom and Klomp (Shell) method (9). This procedure determines the compressive creep modulus.

The tensile creep modulus is needed for reflection cracking analysis, but no procedure for predicting this parameter has been published. If tension creep modulus curves are similar to those in Figure 12, then the implications for thermal reflection cracking analysis and modeling are significant. An incremental analysis that uses the loading time and temperature-dependent creep modulus would be necessary in order to calculate overlay stresses and joint opening. Seasonal changes occur over long periods of time (time required to drop from T_R by a ΔT amount), whereas curling can occur over relatively short time periods (less than half a day) and at all temperatures. The fact that curling occurs over shorter loading times than seasonal uniform temperature change means that a higher Ec should be used for curling load than for uniform temperature change stress calculations. The higher Ec will result in higher overlay stresses that should be considered when comparing seasonal and curling-induced loading conditions.

The data in Figure 11 can be used to compare the two thermal loading conditions. The data in Figure 12 indicate that in the fall (50° to 55°F) an Ec of

Figure 11. Overlay stress versus modulus.

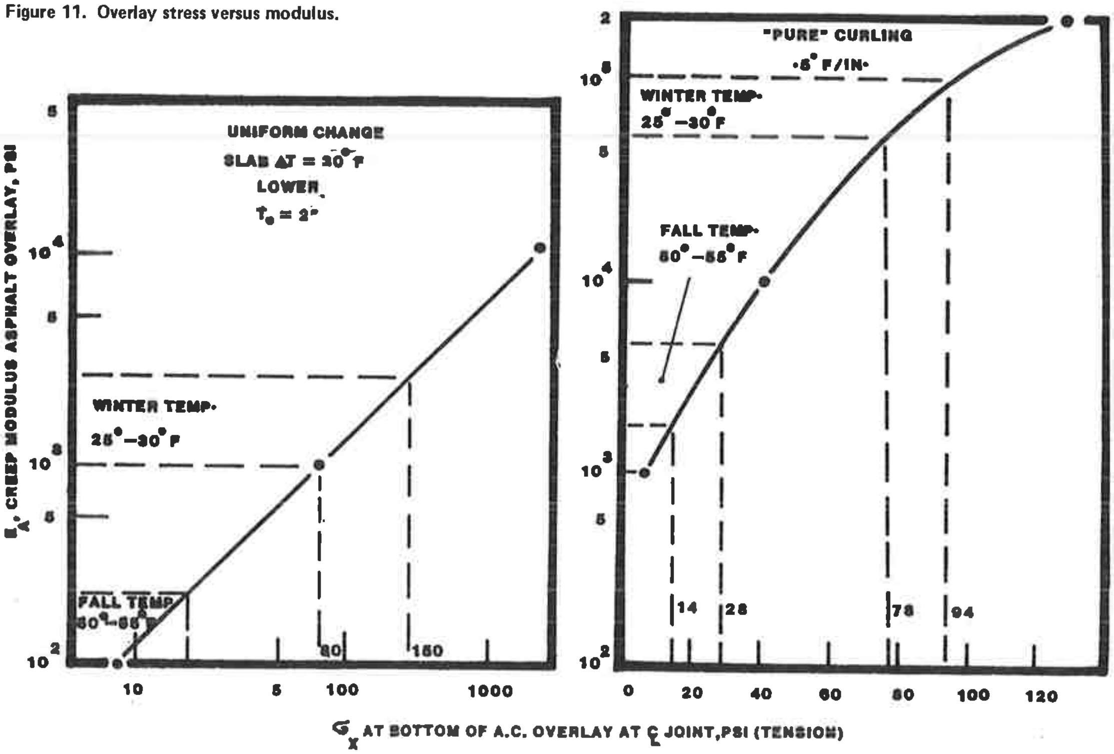


Figure 12. Creep modulus versus time and temperature.

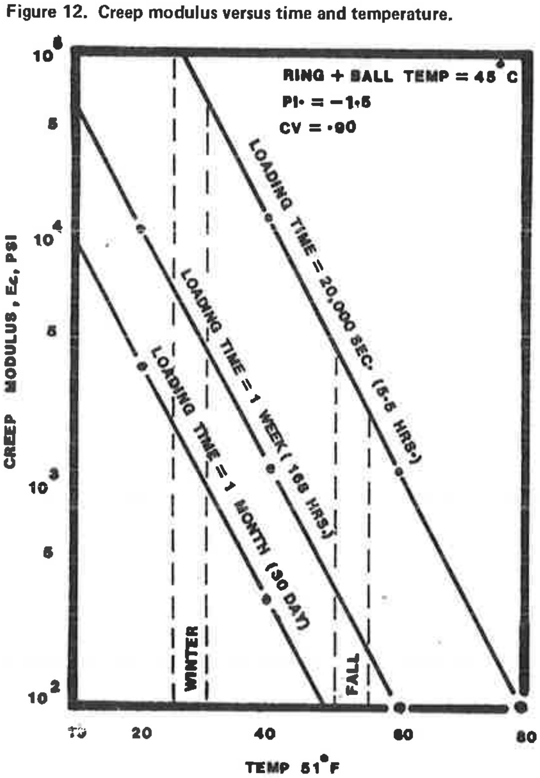


Figure 13. Joint opening versus modulus.

