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MATERIAL PROPERTIES TO MINIMIZE DISTRESS IN ZERO-MAINTENANCE PAVEMENTS

Vol. 1. Models

March 1981

Final Report

DEPARTMENT OF TRANSPORTATION ★ UNITED STATES OF AMERICA ★

Prepared for
FEDERAL HIGHWAY ADMINISTRATION
Offices of Research & Development
Structures and Applied Mechanics Division
Washington, D.C. 20590

FOREWORD

In Volume 1 of this report significant pavement distresses were defined and related to material properties. Pavement response and distress models were investigated for flexible, composite, and three types of rigid pavements. These models were utilized in a preliminary factorial study over practical ranges of material properties. Based on an evaluation of predictive capabilities, a work plan for Phase II of this study was presented.

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Richard E. Hay for
Charles F. Scheffey
Director, Office of Research

NOTICE

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16. Abstract

This first volume report provides results of a detailed study to 1) identify distresses that cause significant loss of serviceability and/or maintenance in pavements; 2) identify material properties that significantly influence the occurrence of distress; 3) select the best theoretical or empirical models for predicting distress using material properties and other engineering parameters; and 4) develop a detailed research plan for utilizing the models selected to study the effects of the significant distresses and to optimize material properties for zero-maintenance pavements.*

The research resulting in the accomplishment of the goals described above also produced other separate and specific results that are reported and should prove useful in future research. These results include: 1) a set of definitions and examples for their use in describing pavement behavior and the occurrence of distress; 2) tabulations of distresses, material properties that affect specific distresses, and the material factors (e.g., asphalt content, type and gradation of aggregate, etc.) that affect specific material properties; 3) discussions of the various predictive models available; and 4) the results of a number of limited sensitivity analyses using various distress models.

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PREFACE

This is the first of two volumes for this research report. The overall project goal is to develop a set of optimum material properties for use in design of zero-maintenance pavements. This volume (1) identifies significant material properties for each distress and pavement type, (2) selects the best distress models to use in studying these material properties, and (3) recommends a research approach for the remaining project work.

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CHAPTER 1. INTRODUCTION

BACKGROUND

The Federal Highway Administration (FHWA) has pursued for several years multiple research studies aimed at producing premium pavement structures for heavily travelled routes. The intention of the Federal Highway Administration's efforts has been to minimize maintenance, which not only disrupts traffic flow but also creates hazards and high user costs. This research effort is called "Premium Pavements for Zero Maintenance". Its goal is the development of pavement structures that will be maintenance free for 20 years and require only routine maintenance for 10 to 20 years thereafter.

Research is underway for upgrading conventional structures by use of improved conventional or new materials including the development of new materials. New and different structural systems are under study utilizing improved conventional and new materials. Field surveys have been conducted to study the nature of existing pavements that have performed essentially as zero maintenance pavements. These diverse studies have produced valuable information for use on this and other zero-maintenance research projects.

FHWA Research Project "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 project includes three tasks as described below:

1. Task A, "Model Selection", includes: a) identification of predicted distresses and related distress mechanisms, which based on past experience, cause loss of serviceability and/or maintenance; b) identification of the material properties that influence the occurrence of distress; c) selection of theoretical or empirical models to predict distress using material properties and other engineering parameters; d) identification of material testing required to properly characterize material properties; and e) preparation of a report to the FHWA providing the details of this study and recommending distresses and predictive models for continued study as well as a detailed research plan for Tasks B and C.

2. Task B, "Model Utilization," includes: a) selection of ranges of material property values for use in studying the five pavement types to be considered (flexible, composite, jointed concrete, jointed reinforced concrete, and continuously reinforced concrete pavement), one set for each of four environmental zones; b) selection of traffic level, thickness of layers, and environmental parameters to be used; c) testing of materials in order to properly characterize them for input to the distress models;

d) design and execution of comprehensive factorial studies utilizing the distress models and ranges of selected material properties; e) analysis of the zero maintenance potential for conventional materials; and f) analysis of the zero maintenance potential for materials recently developed but not in conventional use.

3. Task C, "Optimization of Material Properties," includes: a) utilization of the information developed in Tasks A and B to specify sets of optimum material properties for each component of the five pavement structures and for the four environmental zones; b) verification of the optimum material properties by using the selected models and other appropriate models; and c) preparation of a final project report and coordination of project results with the FHWA.

DEVELOPMENT OF DEFINITIONS

It is important that the terms used to describe categories of distress, specific forms of distress, distress mechanisms, distress manifestations, response mechanisms, responses, material properties, and other descriptors be clearly and concisely defined. Development of these definitions is necessary to ensure consistent usage in this project and to minimize the opportunity for personal interpretation by subsequent users. Most existing definitions were developed for the specific needs of other projects and were based on the level of understanding existent at that time (References 1[1], 2[2], 3[3], 4[4]). For example, a set of definitions was formulated by Hudson, et al, (Reference 3) for use in developing a systems framework. In view of recent advances in understanding of the physical structure, the various loads, and the environment, some of these definitions needed updating; therefore, definitions were reviewed and evaluated for adequacy and consistency. New definitions were developed when needed.

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[1] Hveem, F.N., "Types and Causes of Failure in Highway Pavements," Highway Research Board, Bulletin 187, 1958.

[2] Barenberg, E.J., C.L. Bartholomew and M. Herrin, "Pavement Distress Identification and Repair," Technical Report P-6, Construction Engineering Research Laboratory, Department of the Army, March 1973.

[3] Hudson, W.R., F.N. Finn, B.F. McCullough, K. Nair and B.A. Vallerga, "Systems Approach to Pavement Design, System Formulation, Performance Definition, and Material Characterization," Interim Report NCHRP 1-10, submitted by Materials Research and Development, Inc. to NCHRP, HRB, March 1968.

[4] Hudson, W.R. and F.N. Finn, "A General Framework for Pavement Rehabilitation," Report No. FHWA-RD-74-60, June 1974.

PAVEMENT DISTRESS

In this project, distress is defined as the condition of a pavement structure which reduces serviceability or leads to reduction of serviceability. Occurrence of distress may also lead to maintenance in order to restore serviceability. Distresses that do not directly result in significant losses of serviceability or do not lead to other distresses are of only minor interest in this study.

The identification of distresses affecting the performance of the five types of pavement structures included in this project result from a combination of literature review and experience of staff and consultants. The primary source of information was published field surveys, such as those by Darter and Barenberg (Reference 5[1]), which identify the types of distress observed and generally the frequency of occurrence.

RELATED MATERIAL PROPERTIES

Identification of the material properties that have significant effect on the specific distresses was also obtained from a combination of literature review and the experience of the staff and consultants. Information already exists from sensitivity analyses, such as that reported in Reference 6[2], and regression equations for various types of pavements. These studies are especially useful when the statistical significance of the various material properties is included.

DISTRESS MODELS

There are numerous models that predict stresses and strains in a pavement structure. All of them assume linear elasticity and generally fall into two categories. One category basically analyzes an elastic plate supported by springs (or a semi-dense liquid) and the other analyzes a layered system with individual elastic properties. Included in the first category of models are the Westergard equations, discrete element slab theory, and the finite-element model of Huang and Wang. Elastic layer theory and three dimensional finite element theory are included in the latter category. 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,

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[1] Darter, M.I. and E.J. Barenberg, "Zero-Maintenance Pavements Requirements and Capabilities of Conventional Pavement Systems," Interim Report No. FHWA-RD-76-105, April 1976.

[2] Rauhut, J.B., J.C. O'Quinn and W.R. Hudson, "Sensitivity Analysis of FHWA Structural Model VESYS II," Report No. FHWA-RD-76-24, March 1976.

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.

Building on this capability for predicting pavement responses, more sophisticated models such as VESYS A (Reference 7[1]) and PDMAP (Reference 8[2]) for flexible pavements and RPOD (Reference 9[3]) and JCP-1 (Reference 10[4]) 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 only available for predicting fatigue cracking and rutting for flexible and composite pavements, and fatigue cracking alone for rigid pavements.

Other computer-based analytical procedures have been developed for predicting cracking due to changes in volume as temperature decreases. Examples of these models are the Shahin-McCullough model (References 11[5] and 12[6]), program COLD (References 8 and 13[7]), the Hajek-Haas model

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[1] Rauhut, J.B. and P.R. Jordahl, "Effects on Flexible Highways of Increased Legal Vehicle Weights Using VESYS IIM," Final Report No. FHWA-RD-77-134, January 1978.

[2] Finn, F.N., C. Saraf, R. Kulkarni, K. Nair, W. Smith and A. Abdullah, "Development of Pavement Structural Subsystems," Final Report, NCHRP Project 1-10B, February 1977.

[3] Treybig, H.J., B.F. McCullough, P. Smith and H. Von Quintus, "Overlay Design and Reflection Cracking Analysis for Rigid Pavements, Volume 1, Development of New Design Criteria," Final Report No. FHWA-RD-77-66, January 1978.

[4] Darter, M.I., "Design of Zero-Maintenance Plain Jointed Concrete Pavement, Vol. 1 - Development of Design Procedures," Report ZM-2-77, prepared by the Dept. of Civil Engineering, University of Illinois at Urbana-Champaign for the FHWA, June 8, 1977.

[5] Shahin, M.Y., "Prediction of Low-Temperature and Thermal-Fatigue Cracking of Bituminous Pavements," University of Texas, PhD Dissertation, August 1972.

[6] Shahin, M.Y., "Design System for Minimizing Asphalt Concrete Thermal Cracking," Proceedings, Fourth International Conference on Structural Design of Asphalt Pavements, August 1977.

[7] Christison, J.T., "Response of Asphalt Pavements to Low Temperature," PhD Dissertation, University of Alberta, 1972.

(Reference 14[1]) for predicting low-temperature cracking in flexible pavements, and programs CRCP-2 and JRCP-1 for predicting crack spacing and crack widths in rigid pavements.

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 which can be used to predict the distress in an approximate manner. Such models should prove adequate for optimizing the material properties to minimize these types of distress.

All promising analytical models were studied concurrently with the identification of significant distresses and related material properties.

The more promising models have been exercised and limited preliminary sensitivity analyses have been conducted to both check out the models and gain insight as to the importance of various material properties to the distresses they predict. The results of these model studies were reviewed and those distress models were selected that best predict each type of distress. Simplicity of input, computational efficiency, and nature of output were considered in the selection in cases where two or more models offered essentially the same accuracy.

RECOMMENDED PLANS FOR REMAINDER OF PROJECT

The remainder of the study involves separate factorial studies for each distress identified as significant, evaluation of the zero-maintenance potential for available materials, and the optimization of material properties for each pavement type. Each factorial will include four levels of environment (Wet-Freeze, Dry-Freeze, Wet-No freeze, and Dry-No Freeze) and the material properties significant to the distress being studied.

The development of these factorial studies is described in Chapters 3 and 4, and the proposed approach for utilizing the data from the factorial studies is presented in Chapter 6.

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[1] Haas, R.C.G., "A Method for Designing Asphalt Pavements to Minimize Low-Temperature Shrinkage Cracking," Research Report 73-1, The Asphalt Institute, January 1973.

CHAPTER 2. DEFINITIONS OF TERMS RELATING TO PAVEMENT DISTRESS, MODELS, AND PREDICTIONS OF DISTRESS AND PERFORMANCE

It was felt that a set of definitions to communicate successfully to a broad range of pavement engineers in this country and abroad must be based on terms that are clearly defined to minimize differences in interpretation and misunderstandings. Dictionary definitions were first reviewed and used to the extent possible. In addition, each of the definitions in Reference 3 was reviewed and only those changes were made that appeared necessary to maintain the specificity of the definitions and to define terms needed.

DEFINITIONS OF TERMS

1. A Pavement Structure is an organized combination of materials constructed in layers over a natural soil.

2. Material Properties are those definitive descriptive measures of the quality of the material (Reference 15[1]).

3. Response is the reaction of a pavement structure to load and environment.

4. Primary Responses are those responses which, when carried past some limiting value, initiate distress.

5. Other Responses are those responses which do not contribute directly to distress.

6. Distress is a condition of a pavement structure which reduces serviceability or leads to a reduction of serviceability.

7. Distress Manifestations are the visible consequences of various distress mechanisms, which usually lead to a reduction in serviceability (Reference 3).

8. A Mechanism is the physical or chemical process responsible for an action, reaction, or other natural phenomenon.

9. A Response Mechanism is the physical or chemical process responsible for the response of a pavement structure.

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[1] Murphy, G., "Properties of Engineering Materials," International Textbook Company, 1957.

10. A Distress Mechanism is the physical or chemical process involved in or responsible for distress in pavements.

11. Pavement Roughness is a phenomenon manifested at the pavement surface and experienced by the passenger and operator of a vehicle or airplane traveling over that surface. Pavement surface roughness is a function of the profile of the road surface, the characteristics of the vehicle, including tires, suspension, body mounts, seats, and so on, and of the acceleration and speed sensibilities of the passenger (Reference 62[1]).

12. Serviceability is the ability of a specific section of pavement to serve traffic in its existing condition (Reference 4).

13. Riding Comfort Index is a numerical estimate of serviceability based on pavement roughness.

14. Serviceability History is the time-based representation of the serviceability of the pavement. Serviceability history is sometimes termed performance and is often specified with a performance index as suggested by Carey and Irick (Reference 16[2]). As such, it is a direct function of the present serviceability history of the pavement (Reference 3).

15. Performance is a measure of the accumulated service provided by a facility; i.e., the degree to which a pavement fulfills its purpose.

16. Functional Failure is a level of serviceability below which the service provided by the pavement is unsatisfactory to users.

17. Structural Failure is a fracture or distortion which may or may not cause an immediate reduction of serviceability, but which will lead to a future loss of serviceability.

18. Fracture is the state of a pavement material being broken.

19. Distortion is a permanent change in the shape of the pavement or pavement component.

20. Disintegration is the state of being decomposed or abraded into constitutive elements (Reference 3).

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[1] Haas, R.C.G. and W.R. Hudson, "Pavement Management Systems," McGraw Hill Book Company, 1978.

[2] Carey, W.N., Jr., and P.E. Irick, "The Pavement Serviceability-Performance Concept," Highway Research Board, Bulletin 250, 1960.

21. Bleeding is the condition of free bitumen on the surface of the pavement due to excessive bitumen and/or insufficient void space.

22. Reflection Cracks are cracks occurring in the surface course of a pavement that coincide with and are caused by the relative movement of cracks or joints in underlying layers.

23. Low-Temperature Cracks are cracks (generally transverse) caused when tensile stresses induced by frictional resistance of the underlying layer to thermal contraction of the surface layer exceeds the tensile strength of the surface material.

24. Raveling is the progressive disintegration of an asphalt concrete layer from the surface downward by the dislodgement of aggregate particles. This may be caused by insufficient amount of binder in the mix, hardening of the asphalt binder, wet or dirty aggregate or aggregate with smooth surface texture.

25. Ruts are longitudinal depressions that form in the wheel paths of flexible or composite pavements, resulting from compaction or lateral migration of one or more of the pavement layer materials under the action of traffic and environment.

26. Reduced skid resistance is the reduction of frictional resistance between tires and a pavement surface. This reduction is generally due to abrasive wear of aggregates by traffic.

27. Shrinkage cracks are generally transverse cracks caused when tensile stresses induced by frictional resistance of the underlying layer to drying contraction of the surface layer exceeds the tensile strength of the surface material. These cracks generally occur in portland cement concrete and other cement treated materials.

28. Spalling is cracking, breaking, or chipping of a rigid pavement along joints, edges, or cracks in which small portions of the slab are dislodged.

29. Faulting is a difference in the elevation of two adjacent rigid slabs at the joint or crack interface due to consolidation or swelling of underlying material, inadequate load transfer, or pumping.

30. "D" Cracking is a series of fine, crescent-shaped hairline cracks in a rigid slab surface, usually paralleling a joint or major crack.

31. Steel rupture is the occurrence of a tensile fracture failure in the reinforcing steel when excessive stress is transferred upon fracture of adjacent concrete.

32. Polished Aggregates are surface aggregate particles having smooth, rounded surfaces with fine microtexture, either as original condition or after abrasive wear by traffic.

33. Punchouts are blocks of rigid pavement that are cracked around their periphery and displaced downward relative to the rest of the slab. Punchouts usually occur between closely-spaced transverse cracks that are subsequently connected by longitudinal cracks.

34. Fatigue cracks are cracks in a pavement layer caused by the combination of repetitive strains and apparent reduction of tensile strength due to fatiguing of the layer material. The repetitive strains causing fatigue are usually caused by passing wheel loads, but may include repetitive thermally-induced or other strains.

35. Pavement Structure Models are mathematical formulations that use material property and load inputs to predict pavement responses.

36. Distress Models are formulations that use the calculated responses from pavement structure models along with other parametric input to predict pavement distress.

37. Performance Models are mathematical formulations that use the calculated distresses to predict pavement performance in terms of serviceability with time and/or service life.

38. A Parameter is a physical property whose value affects the behavior of a pavement structure.

39. Model Inputs are values of parameters affecting calculated predictions of pavement responses, distress, or performance.

40. Model Outputs are calculated predictions of pavement response, distress, or performance.

DISCUSSION OF DEFINITIONS FOR THE PHYSICAL PAVEMENT STRUCTURE

Most of the definitions are self-explanatory, but some of the definitions may be profitably clarified by discussion and the use of examples.

Response

The responses of a pavement are defined as the reactions of the pavement structure to load and environment. Examples of responses due to a wheel load are tensile strain, compressive strain, shear strain, and surface deflection. It can be readily seen that tensile strain and shear strain may be primary responses as they can contribute to fracture distress when carried past a limit. Vertical strain may be a primary response for the distortion category of distress. While surface deflection is certainly a response, it does not itself contribute to any form of distress. Instead, surface deflection is an indicator of the presence of other primary responses such as tensile strain, and is therefore categorized as an "other response". Another example of a primary response is loss of adhesion between binder and aggregate in an asphalt mixture. This leads to the distress called stripping, a form of disintegration.

Response and Distress Mechanisms

The definitions for response mechanism and distress mechanism are fairly direct, but the nature of their interaction is often quite complex. In fatigue cracking, the response mechanism would be bending due to a wheel load. Primary response in this case is tensile strain and a fatigue crack will be initiated when the tensile strain reaches or exceeds some limiting value. However, the distress mechanism is much more complex. The distress mechanism would be that process that reduces the resistance of the pavement material to tensile strain as a pavement is subjected to repetitive bending by passing wheel loads. As the pavement material is "fatigued" and its tensile strength reduced by this process, the magnitude of the tensile strain response necessary to initiate a crack (i.e., fatigue cracking distress) is continuously decreased. This process continues along with increased bending at the crack and thus more tensile strain while the crack propagates toward the surface. At some point as the crack approaches the surface, other distress mechanisms may come into play for the final development of the full-depth crack. It should be noted that the use of the term "fatigued" is simplistic since microcracks are generally present in asphalt concrete materials. "Crack initiation" is more accurately described as enlargement of a microcrack, while crack propagation may be described as a continuous process of microcrack interconnections.

A visual outline of these examples will probably be useful in gaining understanding of how the terms defined will be used in this project. Examples of fatigue and low-temperature cracking for asphalt concrete appear in FIGURES 2-1 and 2-2, respectively. As illustrated in FIGURE 2-1, the response mechanism for fatigue cracking is bending and that leads to the responses tensile strain, deflection, compressive strain, and shear strain. The latter three do not have a direct effect and are shown to the side and terminating. The bracket for the distress mechanism is intended to show that it is active long before the limiting tensile strain is reached, and that it continues to lower the response threshold after the crack is initiated and contributes along with increased tensile strain to continued propagation of the crack. The distress in the form of a fatigue crack is shown to have occurred when a crack is initiated, but would manifest itself later as observable cracks at the surface of the pavements.

As shown in FIGURE 2-2, the response mechanism for low-temperature cracking is thermal volume change. The response in this case is tensile strain due to the restrained volume change; i.e., no change in pavement

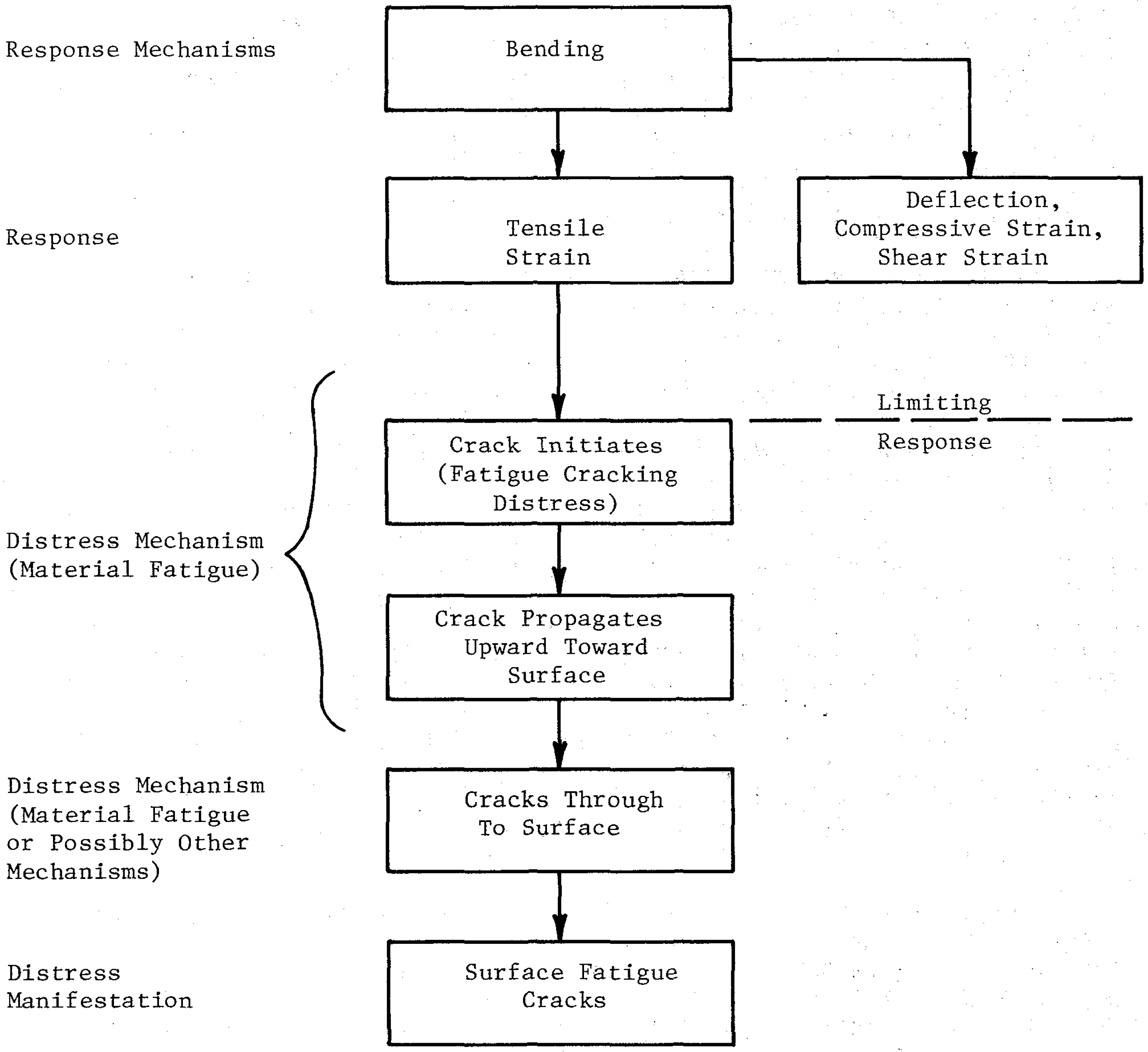

FIGURE 2-1. FATIGUE CRACKING IN AN ASPHALT CONCRETE PAVEMENT STRUCTURE.

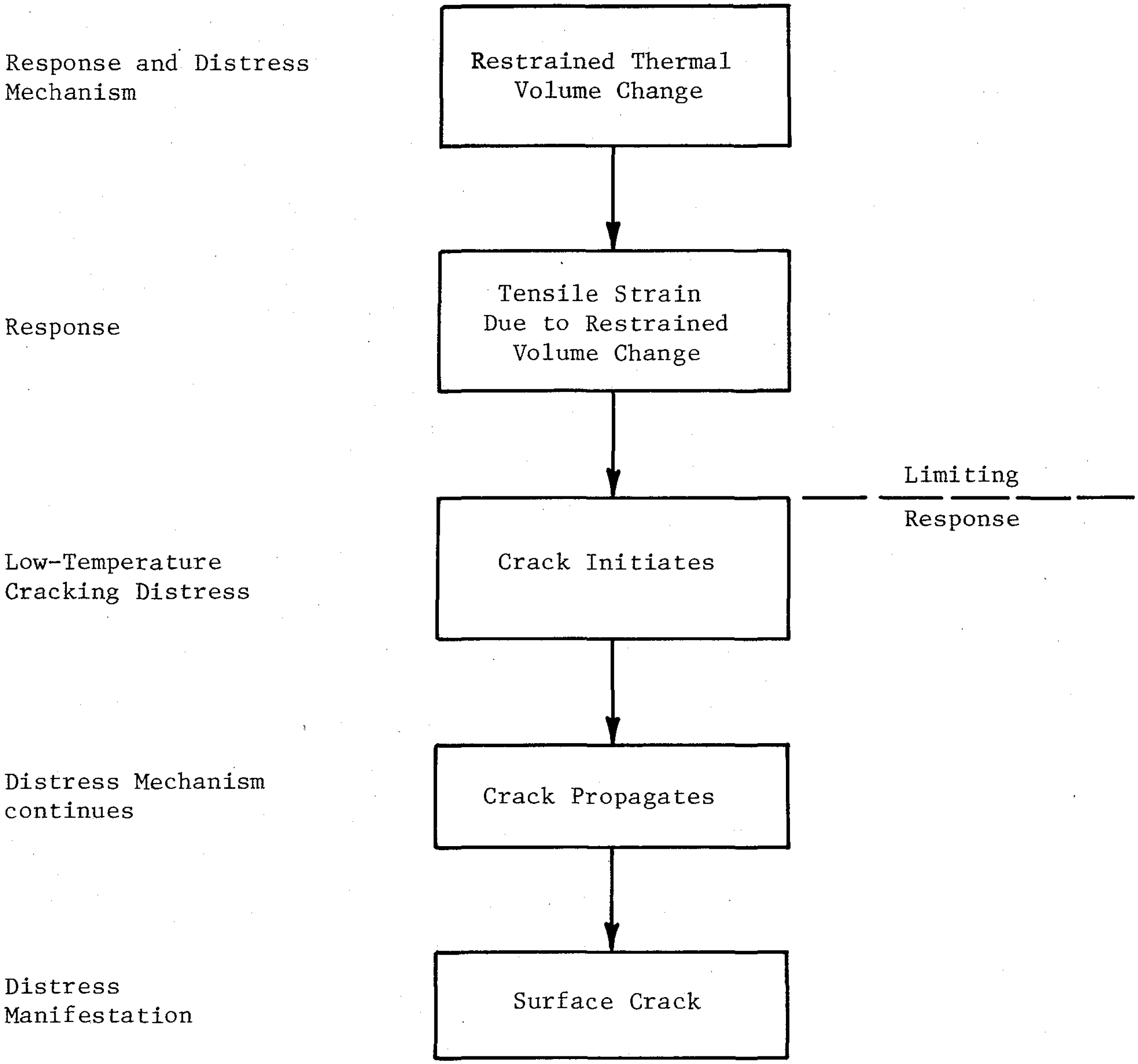

FIGURE 2-2. LOW-TEMPERATURE CRACKING IN AN ASPHALT CONCRETE PAVEMENT STRUCTURE.

length, but internal strain due to the material trying to reduce its volume. Restrained thermal volume change is the distress mechanism leading to crack initiation and thus low-temperature cracking distress. The process continues until the crack propagates through the layer. In many cases, the cracks initiate at the surface and propagate downward. The distress manifestation in this case would occur concurrently with the distress.

