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Response and Distress Models for Pavement Studies

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Results of a detailed study to select mathematical and other models for the prediction of significant distress for flexible, composite, and rigid pavements are presented. Rigid pavements were subdivided for study into nonreinforced jointed concrete pavements (JCP), jointed reinforced concrete pavements (JRCP), and continuously reinforced concrete pavements (CRCP). The models selected are to be used in establishing optimal material properties for zero-maintenance pavements. The published results of field surveys and other experience were used to identify, for each type of pavement, distresses that cause considerable maintenance or loss of serviceability. Material properties that influence the occurrence of significant distresses were then identified, and theoretical or empirical models were selected to predict these distresses by using material properties and other engineering parameters. The distresses found to be most significant for these studies were (a) fatigue cracking for all types of pavement, (b) rutting and reduced skid resistance for flexible and composite pavements, (c) reflection cracking for composite pavements, (d) low-temperature cracking for flexible pavements, (e) spalling for all rigid pavements, (f) faulting for JCP and JRCP, (g) low-temperature and shrinkage cracking for JRCP and CRCP, and (h) punchouts and steel rupture for CRCP. The models considered, the context in which they are to be used, their attributes and limitations, and those finally selected for the study of specific distress for specific pavement types are briefly described.

The Federal Highway Administration (FHWA) research project on Material Property Requirements for Zero-Maintenance Pavements has as its goal the identification of material properties that will provide optimal performance in flexible, rigid, or composite premium or zero-maintenance pavements. This goal is to be accomplished through a combination of empirical and theoretical studies. The published results of field surveys, notably those of Darter and Barenberg (1) and McCullough and others (2), and other experience were used to identify, for each type of pavement, distresses that cause significant loss of serviceability or require significant maintenance. Material properties that influence the occurrence of significant distress were then identified, and theoretical or empirical models were selected to predict these distresses by using material properties and other engineering parameters. A detailed account of these studies appears elsewhere (3).

This paper reports the results of studies of contemporary mathematical models to select those most capable of predicting the distresses of interest in terms of the significant material properties. It includes identification and brief descriptions of the distress models considered and tabular identification of the significant distresses by (a) pavement type, (b) the material properties considered to affect the occurrence of each distress, and (c) the distress model selected to predict each distress.

MODELS OF PAVEMENT RESPONSE AND DISTRESS

There are many models of pavement response that predict stresses and strains in a pavement structure. They all assume linear elasticity, and most fall into two categories: those that basically analyze an elastic plate supported by springs (or a semidense liquid) and those that analyze a layered system with individual elastic properties. Included in this group of models are the Westergaard equations, elastic layer theory, discrete-element slab theory, and finite-element theory. Some versions of these models also consider nonlinearity in materials response through iteration on nonlinear stress-strain curves furnished as input. None of these models are distress models, but they predict pavement behavior under loads. Environmental effects are also considered by some of the models in terms of their effects on the input variables.

By building on this capability for predicting pavement responses, more sophisticated models such as VESYS A (4) and PDMAP (5) for flexible pavements and RPOD (6) and JCP-1 (7) for rigid pavements have been developed to relate load-induced stresses or strains to distress and thus become predictive models for distress. These models are generally available for predicting only fatigue cracking and rutting for flexible and composite pavements and only fatigue cracking for rigid pavements. Other computer-based analytical procedures (2, 5, 8-12) have been developed for predicting cracking that results from changes in volume as temperature decreases.

This leaves other distresses—such as faulting and spalling at joints and cracks—without theoretical or analytical models. For such cases, models may not be mathematical but simply a set of qualitative factors that can be used to predict distress in an approximate manner.

All promising analytical models were studied concurrently with the identification of significant distresses and related material properties. The more promising models have been used, and limited preliminary sensitivity analyses have been conducted both to check out the models and to gain insight into the importance of various material properties to the distress they predict. The results of these model studies were reviewed, and the models that best predict each type of distress were selected.