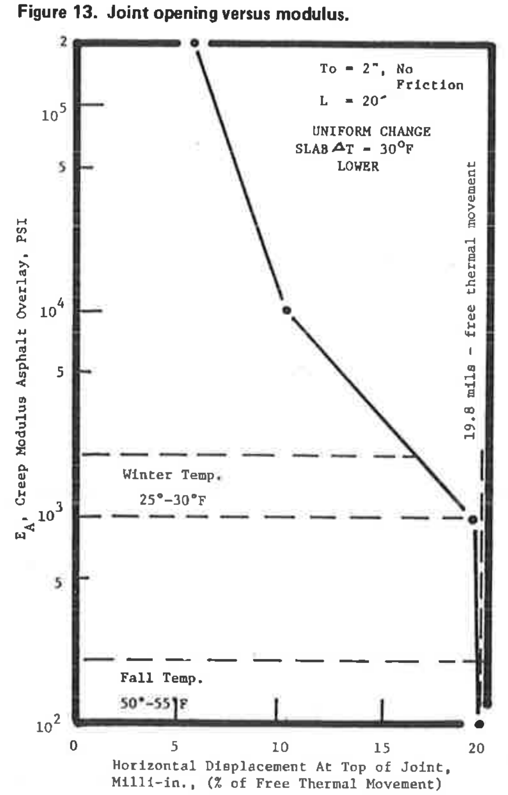
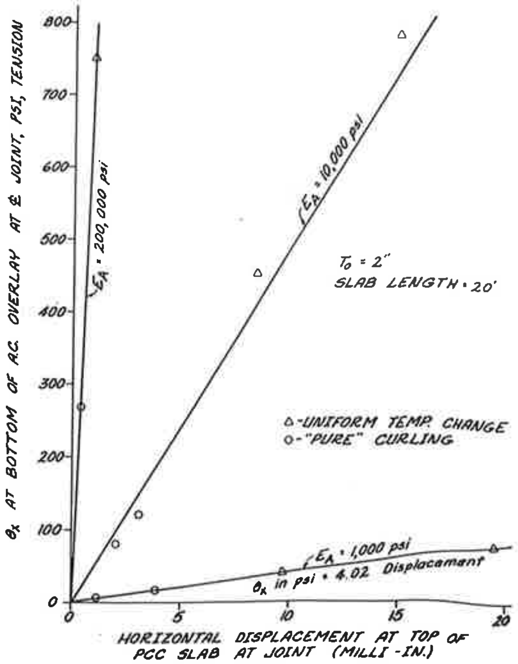


Figure 14. Overlay stress versus joint opening.



100 to 200 psi is obtained for a uniform slab temperature change (1 month loading time) and an Ec of 2,000 to 5,000 psi (5.5-hr loading time) is obtained for curling loading. According to the data in Figure 11, the curling load would produce a stress of about 21 psi, whereas the uniform temperature change (ΔT = 30°F) produces a stress of about 12 psi. On the basis of equal maximum overlay stress, the two loading conditions can be equated by

$$CG = (\sigma_x \text{ curl}/\sigma_x \text{ seasonal})(\Delta T);\ 0.5^\circ\text{F/in.} = 21 \div 12\,(30) = 52.5^\circ\text{F} \quad (11)$$

Therefore a seasonal change of 52.5°F would be required to produce the same overlay stress as curling with CG = 0.5°F/in. Similar analysis for winter temperature ranges (20° to 25°F) yields

$$0.5^\circ\text{F/in. curl} = 22.4^\circ\text{F seasonal change} \quad (12)$$

Because both curling and seasonal change produce a joint opening that induces similar overlay stress distributions, it is reasonable to equate the two loading conditions in this manner. The ability to equate curling loads to seasonal changes is important because laboratory tests need not try to induce curling in the PCC slab. Uniform temperature changes will be simulated by applying horizontal tensile forces on the PCC slab to produce the joint opening. The amount of joint opening is a function of the ΔT and slab length (L) being simulated. Seasonal temperature change (ΔT) could be converted to equivalent CG by using equations similiar to Equations 11 and 12. Therefore, simulated temperature conditions at the time of failure or cracking of the laboratory model could be expressed as either ΔT or CG at the test temperature for a full-scale slab of length L.

The relation between overlay modulus and predicted joint displacement for the finite-element model is shown in Figure 13. For Ec less than 1,500 psi, movement nearly equals that for free unrestrained thermal movement [$\alpha \cdot \Delta T \cdot (L/2)$]. The data in Figure 12 indicate that the expected modulus is below 1,500 psi for long loading times (greater than 1 month) for temperatures greater than 25°F. Laboratory test temperature and loading times are chosen such that the tension creep modulus of the overlay will be less than 1,500 psi. The joint opening can then be calculated by using [$\alpha \cdot \Delta T \cdot (L/2)$]. This will simulate joint openings that occur in real pavements at temperatures greater than about 25°F.

The data in Figure 14 indicate that overlay stress is linearly related to displacement at the top of the joint. The slope of the stress-joint displacement line is a function of overlay modulus. The overlay stresses are independent of thermal load type. At constant overlay modulus, a horizontal displacement (x) will produce the same overlay stress (σ_x), regardless of whether this displacement was produced by slab curling or uniform temperature change. This is further evidence that curling can be equated to seasonal temperature change.

LABORATORY TESTING

Laboratory testing is currently under way to verify the reflection cracking models presented here. The laboratory test plan includes use of engineering fabrics and SAMI and will quantify the performance of the crack-prevention techniques. The model pavements will be subjected to joint openings commensurate with the thermal loadings that occur in full-scale pavements as described in this paper. This research is being sponsored by the Office of Research and Development, U.S. Department of Transportation. Laboratory results will be reported when available.

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