The designation of restrained thermal volume change as the distress mechanism appears reasonable, but could be considered simplistic. Restrained thermal volume change will not initiate a crack unless the rate of volume change exceeds the creep rate of the asphalt concrete or unless the total strain exceeds the failure strain of the material at the particular temperature (Reference 17[1]). Reduction in the limiting response due to fatigue from repetitive cycles of temperature variation also enters in. Thus it would be possible to describe a more sophisticated distress mechanism in terms of rate of restrained volume change, creep rate, failure strain, a fatigue relationship, and other parameters; however, this level of complexity is not useful for a clear description of the concepts proposed.

Secondary Distresses

One of the principal difficulties of establishing satisfactory relationships between distress and serviceability history or performance is the current inability to consider secondary distresses in the relationships. For example, the occurrence of surface cracking in a pavement has very little effect on riding comfort. However, the infiltration of moisture into the base, subbase, and subgrade is one of the principal causes of subsequent loss of riding comfort. In effect, increased moisture creates a change in the nature of the pavement structure that causes it to respond differently to wheel loads than when the structure was uncracked. FIGURE 2-3 illustrates secondary distress due to fatigue cracking and starts with the formation of fatigue cracks. Moisture infiltrates the base, subbase, and subgrade through cracks and has the effect of altering the pavement material properties. The reduced stiffnesses allow more bending and increased tensile strain at new locations; and new cracks are initiated and propagate to the surface, where multiple cracks such as those often called "alligator cracking" result.

A second and parallel mechanism, pumping erosion, could also be initiated (FIGURE 2-4). Thus, the moisture infiltration reduces the moduli of elasticity for the base, subbase, and subgrade, while pumping erosion creates voids in the support under the surface layer. The secondary

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[1] Ruth, B.E., "Evaluation of Flexible Pavement Systems to Determine Low Temperature Cracking Potential," Report submitted to Florida DOT, Engineering and Industrial Experiment Station, University of Florida, August 1975.

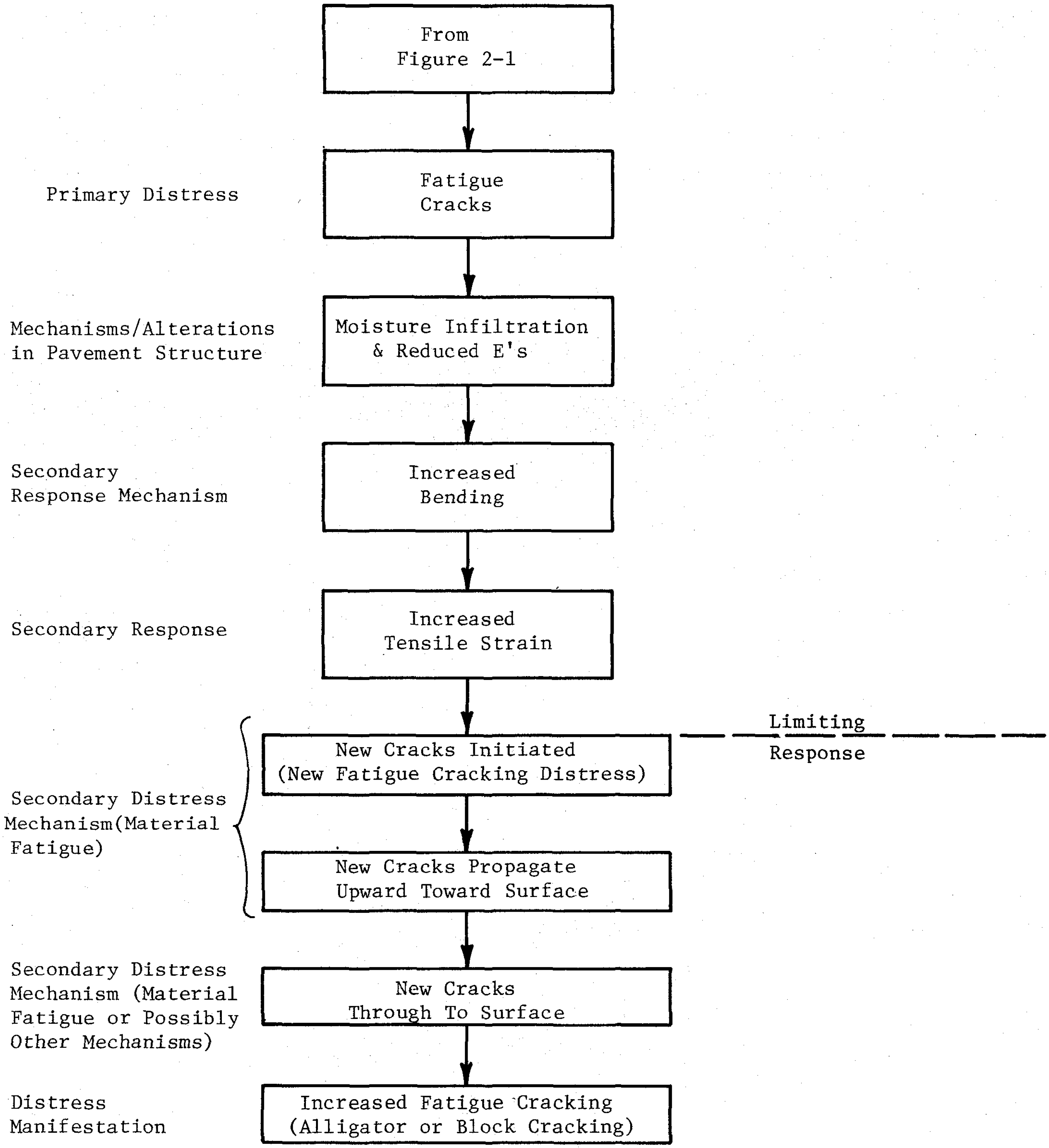

FIGURE 2-3. INCREASED FATIGUE CRACKING (SECONDARY DISTRESS) IN AN ASPHALT CONCRETE PAVEMENT STRUCTURE DUE TO SECONDARY RESPONSE MECHANISMS, RESPONSES AND DISTRESS MECHANISMS RELATED TO MOISTURE INFILTRATION.

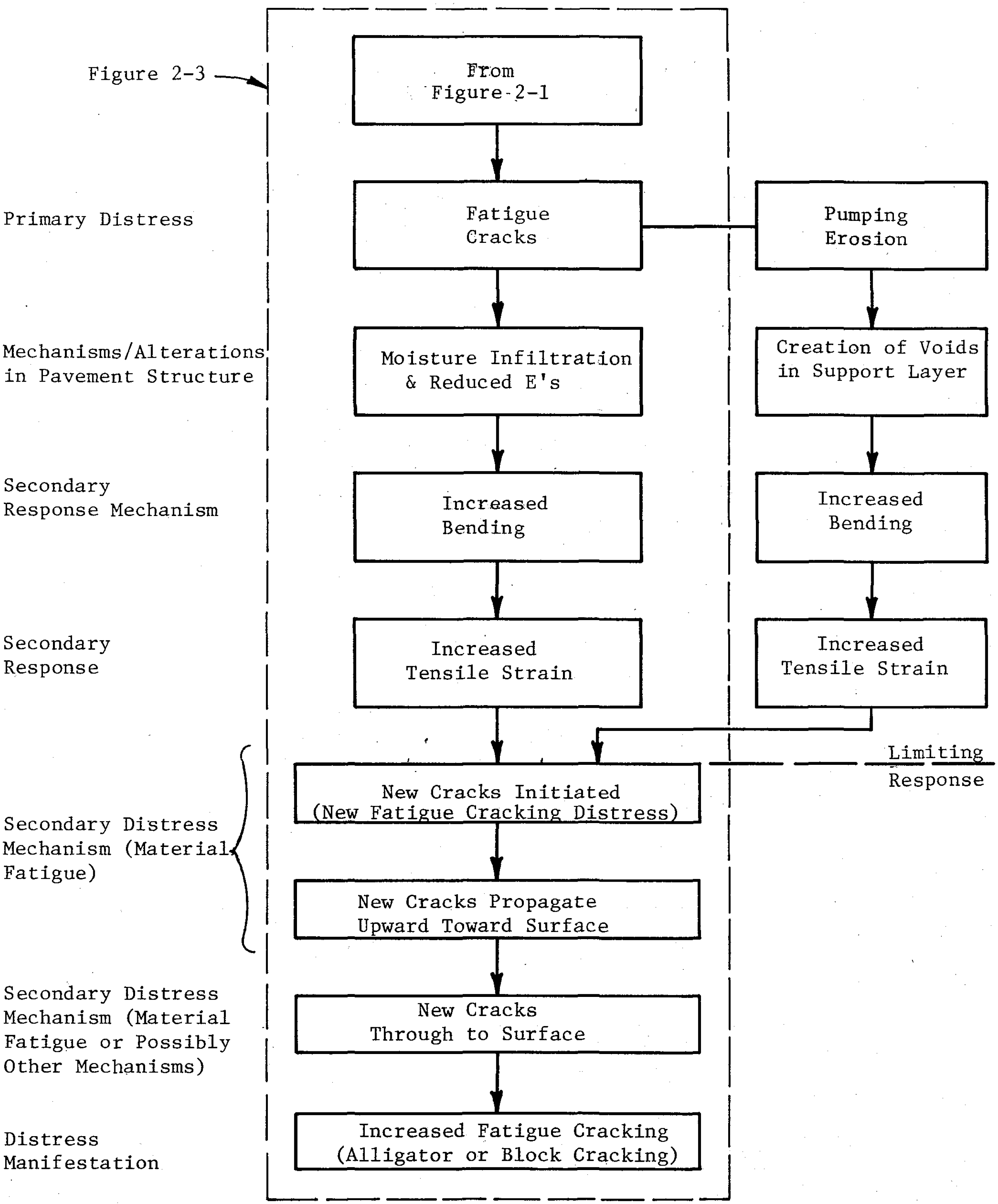

FIGURE 2-4. INCREASED FATIGUE CRACKING (SECONDARY DISTRESS) IN AN ASPHALT CONCRETE PAVEMENT STRUCTURE DUE TO SECONDARY RESPONSE MECHANISMS, RESPONSES AND DISTRESS MECHANISMS RELATED TO PUMPING EROSION.

response mechanisms are increased bending of the surface layer and the secondary responses are increased tensile strain and shear strain. The secondary distress mechanism is again material fatigue, but may include several distress mechanisms as discussed above. The secondary distress is again fatigue cracking, but it has been accelerated and the eventual result will be multiple or alligator cracking.

A similar visual outline could be drawn using both the effects of moisture infiltration, pumping, and the resultant accelerated fatigue cracking to follow through to rutting and formation of "pot holes" as other secondary or tertiary distresses. These last two distresses affect directly the serviceability and create a need for maintenance.

Other forms of distress are not as easy to follow as the more familiar one of fatigue cracking. One such example is that shown for stripping in FIGURE 2-5. For stripping, the response mechanism and the distress mechanism both are the physical-chemical displacement of the asphalt film on the aggregate by water. The result of this process is the response, loss of adhesion. This leads to the distress involving loss of aggregate bond and a consequent change in the pavement structure. The distress manifestation in this case is not at all simple to define as the distress usually manifests itself in some secondary form of distress such as rutting that may result from the deterioration or loss of stability in the pavement structure.

DISCUSSION OF DEFINITIONS FOR PAVEMENT STRUCTURE AND DISTRESS MODELS

It is also useful to discuss and to illustrate the use of models to predict pavement structure responses, to translate structural responses into distresses, and to calculate predicted performance on the basis of the predicted distresses.

FIGURE 2-6 is a diagram intended to illustrate the definitions for and interactions of pavement structure, distress, and performance models. VESYS A was selected for this example because a structural model, distress models, and performance models are all combined into a single computer code. In this case, the required inputs must describe material properties, the wheel loadings, the geometry of the pavement, and the environmental characteristics affecting the response of the pavement. The outputs from the pavement structural model are sets of equations representing both total and elastic displacements at the surface and tensile strains at the bottom of the asphalt concrete surface layer, each as a function of loading time to reflect the viscoelastic nature of the paving materials. There are sets of these equations for each environmental period or "season" of the year selected for input (usually four, but can be any number).

The outputs from the pavement structure models then become inputs for the distress models. These models include:

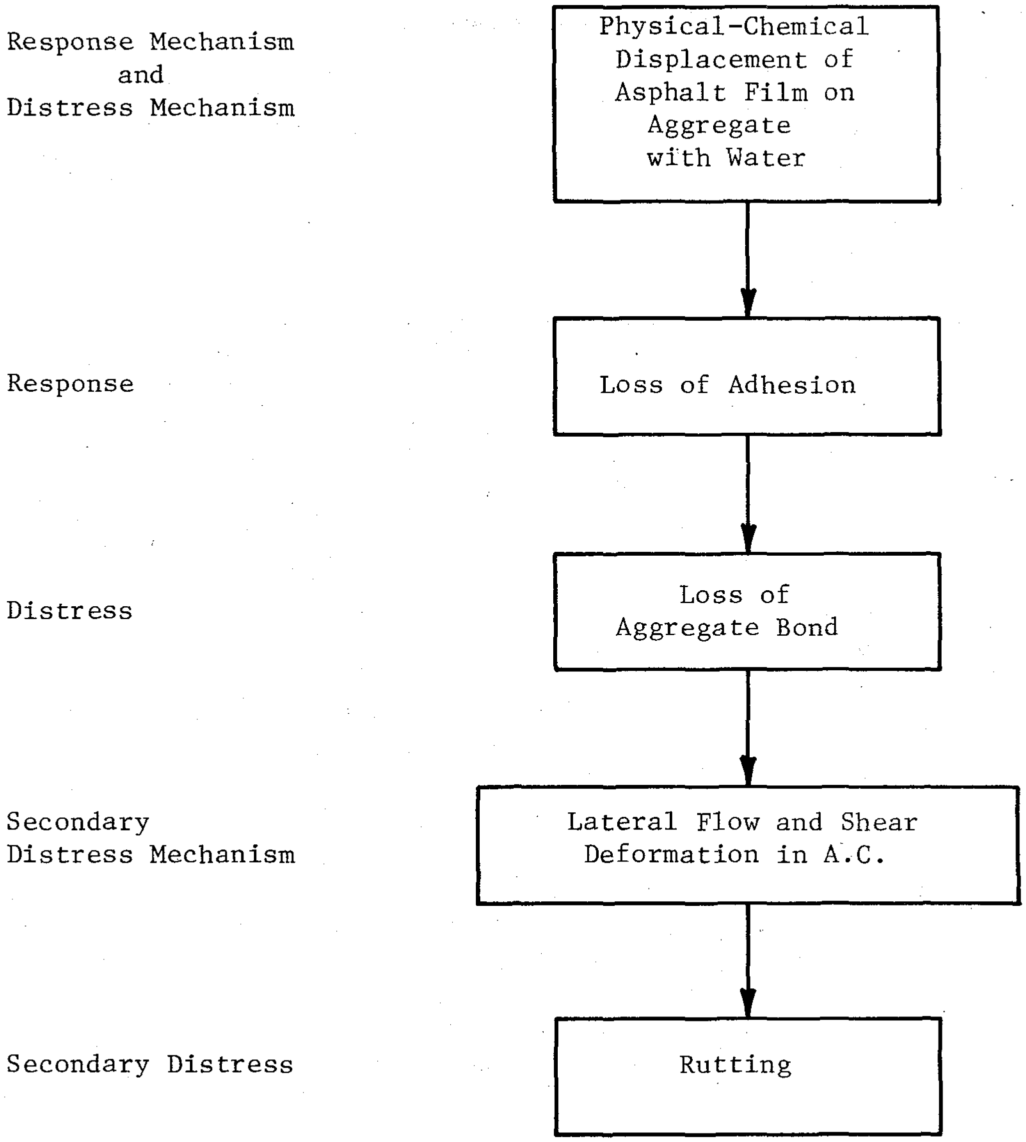

FIGURE 2-5. OCCURRENCE OF STRIPPING IN ASPHALT MIXTURES.

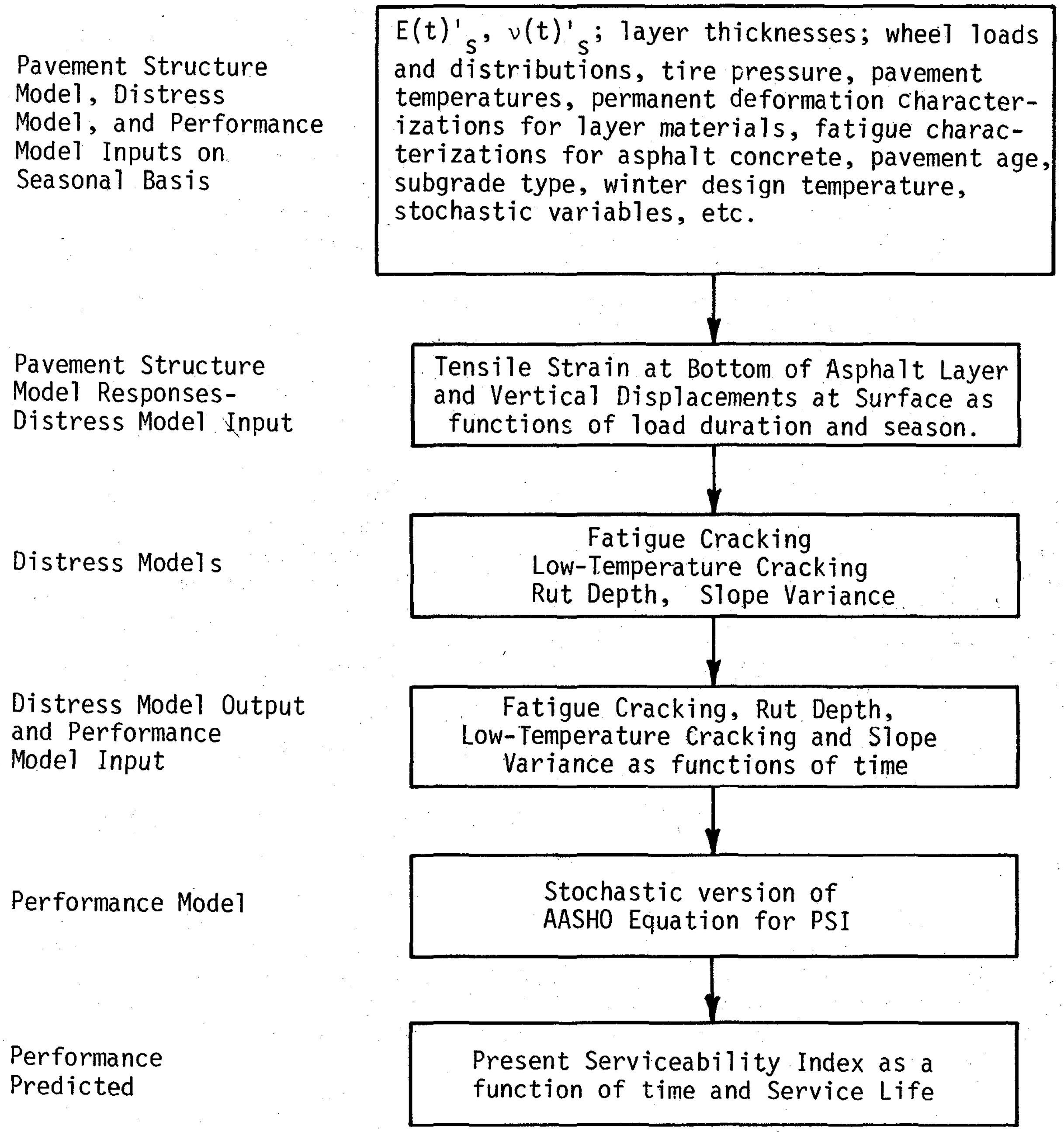

FIGURE 2-6. OUTLINE SHOWING USE OF VESYS A AS AN EXAMPLE OF USING MATHEMATICAL MODELS TO PREDICT DISTRESS AND PERFORMANCE FOR A FLEXIBLE PAVEMENT.

1. A fatigue cracking model that predicts percent of area cracked. This model includes stochastic mathematical relationships that relate the calculated tensile strains, axle load distributions, truck traffic, material fatigue parameters, and the linear summation of cycle ratios, also called Minor's Hypothesis, to arrive at predictions of percent of area cracked with time.

2. A "roughness model" that predicts both rut depth and slope variance as functions of time. This model uses the permanent deformation characterizations for the materials, the calculated vertical displacement responses from the pavement structure model, axle load distributions, and truck traffic.

3. A low-temperature cracking model that predicts percent of area cracked due to thermal volume change effects.

The outputs from the distress model are then used in the performance model to predict slope variance and then Present Serviceability Index as a function of time and the service life for the pavement structure. While predicted slope variance might be minimized and thereby reduce pavement roughness, its prediction is directly and statistically dependent on predicted magnitudes of rut depth and variance in rut depth, so the more direct approach for reducing roughness is to minimize the rut depth. It should be noted that performance models are not required for this project as its objective is only to minimize distress.

There are numerous pavement structure and distress models available and these will be discussed in Chapter 4.

SUMMARY DISCUSSION FOR DEFINITIONS

In summary, a set of definitions have been developed and their general utilization described in examples. A very considerable effort has been applied to obtain concise and specific definitions to encourage logical and systematic use as illustrated in FIGURES 2-1 through 2-6. It is believed that these definitions may be useful for other studies of distress, material properties, and performance.

CHAPTER 3. DISTRESSES AND THE RELATED MATERIAL PROPERTIES

The purpose of this portion of the study was to identify the various distresses, to select those distresses that occur in premium pavements, and to identify and list the related materials properties. This effort was subdivided into the following four objectives:

1. To develop a complete list of distresses for each pavement type, engineering properties related to the distress types, and factors affecting the engineering properties of the materials,
2. To assess the relative importance of distress types in terms of frequency of occurrence and to evaluate the effect on serviceability of pavements, i.e., does it result in a need for immediate or long-term maintenance or does the distress result in initiation of secondary distresses,
3. To assess the relative importance of material properties on each of the important distresses in objective 2, and
4. To summarize the distresses and related material properties having sufficient impact on pavement performance and maintenance requirements to warrant further consideration in this project.

RESEARCH APPROACH

The basic approach used to identify the various distresses and the engineering material properties, subsequently referred to as material properties, which affect these distresses involved an evolutionary process of review and refinement.

The first cycle involved identifying and categorizing various distresses based on the experience of the research team. At the same time, those material properties which affect the specific distresses were identified.

Using the resulting information as a base, a second cycle of review, expansion, and refinement was conducted. Previous identifications of distress from the literature and inputs from this research were introduced at this stage to insure that all pertinent distress types and related materials properties had been considered (References 3 and 5). This study was also expanded at this stage to identify those environmental, mixture design, construction, and traffic factors which influence the material properties.

During this second study cycle, careful consideration was given to each of the previously proposed distresses to ascertain whether it was a distress or a secondary effect. In addition, more definitive relationships between distress and related material properties were developed and a preliminary assessment of the relative importance of the various distresses and their related material properties was made. Finally, the results of this study were carefully reviewed by the project staff and consultants to insure that all pertinent distresses were considered and that the list of related material properties was complete.

The first two cycles produced a complete set of distresses for each pavement type, a complete set of material properties affecting the specific distresses, and a reasonably complete set of independent mixture and construction factors, i.e., type of aggregate, cement factor, and mixing temperature, which affect these material properties. The final cycle involved establishing the relative importance of the distresses and their related material properties. The basis for these decisions were:

1. The results of field surveys and the combined experience of the project staff and consultants which were used to establish distresses warranting consideration. References 5 and 18[1] provided the primary sources of field survey information.

2. The results of the field surveys, sensitivity analyses on both regression and theoretical models, and the combined experience of the project staff and consultants were used to rank the material properties in order of their importance to specific distresses.

In developing these rankings, considerable use was made of the results from Darter and Barenberg (Reference 5) and McCullough et al (Reference 18). In both of these studies, significant efforts were expended to collect condition data for pavements in the United States. As a part of these condition surveys, summaries of the severity of the distress and the frequency of occurrence of distress were prepared. The rankings used in Reference 5 were developed using the results from discussions with 13 state highway agencies in the United States. These discussions provided a basis for transforming the condition survey information into the severity categories used. Examples of the types of summary information prepared by Darter and Barenberg are shown in TABLES 3-1, 3-2, 3-3, 3-4, and 3-5. The information in each table represents the type of moderate to severe distress observed in pavements that exhibited lives consistent with that desired for zero-maintenance pavements. The reader should note that these distress rankings are for pavements which survived for 20 years and may not be applicable to pavements in general. The survival of a particular pavement may have resulted from favorable environmental, traffic and construction rather than optimum material properties.

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[1] McCullough, B.F., A. Abou-Ayyash, W.R. Hudson, and J.P. Randall, "Design of Continuously Reinforced Concrete Pavements for Highways," NCHRP 1-15, National Cooperative Highway Research Program 1975.

TABLE 3-1. SUMMARY OF DISTRESS TYPES FOUND ON FLEXIBLE PAVEMENTS RATED AS MODERATE TO SEVERE. (REFERENCE 5)

	PROJECTS	
Types of Distress	Distresses/Total	Maintained/Distressed
		**
1. Longitudinal Cracking (lane joint in nearly all cases)	11/19	5/11
2. Transverse Cracking (including reflective)	10/19	7/10
3. Alligator (fatigue) cracking	9/19	5/9
4. Polished Aggregate	8/19	0/8
5. Rutting	6/19	1/6
6. Weathering Asphalt	4/19	0/4
7. Depressions	3/19	0/3
8. Alligator or Transverse Cracking*	14/19	9/4
9. Alligator or Transverse or Longitudinal Cracking or Rutting*	17/19	10/17

*Whichever of the distress types was rated highest for each pavement.
**Maintenance performed only for distress indicated.

TABLE 3-2. SUMMARY OF DISTRESS TYPES ON COMPOSITE PAVEMENTS WHERE DISTRESS IS RATED AS MODERATE TO SEVERE. (REFERENCE 5)

Types of Distress	PROJECTS Distresses/Total	Maintained*/Distressed
1. Transverse Cracking	6/7	2/6
2. Rutting	5/7	0/5
3. Longitudinal Cracking	4/7	2/4
4. Edge Cracking	3/7	1/3
5. Random Cracking	3/7	1/3
6. Depression	2/7	0/2
7. Polished Aggregate	2/7	0/2
8. Raveling and Weathering	1/7	0/1

*Maintenance performed for only the distress indicated.

TABLE 3-3. SUMMARY OF DISTRESS TYPES ON JCP RATED AS MODERATE TO SEVERE. (REFERENCE 5)

	PROJECTS	
Types of Distress	Distresses/Total	Maintained*/Distressed
1. Joint Filler Extrusion and/or Stripping	11/11	2/11
2. Shoulder Distress	4/8	1/4
3. Faulting Joints	4/12	2/4
4. "D" Cracking	3/12	1/3
5. Interconnecting Cracking	2/12	0/2
6. Surface Depression	2/12	0/2
7. Transverse Cracking	2/12	2/2
8. Joint Spalling	1/12	0/1

*Maintenance applied to only specific distress indicated.

TABLE 3-4. SUMMARY OF DISTRESS TYPES FOUND ON JRCP RATED AS MODERATE TO SEVERE. (REFERENCE 5)

	PROJECTS	
Types of Distress	Distresses/Total	Maintained*/Distressed
1. Transverse Cracking	14/18	9/14
2. Paved Shoulder Distress	6/8	4/6
3. Faulting of Cracks	11/18	6/11
4. Joint Filler Stripping	11/18	5/11
5. Joint Spalling	9/18	7/9
6. Surface Depressions or Swell	4/18	4/4
7. Corner Cracking	6/18	5/6
8. Longitudinal Cracking	3/18	2/3
9. Blowups	4/18	4/4
10. Diagonal Cracking	8/18	1/8
11. "D" Cracking	2/18	2/2

*Maintenance applied to only specific distress indicated.