These models of pavement structure and distress are discussed below in relation to five types of pavements: flexible, composite, and plain jointed concrete pavement (JCP); jointed reinforced concrete pavement (JRCP); and continuously reinforced concrete pavement (CRCP). The available models for the specific type of pavement under discussion are listed, and the model selections are discussed.

MODELS OF PAVEMENT STRUCTURE THAT USE ELASTIC THEORY

The three general types of computer programs or models of pavement structure that are available include models based on elastic layer theory, plate theory (Westergaard equations, discrete-element slab theory, and two-dimensional finite-element models), and three-dimensional finite-element theory. Excellent discussion and comparisons of these theories are presented by Crawford and Katrona (13). Three-dimensional finite-element programs are very expensive to use and are generally used only for very special problems. The version produced by Huang and Wang (14) has been specialized into two dimensions on Winkler springs and is very similar in final matrix formulation to discrete-element slab theory. Comparisons of results reported by Darter (7) for the Huang and Wang finite-element program and for the same sets of data from the discrete-element SLAB program indicate almost identical results except where vagaries of input or boundary conditions cause differences.

Elastic layer theory has the capability of analyzing many pavement systems, but edge or corner stresses for rigid slabs cannot be directly simulated because of the inherent assumption in elastic layer theory that wheel loads are applied to a surface with infinite horizontal dimensions. This is generally a satisfactory assumption for flexible pavements and for interior wheel loadings for rigid pavements.

Obviously, these theories have their capabilities, strong points, and limitations. Neither the finite-element program of Huang and Wang nor the discrete-element slab theory developed by Hudson and others satisfactorily models the supporting soil. Vesic and Saxena (15) have shown that a constant modulus of subgrade reaction k does not permit accurate predictions of stresses and deflections. The Huang and Wang finite-element model and the discrete-element models also assume that vertical deformations do not occur in the rigid slab and thus that the predicted bending stresses at the top and bottom of the slab are identical, which in reality they are not. These theories do, however, provide capabilities for defining discrete boundaries, varying the bending stiffness of the slab from point to point, simulating cracks in the slab and joints between slabs, creating void spaces in the support for the slab, and calculating curling stresses.

One of the attributes of elastic layer theory is that all the layers in the pavement structure can be characterized individually so that their separate effects on pavement responses can be studied. Elastic layer theory spreads predicted stresses and strains with depth in a more realistic fashion than do the "plate models" discussed above, and it is relatively more economical to operate. The primary limitations of elastic layer theory are its inability to define any horizontal boundaries or to simulate very directly the existence of variations in stiffness in the pavement structure, cracks in the surface, or voids under the surface layer. Despite these limitations, however, elastic layer theory and the distress models that use it as a model of pavement structure offer very useful capabilities for comprehensive study of the various layer materials in this project.

Since elastic layer theory clearly represented one of the models to be used, it was necessary to compare the various computer codes that are available and to select those most suited to project needs. Schnitter (16) compared computer output from the ELSYM5, LAYER15, LAYIT, and BISAR programs for several typical problems over a range of conditions and got essentially the same results from all programs, usually within 1 percent and with a maximum difference of only 3 percent. The most economical program was LAYER5, but it is capable of handling only one wheel load at a time. Of the computer codes considered, ELSYM5 and BISAR can handle multiple loads. ELSYM5 is more economical to operate than BISAR, and five layers are generally sufficient for most problems. BISAR, however, can consider both variable friction at its interfaces and a horizontal load applied at the surface, so it may be useful for special studies.

ELSYM5 serves as the pavement-structure model for the system of rutting prediction used by Monismith and others (17) and for the RPOD program (6). PDMAP (5) uses an elastic layer program called NLAYER, which as the name implies can consider any reasonable number of layers. The Shell method (18) uses BISAR as its structural model. VESYS A (4) uses an elastic layer code that is limited to three layers derived from an early Chevron program.

DISTRESS MODELS FOR FLEXIBLE PAVEMENTS

The distress models studied and considered for use in this project for flexible pavements were as follows:

Type of Distress	Model
Rutting	Shell method (18)
	VESYS A (4)
	PDMAP (5)
	Rutting subsystem, Monismith and others (17)
	DEVPAV (19)
	OPAC (20) and WATMODE (21)
	Huschek rutting-prediction method (22)
Fracture cracking	Shell method
	VESYS A
	PDMAP
	OPAC and WATMODE
Low-temperature cracking	VESYS A
	PDMAP
	Shahin-McCullough model (8,9)
	OPAC and WATMODE
Reduced skid resistance	Studies by Stietle and McCullough (23)
	Studies by Rauhut and McCullough (24)

None of these models considers all four types of distress, and only VESYS A, PDMAP, OPAC, and WATMODE consider rutting, fracture cracking, and low-temperature cracking. The Shell method considers rutting and fatigue cracking. All of the rest consider only the distress under which they are listed.

Because the Shell method was specifically developed to use hand calculations, many of the complexities have been simplified. All rutting is assumed to occur in the asphalt concrete layer, and all strains in base, subbase, and subgrade are assumed to be elastic. However, Shell research indicates that rutting is limited to surface layers when the surface thickness exceeds about 13 cm (5 in) whereas some rutting occurs in underlying layers for thicknesses less than 13 cm (25). Results from the Shell circular test track indicate that rut depth is no longer a function of surface layer thickness (26) for surfaces thicker than 13 cm. In spite of these conflicting data, the procedure assumes that all rutting occurs in the surface layer and that rutting or rut depth is proportional to the thickness of the surface layer.

The Shell research on fatigue cracking of asphalt concrete materials (27) compared the results of "wheel tracking tests" on instrumented asphalt concrete slabs supported by elastic subgrade and beam fatigue tests for a variety of mixes. This work provides excellent insight into the stages of fatigue cracking and crack propagation in a supported slab as opposed to a nonsupported beam. It and the work reported by Van Dijk and Visser (28) also provide valuable data on the energy approach to prediction of fatigue life used in the Shell method. Shell's approach was to provide a design procedure for limiting radial strain in the bottom of the asphalt concrete layer to an acceptable level by using hand computations. Although the fatigue characterizations of materials obtained by using the energy approach are arrived at differently from those obtained in standard laboratory testing, linear summation of cycle ratios (Minor's hypothesis) is used as in other models to estimate damage or the percentage of the fatigue life that has been consumed at any point in time. Consequently, there appears to be no advantage to using the analytical procedures in the Shell method to predict fatigue life, but several references (18,27,28) contain extensive information for developing the fatigue characterizations of the materials.

VESYS A is an improved version of VESYS IIM, a distress model that has been discussed in great detail in the literature (29,30). The capabilities added to VESYS IIM to produce VESYS A were (a) seasonal modification of material properties, (b) incremental breakdown of axle-load distribution by tire radius and corresponding tire pressure, and (c) a low-temperature-cracking model. The details of these revisions and the improvements in the idealization of flexible pavements are discussed by Rauhut and Jordahl (4).

VESYS A is a sophisticated computer code that accepts some 23 control variables and 44 independent variables that describe a flexible pavement structure, the traffic loadings it endures, and, through input of pavement temperatures and seasonal materials characterization, the environment in which it exists. VESYS A then predicts fatigue cracking, rut depth, slope variance, present serviceability index, and expected service life as functions of time correlated with truck traffic. Distress from fatigue cracking is predicted by using the classical fatigue equation and linear summation of cycle ratios (Minor's hypothesis) as well as probability theory to consider the variability of the input parameters on the predictions of damage caused by axle-load distribution and traffic rate. Rutting is calculated as the difference in predicted total and elastic displacements at the surface. The procedure used is very similar to that proposed by Monismith and others (17). In VESYS A, the permanent strains in the layers are accumulated through separate solutions in which the layer stiffnesses are modified; the permanent deformations in the layers are calculated separately and added together to predict the change in displacement at the surface in the Monismith procedure.