TABLE 3-5. SUMMARY OF THE MOST PREDOMINANT DISTRESS TYPES FOUND ON CRCP RATED MODERATE TO SEVERE. (REFERENCE 54)

Types of Distress	PROJECTS Distresses/Total	 Maintained*/Distressed
1. Surface Depression	7/12	0/7
2. Crack Spalling	6/12	2/6
3. Punchouts	4/12	4/4
4. Interconnecting Cracks	4/12	2/4
5. Longitudinal Cracking	2/12	0/2
6. Steel Rupture	2/12	2/2

*Maintenance applied to only specific distress indicated.

In subsequent sections of this chapter, identifications for and rankings of distresses in terms of their relative importance are presented and are in some cases different from those shown in TABLES 3-1 through 3-5. The reasons for these differences are:

1. The distresses noted by Darter and Barenberg (Reference 5) were not identified within constraints such as those imposed by the definitions presented in Chapter 2, so some items were included by them as distresses that do not qualify within these constraints. These are "weathering asphalt" and "polished aggregate".

2. Other distresses noted by Darter and Barenberg fit the definition of distresses, but are not subject to material optimization within the context of this research effort. These distresses include "joint filler extrusion/or stripping", "shoulder distress", "interconnecting cracking", "paved shoulder distress", and "joint filler stripping".

3. Some of the identifications for the distresses in Reference 5 were more in terms of their distress manifestations than by cause of distress. For instance, composite pavement distress included transverse cracking, longitudinal cracking, edge cracking and random cracking; whereas the terminology in this report would encompass all surface cracking in composite pavements within reflection cracking and fatigue cracking. Similarly, corner cracking, longitudinal cracking and diagonal cracking for JRCP are combined in this report as fatigue cracking.

Thus, the identifications of distresses and their importance rankings were developed using those prepared in Reference 5 as a beginning point and modifying these to represent the combined experience and opinion of the research team.

Moderate to severe distresses which occurred frequently were retained for factorial study. Other minor distresses, i.e., distresses which do not occur if design is adequate or which do not require significant maintenance, were eliminated from the factorial study although some will be briefly discussed. Fatigue cracking is typical of distresses considered significant, while shoving or raveling of a flexible surface were omitted from the factorial study since these can be and have been controlled by adequate mixture design.

DISTRESSES

Distress was previously defined as a condition of a pavement structure which reduces serviceability or leads to a reduction of serviceability. Three basic categories of distress have previously been defined (Reference 3) essentially as follows:

1. Fracture is the state of a pavement material being broken.

2. Distortion is a change in the original shape of the pavement surface or an underlying material layer.

3. Disintegration is the result of a process by which a material becomes decomposed or abraded into constitutive elements.

Within each of these categories of distress, there are several manifestations of distress that have been observed in the field. TABLE 3-6 contains a list of the major distresses for each category. On the basis of the definition of distress, a number of effects, which have often been called distress, were eliminated. It is recognized that these affect the development of distress, but they are not themselves distresses. Examples of such effects are curling and pumping.

The number of distresses were also reduced by combining into one distress those subgroups which have been used to account for small variations in the observed distress manifestations. Examples are corner cracking, diagonal cracking, longitudinal cracking, second-stage cracking, third-stage cracking, progressive cracking, random cracking, etc., all of which have been used previously to account for slight variations in the observed crack pattern.

Another group of distresses eliminated from further consideration are those distresses such as shoving, slippage, and corrugations that basically occur in secondary highways and would not be expected to occur in premium pavements. These distresses must be kept in mind, however, in order to insure that distresses that may be avoided by proper design and construction do not result when changes in material and mixture and structural design are made to eliminate other distresses.

There is considerable recent evidence that stripping is an important distress for flexible pavements. However, the process of stripping is a very complicated physical-chemical interaction between the asphalt and the aggregate and the effects of material properties on stripping are not well defined. Since the objective of this project is to optimize material properties and stripping did not show up as a major distress in Reference 5, stripping will not be considered further in this report.

MATERIAL PROPERTIES

Engineering properties are defined as those properties that may be used with a constitutive equation to predict the physical behavior of a material in a particular environment. For example, Hooke's Law can be used to describe the state of stress or strain of a linear, elastic material. Using Hooke's Law, other physical laws, and decision or design criteria, one can assess the suitability of a material with a certain modulus of elasticity (from Hooke's Law) for a particular application.

TABLE 3-6. PAVEMENT DISTRESS BY CATEGORY AND PAVEMENT TYPE

		Distress Category		
		Fracture	Distortion	Disintegration
Pavement Type	Flexible Pavements	Fatigue Cracking Thermal Cracking Slippage Cracking*	Differential Frost Heave Differential Compaction-Swelling Shoving* Rutting Corrugations*	Stripping Raveling Reduced Skid Resistance
	Rigid Pavements	Fatigue Cracking Shrinkage Cracking Thermal Cracking Blowups Spalling	Faulting Differential Frost Heave Differential Compaction-Swell	D-Cracking Scaling Reduced Skid Resistance
	Composite Pavements	Fatigue Cracking Thermal Cracking Slippage Cracking* Reflection Cracking	Differential Frost Heave Differential Compaction-Swell Shoving* Rutting Corrugations*	Stripping Raveling Reduced Skid Resistance

*Not important in premium pavements using current design and construction techniques, but should be considered to ensure that they do not develop.

Since modulus of elasticity is useful in evaluating the application of the material, it is categorized as an engineering property, but is also a property of the material. Material properties then are those engineering properties that are used to represent the materials in mathematical models and equations or in decision criteria. These, in turn, are used to evaluate the behavior and the suitability of materials for particular application.

The materials properties initially identified as having important effects on distresses in premium pavements are contained in TABLE 3-7. Each of the distresses included were considered by the project team to affect the occurrence and magnitude of a distress. For clarity and ease of presentation, the distresses are also listed separately in TABLES 3-8, 3-9, and 3-10 for each pavement type even though several of the distresses occur in more than one pavement type. In each table, the independent material properties affecting a particular distress are coded with a letter, which represents the type of material and the layer for which that property applies. For example, in TABLE 3-8, low-temperature cracking is affected by (1) the mixture stiffnesses of the surface and asphalt-treated base, (2) the coefficient of thermal expansion of the surface and asphalt-treated base, and (3) tensile strength of the asphalt concrete surface and asphalt-treated base.

Dependent material properties have generally not been included in the lists of properties prepared in this study. While dependent material properties can affect the magnitude of the independent property, all too often the relationship is a statistical correlation rather than one of cause and effect. Since the dependent material properties are related to the independent properties and often are more easily or conveniently measured, they may be used in place of the independent material property in engineering analyses. For example, density, aggregate gradation and type, temperature-susceptibility of the asphalt cement, air void characteristics, and several other factors are related to the fatigue characteristics of an asphalt concrete mixture. In this study the fatigue characteristics are included in the optimization studies and not the others. Since the independent properties are to be optimized, it is necessary to optimize the property that produces the effect rather than a second property with which the first may be correlated.

The importance of this approach is illustrated by the number of engineers who believe that increased density is always desirable. An attempt to maximize density does not mean necessarily that distress will be minimized or that other material properties will be maximized. In fact, material properties, in many cases, will not be maximized nor will distress be minimized. For example, fatigue life is not maximum at maximum density. In addition to not producing maximum fatigue life, increased density can lead to other distresses such as bleeding.

In the case of stiffness and air voids, both of these dependent properties were considered to influence the fatigue properties of asphalt mixtures, even though both are dependent on the same factors as the fatigue

TABLE 3-7. MATERIAL PROPERTIES CONSIDERED TO AFFECT DISTRESSES IN PREMIUM PAVEMENTS

Pavement Type			Material Property
Rigid	Flexible	Composite	
X	X	X	Constants of the Fatigue Equation
X	X	X	Tensile Strength
X		X	Shrinkage Characteristics
X	X	X	Coefficient of Thermal Expansion
X	X	X	Aggregate Characteristics
X	X	X	Compaction-Volume Change Characteristics
X			Erodability of Subbase and Subgrade Materials
X	X	X	Frost Susceptibility of Subgrade Soil
X	X	X	Mixture Stiffness*
	X	X	Permanent Deformation Characteristics
X	X	X	Bond (Adhesion)

*Includes stability, creep compliance, and elastic properties.

TABLE 3-8. MATERIAL PROPERTIES AFFECTING DISTRESSES IN PREMIUM FLEXIBLE PAVEMENTS

Material Property	FLEXIBLE PAVEMENT DISTRESS						
	Fatigue Cracking	Low-Temp. Cracking	Rutting	Compaction-Swelling*	Raveling	Stripping	Reduced Skid Resistance
Stiffness**	abcde***	ab	abcde		a	ab	
Coeff. of Thermal Expansion		ab					
Tensile Strength		ab					
Permanent Deformation Characteristics			ab				
Aggregate Characteristics						ab	a
Compaction-Volume Change Characteristic				e			
Frost Susceptibility				e			
Bond (Adhesion)						a	ab
Fatigue Constants	ab						

*Large, Relative Vertical Differential Displacements

**Includes stability, creep compliance, and elastic properties (E, ν)

***LEGEND

a - asphalt concrete surface
b - asphalt-treated material
c - lime-treated material
d - untreated granular material
e - subgrade soil

TABLE 3-9. MATERIAL PROPERTIES AFFECTING DISTRESSES IN RIGID PAVEMENTS

MATERIAL PROPERTY	CRACKING FATIGUE	CRACKING DRYING SHRINKAGE	CRACKING LOW TEMPERATURE	BLOWUPS	D-CRACKING	POLISHING	SPALLING	FAULTING	COMPACTION-SWELLING
Mixture Stiffness*	a,b,c** d,e,f		a,b	a					
Fatigue Constants	a								
Tensile Strength	a	a	a						
Coeff of Thermal Expansion			a	a			a		
Tensile Strength of Paste					a	a			
Permeability of Paste					a				
Pore and air void Characteristic of Paste					a				
Aggregate Characteristics					a	a			
Compaction - Volume Change Characteristics									f
Erodability								b,c,d e,f	
Bond (Adhesion)								b,c d,f	
Frost Susceptibility									f
Shrinkage Characteristic		a							

*Includes stability, creep compliance, and elastic properties (E,ν)

**<u>LEGEND</u>

a. Portland Cement Concrete Surface
b. Asphalt-treated Materials
c. Cement-treated Materials
d. Lime-treated Materials
e. Untreated Granular Material
f. Subgrade Soil

TABLE 3-10. MATERIAL PROPERTIES AFFECTING DISTRESSES IN PREMIUM COMPOSITE PAVEMENTS

MATERIAL PROPERTY	COMPOSITE PAVEMENT DISTRESSES							
	CRACKING							
	FATIGUE	LOW TEMPERATURE	REFLECTION*	RUTTING	COMPACTION - SWELLING**	RAVELING	STRIPPING	REDUCED SKID RESISTANCE
Mixture Stiffness ***	a_2,b,c d,e,f	****	a_1,b,c d,e,f	a ,b,c d,e,f		a_2	a_2,b	
Fatigue Constants	a_2,b,c		a_1			a_2	a_2,b	
Tensile Strength		a_2,b	a_1					
Shrinkage Characteristics			a_1					
Coeff. of Thermal Expansion		a_2,b,c	a_1					
Aggregate Characteristics			a_1					a_2
Compaction - Volume Change Characteristics					f,e			
Permanent Deformation Characteristics ***				a_2,b				
Frost Susceptibility					f	f	f	
Bond (Adhesion)						a_2	a_2,b	

*Reflection cracking can be caused by any cracking of the Portland Cement Concrete layer. See the PCC pavement distress summary for a break-down of the various cracking forms.

**Compaction-Swelling refers to any large, relative vertical differential displacements.

***Includes stability, creep compliance, and elastic properties (E,ν).

***<u>LEGEND</u>

a_1 - asphalt concrete surface
a_2 - portland cement concrete
b - asphalt-treated material
c - cement-treated material

d - lime-treated material
e - untreated granular material
f - subgrade soil

properties. In addition, stiffness can account for the affect of a number of independent factors and has been used extensively, and air voids produce flaws which influences crack propogation.

The extent of observed distress will be affected significantly by the variability in the magnitude of the measured properties of the materials that comprise the pavement structure. This variability has been included as inputs for some probabilistic analysis models and may be treated specifically only in those stocahstic formulations. Since the goal of this study is to establish optimum material properties and since some variation is associated with the set of values that represent those properties, variability in material properties will not be considered in the sensitivity analyses. This assumption is analagous to a statistical statement that the coefficient of variation is constant over the range of values which are expected to be included in the sensitivity analyses. The subject of variability is further complicated by potential changes in value of material properties with time. One such change is "aging" of the asphalt cement in the surface course, which certainly affects the stiffness as well as the strength and other less obvious characteristics. Unfortunately, no known structural models consider changes of material properties with time so such changes cannot be considered directly in this study.

FACTORS AFFECTING MATERIALS PROPERTIES

Factors believed to affect the magnitude of the various materials properties were also identified and appear in Appendix A. This information is primarily needed for FHWA project "Flexible and Composite Structures for Zero-Maintenance Pavements", but also provided valuable insight for evaluating the relative significance of material properties for this project. All factors having an effect on the various materials properties were listed for each property and categorized to indicate whether the factor related to environment, mixture design and materials, construction, traffic, or time.

Summaries of the important factors affecting the material properties are contained in TABLES A-1, A-2 and A-3 of Appendix A. A description and discussion of the actual effects produced by changes in these factors can be found in References 19[1], 20[2], 21[3], 22[4], 23[5], 24[6], and 25[7].

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[1] Finn, F.N., Factors Involved in the Design of Asphaltic Pavement Surfaces," National Cooperative Highway Research Program Report 39, Highway Research Board, 1967.

[2] Hadley, W.O., W.R. Hudson, and T.W. Kennedy, "An Evaluation of Factors Affecting the Tensile Properties of Asphalt-Treated Materials," Center for Highway Research Report 98-2, The University of Texas at Austin, 1969.

Footnotes 3-7 continued on next page.

DISTRESS RANKING

From the previous lists of distresses in tables, it was necessary to select those distresses that are of primary concern in producing premium pavements and that must be considered in the analysis or design of the pavement structures in order to minimize their occurrence and associated effects. Those distresses not included in this list either have been eliminated through improvements in existing design procedures or may be avoided through proper selection of materials or proper construction practices including quality control.

The results from condition surveys reported in References 5 and 18 were extensively used along with the experience of project engineers and consultants to rank order the pavement distresses that are listed in TABLE 3-6. The resulting priority ranking of pavement distresses is shown in TABLE 3-11. The models used to predict the occurrence of these distresses typically have included variables such as material properties, traffic, and environmental effects. In order to evaluate the available models for inclusion of the most significant material properties, a second priority ranking was performed. These priority rankings of material properties affecting distress in premium pavements by layer are included in TABLES 3-12, 3-13, and 3-14. In developing the priority rankings for material properties within a particular distress, the rankings were based on total effect with no consideration given to whether the material property could be controlled or manipulated during design.

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[3] Hadley, W.O., W.R. Hudson, and T.W. Kennedy, "A Method of Estimating Tensile Properties of Materials Tested in Indirect Tension," Center for Highway Research Report 98-7, The University of Texas at Austin, 1970.

[4] Chou, Y.T., "Engineering Behavior of Pavement Materials: State of the Art," U.S. Army Corps of Engineers, Report No. 5-77-9, Waterways Experiment Station, Vicksburg Miss., 1977.

[5] Epps, J.A. and C.L. Monismith, "Fatigue of Asphalt Concrete Mixtures - Summary of Existing Information," Fatigue of Compacted Bituminous Aggregate Mixtures, ASTM STP508, American Society for Testing Materials, 1972, pp. 19-45.

[6] Moore, R.A. and T.W. Kennedy, "Tensile Behavior of Subbase Materials under Repetitive Loading," Research Report 98-12, Center for Highway Research, The University of Texas at Austin, October 1971.

[7] Fourth International Conference on Structural Design of Asphalt Pavements, Volume I, Proceedings, August 1977.

TABLE 3-11. PRIORITY RANKING OF SIGNIFICANT DISTRESSES SELECTED FOR FURTHER STUDY

Priority Ranking	Flexible	Rigid Pavements			Composite Pavements
		JCP	JRCP	CRCP	
1	Fatigue Cracking	Fatigue Cracking	Low-Temp. and Shrinkage Cracking	Crack Spalling	Reflection Cracking
2	Rutting	Joint Faulting	Fatigue Cracking	Fatigue Cracking	Fatigue Cracking
3	Low-Temp. Cracking	Joint Spalling	Crack Faulting	Low-Temp. Cracking	Rutting
4	Reduced Skid Resistance		Joint Spalling	Shrinkage Cracking	Reduced Skid Resistance
5				Punchouts	
6				Steel Rupture	

TABLE 3-12. PRIORITY RANKING[1] FOR MATERIAL PROPERTIES AFFECTING DISTRESS TYPES OCCURRING IN PREMIUM FLEXIBLE PAVEMENTS.

MATERIAL PROPERTY	Layer[2]	Fatigue Cracking	Rutting	Low Temperature Cracking	Reduced Skid Resistance
Fatigue Constants	S	1			
	B	6			
Tensile Strength	S			3	
Coefficient of Thermal Expansion	S			1	
Aggregate Characteristics	S	**	**		1
	B	**	**		
	SB	**	**		
Mixture Stiffness*	S	2	1		
	B	3	5		
	SB	4	7		
	SG	5	3		
Permanent Deformation Characteristics	S		2		
	B		6		
	SB		8		
	SG		4		

[1] Ranking based on the effect of that property on distress not the ability to control that property in design.

[2] Legend
S = Surface layer
B = Base layer
SB = Subbase layer
SG = Subgrade

*Includes stability, creep compliance, and elastic properties of any pavement layer.

**The effect of this variable is included with other properties.

TABLE 3-13. PRIORITY RANKING[1] FOR MATERIAL PROPERTIES AFFECTING MAJOR DISTRESS TYPES OCCURRING IN PREMIUM COMPOSITE PAVEMENTS.

MATERIAL PROPERTY	Layer[2]	Reflection Cracking	Fatigue Cracking	Rutting	Reduced Skid Resistance
Mixture Stiffness*	S	1	4	2	
	B	3	1	3	
Fatique Constants	S		3		
	B		2		
Tensile Strength	S	4			
	B				
Coefficient of Thermal Expansion	S	5			
	B	2			
Aggregate Characteristics	S				1
Permanent Deformation Characteristics	S			1	

*Includes stability, creep compliance, and elastic properties of any pavement layer.

[1] Rankings based on the effect of that property condition not the ability to control that property in design.

[2] Legend
S=Surface layer
B=Base layer (Existing PCC pavement for some situations)

TABLE 3-14. PRIORITY RANKING[1] FOR MATERIAL PROPERTIES AFFECTING MAJOR DISTRESS TYPES OCCURRING IN PREMIUM RIGID PAVEMENTS.

MATERIAL PROPERTY		Layer[2]	DISTRESS					
			Joint and Crack Faulting	Joint and Crack Spalling	Fatigue	Low Temp. & Shrinkage	Punchouts	Steel Rupture
Stiffness*		S		2	2		2	2
		SB			3			
Fatigue Constants		S			1			
Coeff. of Thermal Expansion		S		1		2	1	1
Permeability of Paste		S						
Pore & Air Void Characteristics of Paste		S						
Aggregate Characteristics		S						
Erodability		S						
		SB	1					
		SG	2					
Tensile Strength	Concrete	S			4	1	3	3
	Steel	S						4
Shrinkage Coeff.		S				3		

*Includes stability, creep compliance, and elastic properties on any pavement layer.

[1] Ranking based on the effect of that property on distress not the ability to control that property in design.

[2] Layer Legend
S = Surface
SB = Subbase
SG = Subgrade

SUMMARY OF DISTRESSES AND MATERIAL PROPERTIES STUDY

The distresses which occur with highest frequency and greatest consequence have been noted and ranked in order of importance for each pavement type. The material properties that affect each of the distresses have been noted and ranked in order of importance. In addition, a table of the factors that affect these material properties have been prepared and are included in Appendix A.

In order to determine optimal values of each of these material properties, the effect of change in these properties on the structure must be evaluated. However, it should be noted that some of the important distresses can not be evaluated using structural models and will be investigated in a series of special studies. Chapter 4 includes a detailed discussion of models that predict distress as a function of material properties, load, and environmental factors.

CHAPTER 4. PAVEMENT RESPONSE AND DISTRESS MODELS

The objectives of the effort reported in this chapter were:

1. To identify the available pavement structure models for predicting pavement responses needed to predict distress.
2. To identify the distress models capable of predicting those distresses selected in the previous chapter for further study in this project.
3. To perform a detailed study of the available models to ascertain their capabilities, reliability, feasibility in terms of data availability and/or difficulty in servicing input requirements, the nature of the output predictions, and comprehensiveness in terms of material properties considered.
4. To compare the various models in terms of the characteristics described in Item 3 above to select the best models for use in predicting each response and each distress of interest.

APPROACH FOR MODELS STUDIES AND SELECTIONS

The basic approach used to identify the available models was to first list all those known and then to review the literature. These models were studied individually and their apparent capabilities, limitations and other pertinent information noted in detail. When available from previous studies, the results of sensitivity analyses in the literature were noted for use in determining the effects of material properties on the models. Limited sensitivity analyses were conducted for those models for which previous sensitivity analyses were unavailable. The results of these sensitivity analyses will be discussed in Chapter 5.

The review of available models was conducted separately by type of pavement. While most of the models considered predict pavement responses, those that incorporated the prediction of distress were much fewer in number. For some of the distresses identified such as "D" cracking and joint faulting, mathematical models were not found and separate studies will be made to indicate how the distress may be minimized. However, mathematical models were available for most of the significant distresses.

These pavement structure and distress models are discussed below for each of the five types of pavements to be considered in this study. These five types of pavements include flexible, composite, 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; their characteristics, capabilities, and limitations described; and the model selections discussed.

PAVEMENT STRUCTURE MODELS UTILIZING ELASTIC THEORY

The three general types of computer programs or pavement structure models available are discussed in Chapter 1. These include models based on elastic layer theory, plate theory (Westergaard, discrete element SLAB, and two-dimensional finite-element models) and three-dimensional finite element theory. Excellent discussion and comparisons of these theories are presented in Reference 26[1]. Finite element theory in three dimensions is very expensive to use and is generally only used for very special problems. The version produced by Huang and Wang (Reference 27[2]) has been specialized into two dimensions on Winkler Springs and is very similar in final matrix formulation to discrete element SLAB theory. The Huang and Wang finite element program and the discrete element slab program give 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 due to its inherent assumption 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.

As may be seen, these theories have their capabilities, strong points and limitations. Neither the finite element program of Huang and Wang or the discrete element slab theory developed by Hudson and others satisfactorily model the supporting soil. Vesic and Saxena (Reference 28[3]) 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 and the discrete element models also assume that vertical deformations do not occur in the rigid slab and thus the predicted bending stresses at the top and bottom of the slab are identical, which they are not in reality. 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.

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[1] Crawford, J.E. and M.G. Katrona, "State-of-the-Art for Prediction of Pavement Response," Report No. FAA-RD-75-183, U.S. Army Engineer Waterways Experiment Station, September 1975.

[2] Huang, Y.H. and S.T. Wang, "Finite-Element Analysis of Concrete Slabs and its Implications for Rigid Pavement Design," Highway Research Record 466, 1973.

[3] Vesic, A.S. and Saxena, S.K., "Analysis of Structural Behavior of AASHO Road Test Rigid Pavements," NCHRP Report 97, 1970.

One of the attributes of elastic layer theory is the fact that all the layers in the pavement structure can be characterized individually and their separate effects on pavement responses studied. Stresses and strains predicted by elastic layer theory are spread with depth in a more realistic fashion than for the "plate models" discussed above, and it is relatively more economical to operate. The primary limitations of elastic layer theory are inability to define any horizontal boundaries and inability 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 those distress models using it as a pavement structure model offer very useful capabilities for comprehensive study of the various layer materials in this project.

Since elastic layer theory clearly represents one of the models to be used for this project, it was necessary to compare the various computer codes that are available and to select those most suited to project needs. A study by Schnitter (Reference 29[1]) was reviewed for these comparisons. In his study, Schnitter operated computer codes for ELSYM5, LAYER5, LAYER15, LAYIT and BISAR for several typical problems over a range of conditions. All of the programs gave essentially the same results, usually within one percent and with a maximum difference of only three percent. A tabulated comparison of the elastic layer programs appears in TABLE 4-1. The most economical program for use was LAYER5, but it is capable of handling only one wheel load at a time. As can be seen, only ELSYM5 and BISAR can handle multiple loads. ELSYM5 is more economical to operate than BISAR and five layers are generally sufficient for the problems anticipated in this project. BISAR, however, can consider both variable friction at its interfaces and a horizontal load applied at the surface, so it may have utility for special studies. Based on the study of elastic layered programs, ELSYM5 was judged to be the best overall elastic layer computer code for use on this project.

ELSYM5 serves as the pavement structure model for the rutting prediction system by Monismith, et al. (Reference 30[2]) and for RPOD (Reference 9). PDMAP (Reference 8) uses an elastic layer program called NLAYER, which as the name implies may consider any reasonable number of layers desired. VESYS A (Reference 7) uses an elastic layer code limited to three-layers

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[1] Schnitter, O., "Comparison of Stresses, Strains, and Deflections Calculated with Various Layer Programs," Pavement Design Course Term Project, University of Texas at Austin, Spring 1977.

[2] Monismith, C.L., K. In Kabi, C.R. Freena, and D.E. McLean, "A Subsystem to Predict Rutting in Asphalt Concrete Pavement Structures," Proceedings, Fourth International Conference on Structural Design of Asphalt Pavements, Volume I, August 1977.

TABLE 4-1. COMPARISON LAYERED PROGRAMS (REFERENCE 29)

	ELSYM5	LAYER5	LAYER15	LAYIT	BISAR
1. PROGRAM DIMENSIONS:					
a. Material Properties	Elastic	Elastic	Elastic	Elastic	Elastic
b. Boundary Conditions:					
(1) At Interfaces	Full friction. Allows slip if rigid base	Full friction	Full friction	Full friction	Full friction or varying amount of slip
(2) At bottom layer	Infinite or finite depth	Infinite depth	Infinite depth	Infinite depth	Infinite depth
2. MAJOR FEATURES:					
a. Number of layers	5	5	15	5	10
b. Number of loads	10	1	1	1	10
c. Possibility of applying horizontal loads	No	No	No	No	Yes
3. INPUT REQUIREMENTS:					
a. Material Properties	Modulus (E) Poisson's Ratio (ν)	Modulus (E) Poisson's Ratio (ν)	Modulus (E) Poisson's Ratio (ν)	Initially Assumed Modulus (E) Poisson's Ratio (ν), Modulus vs summation of principal stresses	Modulus (E) Poisson's Ratio (ν)

TABLE 4-1 COMPARISON LAYERED PROGRAMS (continued)

	ELSYM5	LAYER5	LAYER15	LAYIT	BISAR
b. Dimensions	Layer Thicknesses (Bottom layer semi infinite or finite)	Layer Thicknesses (Bottom layer semi infinite)	Layer Thicknesses (Bottom layer semi infinite)	Layer Thicknesses (Bottom layer semi infinite)	Layer Thicknesses (Bottom layer semi infinite)
c. Load	Any two of Load, area or tire pressure	Load Tire pressure	Load Tire pressure	Load Tire pressure	Load or stress and radius of loaded area
d. Coefficient of slippage	No slip except with rigid base	No slip	No slip	No slip	Coefficient of slippage to be specified
e. Unit weight of materials	Weightless	Weightless	Weightless	Required	Weightless
4. MODEL OUTPUT					
a. Displacement of top layer	Yes	Yes	Yes	Yes	Yes
b. Strain at surface away from load	Yes	Yes	Yes	Yes	Yes
c. Strain at interfaces	Yes	Yes	Yes	Yes	Yes
d. Strain at top of subgrade	Indirectly	No	No	No	Yes
e. Stress throughout base	Yes	Yes	Yes	Yes	Yes

TABLE 4-1 COMPARISON OF LAYERED PROGRAMS (continued)

	ELSYM5	LAYER5	LAYER15	LAYIT	BISAR
5. COMPUTER COST (Compared to LAYER 15 - %)	125-140	100	*	110-130	380-460
6. EASE OF INPUT	Easy	Easy	Easy	Easy	Time Consuming Difficult Format
7. EASE OF INTERPRETING OUTPUT	Easy	Easy	Easy	Easy	Difficult to read

*With LAYER15 each layer was divided into two, each with half the original thickness - no cost comparison could be made.

derived from an early CHEVRON program. A version of the VESYS program has been modified for the FHWA by Dr. James Lai to include any reasonable number of layers, and this new version is called VESYS G. VESYS G also allows fatigue cracking in layers other than the surface layer (such as asphalt concrete or cement-treated base). The FHWA has recently combined the desirable capabilities of VESYS G and VESYS A. It is possible that this new computer program may be checked out and available for Tasks B and C.

MODELS FOR FLEXIBLE PAVEMENTS

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

1. Rutting Distress:
    a. The Shell method (Reference 31[1]).
    b. VESYS A (Reference 7).
    c. PDMAP (Reference 8).
    d. Rutting subsystem-Monismith et al (Reference 30).
    e. DEVPAV (Reference 32[2]).
    f. OPAC (Reference 33[3]) and WATMODE (Reference 34[4]).

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[1] Claessen, A.I.M., J.M. Edwards, P. Sommer and P. Vg'e, "Asphalt Pavement Design - The Shell Method," Proceedings Fourth International Conference on Structural Design of Asphalt Pavements, Volume I, August 1977.

[2] Kirwan, R.W., M.N. Snaith and T.E. Glynn, "A Computer-Based Subsystem for the Prediction of Pavement Deformation," Proceedings, Fourth International Conference on Structural Design of Asphalt Pavements, Volume I, August 1977.

[3] Meyer, F.R.P. and R.C.G. Haas, "A Working Design Subsystem for Pavement Deformation in Asphalt Pavements," Proceedings, Fourth International Conference on Structural Design of Asphalt Pavements Volume I, August 1977.

[4] Meyer, F.R.P., A Cheetham and R.C.G. Haas, "A Coordinated Method for Structural Distress Predictions in Asphalt Pavements," a paper presented at the Meeting of the Associates of Asphalt Paving Technologists, Lake Buena Vista, Florida, February 1978.

   g. The Huschek Rutting prediction method (Reference 35[1]).

2. Fracture Cracking Distress:
   a. The Shell Method.
   b. VESYS A.
   c. PDMAP.
   d. OPAC and WATMODE.
3. Low-Temperature Cracking:
   a. VESYS A.
   b. PDMAP.
   c. Shahin-McCullough Model (References 11 and 12).
   d. OPAC and WATMODE.
4. Reduced Skid Resistance:
   a. Steitle-McCullough Studies (Reference 36[2]).
   b. Rauhut-McCullough Studies (Reference 37[3]).

None of the models listed above consider all four distresses 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.

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[1] Huschek, S., "Evaluation of Rutting Due to Viscous Flow in Asphalt Pavements," Proceedings, Fourth International Conference on Structural Design of Asphalt Pavements, Volume I, August 1977.

[2] Steitle, D.C. and B.F. McCullough, "Skid Resistance Considerations in the Flexible Pavement Design System," Research Report 123-9, published jointly by Texas Highway Department; Texas Transportation Institute; Texas A & M University; and Center for Highway Research, The University of Texas at Austin, April 1972.

[3] Rauhut, J.B., and B.F. McCullough, "Development of Guideway Skid Control Requirements for Dual Mode Vehicle Systems," submitted to ABAM Engineers by ARE Inc, January 1974.

The Shell Method

The Shell Method is the result of a substantial amount of study by Shell researchers and therefore includes a wealth of information. It was, however, specifically developed as a design procedure to be exercised by hand calculations, so many of the complexities have been simplified. The structural model used in developing the procedure was BISAR, but the results of the BISAR calculations are simplistically characterized by a "Z-Factor" or implicitly considered. The Z-Factor is calculated using the radius of loaded contact area, asphalt layer thickness, dynamic modulus of the asphalt layer and dynamic modulus of the subgrade as independent variables. The contact stress between the tire and the pavement is multiplied by the Z-Factor to arrive at a prediction of the "average stress in the pavement under the moving wheel". The Z-Factor approximates 0.5 for most practical cases.

The Shell procedure for permanent deformation is discussed below in detail as the procedure produces predicted rut depths and is therefore a serious candidate for studying rutting distress. Since the charts provided for design to minimize fatigue cracking are generally in terms of limiting strains, the Shell procedure is not a strong candidate for studying fatigue cracking distress and is only discussed briefly.

Rutting Distress. All rutting is assumed to occur in the asphalt concrete layer with all strains in base, subbase and subgrade assumed to be elastic. Rutting is calculated as the reduction in layer thickness, ΔH, as follows:

$$\Delta H = C_M H_o \frac{\sigma_{av}}{S_{mix}} \text{ in mm} \qquad (1)$$

Where:

C_M = correction factor for the so-called "dynamic effect", which takes account of differences between creep and rutting behavior. This factor is dependent on the type of mix and must be fixed empirically (Reference 38).

H_o = design thickness of the asphalt layer, mm.

σ_{av} = the average stress in the pavement under the moving wheel

$$\sigma_{av} = Z \cdot \sigma_o \qquad N/m^2 \qquad (2)$$

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[1] Van de Loo, P.J., "Creep Testing, A Simple Tool to Judge Asphalt Mix Stability," Proceedings, The Association of Asphalt Paving Technologists, Volume 43, 1974. (Shell Reprint)

σ_o = contact stress between tire and pavement

S_{mix} = the value of the stiffness of the mix in N/m^2 as related to a particular bitumen stiffness as described later.

H_o and σ_{av} may be expected to be fairly constant for particular pavement sections and axle loads, so S_{mix} is the primary variable in Equation (1). C_M is also a function of the type of mix and usually has a value between 1 and 2. This method considers rutting to be primarily a function of the stiffness of the mix.

The characterization of the mixture stiffness is based on a relationship between the creep stiffness of the mixture and the creep stiffness of the bitumen. Shell researchers (References 38, 39[1], 40[2], 41[3], 42[4], 43[5], and 44[6]) have developed this characterization and have used it extensively in their analytical procedures. FIGURE 4-1 shows the relationship between mixture stiffness S_{mix} and asphalt stiffess S_{bit} based on test results for a range of sheet asphalt mixtures and indicates the variation that may result from mix variables. FIGURE 4-2 shows the relationship between S_{mix} and S_{bit} for one asphalt concrete mix and indicates how sensitive the results are to specimen preparation and compaction. Note that the important effects of temperature are embodied in the bitumen stiffness, S_{bit}.

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[1] Hills, J.R., "The Creeep of Asphalt Mixes," Journal of the Institute of Petroleum, November 1973 (Shell Reprint).

[2] Hills, J.F., Brien, D. and Van de Loo, P.J., "The Correlation of Rutting and Creep Tests on Asphalt Mixes," Journal of Petroleum Paper IP74-001, January 1974. (Shell Reprint)

[3] Uge, P. and Van de Loo, P.J., "Permanent Deformation of Asphalt Mixes," Proceedings, Canadian Technical Asphalt Association, Volume 19, 1974.

[4] Heukelom, W., "An Improved Method of Characterizing Asphaltic Bitumens with the Aid of Their Mechanical Properties," Proceedings of the Association of Asphalt Paving Technologists, Volume 42, 1973. (Shell Reprint)

[5] Edwards, J.M., "Creep Tests on Asphalt Mixes," publisher and date unknown.

[6] Edwards, J.M., "Asphalt Pavements in High Temperature Regions - Structural and Mix Design," paper prepared for the Second Conference on Asphalt Pavements for Southern Africa, 1974, Durbon. (Shell Reprint)

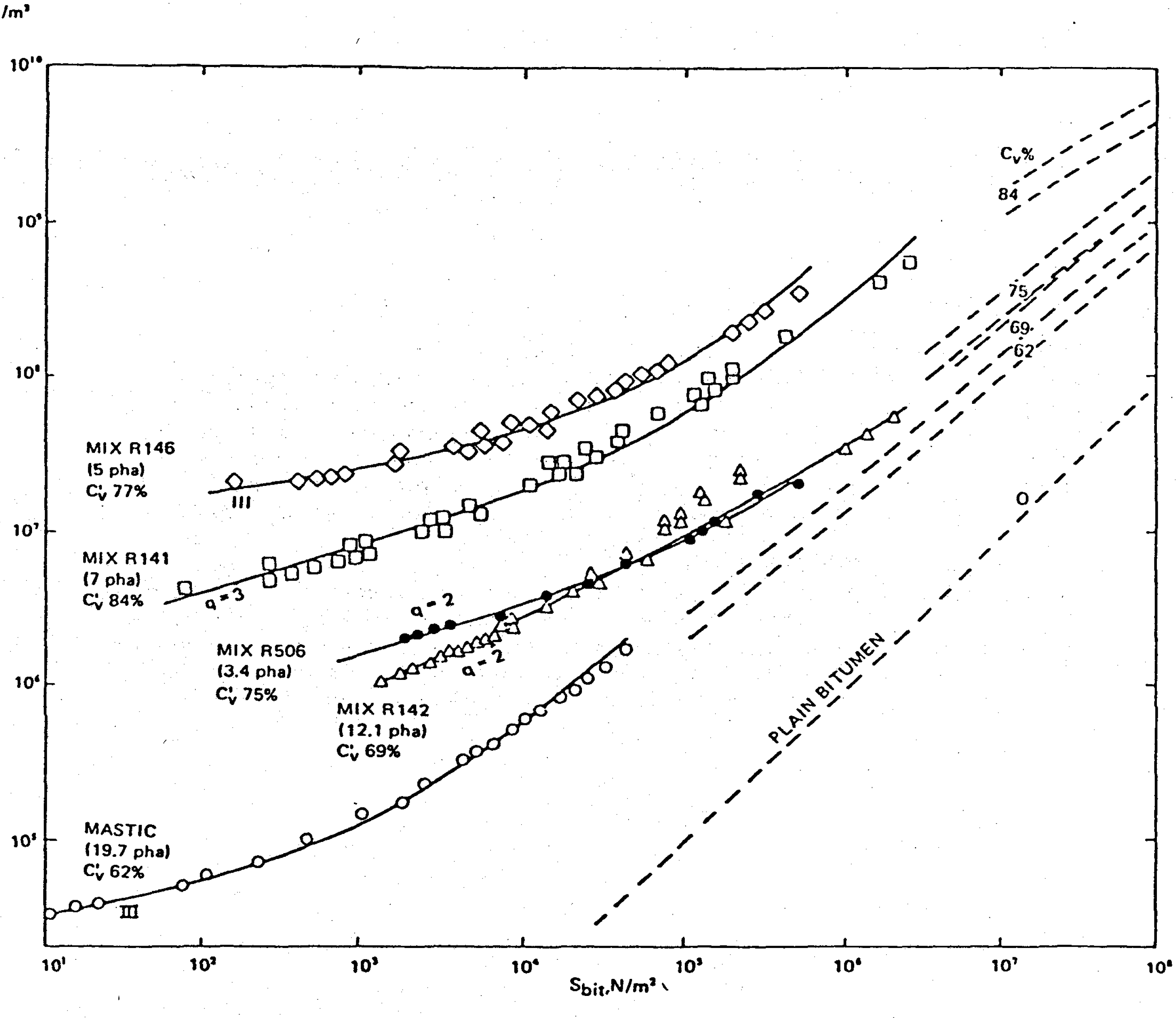

FIGURE 4-1. CREEP BEHAVIOR OF A WIDE RANGE OF MIXES COMPARED WITH THE CORRESPONDING 'C_v' CURVES FOR HIGHER VALUES OF S_{bit}. (REFERENCE 40)

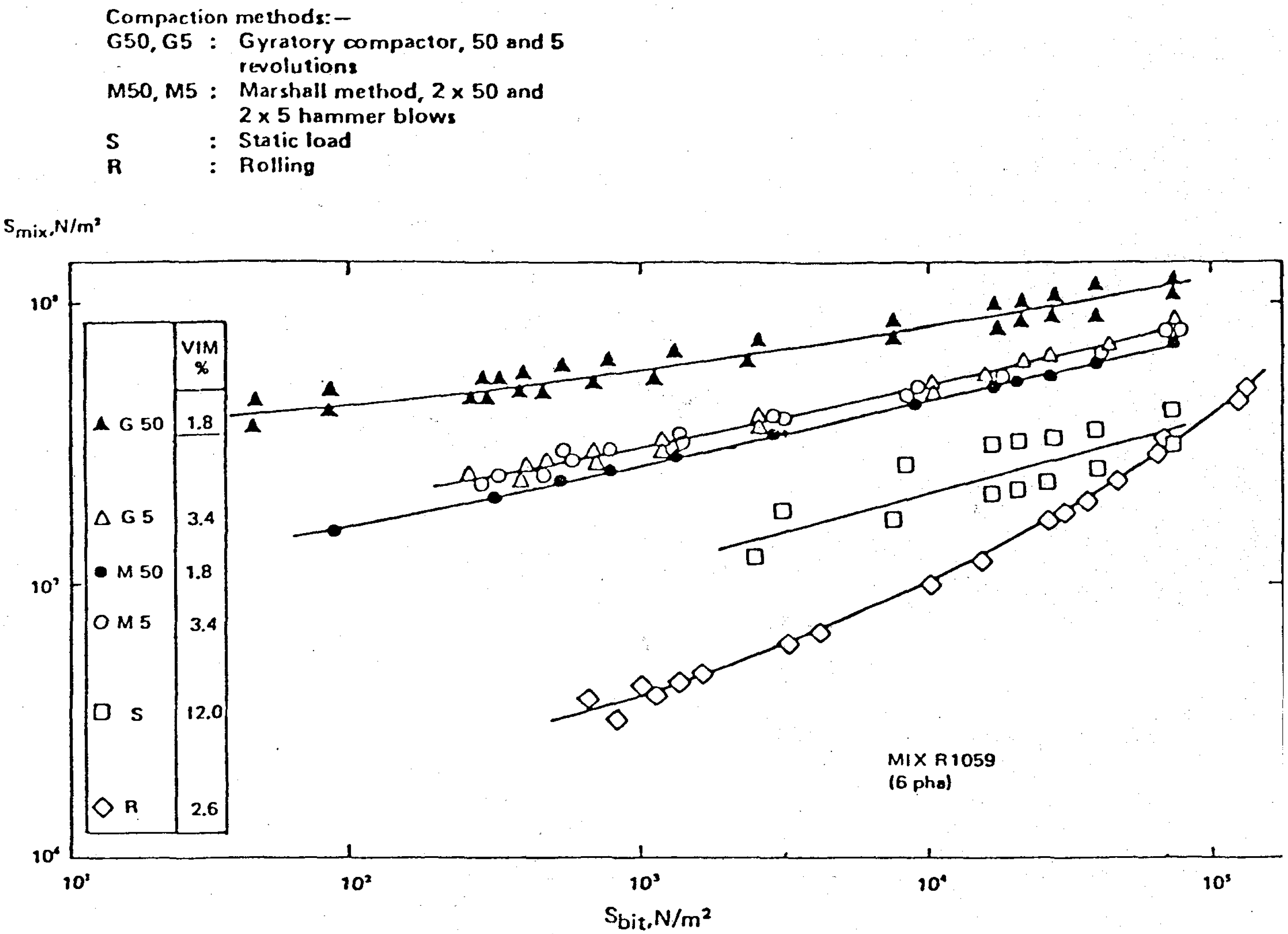

FIGURE 4-2. THE EFFECTS OF VARIOUS METHODS OF COMPACTION ON THE CREEP BEHAVIOR OF AN ASPHALTIC CONRETE MIX. (REFERENCE 40)

As mix stiffness is an important parameter, it is important to consider the parameters that affect it. The results of creep testing are mixture stiffness as a function of loading time and temperature. If either the ring-and-ball softening point or the temperature for an 800 mm penetration, t_{800}, and the standard penetration are known, the penetration index for the bitumen may be determined from several available charts, including one developed by Pfieffer and Van Doormaal (Reference 45[1]). Once the penetration index is established, Van der Poel's nomograph (Reference 46[2]) may be used to arrive at a stiffness modulus for the bitumen for any temperature and load time combination. Bitumen stiffness and mix stiffness are then plotted on log paper as shown in FIGURES 4-1 and 4-2 for the same loading times and temperatures. This material characterization is essentially independent of stress, but is dependent on temperature through the bitumen stiffness.

The value of mix stiffness used in Equation (1) is taken from the log-log plot of mix stiffness vs. bitumen stiffness at a specific point of bitumen stiffness called $S_{bit,visc.}$, which represents the viscous or non-elastic component of the bitumen stiffness. This value for a specific temperature is calculated from the following formula:

$$S_{bit,visc.} = \frac{3}{\frac{Wt}{\eta}} \quad N/m^2 \qquad (3)$$

Where: W = Number of wheel passes

t = Time for one wheel pass (Shell uses 0.02 sec)

η = Bitumen viscosity, $N \cdot sec/m^2$

If t is taken at the recommended value of .02 seconds, then Equation (3) becomes:

$$S_{bit,visc.} = \frac{150\eta}{W} \quad N/m^2 \qquad (4)$$

As can be seen, Equation (4) implies that the viscous component of the bitumen stiffness is a linear function of total loading time and is taken to be the average wheel load duration multiplied by the number of wheel passes. This is difficult to accept.

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[1] Pfeiffer, J. and P.M. Van Doormaal, "The Rheological Properties of Asphaltic Bitumen," Journal, Institution of Petroleum Technologists, No. 22, 1963.

[2] Van der Poel, C., "A General System Describing the Viscoelastic Properties of Bitumens and Its Relation to Routine Test Data," Journal of Applied Chemistry, Volume 4, Part 5, May 1954.

Once the value of $S_{bit,visc.}$ is established, that value is used for the bitumen stiffness in the logarithmic relationship between mixture stiffness to obtain the mix stiffness for use in Equation (1).

Reviewing Equation (1), it can be seen that the Shell Method considers rut depth to be a function of the thickness of the bituminous layer; the average pavement stress under the moving wheel; and a value of the mixture stiffness that is dependent on pavement temperature, asphalt cement viscosity and penetration index, other mix properties, the number of passes of an equivalent standard wheel, and the load duration of the moving wheel at a point. The average stress in the pavement is itself a function of the tire pressure, the radius of the loaded area, the bituminous layer thickness, and the ratio of the bituminous layer stiffness to subgrade stiffness. These variables are essentially the same ones found to be important during the sensitivity analysis for computer program VESYS IIM (Reference 6). However, the VESYS system uses permanent deformation parameters called ALPHA (1) and GNU (1), which are derived from long-term measurements of permanent strains in compression tests to characterize permanent deformation properties of the mix with no assumptions to limit changes in permanent strain with number of wheel loads.

To further evaluate the Shell rut prediction procedure, a fairly typical asphalt concrete mix identified as Mix No. R1059 in Reference 40 (FIGURE 4-2) was used with the following levels of parameters to arrive at predicted rut depths for 1 million applications of an 18-kip (80 kN) axle load:

1. Average Pavement Temperatures:
    a. Winter - 40°F (4.4°C)
    b. Summer - 90°F (32.2°C)
2. Tire Pressures - 70 and 90 psi (482 and 621 kPa)
3. Surface Layer Thickness - 3, 6 and 10 inches (76, 152, and 254 mm)
4. Ratios of Surface Layer Stiffness to Subgrade Stiffness:
    a. Winter - 100 or greater
    b. Summer - 5

The results of this small factorial study appear in FIGURE 4-3. As can be seen, increasing tire pressure increases rut depth predictions, varying from a minor amount in thin surface layers to an appreciable amount in the thicker surface layers. For the same amount of traffic and same pavement thickness, the predicted rut depths for summer were 3 to 5 times those predicted for winter. The magnitudes predicted do not appear to be unreasonable, but cannot be corroborated. They may be modified

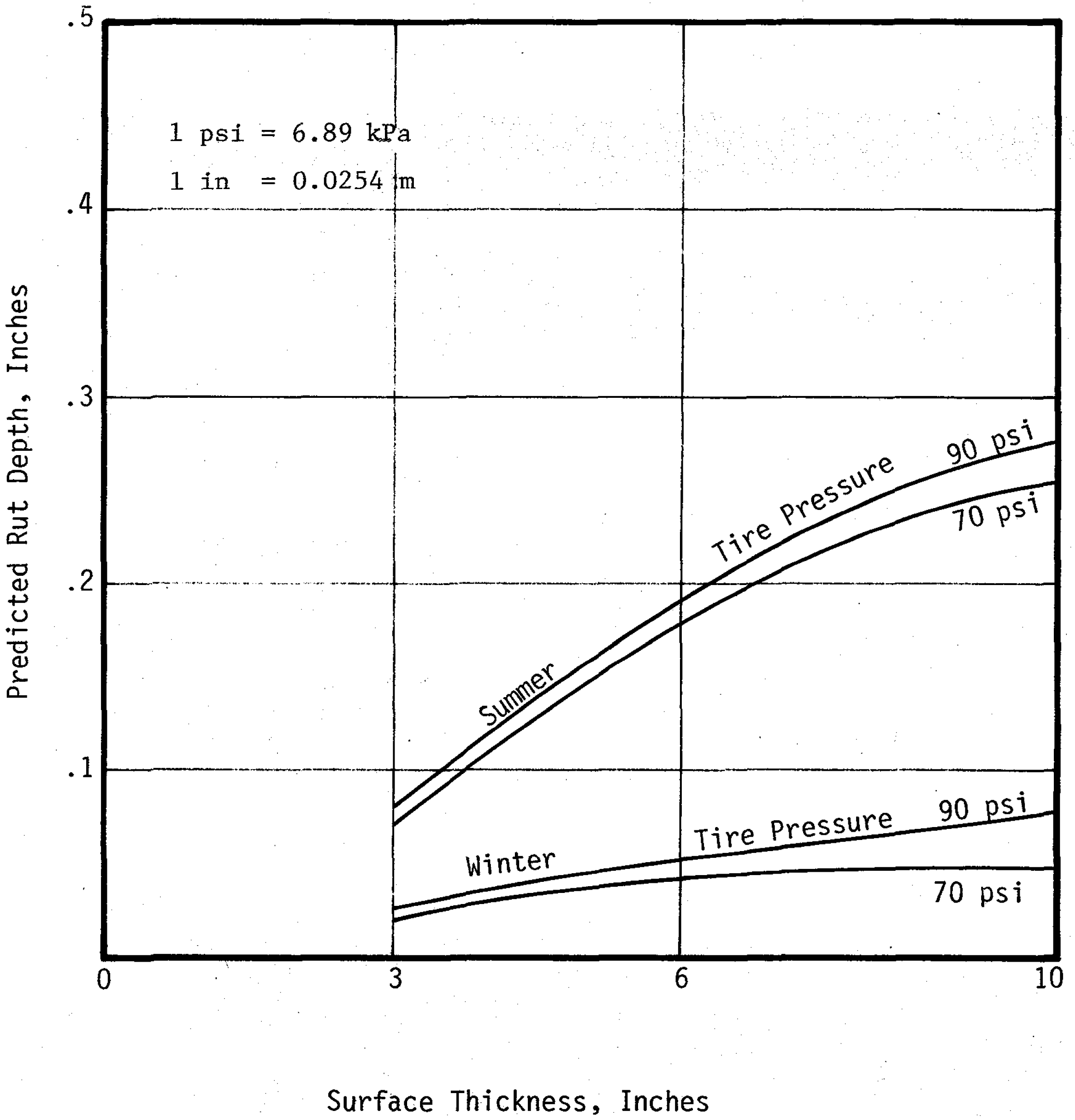

FIGURE 4-3. PLOTS OF PREDICTED RUT DEPTH VERSUS SURFACE LAYER THICKNESS FOR ONE MILLION 18-KIP (80 kN) AXLE LOADS FOR TWO LEVELS OF PAVEMENT TEMPERATURE AND TWO LEVELS OF TIRE PRESSURE.

greatly by choice of the value C_M in Equation (1), which is not well-defined.

In order to determine the effects of increased traffic $S_{bit,visc.}$ and S_{mix} were obtained for five times as many standard axles ($5x10^6$) and the predicted rut depths increased about 65 percent for the additional 400 percent increase in traffic. These results appear to be reasonable and are generally consistent with permanent deformation test data from both creep compliance and long-term repetitive load tests.

Shell research indicates that rutting occurs in the surface layer alone when the bituminous surface layer thickness exceeds about 5 inches (0.129 m), while part of the rutting occurs in underlying layers for thicknesses less than 5 inches (0.129 m) (Reference 41). As the thickness exceeds 5 inches (0.127 m), results from the Shell circular test track indicate that rut depth is no longer a function of surface layer thickness (Reference 45). 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 surface layer thickness. This apparent shortcoming in the model, the fact that no contributions to rutting are included in the model for base and subgrade, and lack of direct consideration of stiffnesses for and stress states in all layers indicates that the Shell Rutting Model as simplified for hand computations is not as theoretically comprehensive as some of the other models to be discussed subsequently and would be more laborious to use. However, it may prove useful for factorials of limited size to study specific parameters with pavement thickness held constant.

Fatigue Cracking Distress. As for rutting, Shell researchers have also been active for years in developing better characterizations for fatigue cracking of asphalt concrete materials (Reference 47[1], 48[2]). The work reported in Reference 47 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 provided excellent insight into the stages of fatigue cracking and crack propagation in a supported slab as opposed to a non-supported beam. It and the work reported in Reference 48 also provided valuable data on the energy approach to prediction of fatigue life utilized in the Shell Method. Shell's approach was to provide a design procedure for limiting radial strain in

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[1] Van Dijk, W., "Practical Fatigue Characterization of Bituminous Mixes," paper presented at the Annual Meeting of the Association of Asphalt Paving Technologists, Phoenix, Arizona, February 1975.

[2] Van Dijk, W. and W. Visser, "The Energy Approach to Fatigue for Pavement Design," paper presented at the Annual Meeting of the Association of Asphalt Paving Technologists, San Antonio, Texas, February 1977.

the bottom of the asphalt concrete layer r to an acceptable level using hand computations. While fatigue characterizations of materials using energy approach are arrived at differently from those obtained from standard laboratory testing, linear summation of cycle ratios (Minor's Hypothesis) is used as in other models to estimate the damage or what percent of the fatigue life has been consumed at any point in time. Consequently, there appears to be no advantage to utilizing the analytical procedures in the Shell Method for predicting fatigue life, but References 31, 47, and 48 are rich in information that may be used to arrive at the fatigue characterizations of the materials.

VESYS A

VESYS A is an improved version of Program VESYS IIM, a distress model that has been discussed in great detail in the literature (References 6, 49[1]). The capabilities added to VESYS IIM to produce VESYS A were:

1. Seasonal modification of material properties,
2. Incremental breakdown of the axle load distribution by tire radius and corresponding tire pressure, and
3. Addition of a low-temperature cracking model.

The details of these revisions and the improvements in the idealization of flexible pavements are discussed in Reference 7.

VESYS A is a sophisticated computer code that accepts some twenty-three control variables and fourty-four independent variables describing 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. Using this input, it then predicts fatigue cracking, rut depth, slope variance, present serviceability index and expected life as functions of time correlated to truck traffic.

Fatigue cracking distress is predicted using the classical fatigue equation and linear summation of cycle ratios (Minor's Hypothesis) to predict the damage at any point in time due to an established axle load distribution and traffic rate. The primary difference between the VESYS formulations and those in common use is that the VESYS equations have been expanded using probability theory so that variability of the input parameters

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[1] Kenis, W.J., "Predicted Design Procedures - A Design Method for Flexible Pavements Using the VESYS Structural Subsystem," Proceedings, Fourth International Conference on Structural Design of Asphalt Pavements, Volume I, August 1977.

is taken into consideration in the predictions. This is a definite improvement because cracking generally occurs for conditions varying from the mean rather than for the mean condition of the pavement.