The low-temperature-cracking model used in VESYS A was developed by Haas and Hajek (11) by using multiple-regression equations from data on pavements in Canada. The independent variables used were age of the pavement, thickness of the bituminous layers, type of subgrade soil in a numerical code, winter design temperature, and stiffness of the original asphalt cement. Although this model does a relatively acceptable job of predicting low-temperature cracking, other models such as the COLD program and the Shahin and McCullough models include more detailed consideration of material properties.

Currently, VESYS A is perhaps the most complete model of distress in flexible pavements. It considers a broad range of material properties in its distress subsystems. Some of the input variables, such as those for the permanent deformation characterization of materials, are relatively new to the engineering profession, but considerable data have been accumulated on these variables for a variety of materials and sources.

The term PDMAP stands for probabilistic distress models for asphalt pavement. The distress models included are for fatigue cracking and rutting. The low-temperature-cracking distress model is actually a separate computer program called COLD. Models for both fatigue-cracking distress and rutting in PDMAP are based on multiple regressions on data from the AASHO Road Test, but they depend on an elastic layer structural model to predict needed pavement responses. Complete descriptions of PDMAP and COLD and their development are given by Finn and others (5).

The rutting model for PDMAP predicts the seasonal rate of rutting for permanent deformation per equivalent load application. Seasonal changes in the elastic constants used for the various layers are considered as rutting accumulates with time. The rutting predictions are displayed at different confidence levels on the basis of the stochastic characteristics of the elastic materials characterizations.

The model of fatigue distress is very similar to that used in most fatigue predictions except that a term has been added to consider the effects of asphalt concrete stiffness.

It is believed that the model of rutting distress has some limitations that restrict its value to research. These are the following:

1. The regression model is based entirely on elastic material properties and elastic responses and includes no permanent deformation characterization of the materials at all. Consideration of the permanent deformation characteristics of materials in this regression model is entirely implicit and would only apply directly to those materials in the pavements of the AASHO Road Test.
2. The three regression coefficients in the model for the rate of rutting prediction are based entirely on AASHO Road Test materials and conditions and, according to Christison (10), require reestablishment for use under other conditions.

The design subsystem presented by Monismith and others (17) estimates the amount of permanent deformation or rutting that results from repeated traffic loading. Relations between applied stress and permanent strain defined by repeated-load triaxial compression tests are used for fine-grained soils, granular materials, and asphalt concrete. Stresses that result from wheel loads are estimated through use of one of the ELSYM computer programs. The stresses in turn permit estimation of permanent deformation in each layer of a specific pavement: The permanent strain at a number of points within the layer is computed so as to define strain variations with depth, and then the products of the average permanent strains and the corresponding differences in depths between the locations at which the strains were determined are summed. Total rut depth is estimated by summing the contributions from each layer.

Although this is a fairly straightforward, promising method, two serious drawbacks limit its use:

1. The materials characterizations are complex and require a very detailed test program to arrive at the values of the many parameters included in the equations.
2. Laborious hand calculations are required for large factorial studies.

Since both this rutting prediction model and that of VESYS A effectively accumulate the permanent deformations in each layer as permanent displacement at the surface, similar results are to be expected if the permanent deformation characterizations are based on the same test data.

DEVPAV is a finite-element program that has been under development by Kirwan and others (19) for some years in Ireland. In addition to the usual loading information, the permanent deformation characterizations are apparently based on multiple-regression studies.

The equation for permanent strain contains temperature, number of load cycles, and applied stress as independent variables. Kirwan and others compared calculated and measured rut depths for the Shell (31) and Nottingham Test Tracks and reported that the computed values of rut depth were in all cases substantially higher than those actually measured but that the shapes of the plots of rut depth versus applications were similar. General use of this model is limited because materials characterizations for permanent deformations are available only for the two materials recorded by Kirwan and others (19), and the finite-element program has been revised so that the lateral strain of one column of elements is prevented from affecting the adjoining column.