Rutting is calculated as the difference in predicted total and elastic displacements at the surface. This is accomplished by separate sets of solutions from the elastic layer stuctural model, one with the normal elastic moduli and the other with the moduli modified by permanent deformation characterizations to delete the permanent strains. This procedure is very simular in effect to that proposed by Monismith et al (Reference 30). In VESYS A, the permanent strains in the layers are accumulated through separate solutions with the layer stiffnesses modified, while 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 (Reference 14). While this model does a relatively acceptable job of predicting low temperature cracking, it is based on multiple regressions for pavements in Canada alone and uses the five following parameters:

1. Age of pavement,
2. Thickness of the bituminous layers,
3. Subgrade soil type in a numerical code,
4. Winter design temperature, and
5. Stiffness of original asphalt cement.

Other models such as program COLD and the Shahin-McCullough models mentioned above include more detailed consideration of material properties.

In summary, VESYS A is perhaps the most complete flexible pavement distress model in existence today and considers a broad range of material properties in its distress subsystems. Some of the input variables, such as those for the permanent deformation characterizations of materials, are relatively new to the engineering profession; however, these variables are not new to the project staff as much of the available data for these parameters were developed by them in two previous contracts for the FHWA (References 6, 7).

PDMAP

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 Program COLD, but it was an integral part of NCHRP Project 1-10B research and was presented as a part of the PDMAP system (Reference 8). Both the fatigue cracking distress and the rutting models in PDMAP are based on multiple regressions on data from the AASHO Road Test, but depend on an elastic layer structural model to predict needed pavement responses. Complete descriptions of Program PDMAP, Program COLD, and their development are included in Reference 8.

The rutting model for PDMAP predicts seasonal rate of rutting for permanent deformation per equivalent load application as a function of the following variables:

1. The elastic deflection at the surface of the pavement under an 18-kip (80 kN) axle load,
2. The vertical compressive stress of the asphalt concrete under an 18-kip (80 kN) axle load, and
3. The total equivalent number of 18-kip (80 kN) single axle loads up to and including the season for which rate of rutting is to be calculated.

The model considers seasonal changes in the elastic constants used for the various layers and takes these into consideration as it accumulates rutting with time. The rutting predictions are displayed at different confidence levels on the basis of the stochastic characteristics of the elastic materials characterizations.

The fatigue distress model is very similar to that used in most fatigue predictions, except that an additional term has been added to take into account the effects of asphalt concrete stiffness. The resulting equation is as follows:

$$N = K_1 \left(\frac{1}{\varepsilon} \right)^{K_2} \left(\frac{1}{|E^*|} \right)^{K_3} \qquad (5)$$

Where:

N = Number of Equivalent 18-kip single axle loads to first crack,

K_1, K_2 and K_3 are fitting coefficients,

ε = Maximum tensile strain in lower fibers of asphalt concrete, and

$|E^*|$ = Complex modulus of asphalt concrete.

The approach taken to arrive at the fitting coefficients for Equation (5) is aimed at overcoming the known limitations of laboratory beam testing and for correlating the results of such testing with field experience. The approach taken was to conduct a multiple regression analysis on laboratory beam test data developed by Monismith et al (Reference 50[1]) and other test data developed during the NCHRP 1-10B project. The resulting coefficients for K_1, K_2, and K_3 were 14.82, 3.291, and 0.854, respectively. The resulting equation grossly underpredicts fatigue life (as does almost all data from laboratory fatigue tests data). "Shift factors" were developed on the basis of comparisons to AASHO Road Test results to extrapolate those data to field conditions. The results of this study indicated that it took 13 to 18 times the number of strain replications predicted by the laboratory fatigue tests to actually propogate cracks to the surface of a real pavement. These results are fairly consistent with those resulting from wheel tracking tests conducted by Shell Laboratories (Reference 47).

As a relationship between dynamic modulus and temperature was known for the asphalt concrete used in the AASHO Road Test (Reference 51[2]), it was possible to compare the PDMAP fatigue cracking relationships on the basis of varying stiffness to those developed by Rauhut et al (Reference 6) on the basis of temperature. It was found that the variation in predicted fatigue life with stiffness or temperature was much smaller than the variations found by other researchers for seven different materials. Although the variation in predicted fatigue life with material stiffness seems to be much more limited than that found by other researchers, the fatigue relationship at 70°F (21.1°C.) is quite close to that one selected by Rauhut et al (Reference 6) as a mean fatigue damage relationship for the sensitivity analysis on VESYS IIM.

The structural model itself has several useful features as listed below:

1. The stiffnesses for all layers are input as variables. The stiffness for the asphalt concrete is a function of temperature, while the stiffnesses of base, subbase, and subgrade layers are functions of either lateral stress or sum of principal stresses at the selection of the user. This allows iterative solutions to compatibility between stiffness and stress in the soil layers.

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[1] Monismith, C.L., J.A. Epps, D.A. Kasiancheck and D.B. McLean, "Asphalt Mixture Behavior in Repeated Flexure," Institute of Transportation and Traffic Engineering Report No. TE-70-5, University of California, Berkeley, 1972.

[2] ARE Inc, "Asphalt Concrete Overlays of Flexible Pavements, Vol. 1, Development of New Design Criteria," Report No. FHWA-RD-75-76, June 1975.

2. The temperatures of the asphalt layers are calculated from environmental data based on the Barber method (Reference 52[1]).

3. Coefficients of variation for the stiffnesses for the various layers are furnished and used to arrive at the probabilistic response predictions. PDMAP like VESYS A produces families of predicted responses for each "season" of the year and uses these families of solutions in a systematic manner to predict distresses with time.

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

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. The consideration of the permanent deformation characteristics of materials in this regression model are 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 rate of rutting prediction model are based entirely on AASHO Road Test materials and conditions and, according to the authors of Reference 8, require reestablishment for use under other conditions.

The fatigue cracking distress model as used in the program also requires establishment of three regression coefficients. However, similar fatigue damage relationships have to be established regardless of the model considered if realistic results are to be expected. The basic nature of the fatigue models of each of the four fatigue cracking distress models under consideration are essentially the same.

Program COLD is a very sophisticated procedure and basically estimates the temperature in the pavement, the thermal stresses in the pavement, and when low-temperature cracking is likely to occur. Temperatures in the pavement are estimated at two-hour increments for each day included in the study. Strength-temperature relationships are provided as input to the program and are compared with the thermally induced stresses at 2-hour intervals. The program indicates the expected time at which low-temperature cracking will occur. The materials inputs for Program COLD include absorptivity, emissivity, and convection coefficient of the surface; thermal conductivity of the material (both unfrozen and frozen); heat capacity of the material (unfrozen and frozen); dry density and moisture

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[1] Barber, E.S., "Calculation of Maximum Pavement Temperatures from Weather Reports," Highway Research Board Bulletin 168, 1957.

content of the materials; thicknesses of the layers; and both stiffness modulus and strength values as functions of temperature.

Rutting Subsystem - Monismith et al

The design subsystem presented by Monismith et al (Reference 30) estimates the amount of permanent deformation or rutting resulting from repeated traffic loading. Relationships 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 resulting from the wheel loads are estimated through use of one of the ELSYM computer programs as a structural model. The stresses in turn permit estimation of permanent deformation in each layer of a specific pavement by:

1. Computing the permanent strain at a number of points within the layer, the number being sufficient to define the strain variations with depth, and

2. Estimating the deformation by summing the products of the average permanent strains and the corresponding differences in depths between the locations at which the strains were determined. Total rut depth is estimated by summing the contributions from each layer.

The general equation used for prediction of rut depth is

$$\delta_i^P(x, y) = \left\{ \sum_{i=1}^{n} \varepsilon_i^P \cdot \Delta Z_i \right\} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(6)$$

where:

$\delta_i^P(x, y)$ = rut depth in i^{th} position at point (x, y) in horizontal plane

ε_i^P = average permanent strain at depth $(z_i + \Delta z_i/2)$

Δz_i = difference in depth

The permanent strain at a point in the pavement structure in the vertical direction is calculated as

$$\varepsilon_z^P = R \left\{ \sigma_z - 1/2(\sigma_x + \sigma_y) \right\} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(7)$$

where:

$\sigma_z, \sigma_y, \sigma_x$ = stresses in vertical, radial, and tangential directions respectively.

$R = \frac{\bar{\varepsilon}^{p}}{\bar{\sigma}}$ = the ratio of total "effective" strain to the "equivalent stress"

While this seems straightforward, the value of R for use in Equation (7) is difficult to obtain. The constitutive relationships for R proposed in Reference 30 follow in Equations (8), (9), and (10):

a. Fine-grained soils:

$$R_s = \frac{\ell}{1 - m\bar{\sigma}} \left\{ \frac{N}{N_o} \right\}^{b} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Where:

N = number of stress repetitions

ℓ, m, b = experimentally determined coefficients

N_o = number of repetitions at which coefficients are determined

b. Untreated granular materials:

$$R_g = \frac{1/K\sigma_3^{n}}{1 - \frac{\bar{\sigma}\, R_f (1 - \sin\phi)}{2(C \cdot \cos\phi + \sigma_3 \sin\phi)}} \left\{ \frac{N}{N_o} \right\}^{b} \quad \ldots\ldots\ldots\ldots\ldots (9)$$

where:

R_f = ratio of compressive strength of material to asymptotic stress difference when stress vs. strain characteristics are plotted in hyperbolic form; $0.75 < R_f < 1$

c. Asphalt concrete:

$$\frac{\partial R_b}{\partial t} = \delta(T) \cdot N^{\alpha} \cdot \bar{\sigma}^{\,n-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

where:

$\delta(T)$ is a function of temperature, T (absolute), with one form as:

$$\delta(T) = Te^{-A/T}$$

α, n, A = experimentally determined coefficients

An ELSYM elastic layer program is used to arrive at the predictions of stress and the permanent deformations in each layer are then calculated separately, using the equations cited above for each month by hand and accumulating the results in tables. Examples of these results are shown in FIGURES 4-4 and 4-5. Monismith et al indicate that there is no basis for comparison to real data, but that the results shown indicate that the predictions are reasonable. They make no claim other than that the procedures may be used to check designs or existing pavements to ascertain if excessive rutting may be expected. If so, appropriate action could be taken in the pavement structure design to limit the rutting.

While this is a fairly straightforward method and indicates promise, there are two serious drawbacks to its use:

1. The characterizations given are quite complex and are dependent on a very detailed test program for specific materials used in order to arrive at the values of the many parameters included in the equations for R, and
2. The hand calculations would be extremely laborious and would have to be committed to computer before use 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 could be expected if the permanent deformation characterizations were based on the same test data.

DEVPAV

DEVPAV is a finite element program that has been under development by Kirwan et al (Reference 32) for some years in Ireland. In addition to the usual loading information, it uses permanent deformation characterizations for the various layers that were apparently developed by multiple regressions.

The equation developed for induced permanent strain ε_n for a particular Dublin boulder clay is as follows:

$$\varepsilon_n \; (\%) = \left[0.01042 \times \sqrt{\text{Log}_{10} N} \; \nabla \right]^{1.75} \quad \ldots\ldots\ldots\ldots\ldots\ldots(11)$$

This equation is in terms of both number of applications N and the applied stress ∇ in kPa. This is an interesting development because this equation is in the form of a constant times stress to a power in lieu of the constant times number of applications to a power used in the VESYS A System.

The following equation was also given for a dense bituminous macadam tested at the University of Nottingham:

$$\varepsilon_n \; (\%) = \left[0.0015 \; (0.68 + 0.0008 \; T^2 \; \text{Log}_{10} \; N)^{1.9} \; \nabla \right]^{1.75} \quad \ldots\ldots\ldots(12)$$

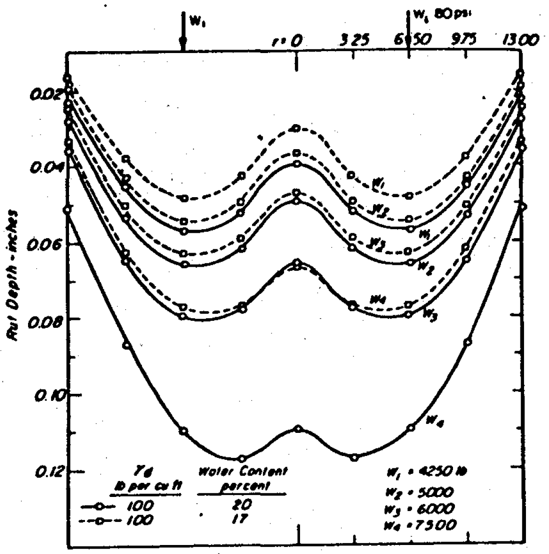

FIGURE 4-4. INFLUENCE OF LOAD MAGNITUDE AND SUBGRADE WATER CONTENT ON RUT DEPTH; SUBGRADE COMPACTION - 85 PERCENT OF MODIFIED AASHTO COMPACTIVE EFFORT. (REFERENCE 30)

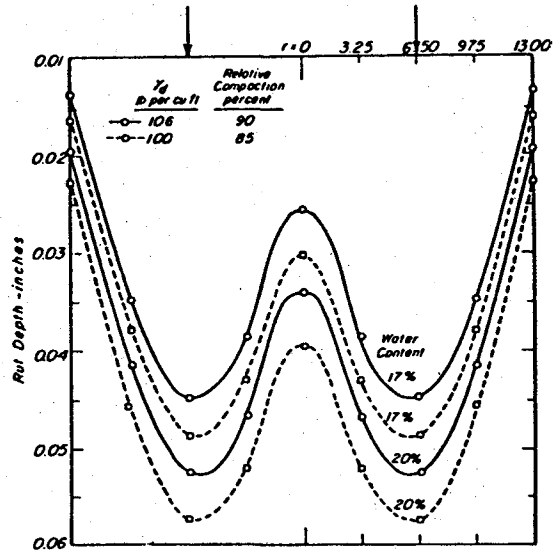

FIGURE 4-5. INFLUENCE OF WATER CONTENT AND DEGREE OF COMPACTION ON SUBGRADE RUTTING; WHEEL LOAD EQUALS 19,000 N. (REFERENCE 30)

Note that this equation contains three variables including temperature T, number of load cycles N, and applied stress V; and that the power of 1.75 is the same as for the clay. These characterizations, like those used by Monismith et al, appear to be more complete than those for VESYS A. However, applied stress and pavement temperature are usually considered from VESYS A through selection of the input values ALPHA(1) and GNU(1) for designated seasons, so the characterizations utilized by Monismith et al, Kirwan et al, and VESYS A may all consider the same independent variables.

Kirwan et al compared calculated and measured rut depths for the Shell Test Track (Reference 53[1]) and the Nottingham Test Track. The computed values of rut depth were reported in all cases to be substantially higher than those actually measured, but the shape of the plots of rut depth versus number of wheel passages were very similar and reasonably accurate characterizations might have been obtained if the proper calibration factors were known and applied.

While this is an interesting model, it does not seem to be a serious contender for use in this project because of the following:

1. It does not appear to do a better job of predicting rut depth than the readily available VESYS A,
2. The program is not readily available and is of the finite element type, which means that it would be very expensive to operate on a large factorial,
3. Materials characterizations for permanent deformations in this format are not available except for the two materials recorded in Reference 32, while much more general information is available for other forms of material characteristics. and
4. The finite element program has been revised so that the lateral strain of one column of elements is prevented from affecting the adjoining column. This is believed by Kirwan et al to account for part of the differences in predicted rut depths and measured rut depths.

The plots of permanent strain versus number of load cycles and stress levels allowed calculation of approximate values of ALPHA(1) and GNU(1), permanent deformation parameters used by VESYS A, for the dense

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[1] Hofstra, A. and A.J.G. Klomp, "Permanent Deformation of Flexible Pavements Under Simulated Road Traffic Conditions," Proceedings, Third International Conference on the Structural Design of Asphalt Pavements, Vol. I., London, 1972.

bituminous macadam at 20°C. Other tests by Brown and Pell (Reference 54[1]) for the same materials at a higher test temperature of 30°C gave larger values of ALPHA(1) than those by Kirwan et al, although the reverse should have resulted. Also, the values by Brown and Pell are more consistent with those from previously known testing of bituminous materials.

There is little question that utilization of the material test results of Kirwan et al would also have resulted in high rut predictions using VESYS A. It is quite possible or even probable that DEVPAV is a better model than Kirwan et al concluded and that the material characterizations were the primary source of error.

OPAC and WATMODE

OPAC is a pavement design system developed for the Province of Ontario, Canada by Meyer, Haas, and others (Reference 33). It has been further developed into a later form called WATMODE (Reference 34), which stands for Waterloo Model of Distress Estimation. Both of these models predict rutting, fatigue cracking, and low temperature cracking distresses.

These models are generally based on statistical analyses that relate laboratory tests on the Brampton and St. Anne's Road Tests in Ontario to measured roadway responses. As a result, they give very good correlations between predicted and measured distress for those road tests, but are not statistically applicable to pavement structures in the United States or other more temperate climates than that in Canada. Consequently, they will not be considered further for use on this project. However, there are some very useful developments described below that may be of value.

One of the very useful developments incorporated into WATMODE is a multiple regression equation developed from a factorial study over a range of independent variables using Shell's computer program BISAR. This equation has a multiple correlation coefficient R^2 of 0.996, so may be expected to provide a reasonably accurate prediction with minimal computational effort of the maximum tensile strain at the bottom an an 18-kip (80 kN) single axle load. Such an equation makes it possible to predict the maximum tensile strain at the bottom of the asphalt concrete layer with a simple programmable calculator and to subsequently predict fatigue distress by substitution of the calculated tensile strains into the established fatigue damage relationship.

Although not considered directly usable for this project the multiple regression model for predicting rut depth indicates that the only significant variables were:

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[1] Brown, S.F. and C.A. Bell, "The Validity of Design Procedures for the Permanent Deformation of Asphalt Pavements," Proceedings, Fourth International Conference on Structural Design of Asphalt Pavements, Volume I, August 1977.

1. The equivalent asphalt thickness,
2. Elastic modulus of the asphalt,
3. The resilient subgrade modulus, and
4. The number of 18-kip (80 kN) equivalent single-axle load applications.

This implies, at least for the road tests in Canada upon which the model is based, that the permanent deformation characterizations of the materials can be bypassed without significant loss of predicted capability. It is believed that this is because the permanent deformation characteristics of the materials are highly correlated to the elastic moduli of the material.

Another development having potential use is the development of a regression equation for the relationship developed by Rauhut et al (Reference 6) between the fatigue coefficient $K_1(T)$ and K_1(70°F or 21.1°C).

The subroutine for prediction of low temperature cracking is the Hajek-Haas model.

Huschek Rutting Prediction Method

The Huschek method (Reference 35) is very similar to that described above for Monismith et al, except the structural model is the elastic layer program BISAR and the permanent deformation characterization for the asphalt concrete is based on cyclic creep compliance tests. The rutting is again predicted by summing the permanent deformations in the separate layers as is done by Monismith et al and indirectly by VESYS A.

Calculated results from this procedure were compared to measured rutting on a test road near Zürich, Switzerland and comparisons were reasonably good.

Shahin-McCullough Model

The Shahin-McCullough model for prediction of low temperature or thermal cracking is described in detail in References 11 and 12 and will be summarized below.

The steps for predicting low temperature cracking in asphalt concrete pavements are indicated in FIGURE 4-6. As can be seen, there are four different submodels as follows:

1. The pavement temperature model, which is an improved version of the model developed by Barber (Reference 52), is used to predict an hourly pavement temperature as a function of air temperature, wind velocity, solar radiation, asphalt mixture thermal properties, and depth from the pavement surface.

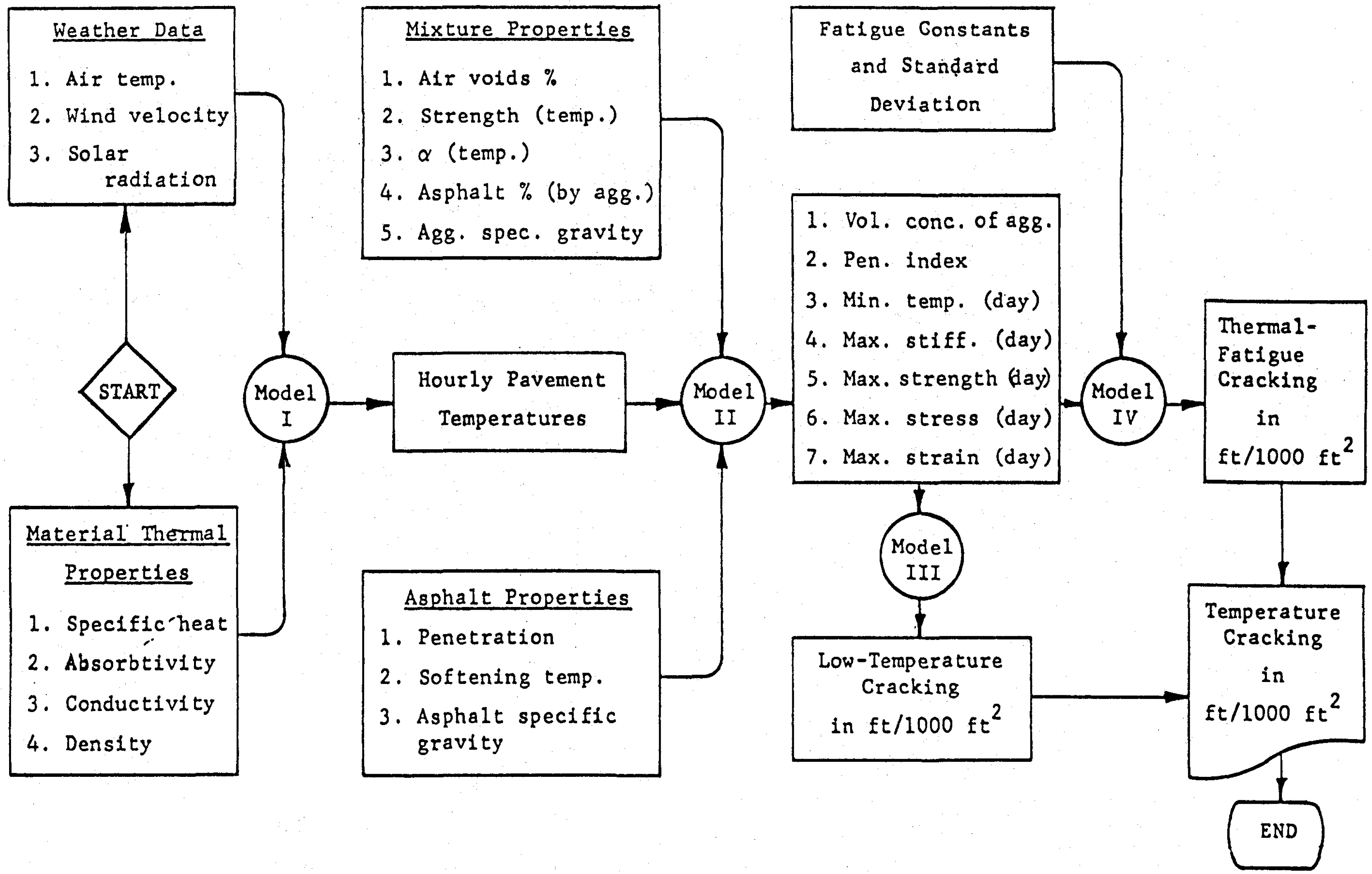

FIGURE 4-6. STEPS FOR PREDICTING ASPHALT TEMPERATURE THERMAL CRACKING AS FUNCTION OF TIME. (REFERENCE 11)

2. The thermal stress model calculates the thermal stresses and strains in the asphalt mixture as a function of its stiffness and the temperature changes. This model in turn consists of four interactive submodels for determining asphalt stiffness, asphalt aging, asphalt mixture stiffness, and thermal stresses and strains.

3. The low temperature cracking model predicts the percent of surface area cracking using probabilistic methods to predict whether the thermal stresses will exceed the mixture strength. Both the thermal stress and the thermal strength are assumed to vary and these variabilities are defined in terms of their standard deviations. The thermal stress is a function of the asphalt mixture stiffness, which varies with temperature and loading time. The asphalt mixture strength is also a function of the same variables.

4. The thermal fatigue cracking model adds thermal fatigue cracking caused by the daily temperature cycling to the low temperature cracking.

The thermal-fatigue cracking model 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 the northern zones having 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 Program COLD might then be thought of as "one cycle fatigue cracking" due to relatively much higher strains that would not require repetitive loading to produce a failure.

This model is generally much more thorough than the low temperature cracking models previously discussed. It not only provides predictions of pavement temperatures, but also it provides predictions of asphalt cement stiffness at these temperatures, the changes in stiffness due to asphalt aging in time, and the asphalt mixture stiffness. However, this thoroughness exacts a price in that a large number of input values are required to operate the model. For this research, the remaining material inputs would represent little difficulty once the four sets of regional environmental inputs are established.

Comparisons between measured and calculated low-temperature cracking for the St. Ann test road, Ontario Test Road, and a runway in Fairbanks, Alaska are given in Reference 12. The predictions were reasonable considering the variability in occurrence of low-temperature cracking in the field; i.e., significant differences in amount of cracking are generally found between apparently identical sections for the same environmental conditions.

Reduced Skid Resistance Studies

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 (Reference 36) reported statistical relationships between measured skid numbers, number of vehicle applications with trucks and cars counted equally, a "field constant" for each aggregate that depends on its traffic polishing characteristics, and a skid number taken after a specific number of vehicle applications. This relationship is

$$N_{initial} \left(SN_{initial}/SN\right)^{\frac{1}{b_{field}}} = 365 \quad r_o t + \left[\frac{(r_{20} - r_o)t}{40}\right]\left[LDF\right] \qquad \ldots(13)$$

Where:

$N_{initial}$ = Number of vehicle applications at which $SN_{initial}$ was measured. (50,000 for correlations to British Portable Tester Number),

$SN_{initial}$ = Skid number taken after $N_{initial}$ vehicle applications with a standard skid trailer with wheels locked at 40 mph,

SN = Skid number at any time t,

b_{field} = slope of line plot of log SN versus log of vehicle applications,

r_o = average daily traffic in one direction at initial pavement construction,

r_{20} = average daily traffic in one direction at the end of the design life assumed as 20 years. If the design life is other than 20 years, the term $(r_{20} - r_o)/40$ should be replaced by $(r_c - r_o)/2c$, where r_c is the average daily traffic in one direction at the end of the design life c.

t = time after initial construction in years, and

LDF = Lane distribution factor of the most heavily traveled lane.

The value b_{field} may only be produced by long term studies. Fortunately, some values are available and are included as TABLE 4.2. While only a limited data exists on the input b_{field} necessary to this model, it

TABLE 4-2. MATERIAL SKID AND POLISH CHARACTERISTICS FOR CENTRAL TEXAS AGGREGATES. (REFERENCE 36)

	Ranger Expanded Shale	Burnet Dolomite	Knippa Trap-rock	Georgetown Limestone	Iron Slag
$SN_{initial}$	67	58	58	52	56
b_{field}	0.41	0.121	0.096	0.136	0.063

does represent a basis that may be used for this project to consider the general effects of abrasive wear of surface aggregates on reductions in skid resistance.

Predictive Models Selected for Flexible Pavements

A careful evaluation indicates that none of the models discussed above have better capabilities for predicting rutting and fatigue cracking distress than VESYS A, and that those with essentially equal capabilities would require much more project staff time in order to gain familiarity with their material characterizations. A detailed study and materials test program would also be required in order to characterize the materials at a sufficiently high confidence level. Since none of the other models offered any apparent advantage over VESYS A for prediction of these two distresses, it was felt that the VESYS system should be used and the resultant savings in project effort utilized to enhance other project studies.

Program COLD was not considered useful for this study since it predicts only stresses in a pavement at a point and when a crack will occur. It does not include any predictions of crack spacing or area cracked both of which may be obtained from the other two low temperature cracking models considered.

As the Hajek-Haas model for low-temperature cracking has only Canadian data as a basis, it was not felt that it should be the primary model for this study. The Shahin-McCullough model has a much more thorough theoretical base and offers much more generality for the studies required for this project. Limited studies using the Hajek-Haas model can be conducted to obtain supplementary information while using VESYS A for studies of rutting and fatigue cracking distress.

The Steitle-McCullough study on the effects of aggregate polishing will be used to study loss of skid resistance, but the amount of field data necessary to the study is so limited that only qualitative results may be expected.

MODELS FOR COMPOSITE PAVEMENTS

The choice of models for prediction of distress in composite pavements is much more limited than for flexible pavements. A composite pavement for this study is considered to be one having a flexible surface over a very stiff subbase, composed of either a portland cement concrete pavement layer or a portland cement treated granular base layer. While the composite pavement studies will be similar to those for flexible pavements, special modeling will be required since the strongest pavement layer does not occur at the surface. For instance, rutting distress and reduced skid resistance distress may be studied with the same models as for flexible pavements, but the fatigue model must be capable of considering fatigue in the more rigid underlying layer of portland cement concrete or cemented treated base. Also, the serious problem of reflection cracking in the surface layer, induced by movements of the underlying layer at its joints or cracks, introduces a need for an entirely different kind of a model.

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

1. Rutting distress - VESYS A
2. Fatigue Cracking Distress:
    a. Computer program ELSYM5 for predicting stresses and strains at the bottom of the flexible and rigid layers, supplemented by fatigue relationships.
    b. RPOD. (References 9, 55[1])
3. Reflection Cracking Distress - RFLCR1. (Reference 9)
4. Reduced skid resistance - to be studied concurrently with the flexible pavement study.

No models were available that were developed specifically for predictions of rutting in composite pavements; so VESYS A, the model selected from study of the same distress in flexible pavements, is proposed also for composite pavements.

Program RPOD was developed by Austin Research Engineers specifically for the design of either flexible or rigid overlays for rigid pavements, and includes a fatigue cracking distress model utilizing ELSYM5 as a pavement structure model. The alternatives for study of fatigue cracking distress are (1) modify ELSYM5 to add a fatigue cracking distress model to the present pavement structure model or (2) bypass most of RPOD's subroutines to use only the ELSYM5 pavement structure model and its fatigue cracking distress model. A study of the staff and computational time involved indicated that it would be more economical to modify ELSYM5, so that will be the approach taken. RPOD uses ELSYM5 as a pavement structure model, so the results would be identical for either RPOD or ELSYM5.

RFLCR1 is the only available model for predicting reflection cracking is described below.

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[1] Treybig, H.J., B.F. McCullough, P. Smith and H. Von Quintus, "Overlay Design and Reflection Cracking Analysis for Rigid Pavements, Vol. 2, Design Procedures," Report No. FHWA-RD-77-67, submitted by ARE Inc to the FHWA, August 1977.

Program RFLCR1

The reflection cracking model RFLCR1 includes analysis of two types of distress mechanisms. One is a form of reflection cracking in the overlay due to horizontal movements of the rigid slab caused by temperature and moisture changes. The second is shear cracking due to differential vertical movements at joints or cracks in the underlying rigid pavements.

The reflection cracking analysis consists of evaluating overlay thickness using the following concept:

$$C_R = f\ (E_o, E'_o, D, \Delta T, \alpha, F_i, w_d, X_{BB}) \quad \ldots\ldots\ldots\ldots\ldots\ldots (15)$$

where:

C_R = reflection cracking,

E'_o = dynamic modulus of asphalt or concrete,

E_o = creep modulus of asphalt or concrete,

D = thickness of existing pavement or overlay,

ΔT = temperature change of pavement materials,

α = coefficient of volume change for pavement materials,

F_i = force-movement relationship between pavement layers resulting from friction, adhesion, bearing, etc.,

w_d = differential deflection at crack or joint, and

X_{BB} = width of bond breaker.

The derivations for the reflection cracking prediction equations are quite complex and the reader is referred to Reference 9.

In studying the effects of material properties on reflective cracking, most of the relationships in Equation (15) will be held constant. The exceptions will be the stiffness modulus and creep compliance for the flexible overlay and the thermal coefficient of the stiffer underlying layer. Each of these properties and the temperature change in the pavement materials will also be dependent on environmental zone, so there will, in effect, be a separate study for each of the four environmental zones.

MODELS FOR RIGID PAVEMENTS

The category of rigid pavements includes JCP, JRCP, and CRCP. Since the steel provided in JRCP or CRCP is not normally placed in the right position nor is it sufficient to provide additional structural capacity, a common pavement structure model may be used for the prediction of stresses and strains in JRCP, CRCP and JCP. This means that the studies of fatigue cracking distress may be combined for the three types of pavements. The distress mechanisms for faulting at cracks and joints and joint spalling are also essentially the same for JRCP and JCP; so these distresses may also be studied simultaneously.

Thermal and shrinkage cracking are generally not serious problems for JCP if the joint spacings for JCP are short. Future designs should not include joint spacing any greater than 15 feet if the recommendations of Darter (Reference 10) for Zero-Maintenance pavements are followed. Since longer joint spacings are sometimes used for JRCP, thermal and shrinkage cracking should be considered for this type of pavement. The only known model for predicting this distress in a JRCP is a computer program called JRCP-1 (Reference 56[1]), and an improved version called JRCP-2, unless the classical subgrade drag theory is considered.

The fatigue cracking model for JRCP may also be utilized for CRCP, but CRCP's distinctive nature also requires special distress models for thermal and shrinkage cracking. The only relatively complete models developed specifically for the analysis of CRCP are program CRCP-1 developed by McCullough et al (Reference 18) and CRCP-2 developed by Ma (Reference 57[2]), which is an improved version of CRCP-1. Follow-on studies by Strauss (Reference 58[3]) and others at the Center for Highway Research, The University of Texas at Austin offer additional statistical insight into the effects of material properties on CRCP distress. Programs CRCP-2 and JRCP-2 will both be discussed subsequently, CRCP-2 first because much of the theory of CRCP-1 was utilized in the development of JRCP-2.

There are several pavement structure models that could be used to predict stresses and strains for the fatigue cracking analysis. Several of these are discussed briefly in Chapter 1 and in more detail early in

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[1] Rivero-Vallejo and B.F. McCullough, "Drying Shrinkage and Temperature Drop Stresses in Jointed Reinforced Concrete Pavement," Report 177-1, Center for Highway Research, The University of Texas at Austin, August 1975.

[2] Ma, J.C.M., "CRCP-2, An Improved Computer Program for the Analysis of Continuously Reinforced Concrete Pavement," University of Texas at Austin, Master Thesis, August 1977.

[3] Strauss, P., B.F. McCullough, and W.R. Hudson, "Continously Reinforced Concrete Pavements: Structural Performance and Design Construction Variables," Research Report 177-7, Center for Highway Research, The University of Texas at Austin, May 1977.

this chapter. Because of the limitations of plate theory, elastic layer theory has been selected as the pavement structure model most responsive to the needs of this project for considering all pavement layers, but the special capabilities of the discrete element and finite element models may also be used for special studies. Since ELSYM5 was selected as the best elastic layer program for this project and will be modified to add a fatigue distress model for composite pavements, it has also been selected as the fatigue cracking distress model for rigid pavements.

Although not selected for further use because it is subject to the same limitations as the Huang and Wang model (Reference 27) upon which it is based, Computer Program JCP-1 was also considered as a potential fatigue cracking model. This model is described below.

Model JCP-1 for Fatigue Cracking Distress

Program JCP-1 provides fatigue and serviceability data for a design procedure developed by Darter (Reference 10) for JCP. JCP-1 includes multiple regression equations for predicting pavement stress and the fatigue cracking model described below.

The procedure used by Program JCP-1 for the fatigue analysis is as follows:

1. Select trial slab thickness

2. Compute fatigue damage by the following equation:

$$D = \sum_{k=1}^{k=p} \sum_{j=1}^{j=2} \sum_{i=1}^{i=m} \frac{n_{ijk}}{N_{ijk}} \qquad \text{.........................(16)}$$

where:

D = fatigue damage,

$\sum_{k=1}^{k=p}$ = accumulation of traffic from the 1st month to the final month,

$\sum_{j=1}^{j=2}$ = accumulation of traffic for day and night,

$\sum_{i=1}^{i=m}$ = accumulation of total number of single and tandem axle load groups,

N_{ijk} = allowable load applications,

n_{ijk} is the actual load applications computed by following equation:

$$n_{ijk} = (ADTm)(T/100)(DD/100)(LD/100)(A)(30)(P/100)(C/100)(DN/100)(TF/100)(CON/100)$$

ADT_m = average daily traffic at the end of the specific month under consideration

T = percent trucks of ADT,

DD = percent traffic in direction of design lane,

P = percent axles in i^{th} group,

C = percent of total axles in the lane that are within 6 inches of the edge,

DN = percent of trucks during day or night,

TF = factor to either increase or decrease truck volume for the specific month,

CON = 1 for single axles, 2 for tandem axles,

N_{ijk} is computed using the following equation:

$$\log N_{ijk} = 16.61 - 17.61 \frac{\sigma_{tot}}{F}$$

F = modulus of rupture of PCC,

$\sigma_{tot} = \sigma_{load} + R\ \sigma_{curling}$, and

R = adjustment factor for curling stress so that it can be combined with the load stress.

The curling stress, $\sigma_{curling}$, and the load induced stress, σ_{load} are calculated by regression equations in the computer program, which are based on analytical solutions from the Huang and Wang finite element program.

The procedure includes the superposition of stresses created by wheel loads and curling of the slab. While this is conceptually logical, experience derived from the AASHO Road Test and other road tests, where curling stresses were estimated based on strain gauge or other types of measurements, does not corroborate that these stresses are directly additive. Instead, it is believed that the interactive effects of changes in support for the combination of wheel loads and curling produce a combined stress substantially smaller than that assumed by direct superposition. Also, the calculated stresses only consider the wheel loadings located on the outer six inches of the slab. The experience gained by Darter (References 5 and 10) through field surveys of jointed concrete pavements indicated that the fatigue cracking started at the edge of the pavement. In addition, a detailed analysis of the accumulated fatigue damage at different wheel locations indicated that a very small portion of the truck traffic wandering near the edge of the pavement would create more damage due to the higher stresses than the remainder of the traffic further in from the edge of the slab. This assumption appears quite reasonable when using the fatigue relationship based on laboratory beam tests utilized in the computer program. However, there is considerable evidence that fatigue relationships based on laboratory beam tests may very considerably overpredict load repetitions to failure for pavements outside the laboratory. This appears to be corroborated by the fact that the predicted damage index of 0.0001 using the JCP-1 fatigue relationship correlated with the beginning of cracking on the real pavements surveyed, and that this value of 0.0001 for damage index was incorporated into the design procedures as a limiting criterion on fatigue damage. The wheel loads in the outer six inches may or may not control for other more realistic fatigue damage relationships.

While Program JCP-1 was not selected for use in this project to predict fatigue cracking because of the limitations discussed above, it provided supplementary information as to significance of material properties as discussed subsequently in Chapter 5.

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 edge because of the magnitudes of stresses they create is also considered to be significant. The comments above relative to curling stresses and the fatigue damage relationship are not intended to suggest that JCP-1 will not produce reasonable designs. Darter has, in effect, calibrated the model to distresses in real pavements by detailed comparative studies and selection of a limiting damage criterion. The reason for previous comments is to suggest second generation refinements that may be considered as more accurate predictions of the combined effects of wheel loading and curling are developed and a fatigue relationship more consistent with field pavements is defined.

Program CRCP-2

The dimensional changes in a continuously reinforced concrete pavement, caused by drying shrinkage of the concrete and temperature variation after curing, were investigated by McCullough et al and the design method utilizing Program CRCP-1 was developed in the study described in Reference 18. This computer program was subsequently improved by Ma (Reference 57). The method also considers stresses imposed by wheel loads.

FIGURE 4-7 shows the geometric model used to develop the basic equations for the CRCP-2 design method. Due to the accumulated friction and the terminal treatments used in the construction, the slab model assumes an anchorage at each end so that the pavement within the anchorages will maintain a fixed length.

The difference in the thermal coefficients of the steel and the concrete together with the drying shrinkage of the concrete enable determination of the internal stress in the reinforced slab. FIGURE 4-8 shows a simplified thermal contraction model with and without bond between steel and concrete and on a frictionless base. Using the friction-movement characteristic of the slab and the soil determined by controlled experiments, the degree of restraint due to the soil frictional resistance can be estimated. By assuming equilibrium in the system, the stress of one material can be correlated to the stress of the adjacent material. Finally, an incremental approach was adopted to predict the formation of the transverse cracks as a function of time by comparing the concrete stress with the strength of the concrete.

In the development of the model, the following assumptions were made:

1. A crack occurs when the concrete stress exceeds the concrete strength, and after cracking, the concrete stress at the location of the crack is zero.

2. The concrete and steel properties are linearly elastic.

3. In the fully bonded sections of the concrete slab, there is no relative movement between the steel and the concrete.

4. The force-displacement curve which characterizes the frictional resistance between the concrete slab and the underlying base is elastic.

5. Temperature variations and shrinkage due to drying are uniformly distributed throughout the slab, and hence, a one-dimensional axial structural model is adopted for the analysis of the problem.

6. Material properties are independent of space.

7. The effects of concrete creep and slab warping are neglected.

The spacing of transverse cracks that occur naturally in CRCP is perhaps the most important variable affecting the behavior of the pavement. Relatively large distances between cracks result in a higher accumulation of drag forces from the subgrade due to frictional resistance, thus producing high steel stress at the crack and wide crack widths. Closer crack spacing reduces the frictional restraint, thus the steel stress and the crack width. It is clear that the transverse cracks in CRCP are due to the thermal contraction and shrinkage of the concrete slab. Assumption 5 above is certainly questionable as there would be some temperature

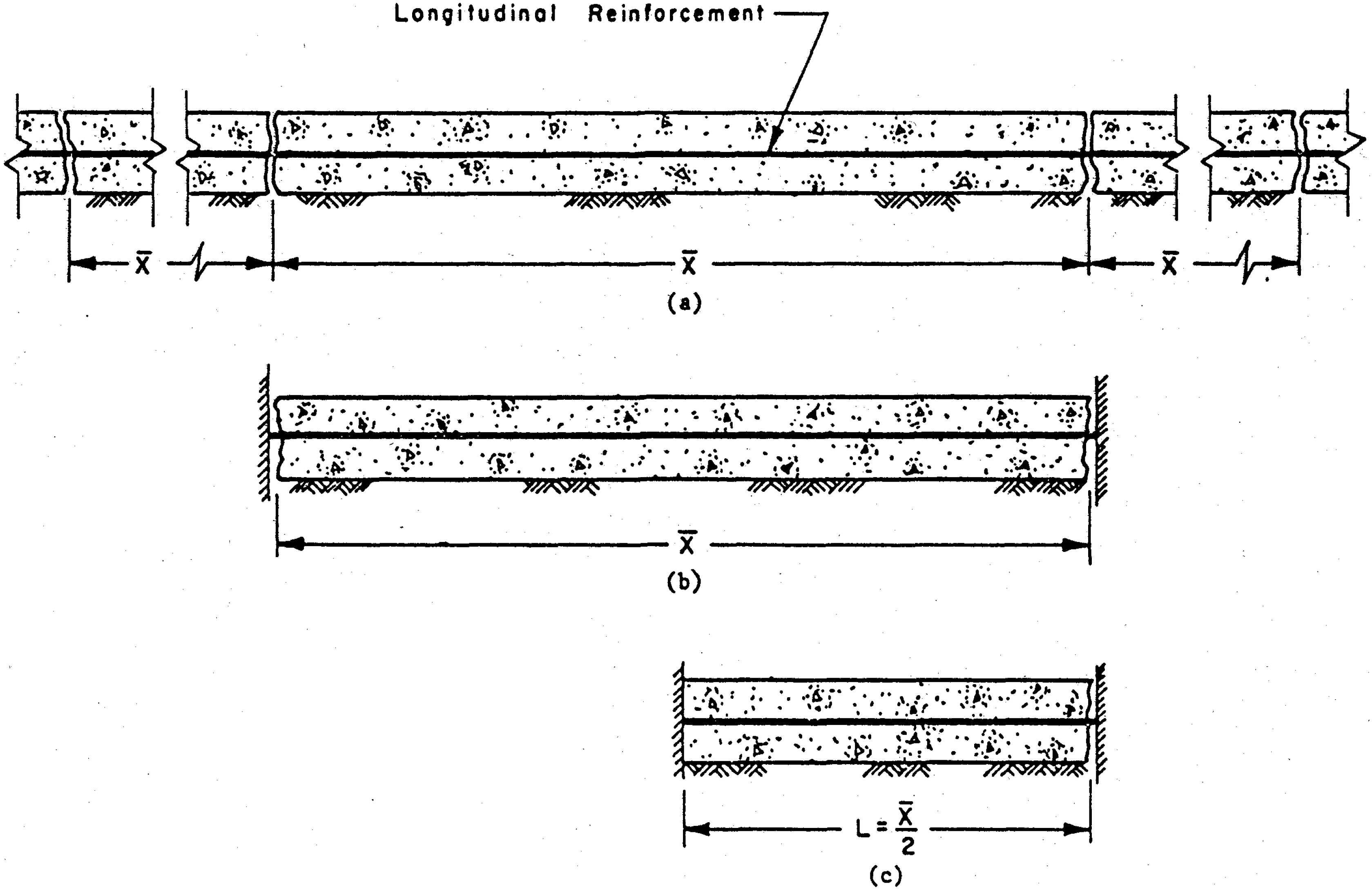
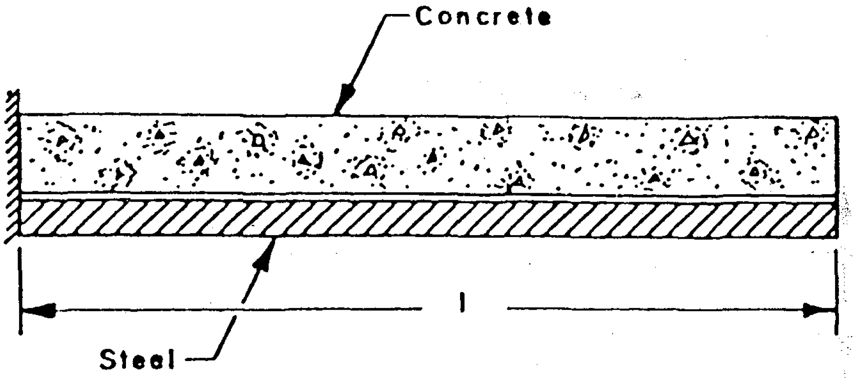
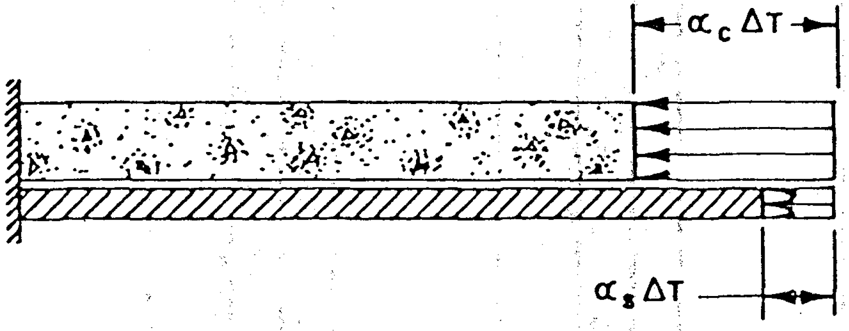


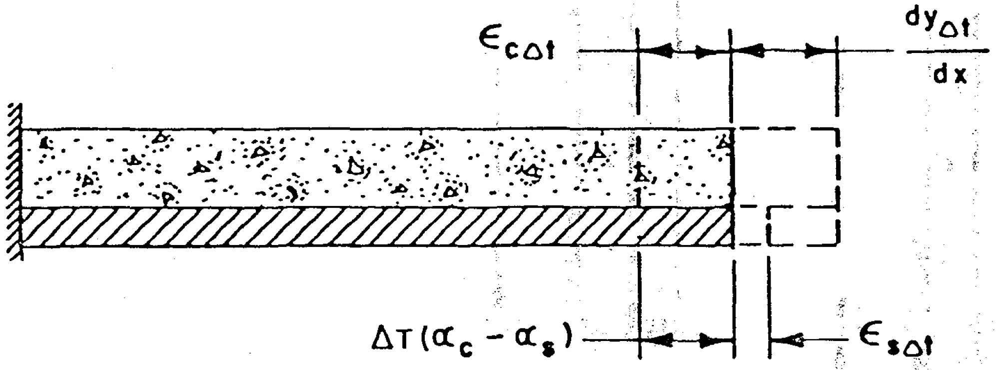
FIGURE 4-7. CONTINUOUSLY REINFORCED CONCRETE PAVEMENT GEOMETRIC MODEL. (REFERENCE 18)



(a) Initial state



(b) No restraint



(c) No slippage between concrete steel

FIGURE 4-8. BEHAVIOR OF A REINFORCED SLAB SUBJECTED TO TEMPERATURE DROP. (REFERENCE 18) gradient in the slab and shrinkage is known to start at the surface and progress downward over a period of days or months. However, the one-dimensional axial model used in this method is the only rational model available which considers the internal forces caused by the difference in thermal coefficient between the concrete and the steel material and therefore is a valuable tool for the analysis of CRC pavements. For the comparative purposes of this project, the error from Assumption 5 should not be important.

In 1959, the Texas Highway Department began the Falls-McClennan County Project to evaluate the performance of continuously reinforced concrete pavements. Intensive crack spacing surveys were conducted at ages varying from 20 days to 15 years. The results obtained from the survey were compared to the CRCP-2 computer prediction. The good correlation shown in FIGURE 4-9 indicates that this method gives reasonable and reliable predictions.

The material properties considered in the CRCP-2 model are:

1. Modulus of Elasticity of Concrete, E_c
2. Thermal Coefficent for the Concrete, α_c
3. Thermal Coefficient for the Steel, α_s
4. Shrinkage coefficient for the Concrete, Z_c
5. Flexural Strength for the Concrete, fu
6. Slab-base friction, F/Y

Based on regression models developed during Project NCHRP 1-15 (Reference 18), the material properties listed above were found to affect the performance of CRC pavements. To further identify the material properties requirements for zero maintenance pavements, the CRCP-2 computer model is believed to be the best simulative pavement structural model available for continuously reinforced concrete pavement. This model deals directly with the external (wheel load) and internal (environmental) forces that cause the formation of the transverse cracks and influence the width of the crack. The predictions of crack width and the crack spacing using this model will allow testing of the effects of varying material properties over an appropriate range of values. By considering limiting criteria for crack width and the crack spacing based on field observations of distress and analysis, optimized material properties can be determined. Although distresses such as spalling, longitudinal cracking, etc., are not included in this model, they are closely correlated to crack width and crack spacing and may be optimized on that basis. Regression equations for the Distress Index in Reference 18 and the statistical developments of Strauss (Reference 58) should also provide supplementary information useful for this optimization.

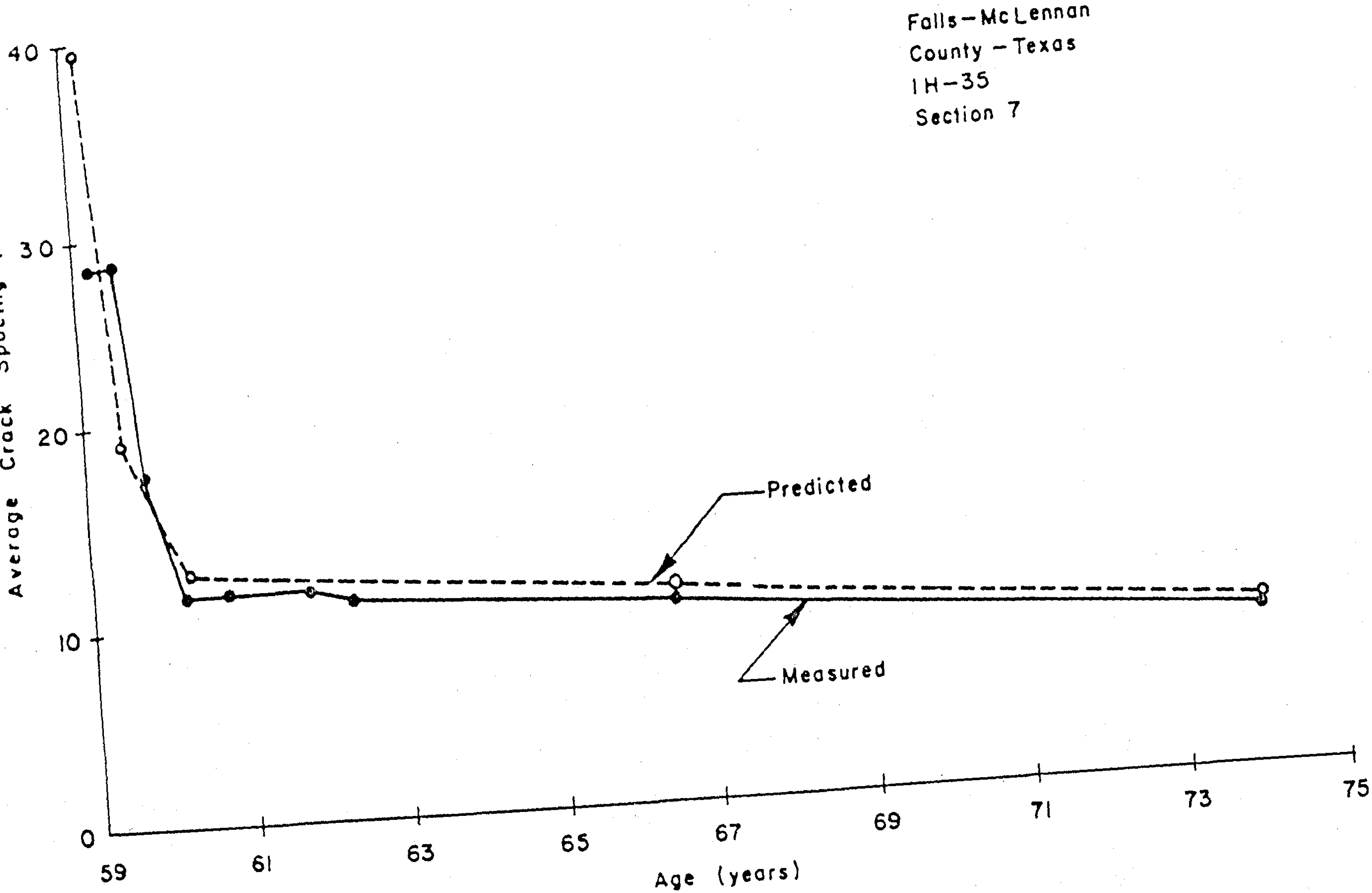


FIGURE 4-9. MEASURED AND PREDICTED AVERAGE CRACK SPACING AS A FUNCTION OF TIME FOR SECTION 7 IN FALLS-McLENNNAN COUTIES, IH 35. (REFERENCE 18)

Program JRCP-2

Program JRCP-2 was developed by Rivero-Vallejo and McCullough (Reference 56) and uses many of the concepts developed for CRCP-2. However, the geometry and boundary conditions for this model are considerably different from 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 the shrinkage coefficient of the concrete; the temperature drops anticipated in time; the slab length; the percent reinforcement; the bar diameter; the yield stress of the steel; the 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 theoretically will proceed with analysis until the first crack forms and then will 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, and crack width as a function of time, and the same data for second cracks if they are formed.