OPAC is a system of pavement design developed for the province of Ontario, Canada, by Meyer and Haas (20) and others. It has been further developed into a later form called the Waterloo model of distress estimation (WATMODE) (21). Both models predict distresses from rutting, fatigue cracking, and low-temperature cracking.

These models are generally based on statistical correlations between laboratory tests on materials from the Brampton and Ste. Anne Test Roads in Ontario and measured roadway responses. The correlations between predicted and measured distress are very good for those road tests but may not be generally applicable to more temperate climates. These procedures can be used in other locations and with different materials only after careful validation. However, there are some very useful developments in WATMODE (3, 20).

The Huschek method (22) is very similar to that of Monismith and others (17) described above except that the structural model is the elastic layer program BISAR and the permanent deformation characterization for asphalt concrete is based on cyclic creep compliance tests. Rutting is again predicted by summing the permanent deformations in the separate layers, as done by Monismith and others and indirectly by VESYS A. Calculated results from this procedure compared reasonably well with rutting measurements taken on a test road near Zurich, Switzerland.

The Shahin and McCullough model for prediction of low-temperature or thermal cracking, which is described in detail elsewhere (8, 9), includes separate models for pavement temperature, thermal stress, low-temperature cracking, and thermal fatigue cracking. The model for thermal fatigue cracking grew out of the realization that thermal cracking of asphalt concrete pavements occurs in the more temperate zones of the United States as well as in the northern zones that have relatively lower temperatures. Study has attributed this occurrence of thermal cracking at relatively low levels of strain to the fatigue effects of daily temperature cycling. In this context, the cracking predicted by the COLD program might then be thought of as "one-cycle fatigue cracking" because of relatively much higher strains that would not require repetitive loading to produce a failure.

Comparisons between measured and calculated low-temperature cracking from the Shahin and McCullough model for the Ste. Anne and Ontario Test Roads and a runway in Fairbanks, Alaska, are given by Shahin (9). The predictions were reasonable considering the variability in occurrence of low-temperature cracking in the field; i.e., significant differences in the amount of cracking are generally found between apparently identical sections for the same environmental conditions.

Most of the literature on skid resistance is concerned with the magnitudes of skid numbers for different types of pavements and the reductions in measured skid numbers over periods of time. Steitle and McCullough (23) have reported statistical relations between measured skid numbers, number of vehicle applications (in which trucks and automobiles are counted equally), a "field constant" for each aggregate that depends on its polishing characteristics under traffic, and a skid number taken after a specific number of vehicle applications. The values for the field constants can only be produced by long-term studies. Fortunately, some values are available and represent a limited basis for considering the general effects of abrasive wear of surface aggregates on reductions in skid resistance.

A careful evaluation indicates that none of the models discussed above have better capabilities for predicting rutting and fatigue cracking distress than VESYS A. Since none of the other models offered any apparent advantage over VESYS A for prediction of these two distresses, the VESYS system was selected because it predicts both distresses and because considerable information on permanent deformation characterizations for a range of materials is available for study.

The COLD program was not selected because it predicts only the point at which a crack will occur and when. It does not predict crack spacing or area cracked, both of which may be obtained from the other two low-temperature-cracking models considered.

The Haas and Hajek model for low-temperature cracking is based on Canadian data only but has been found to correlate reasonably for some pavements in North America. The Shahin and McCullough model has a much more thorough theoretical base and offers much more generality, but the Haas and Hajek model is relatively simpler to use and can be used independently while VESYS A is used for studies of rutting and fatigue-cracking distress.

The study by Steitle and McCullough on the effects of aggregate polishing (23) can be used to study loss of skid resistance, but the field data necessary to the study are so limited that only qualitative results can be expected.

DISTRESS MODELS FOR COMPOSITE PAVEMENTS

The choice of models for prediction of distress is much more limited for composite pavements than for flexible pavements. A composite pavement is considered to be one that has a flexible surface over a very stiff subbase, composed of either a portland cement concrete (PCC) pavement layer or a portland-cement-treated granular base layer. Although the studies of composite pavements will be similar to those of flexible pavements, special modeling will be required since the strongest pavement layer does not occur at the surface. For instance, distress from rutting and reduced skid resistance can be studied by using the same models as those used for flexible pavements, but the fatigue model must be capable of considering fatigue in the more rigid underlying layer of PCC or cement-treated base. In addition, the serious problem of reflection cracking in the surface layer, induced by movements of the underlying layer at the joints or cracks, introduces a need for an additional and entirely different model.

The distress models reviewed and considered for use in studying composite pavements are as follows:

1. For rutting distress, VESYS A;
2. For fatigue-cracking distress, (a) computer program ELSYM5 for predicting stresses and strains at the bottom of the flexible and rigid layers, supplemented by fatigue relations, and (b) RPOD (6, 32); and
3. For reflection-cracking distress, RFLCR1 (6).

Reduced skid resistance is to be studied concurrently with the flexible pavement study. Since none of the available models have been developed specifically for predicting rutting in composite pavements, VESYS A will be used with one minor revision.

The RPOD program was developed by Austin Research Engineers specifically for the design of either flexible or rigid overlays for rigid pavements and includes a model for fatigue-cracking distress that uses ELSYM5 as a model of pavement structure. The alternatives for study of fatigue-cracking distress are (a) modify ELSYM5 to add a model for fatigue-cracking distress to the present model of pavement structure or (b) bypass most of RPOD's subroutines to use only the ELSYM5 model of pavement structure and its model of fatigue-cracking distress. A study of the staff and computation time involved indicated that it would be more economical to modify ELSYM5, so that approach was selected.

RFLCR1 is the only available model for predicting reflection cracking. It includes analysis of two types of distress mechanisms: (a) a form of reflection cracking in the overlay caused by horizontal movements of the rigid slab in response to temperature and moisture changes and (b) shear cracking caused by differential vertical movements at joints or cracks in the underlying rigid pavements.

DISTRESS MODELS FOR RIGID PAVEMENTS

Rigid pavements include JCP, JRCP, and CRCP. Since the steel provided in JRCP or CRCP is neither positioned properly nor of sufficient quantity to provide additional structural capacity, a common model of pavement structure can be used for the prediction of stresses and strains in JRCP, CRCP, and JCP. As a result, the studies of fatigue-cracking distress can be combined for the three types of pavements. Since the distress mechanisms for faulting at cracks and joints and joint spalling are also essentially the same for JRCP and JCP, these distresses can also be studied simultaneously.

Thermal cracking and shrinkage cracking are generally not serious problems for JCP if the joint spacings are short. Future designs should not include joint spacing any greater than 4.5 m (15 ft) if the recommendations of Darter for zero-maintenance pavements (7) are followed. Since longer joint spacings are sometimes used for JRCP, thermal and shrinkage cracking should be considered. The only models available for predicting this distress in a JRCP are a computer program called JRCP-1 (34) and an improved version called JRCP-2 (unless the classical subgrade drag theory is considered).

The fatigue-cracking model for JRCP may also be used for CRCP, but the distinctive nature of CRCP also requires special distress models for thermal and shrinkage cracking. The only relatively complete models developed specifically for the analysis of CRCP are the CRCP-1 program developed by McCullough and others (2) and CRCP-2, an improved version of CRCP-1 developed by Ma (34). Follow-up studies by Strauss (35) and others at the Center for Highway Research of the University of Texas at Austin offer additional statistical insight into the effects of material properties on CRCP distress.