It is believed that Program 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, nor does it correctly predict stresses in concrete and steel. Consequently, predictions for crack widths are questionable. The results of a preliminary sensitivity analysis are discussed in Chapter 5 and give some indication of these problems. Since JRCP-2 appears to be theoretically correct and is the only suitable model for JRCP it has been selected for study of distresses pending correction of the deficiencies.

SUMMARY OF MODEL STUDY RESULTS

The available pavement structure response and pavement distress models for the distresses to be considered have been discussed in detail previously in this chapter and those models selected for use during Tasks B and C identified. TABLES 4-3 through 4-7 shows 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, but will be studied separately from the factorial study and the optimum material properties for those distresses will be considered in the optimization during Task C. This is because no suitable mathematical models were found for prediction of these distresses.

The models selected either have been exercised in the recent past by members of the project staff or have been exercised and studied during

TABLE 4-3. DISTRESS, RELATED MATERIAL PROPERTIES, DISTRESS MODELS SELECTED AND SIZE OF INITIAL STUDY FACTORIALS FOR FLEXIBLE PAVEMENTS.

Distresses that have Significant Effects on Pavement Performance and/or Maintenance Requirement	FATIGUE CRACKING	RUTTING	LOW-TEMPERATURE CRACKING	REDUCED SKID RESISTANCE
Material Properties that have significant effects on the distresses	1) Fatigue Constants K_1 (T), K_1 (T) for AC Surface. 2) Stiffness Modulus for AC Surface. 3) Stiffness Modulus for Base Materials.	1) Stiffness Modulus for AC Surface. 2) Permanent Deformation Parameters for AC Surface. 3) Stiffness Modulus for Subgrade Soil. 4) Permanent Deformation parameters for Subgrade Soil.	1) Coefficient of Thermal Expansion for AC. 2) Stiffness Modulus for AC. 3) Tensile Strength for AC.	1) Abrasive Wear Potential.
Models Selected for Distress Studies	VESYS A	VESYS A	SHAHIN-MCCULLOUGH "Low-Temperature Cracking Model"	Study Separate from Primary Factorial
Number of Solutions in Initial Factorial	32	32	32	-

TABLE 4-4. DISTRESS, RELATED MATERIAL PROPERTIES, DISTRESS MODELS SELECTED AND SIZE OF INITIAL STUDY FACTORIALS FOR COMPOSITE PAVEMENTS.

Distress that have Significant Effects on Pavement Performance and/or Maintenance Requirement	REFLECTION CRACKING	FATIGUE CRACKING	RUTTING	REDUCED SKID RESISTANCE
Material Properties that have Significant Effects on the Distresses	1) Stiffness Modulus, for AC Overlay. 2) Thermal Coefficient for Existing Pavement. 3) Creep Modulus for AC Overlay	1) Stiffness Modulus for PCC or Cement Treated base. 2) Fatigue Constants for AC Overlay or PCC. 3) Stiffness Modulus for AC Overlay.	1) Permanent Deformation Parameters for AC Overlay. 2) Stiffness Modulus for AC Overlay.	1) Abrasive Wear
Models Proposed for the Sensitivity Analysis	RFLCR1	* ELSYM5	VESYS A	Study Concurrently with Flexible Pavement
Number of Solutions in Initial Factorial	32	32	16	-

* The stresses predicted by ELSYM5 are essentially "Interior Slab Stresses", and will be multiplied by a suitable stress factor to approximate stresses near the edge of the slab.

TABLE 4-5. DISTRESS, RELATED MATERIAL PROPERTIES, DISTRESS MODELS SELECTED AND SIZE OF INITIAL STUDY FACTORIALS FOR JOINTED REINFORCED CONCRETE PAVEMENT.

Distresses that have Significant Effects on Pavement Performance and/or Maintenance Requirements	LOW-TEMPERATURE AND SHRINKAGE CRACKING	FATIGUE (TRANSVERSE OR CORNER CRACKING)	FAULTING AT CRACKS	JOINT SPALLING
Material Properties that have Significant Effects on the Distresses	1) Tensile Strength for PCC. 2) Thermal Coefficient. 3) Shrinkage Coefficient.	1) Fatigue Constants for PCC. 2) Stiffness Modulus for PCC. 3) Stiffness Modulus for Subbase Material.		1) Volume change Characteristics for PCC Surface. 2) Tensile Strength for PCC. 3) Stiffness MOdulus for PCC.
Models Proposed for the Sensitivity Analysis	JRCP-2	* ELSYM5	Study Separate From Primary Factorial	Study Separate From Primary Factorial
Number of Solutions in Initial Factorial	32	32	-	-

* The stresses predicted by ELSYM5 are essentially "Interior Slab Stresses", and will be multiplied by a suitable stress factor to approximate stresses near the edge of the slab.

TABLE 4-6. DISTRESS, RELATED MATERIAL PROPERTIES, DISTRESS MODELS SELECTED AND SIZE OF INITIAL STUDY FACTORIALS FOR JOINTED CONCRETE PAVEMENT.

Distresses that have Significant Effects on Pavement Performance and/or Maintenance Requirement	FATIGUE CRACKING	JOINT FAULTING	JOINT SPALLING
Material Properties that have Significant Effects on the Distresses	1) Fatigue Constants for PCC. 2) Stiffness Modulus for PCC. 3) Stiffness Modulus for Subbase Materials.	1) Erodability of Subbase. 2) Erodability of Subgrade. 3) Tensile Strengh of PCC.	
Models Proposed for The Sensitivity Analysis	*ELSYM5 (Concurrent with Studies for JRCP & CRCP)	Study Separate from Primary Factorial	Concurrent with Study for JRCP
Number of Solutions In Initial Factorial	-	-	

* The stresses predicted by ELSYM5 are essentially "Interior Slab Stresses", and will be multiplied by a suitable stress factor to approximate stresses near the edge of the slab.

TABLE 4-7. DISTRESS, RELATED MATERIAL PROPERTIES, DISTRESS MODELS SELECTED AND SIZE OF INITIAL STUDY FACTORIALS FOR CONTINUOUSLY REINFORCED CONCRETE PAVEMENT.

Distresses that have Significant Effects on Pavement Performance and/or Maintenance Requirements	FATIGUE CRACKING	LOW TEMPERATURE AND SHRINKAGE CRACKING	PUNCHOUTS	CRACK SPALLING	STEEL RUPTURE
Responses to Thermal and Shrinkage Strains that may be Optimized to Minimize Distresses	- -	- -	1) Crack Width 2) Crack Spacing Narrow cracks generally do not spall and punchouts do not generally occur except when crack spacing is close. Since crack width and crack spacing are negatively correlated, only one must be optimized.		
Material Properties that have Significant Effects on the Distresses	1) Fatigue Constants for PCC. 2) Stiffness Modulus for PCC. 3) Stiffness Modulus for Subbase.	1) Thermal Coefficient for PCC. 2) Shrinkage Coefficient for PCC. 3) Tensile Strength for PCC.	Same as for Low Temperature and Shrinkage Cracking.		
Models proposed for the Sensitivity Analysis	*ELSYM5 (Concurrent with Study for JRCP)	CRCP-2	CRCP-2 (Concurrent with Study for Low Temperature and Shrinkage Cracking for CRCP).		
Number of Solutions in Initial Factorial	-	32	-	-	-

* The stresses predicted by ELSYM5 are essentially "Interior Slab Stresses", and will be multiplied by a suitable stress factor to approximate stresses near the edge of the slab.

this project to evaluate out their utility. In all cases, a number of solutions have been obtained to evaluate the changes in responses to varying values of material properties. These preliminary sensitivity analysis results appear in Chapter 5.

CHAPTER 5. PRELIMINARY SENSITIVITY ANALYSIS AND FINAL SELECTION OF MATERIAL PROPERTIES FOR STUDY

In Chapter 3, various distresses and related material properties associated with each pavement type were identified. In Chapter 4, models to predict pavement response and distress under the influence of external loadings and environmental effects were identified and selected. The models selected have either been exercised in the recent past by project staff or by conducting "preliminary" sensitivity analyses as part of Task A to:

1. Evaluate the capability of each model to predict the specific distress it was selected to predict.

2. Gain insight as to the sensitivities of each model to variations in the significant material properties.

These sensitivity results also served as supplementary information for the final selections of material properties reported in Chapter 3 and will be useful for factorial design during Task B.

The results from these preliminary sensitivity analyses are summarized and discussed below by pavement type and by distress. In some cases, results obtained using other models considered during Task A are included as additional useful information.

FLEXIBLE PAVEMENTS

TABLE 4-3 listed the four distresses for flexible pavements found to be sufficiently significant for further study. These distresses are fatigue cracking, rutting, low temperature cracking, and reduced skid resistance. As discussed in Chapter 4, reduced skid resistance will be studied separately as sufficient data are not available for a factorial study. The results of preliminary sensitivity studies for the other three distresses appear below.

Fatigue Cracking

A very detailed sensitivity analysis was conducted for VESYS IIM (Reference 6). Since the fatigue model for VESYS A is identical to that for VESYS IIM, the results of that detailed sensitivity analysis are summarized below.

Only two material properties were found to be statistically significant. By far the most significant was the fatigue life potential or fatigue damage relationship for the asphalt concrete, which is defined for a particular temperature by the fatigue constants $K_1(T)$ and $K_2(T)$. The other significant material property was stiffness of the asphalt concrete.

The stiffness of the base material was not found to be a significant parameter; however, this was probably because of the very significant effects of nonmaterial factors such as traffic, wheel load magnitude, and thickness of the asphalt concrete. Since the project staff felt that it was important, the stiffness of the base material was included in the preliminary sensitivity analysis for the factorial shown in TABLE 5-1. The regression equation for radial strain from WATMODE (Reference 34) was used for this factorial study. Each parameter was studied at a low and high value while all other parameters were held constant at their median values. The fatigue relationships were also varied as functions of stiffness as follows:

Stiffness	$K_1(T)$	$K_2(T)$
100,000 psi (690,000 kPa)	1.2×10^{-10}	4.88
600,000 psi (4,138,000 kPa)	5.7×10^{-13}	4.97
1,200,000 psi (8,276,000 kPa)	1.8×10^{-14}	5.08

The results of this limited study appear in FIGURE 5-1 in the form of 18-kip (80 kN) equivalent single axle loads (ESAL) to failure N_f and layer stiffnesses. These data indicate that the stiffness of the asphalt concrete surface is the most important property affecting the radial strain occurring at the bottom of the surface layer, that the stiffness of the base material is significant, but that the stiffness of the subgrade is not significant. This limited study supported the opinion of the project staff that the stiffness of the base materials should be included in the factorial studies.

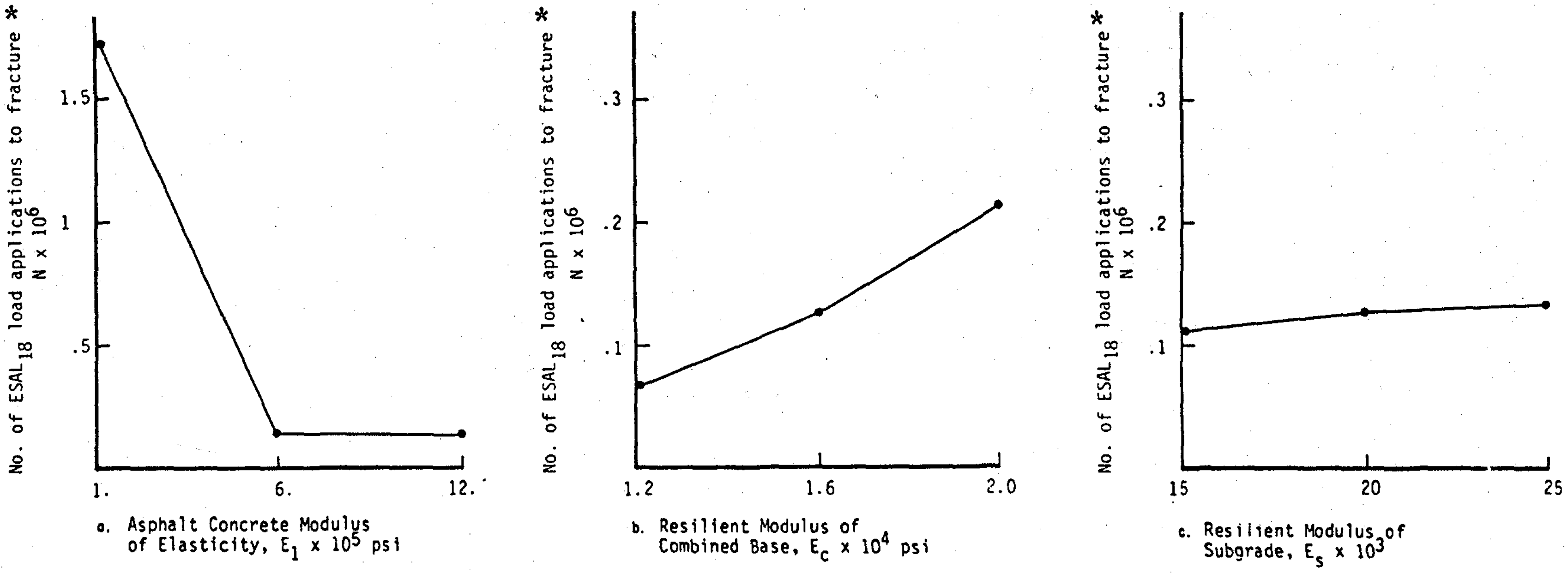
Rutting

The material properties considered significant to rutting are the stiffness moduli and permanent deformation characteristics for the asphalt concrete surface and for the subgrade soil. The comprehensive sensitivity study on VESYS IIM utilized for fatigue cracking distress was again used to determine the significance of the various material properties on rutting. TABLE 5-2 summarizes the relative importance of the various material properties. This table shows both the sense (i.e., increase or decrease) and the magnitude of the effect. The model is designated as "Insensitive" to a material property if its variation caused no significant change in the response. A change less than one third of the maximum change calculated for any variable was designated as a slight increase or decrease, a change between one third and two thirds an increase or decrease, and that above two thirds a great increase or decrease. Changes of over one third of the maximum change were considered significant. Those below one third were designated as marginally significant on the basis of judgement after review of the numerical results of the sensitivity analysis. The permanent deformation characteristics for the asphalt concrete surface layer and the subgrade soil have the greatest effect on rut depth, while the stiffness of the subgrade is next in significance and the stiffness of the asphalt concrete barely significant.

TABLE 5-1. SENSITIVITY ANALYSIS FACTORIAL FOR FATIGUE CRACKING USING WATMODE REGRESSION EQUATION FOR RADIAL STRAINS.

Tested Variables	Low	Medium	High
Asphalt Conc. Stiffness E_1 (psi x 10^5)	1.0	6.0	12.0
Resilient Modulus of Comb. Base, E_c (psi x 10^4)	1.2	1.6	2.0
Resilient Subgrade Modulus E_s, (psi x 10^3)	15	20	25

Constants:
A.C. Thickness = 4 inches (0.10 m)
Base Thickness = 18 inches (0.46 m)
1 psi = 6.89 kPa



*1 psi = 6.89
1 $ESAL_{18}$ load = 1 80 kN Equivalent Single Axle Load

FIGURE 5-1. PRELIMINARY SENSITIVITY ANALYSIS ON FATIGUE CRACKING BASED ON FATIGUE EQUATION BY MEYER ET AL (REFERENCE 34).

TABLE 5-2. SUMMARY OF SENSITIVITY ANALYSIS FOR VESYS IIM ON RUTTING (REFERENCE 6), VALUES OF MATERIAL PROPERTIES INCREASING.

Material Properties	Effects on Rut Depth
ALPHA(1), Permanent Deformation Parameter, for Surface Layer	Great Decrease
GNU(1), Permanent Deformation Parameter for Surface Layer	Increase
ALPHA(3), Permanent Deformation Parameter for Subgrade	Decrease
GNU(3), Permanent Deformation Parameter for Subgrade	Insensitive
LAYER3, Stiffness Modulus for Subgrade	Increase
LAYER1, Stiffness Modulus for Surface	Slight Increase
LAYER2, Stiffness Modulus for Base	Slight Increase
ALPHA(2), Base Material	Insensitive
GNU(2), Base Material	Insensitive

The stiffness of the base material also produced a slight effect, but Reference 6 indicates that this effect was only one-third that produced by the stiffness of the asphalt concrete and only 8 percent of the effect produced by ALPHA(1), the strongest of the two parameters describing the permanent deformation characteristics of the asphalt concrete. Consequently, stiffness of the base material was not selected for subsequent study in Task B.

It should be noted that GNU(3) was found to be insensitive, while ALPHA(3) is significant. Since both of these parameters are required to describe the permanent deformation characteristics of the material, they both must be considered in the study; however, emphasis will be placed on ALPHA(3).

Low Temperature Cracking

The material properties that control low temperature cracking in flexible pavements were found to be the thermal coefficient (or coefficient of contraction), the stiffness modulus, and the tensile strength for the asphalt concrete surface.

For a brief sensitivity analysis on thermal fatigue cracking using the Shahin-McCullough model (Reference 11), each independent variable was assigned a fixed average value and an average area having fatigue cracks was determined. Each variable was then increased by 10 percent while all other variables were held constant. FIGURE 5-2 depicts graphically the importance of the independent variables on the response of the model as determined from the analysis. The figure indicates that the thermal coefficient for the asphalt concrete surface; the mix design parameters such as percent asphalt, specific gravities of the asphalt and the aggregate, and percent air voids; and the environmental properties defining the pavement temperatures are all significant. The mix design parameters and the pavement temperatures are utilized by the program to calculate asphalt concrete stiffness and tensile strength, so these study results indirectly corroborate the significance of these material properties for the model.

COMPOSITE PAVEMENTS

TABLE 4-4 listed the distresses found to be significant for composite pavements. These distresses are reflection cracking, fatigue cracking, rutting, and reduced skid resistance. Reduced skid resistance will not be studied specifically for composite pavements as the study for flexible pavements may be applied directly.

Rutting

Since VESYS A was selected as the rutting model, the sensitivity analysis discussed under "Flexible Pavements" generally applied for composite as well as flexible pavements. The stiffness and permanent deformation parameters for the subgrade will be omitted for composite pavements as

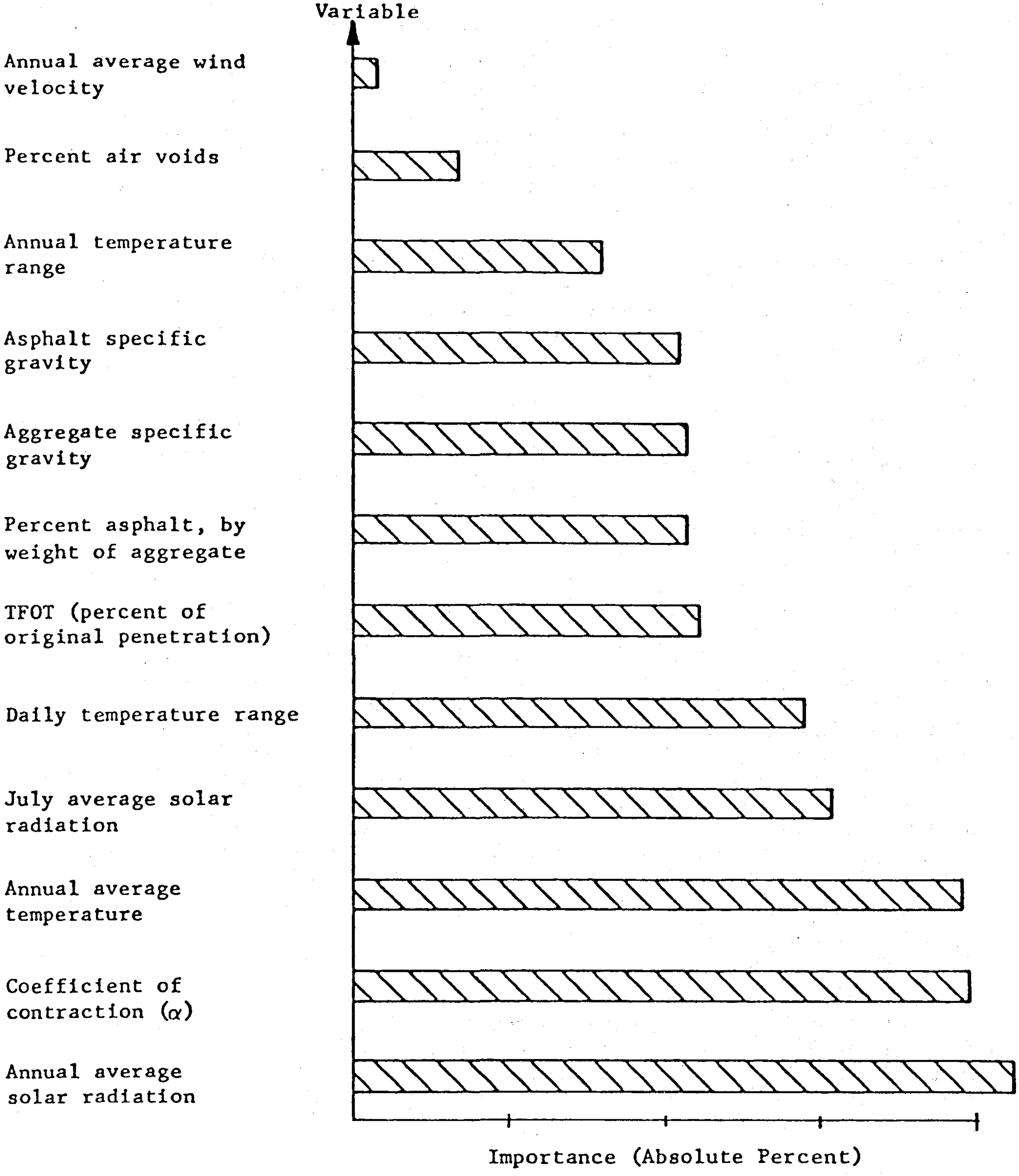


FIGURE 5-2. IMPORTANCE OF INDIVIDUAL VARIABLES REGARDING THE EFFECT ON THERMAL-FATIGUE CRACKING. (REFERENCE 11)

the rigid layer will serve to spread the wheel loads so that the characteristics of the subgrade will not be significant for rutting. The study of reduction in skid resistance will be accomplished concurrently with the study for flexible pavements.

Reflection Cracking

Reflection cracking in composite pavements will be studied with Program RFLCR1. Results from a brief sensitivity analysis conducted by Schnitter (Reference 59[1]) using RFLCR1 provided an indication of the relative significance of the various material properties to the model.

Program RFLCR1 considers two different modes of failure, horizontal tensile failure due to thermal movement of the underlying layer and vertical shear failure due to inadequate load transfer across a joint or a crack in the existing pavement. In Schnitter's sensitivity experiment, the following types of composite pavement were analyzed:

1. An asphalt concrete overlay on an uncracked JCP existing pavement with a bond-breaker and without any overlay reinforcement.

2. An asphalt concrete overlay on a cracked CRCP existing pavement without a bond-breaker or overlay reinforcement.

The material properties determined by Schnitter to be important are listed in TABLE 5-3 in descending order of importance. For both types of composite pavements, the same material properties were found to be important for each failure mode. The overlay stiffness modulus is important for vertical shear failure, and the creep modulus and thermal coefficient for the existing pavement are important properties for horizontal tensile failure.

Fatigue Cracking

Fatigue cracking for composite pavements as well as all three types of rigid pavements will be investigated using a modified version of ELSYM5 that includes a fatigue damage relationship.

FIGURE 5-3 shows a typical composite pavement with constant input magnitudes identified and variable input properties designated. A preliminary sensitivity analysis was conducted for this pavement with variables at levels of input magnitudes as shown in TABLE 5-4. The variables included in the study were three levels of AC surface elastic modulus E_1,

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[1] Schnitter, O., "Rigid Pavement Overlay Design Procedure for Texas SDHPT," University of Texas at Austin, Master Thesis, August 1978.

TABLE 5-3. MATERIAL PROPERTIES FOUND TO BE IMPORTANT BY A LIMITED SENSITIVITY ANALYSIS ON PROGRAM RFLCR1

Composite Pavement Type	Material Properties Indicated Important in RFLCR1	
	Horizontal Tensile Failure	Vertical Shear Failure
AC over Uncracked JCP with bond-breaker	1) Overlay Creep Modulus 2) Thermal coefficient of existing pavement	1) Overlay Stiffness Modulus
AC over Cracked CRCP without bond-breaker	1) Overlay creep modulus 2) Thermal coefficient of existing pavement	1) Overlay Stiffness Modulus

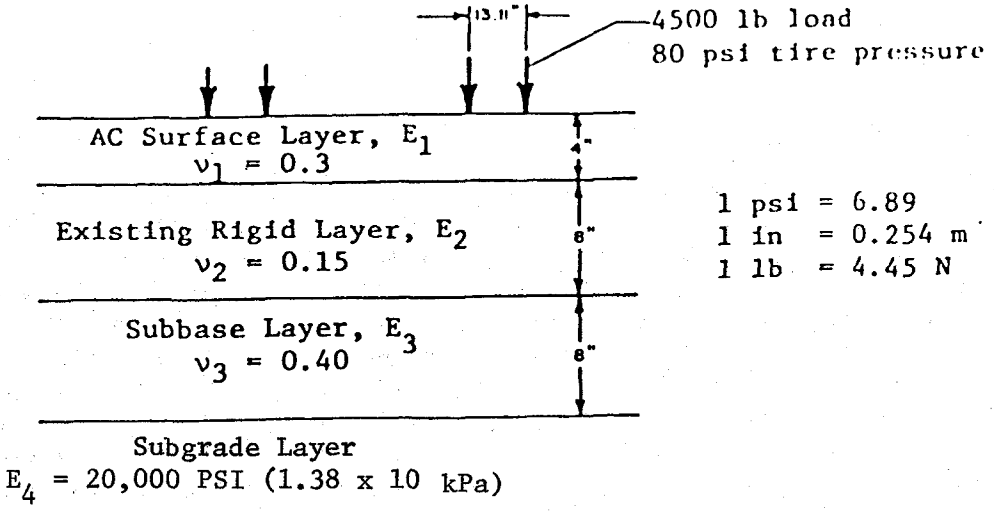


FIGURE 5-3. TYPICAL COMPOSITE PAVEMENT FOR ANALYSIS

TABLE 5-4. PRELIMINARY SENSITIVITY ANALYSIS FOR FATIGUE IN COMPOSITE PAVEMENTS USING THE CRACKING ELSYM5 MODEL AND THE FATIGUE RELATIONSHIP $N_F=K_1\ \left(\frac{\text{FLEXURAL STRENGTH}}{\text{CONCRETE STRESS}}\right)3.21$

Fatigue Coefficient K_1	Subbase Modulus, $E_3 \times 10^5$, PSI	Rigid Layer Modulus, $E_2 \times 10^5$, PSI	AC Surface Modulus, E_1, PSI: 1×10^5	6×10^5	12×10^5
K_1=106,000	.2	5	$54/0.195\times10^6$*	$43/0.406\times10^6$	$39/0.555\times10^6$
		30	$109/6.45\times10^6$	$92/11.1\times10^6$	$82/16.1\times10^6$
		60	$131/33.08\times10^6$	$118/46.3\times10^6$	$107/63.3\times10^6$
	.5	5	$42/0.438\times10^6$	$35/0.78\times10^6$	$33/0.949\times10^6$
		30	$100/8.5\times10^6$	$86/13.8\times10^6$	$77/19.68\times10^6$
		60	$124/39.4\times10^6$	$112/54.7\times10^6$	$103/71.6\times10^6$
K_1=23,440	.2	5	0.043×10^6	0.09×10^6	0.123×10^6
		30	1.43×10^6	2.46×10^6	3.56×10^6
		60	7.32×10^6	10.23×10^6	14.0×10^6
	.5	5	0.097×10^6	0.174×10^6	0.21×10^6
		30	1.88×10^6	3.05×10^6	4.35×10^6
		60	8.73×10^6	12.1×10^6	15.83×10^6

1 psi = 6.89 kPa

*LEGEND

Principal stress in PSI / No. of application to failure

three levels of the rigid layer elastic modulus E_2, two levels of subbase elastic modulus E_3, and two levels of fatigue life potential introduced by varying the multiplier K_1. While not shown, flexural strength of the PCC is also varied with modulus of elasticity of the PCC in consideration of the established correlations between tensile strength and modulus of elasticity. This means that both the flexural strength and the tensile stress in the ratio of imposed tensile stress to flexural strength, used in rigid pavement fatigue cracking distress predictions will vary as the PCC elastic modulus is varied. The rigid layer for composite pavements is generally critical for fatigue distress and an increase in its elastic modulus will increase both the predicted tensile stress and the tensile strength based on strength-modulus relationships.