There are several models of pavement structure that could be used to predict stresses and strains for fatigue-cracking analysis. Several of these have already been discussed. Because of the limitations of plate theory, elastic layer theory is considered to be the appropriate model of pavement structure when one wants to consider all pavement layers, but the special capabilities of the discrete-element and finite-element models can also be used for special studies.

Although the JCP-1 program is subject to the same limitations as the Huang and Wang model (14) on which it is based, JCP-1 was also considered as a potential fatigue-cracking model. JCP-1 provides fatigue and serviceability data for a design procedure developed by Darter and Barenberg for JCP (7). Multiple-regression equations based on analytical solutions from the Huang and Wang finite-element program predict pavement stress for an 80-kN [18 000 lb (18-kip)] axle load with the outside tire on the outer 15.4 cm (6 in) of the slab. The procedure also includes prediction of daytime and nighttime curling stresses and their superposition with stresses created by wheel loads. A very detailed fatigue-cracking model is then applied to predict fatigue damage.

The approach of including the effects of curling and accumulating fatigue damage separately by day and by night to more accurately apply the effects of curling during these periods is considered to be excellent. The emphasis given to the greater importance of wheel loads near the slab edge because of the magnitudes of stresses they create is also considered to be significant. The procedure is based, however, on certain "built-in" assumptions that limit its general applicability to these studies; therefore, it was not selected as a primary model. A detailed discussion of JCP-1 and reasons for its limited use appear elsewhere (3).

The dimensional changes in a CRCP caused by drying shrinkage of the concrete and temperature variation after curing were investigated by McCullough and others, and the design method using the CRCP-1 program was developed in their study (2). This computer program was subsequently improved by Ma (34) and designated CRCP-2.

The spacing of transverse cracks that occur naturally in CRCP is perhaps the most important variable that affects the behavior of the pavement. Relatively large distances between cracks result in a greater accumulation of drag forces from the subgrade as a result of frictional resistance, thus producing high steel stress at the crack and wide crack widths. Closer crack spacing reduces frictional restraint and thus steel stress and crack width. It is clear that the transverse cracks in CRCP are caused by the thermal contraction and shrinkage of the concrete slab. The one-dimensional axial model used in this method is the only available rational model that considers the internal forces caused by the difference in thermal coefficient between the concrete and the steel material and is therefore a valuable tool for the analysis of CRCP.

In 1959, the Texas Highway Department began the Falls-McClennan County Project to evaluate the performance of CRCP. Intensive surveys of crack spacing were conducted at ages that varied from 20 d to 15 years. The results of the survey were compared with the CRCP-2 computer prediction, and the good correlation obtained indicates that this method gives reasonable predictions.

The JRCP-2 program developed by Rivero-Vallejo and McCullough (33) uses many of the concepts developed for CRCP-1, but the geometry and boundary conditions for the JRCP-2 model are considerably different from those for CRCP-2. JRCP-2 also considers the stresses in the concrete and reinforcing steel with time and location. These stresses are affected by the frictional resistance of the subbase; the stiffness, tensile strength, and shrinkage coefficient of the concrete; temperature drops anticipated over time; slab length; percentage of reinforcement; bar diameter; the yield stress and elastic modulus of the steel; the unit weight of the concrete; and the ages at which cracking is to be considered. Given this information, JRCP-2 will theoretically proceed with analysis until the first crack forms and then restructure the problem for subsequent consideration for the formation of a second crack between the joint and the first crack. The output includes the time when the first crack is formed, concrete stress, steel stress, joint width,

Table 1. Distresses, related material properties, and distress models selected for flexible pavement, composite pavement, JRCP, and JCP.

Type of Pavement	Distress	Material Properties That Significantly Affect Distress	Model Selected for Distress Studies
Flexible	Fatigue cracking	Fatigue constants $K_1(T)$, $K_2)T)$ for AC surface Stiffness modulus for AC surface Stiffness modulus for base materials	VESYS A
	Rutting	Stiffness modulus for AC surface Permanent deformation parameters for AC surface Stiffness modulus for subgrade soil Permanent deformation parameters for subgrade soil	VESYS A
	Low-temperature cracking	Coefficient of thermal expansion for AC Stiffness modulus for AC Tensile strength for AC	Shahin and McCullough low-temperature-cracking model
	Reduced skid resistance	Abrasive wear potential	Study separate from primary factorial study
Composite	Reflection cracking	Stiffness modulus for AC overlay Thermal coefficient for existing pavement Creep modulus for AC overlay	RFLCR1
	Fatigue cracking	Stiffness modulus for PCC or cement-treated base Fatigue constants for AC overlay or PCC Stiffness modulus for AC overlay	ELSYM5[a]
	Rutting	Permanent deformation parameters for AC overlay Stiffness modulus for AC overlay	VESYS A
	Reduced skid resistance	Abrasive wear	Concurrent with study for flexible pavement
JRCP	Low-temperature and shrinkage cracking	Tensile strength for PCC Thermal coefficient Shrinkage coefficient	JRCP-2
	Fatigue (transverse or corner cracking)	Fatigue constants for PCC Stiffness modulus for PCC Stiffness modulus for subbase material	ELSYM5[a]
	Faulting at cracks		Study separate from primary factorial study
	Joint spalling	Volume-change characteristics for PCC surface Tensile strength for PCC Stiffness modulus for PCC	Study separate from primary factorial study
JCP	Fatigue cracking	Fatigue constants for PCC Stiffness modulus for PCC Stiffness modulus for subbase materials	ELSYM5[a] (concurrent with studies for JRCP and CRCP)
	Joint faulting	Erodibility of subbase Erodibility of subgrade Tensile strength of PCC	Study separate from primary factorial study
	Joint spalling		Concurrent with study for JRCP

[a]Stresses predicted by ELSYM5 are essentially interior slab stresses and will be multiplied by a stress factor to approximate slab edge stresses.

Table 2. Distresses, responses to thermal and shrinkage cracking, related material properties, and distress models selected for CRCP.

Distress	Response to Thermal and Shrinkage Cracking That Can Be Optimized to Minimize Distress	Material Properties That Significantly Affect Distress	Model Proposed for Sensitivity Analysis
Fatigue cracking	-	Fatigue constants for PCC Stiffness modulus for PCC Stiffness modulus for subbase	ELSYM5[a] (concurrent with study for JRCP)
Low-temperature and shrinkage cracking	-	Thermal coefficient for PCC Shrinkage coefficient for PCC Tensile strength for PCC	CRCP-2
Punchouts, crack spalling, and steel rupture	Crack width and spacing[b]	Thermal coefficient for PCC Shrinkage coefficient for PCC Tensile strength for PCC	CRCP-2 (concurrent with study for low-temperature and shrinkage cracking for CRCP)

[a]Stresses predicted by ELSYM5 are essentially interior slab stresses and will be multiplied by a stress factor to approximate slab edge stresses.
[b]Narrow cracks generally do not spall, and punchouts do not generally occur except when crack spacing is close. Since crack width and spacing are negatively correlated, only one must be optimized.

and crack width as a function of time and the same data for second cracks if they are formed.

It is believed that JRCP-2 is the only thorough model available for the study of the effects of material properties on drying shrinkage and thermal cracking in JRCP. Unfortunately, our use of the model indicates that the computer program is not completely debugged and that it does not predict cracking or correctly predict stresses in concrete and steel. Consequently, the predictions for crack widths are questionable. But since it appears to be theoretically correct and is the only suitable model for JRCP, it has been selected for study of JRCP distresses assuming correction of its deficiencies.

SUMMARY OF RESULTS

Tables 1 and 2 give the distresses, material properties, and models selected for flexible pavements, composite pavements, JRCP, JCP, and CRCP. Some distresses have not been assigned a specific model because no suitable mathematical models for prediction of these distresses were found. These distresses will be studied separately from the factorial study, and the optimal material properties for them will be considered in the optimization.

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