TABLE 5-4 shows both the stresses and the predicted stress repetitions to cracking "failure" N_f for the different combinations of primary variables. For E_2 = 3,000,000 psi (2.07×10^7 kPa) and E_3 = 20,000 psi (137,800 kPa), an increase in the AC surface modulus E_1 from $1\text{x}10^5$ to $12\text{x}10^5$ psi (6.89×10^5 to 8.28×10^6 kPa) resulted in a decrease in concrete tensile stress from 109 to 82 psi (751 to 564 kPa). This resulted in an increase in predicted stress repetitions to failure from 6,450,000 to 16,100,000.

As indicated by the composite pavement experiment, the modulus of elasticity E_2 for the rigid layer is the most sensitive material property. For an increase of E_2 from $5\text{x}10^5$ to $30\text{x}10^5$ psi (3.45×10^6 to 2.07×10^7 kPa), predicted concrete tensile stresses increase around 100 percent while N_f increases around 1,800 to 3,000 percent. This approximates a difference between cement treated base and a weak PCC. A high quality PCC having an elastic modulus of 60×10^5 psi (4.14×10^7 kPa) would offer four to five times as much fatigue life as the weak PCC.

The use of two levels of K_1 in the fatigue relationship in effect amounts to multiplying the lower value of N_f by 4.52 to obtain the higher value as the exponent K_2 was held constant. This represents a reasonable range of fatigue life potential based on relationships developed from field data and is only useful for indicating relative change that may result from considering this important material property.

JOINTED REINFORCED CONCRETE PAVEMENTS

TABLE 4-5 lists the distresses to be studied for JRCP. As indicated, faulting, joint spalling, and "D" cracking will be studied separately from the primary factorial. Thermal and shrinkage cracking distress will be studied with Program JRCP-2 and fatigue cracking will be studied with the modified ELSYM5 model.

Thermal and Shrinkage Cracking

A brief sensitivity analysis was conducted on the JRCP-2 model to test the impact of several material properties on JRCP. The three material properties tested were concrete tensile strength, concrete thermal coefficient, and the concrete shrinkage coefficient. The three levels of values considered for each of these material properties are given in TABLE 5-5. Also shown in the table are predicted results obtained from the analysis using the JRCP-2 model. To limit the number of computer runs, one parameter at a time was varied from low to high values with all other parameters held at the medium levels.

The responses of JRCP due to changes in concrete tensile strength are plotted in FIGURE 5-4a. The steel stress at the crack, the crack width, and the joint width remain essentially constant for all three levels of concrete tensile strength. This would not be logical for prediction of crack occurrence since concrete tensile strength controls the formation of transverse cracks, but is logical for this case because of the assumption that a crack already exists necessitated by present inability of the model to predict formation of cracks.

The effects of varying the concrete thermal coefficient are plotted in FIGURE 5-4b. While crack width and joint width show a significant increase for increases in concrete thermal coefficient, steel stress at the joint does not appear to be affected by the movement of the slab. This is not reasonable as the steel is being strained as the joint opens.

FIGURE 5-4c shows an increase in all three responses as the shrinkage coefficient increases from the low to the medium level. For the high level shrinkage coefficient, however, the JRC slab movement exceeded that required to develop the maximum friction coefficient, which caused sliding of the JRC slab. The sliding of the slab will maintain a constant concrete stress while the crack width, joint width, and steel stress increase. The JRCP-2 model predicted, however, that the steel stress and crack width both approached zero, which implies that the crack closed. This also does not appear to be reasonable.

As discussed in Chapter 4, this model is currently not working properly and the developing agency is attempting to correct the deficiencies.

Fatigue Cracking

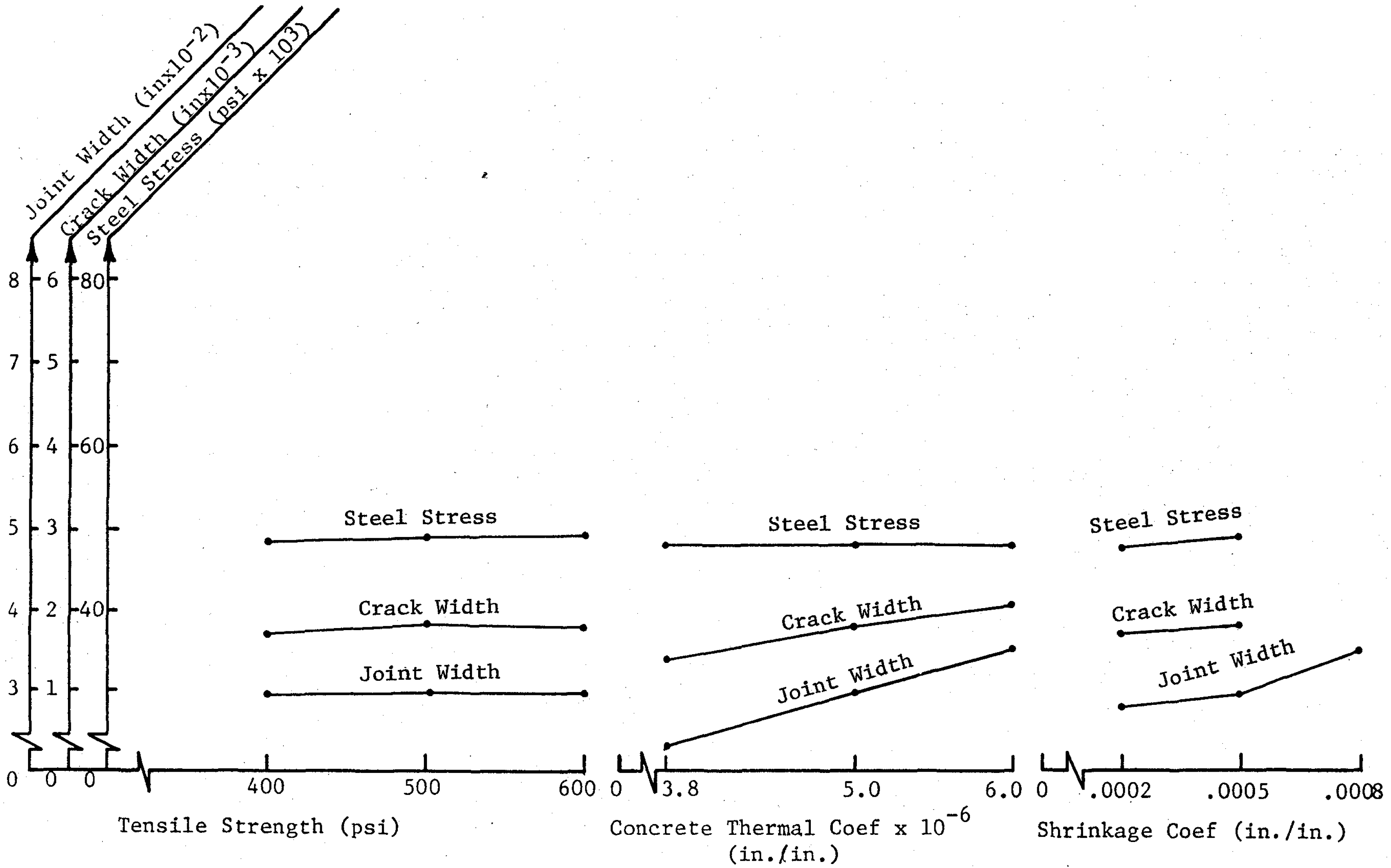
FIGURE 5-5 shows a typical rigid pavement with constant input magnitudes identified and variable input properties designated. A preliminary sensitivity analysis was conducted for this pavement with variables at the levels of input magnitudes shown in TABLE 5-6.

The variables tested for rigid pavements were three levels of PCC surface layer elastic modulus E_1, three levels of subbase elastic modulus E_2, and two levels of fatigue life potential introduced by varying the multiplier K_1. As for the composite pavement study, the flexural strength of the PCC is also varied with modulus of elasticity of the PCC.

TABLE 5-5. RANGE OF VALUES FOR THE MATERIAL PROPERTIES CONSIDERED AND THE OUTPUT OBTAINED FROM JRCP-2 COMPUTED MODEL.

Conc. Shrinkage Coef. (in./in.)	Conc. Thermal Coef.x10^{-6}(in/in)	Conc. Tensile Strength (PSI)	PREDICTED RESPONSES		
			Steel Stress (psix10^3)	Crack Width (in.)	Joint Width (in.)
.0002	3.8	400			
		500			
		600			
	5.0	400			
		500	47.4	.0017	.0279
		600			
	6.0	400			
		500			
		600			
.0005	3.8	400			
		500	48.8	.00137	.0233
		600			
	5.0	400	48.3	.0017	.0296
		500	48.8	.0017	.0296
		600	49.2	.0018	.0298
	6.0	400			
		500	48.8	.0021	.0350
		600			
.0008	3.8	400			
		500			
		600			
	5.0	400			
		500	--	--	.0350
		600			
	6.0	400			
		500			
		600			

1 psi = 6.89 kPa
1 in = .0254 m



1 psi = 6.89 Kpa
1 in = .0254 m

(a) (b) (c)

FIGURE 5-4. PRELIMINARY SENSITIVITY ANALYSIS ON JOINTED REINFORCED CONCRETE PAVEMENT BASED ON JRCP-2 MODEL.

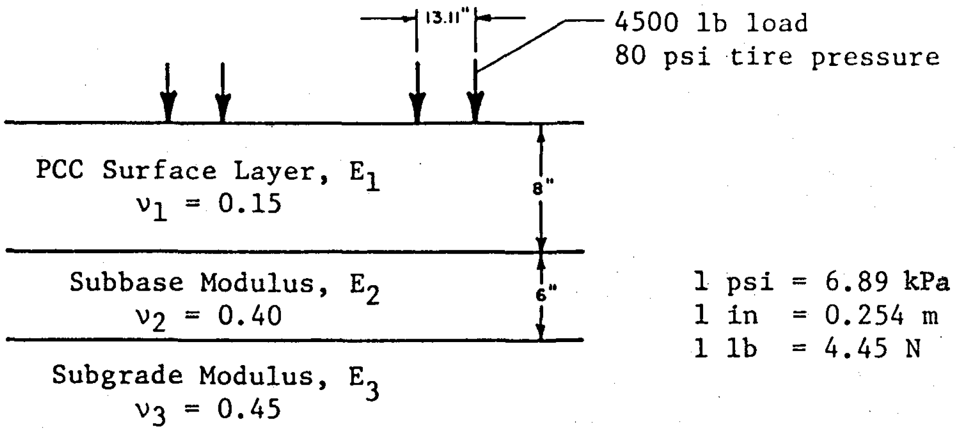


FIGURE 5-5. TYPICAL RIGID PAVEMENT FOR ANALYSIS

TABLE 5-6. PRELIMINARY SENSITIVITY ANALYSIS FOR FATIGUE CRACKING IN RIGID PAVEMENTS USING THE ELSYM5 MODEL AND THE FATIGUE RELATIONSHIP $N_F=K_1 \left(\frac{\text{FLEXURAL STRENGTH}}{\text{CONCRETE STRESS}}\right)$

Fatigue Coefficient K_1	Subbace Modulus, E_2x10^5	PCC Surface Modulus, E_1, PSI: 30×10^5	45×10^5	60×10^5
K_1=106,000	0.3	125/4.16x10^{*6}	138/11.1x10^6	148/22.36x10^6
	1.0	111/6.08x10^6	127/14.5x10^6	137/28.65x10^6
	5.0	67/30.7x10^6	87/48.9x10^6	102/73.86x10^6
K_1=23,440	0.3	.919x10^6	2.46x10^6	4.94x10^6
	1.0	1.35 x10^6	3.21x10^6	6.34x10^6
	5.0	8.80 x10^6	10.81x10^6	16.33x10^6

*LEGEND

Principal stress in PSI	No. of Application to failure

TABLE 5-6 shows the range of values tested, the stresses calculated, and the values of N_f predicted. Review of these results indicates that the modulus of elasticity for both the PCC surface and the subbase significantly affect the fatigue life predictions for the rigid pavement.

JOINTED CONCRETE PAVEMENT

TABLE 4-6 lists the distresses found to be significant for JCP. Joint faulting will be studied separate from the primary factorial and "D" cracking, joint spalling and fatigue cracking will be studied concurrently with these same distresses for JRCP. Although a preliminary sensitivity analysis has already been presented for fatigue cracking of rigid pavements as a group in the JRCP section above, a second study of fatigue cracking using Program JCP-1 is also discussed briefly below.

JCP-1 Fatigue Cracking Study

During investigations of the models for the analyses of the distresses for JCP, the JCP-1 computer program developed by Darter and Barenberg (Reference 10) for Zero Maintenance Jointed Concrete Pavement was reviewed. With the aid of a programmable calculator, a brief sensitivity analysis based on the regression equations appearing in the JCP-1 model was carried out to investigate the importance of different material properties to fatigue cracking as predicted by this model.

The primary variables included in this study were three levels each of slab thickness, modulus of subgrade reaction k, and concrete modulus of rupture. Values of slab thickness and the two material properties appeared in TABLE 5-7.

The total number of allowable load applications, N_{ijk}, was computed by the following fatigue equation for each case:

$$\log N_{ijk} = 16.61 - 17.61 \left(\frac{\sigma_{tot}}{F}\right)$$

where:

F = modulus of rupture of PCC

$\sigma_{tot} = \sigma_{load} + R\,\sigma_{curling}$

R = adjustment factor for curling stress so that it can be combined with the load stress.

The curling stress $\sigma_{curling}$ and the load induced stress σ_{load} are normally calculated by regression equations from the computer program. These equations were based on regressions of results obtained using the finite element model developed by Huang and Wang (Reference 27). For

TABLE 5-7. PREDICTED FATIGUE LIFE FROM JCP-1 REGRESSION EQUATION IN MILLIONS OF 18-KIP ESAL.

Flexural Strength, psi	k, pci	Thickness, Inches 8	10	12
500	100	0.02	119.	22,244.
	300	1.45	1,563.	115,076.
	500	11.00	5,591.	271,070.
700	100	67.00	32,568.	1,369,563.
	300	1,400.00	205,488.	4,430,132.
	500	6,007.00	511,280.	8,169,621.
900	100	6,014.00	737,503.	13,510,608.
	300	63,809.00	3,089,903.	33,667,663.
	500	198,021.00	6,278,356.	54,191,953.

1 in. = 0.0254 m
1 pci = 271.5 Kpa/m
1 psi = 6.89 Kpa
18-Kip ESAL = 80 kN ESAL

TABLE 5-8. RESULTS IN TABLE 5-7 NORMALIZED BY 18-KIP ESAL FOR A FLEXURAL STRENGTH OF 500 PSI.

Flexural Strength, psi	k, pci	Thickness, Inches 8	10	12
500	100	1.00	1.00	1.00
	300	1.00	1.00	1.00
	500	1.00	1.00	1.00
700	100	3360.00	275.00	62.00
	300	966.00	132.00	38.00
	500	541.00	91.00	30.00
900	100	300695.00	6218.00	607.00
	300	44006.00	1977.00	293.00
	500	17840.00	1121.00	200.00

simplification, ERODABILITY was assumed zero (no void at the edge of the slab) and the effects of the curling stresses were omitted since the direct superposition of curling stresses and wheel-load induced stresses is controversial.

The numbers of 18-kip (80 kN) ESAL to failure calculated using the fatigue equation appear in TABLE 5-7. The calculated 18-kip (80 kN) ESAL to failure ranged over 54 trillion, which is considered to be much too high. This is partially due to omission of the curling stress and the term ERODABILITY, but is also greatly increased by the fatigue relationship developed from evaluating laboratory beam tests. For a 12-inch (0.30 m) slab with 12 inches (0.30 m) of erosion, the number of 18-kip (80 kN) ESAL to failure for a modulus of subgrade reaction k of 500 pci (135,250 kPa per m) and for flexural strength of 500 psi (3,450 kPa), will be 1.9 million instead of 271 billion shown in TABLE 5-7.

TABLE 5-8 shows the effect of flexural strength on the load applications to cracking. The results were normalized with respect to 18-kip (80 kN) ESAL for a flexural strength of 500 psi (3,450 kPa). For an increase in flexural strength from 500 to 700 psi (3,450 to 4,830 kPa), while k is held constant at 100 pci (27,150 kPa/m), the number of applications are 3360, 275, and 62 times greater for 8, 10, and 12 inch (0.2, 0.25, and 0.3 m) slabs, respectively. For an increase in flexural strength from 700 to 900 psi (4,830 to 6,210 kPa), while k is held constant at 100 pci (27,150 kPa/m), the number of load applications are 90, 23, and 10 times greater for 8, 10, and 12 (0.2, 0.25 and 0.3 m) inch slabs, respectively. This indicates that the flexural strength has a strong influence on the fatigue life of JCP slabs, it is more influential for thinner slabs than for thicker slabs, and the effect on allowable load applications is much greater at lower levels of flexural strength than at the higher levels.

The results in TABLE 5-7 have also been normalized with respect to 18-kip (80 kN) ESAL for a k-value of 100 pci (27,150 kPa/m) in TABLE 5-9 and with respect to a slab thickness of 8 inches in TABLE 5-10. As can be seen, fatigue life is very sensitive to a change in the modulus of subgrade reaction for weaker or thin slabs and less sensitive for strong or thick slabs. It is very sensitive to slab thickness for a weak concrete or subbase, but less sensitive for a stronger concrete or subbase.

In summary, this study indicates that concrete flexural strength and the modulus of subgrade reaction k have a significant effect on predictions of fatigue cracking in rigid pavements using Program JCP-1. The importance of k also implies that material properties affecting its magnitude, including moduli of elasticity for the subbase and subgrade would also be important. It should be noted that the modulus of elasticity E_1 of the PCC does not appear in the JCP-1 regression model for distress, but this may be because of the correlation between E_1 and the flexural strength.

TABLE 5-9. RESULTS IN TABLE 5-7 NORMALIZED BY 18-KIP ESAL FOR A MODULUS OF SUBGRADE REACTION k OF 100 PCI.

Flexural Strength, psi	k, pci	Thickness, Inches 8	10	12
500	100	1.00	1.00	1.00
	300	72.5	13.1	5.2
	500	550.0	47.0	12.2
700	100	1.00	1.00	1.00
	300	20.9	6.3	3.2
	500	89.7	15.7	6.0
900	100	1.00	1.00	1.00
	300	10.6	4.2	2.5
	500	32.9	8.5	4.0

1 in. = 0.0254 m
1 pci = 271.5 kPa/m
1 psi = 6.89 kPa
18-Kip ESAL = 80 kN ESAL

TABLE 5-10. RESULTS IN TABLE 5-7 NORMALIZED BY 18-KIP ESAL FOR A SLAB THICKNESS OF 8 INCHES.

Flexural Strength, psi	k, pci	Thickness, Inches 8	10	12
500	100	1.00	5950.	1112200.
	300	1.00	1078.	79363.
	500	1.00	508.	24643.
700	100	1.00	486.	20441.
	300	1.00	147.	3164.
	500	1.00	85.	1360.
900	100	1.00	123.	2247.
	300	1.00	48.	528.
	500	1.00	32.	274.

CONTINUOUSLY REINFORCED CONCRETE PAVEMENT

The five major distresses found in CRCP were listed in TABLE 4-7. As shown, fatigue cracking for CRCP will be studied concurrently with JRC pavement.

Spacing of transverse cracks that occur in continuously reinforced concrete pavement is perhaps the most important variable affecting the behavior of the pavement. Relatively large distances between cracks result in a higher accumulation of drag forces from the subgrade due to frictional resistance, thus producing high steel stress at the crack and wide crack widths. Closer crack spacing reduces the frictional restraint, and thus reduces the steel stress and the crack width. In general, wider cracks suffer crack spalling while close crack spacing induces punchouts. As narrow cracks and close crack spacing are negatively correlated, they must be optimized.

Thermal and Shrinkage Cracking

A brief sensitivity analysis on different material properties for CRC pavement was conducted using the CRCP-2 computer model. The primary variables included were three levels of concrete tensile strength, three levels of concrete shrinkage coefficient, and three levels of thermal coefficient ratio between the concrete and the steel reinforcement. To limit the number of computer runs, medium levels for all parameters were used, except for one parameter that was varied from low to high values.

The results from the sensitivity analysis in TABLE 5-11 show that the pavement responses were sensitive to the concrete strength. A 28 percent increase in tensile strength doubled the crack width prediction and increased the steel stress predicted by 35 percent. Crack width only changed 8 percent when the thermal coefficient of contraction for the concrete was varied from a low of 4.8×10^{-6} in./in. to a high of 7.2×10^{-6} in./in., indicating that predicted pavement responses are probably not very sensitive to the thermal coefficient property.

Changes in the shrinkage produced greater effects on the pavement responses, especially at the high level. An increase of 25 percent from a medium shrinkage coefficient of .0004 to a high of .0005 decreased the calculated crack width from 0.07 to 0.055 inch (1.78 to 1.40 mm). FIGURE 5-6 shows plots for calculated crack spacing as a function of steel stress follow the same general trend of decreases with increases in the coefficient of thermal contraction and shrinkage coefficint in the concrete, but both increased with an increase in concrete tensile strength.

In summary, this study indicates that the concrete tensile strength and the drying shrinkage coefficient are the two most important material properties affecting the CRCP behavior as predicted by Program CRCP-2.

TABLE 5-11. CRACK SPACING, CRACK WIDTH AND STEEL STRESS PREDICTED BY CRCP-2 COMPUTER PROGRAM FOR A PRELIMINARY SENSITIVITY ON STRENGTH, SHRINKAGE COEFFICIENT AND THERMAL COEFFICIENT PROPERTIES FOR CRC PAVEMENT.

Factorial for Sensitivity Analysis			CRCP-2 RESULTS		
Tensile Strength, psi	Shrinkage Coefficient, in./in.	Thermal Coef. Ratio (α_c/α_s)*	Crack - Spacing, ft.	Crack - Width, in.	Steel - Stress, psi
335.0	.0003	0.8	-	-	-
		1.0	-	-	-
		1.2	-	-	-
	.0004	0.8	-	-	-
		1.0	4.6	.035	61800.
		1.2	-	-	-
	.0005	0.8	-	-	-
		1.0	-	-	-
		1.2	-	-	-
469.0	.0003	0.8	-	-	-
		1.0	12.3	.078	103900.
		1.2	-	-	-
	.0004	0.8	9.8	.068	94800.
		1.0	9.2	.070	94900.
		1.2	7.3	.062	86000.
	.0005	0.8	-	-	-
		1.0	6.2	.055	78700.
		1.2	-	-	-
603.0	.0003	0.8	-	-	-
		1.0	-	-	-
		1.2	-	-	-
	.0004	0.8	-	-	-
		1.0	14.8	.116	127400.
		1.2	-	-	-
	.0005	0.8	-	-	-
		1.0	-	-	-
		1.2	-	-	-

* Steel thermal coefficient of contraction is fixed at 6×10^{-6} in./in., while concrete thermal coefficient of contraction varies from 4.8×10^{-6} to 7.2×10^{-6}.

1 psi = 6.89 kPa
1 ft. = 0.305 m
1 in. = 0.025 m

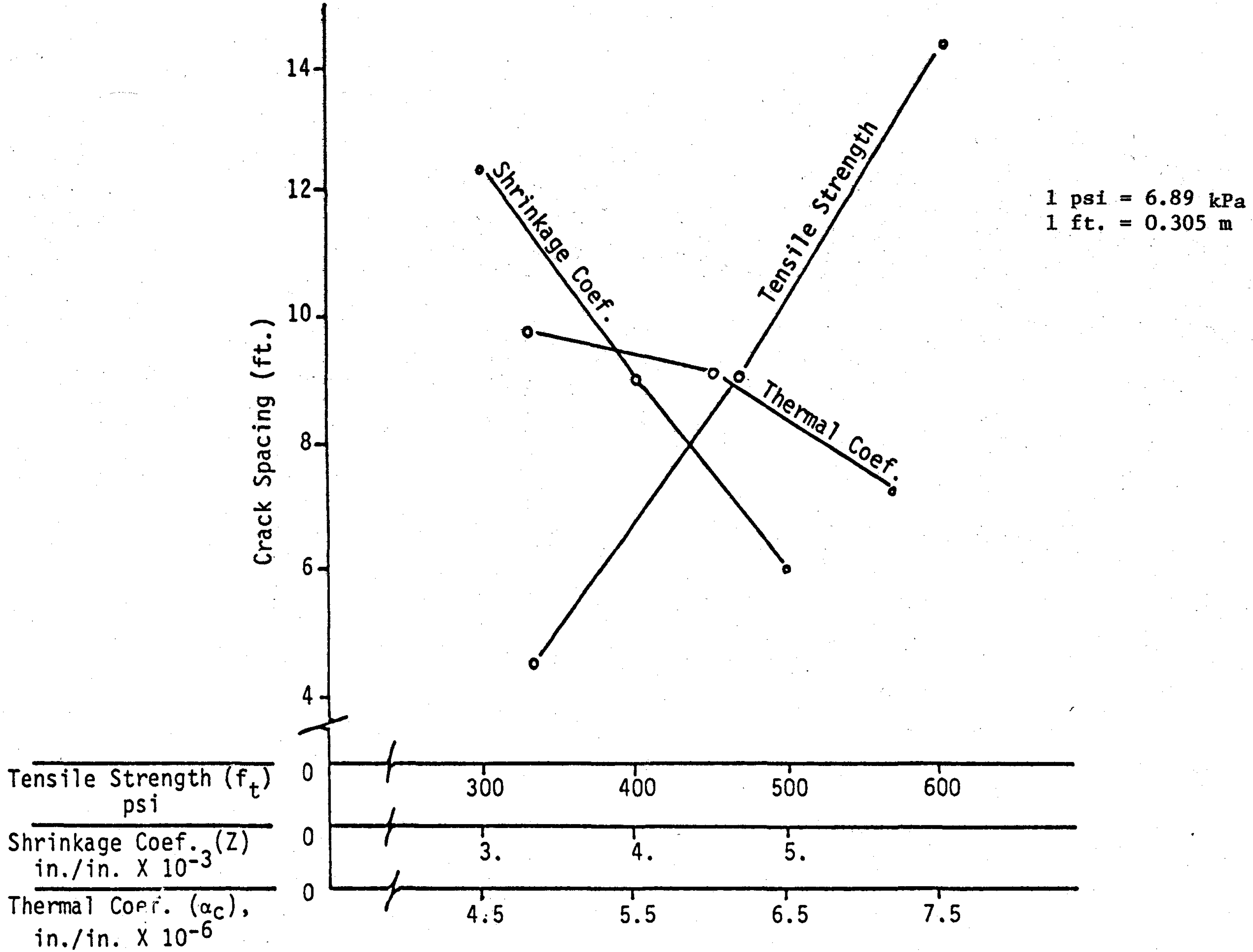


FIGURE 5-6. CRACK SPACING PREDICTED BY CRCP-2 MODEL FOR A PRELIMINARY SENSITIVITY ON CONCRETE STRENGTH, SHRINKAGE COEFFICIENT AND THERMAL COEFFICIENT PROPERTIES FOR CRC PAVEMENT.

SUMMARY

In this chapter, the models described in Chapter 4 were exercised with selected values of material properties input at high and low values of their practical ranges while other parameters were held constant at a median value. The calculated distresses or responses were either plotted or tabulated as functions of the particular material property of interest so that the importance of each material property can be observed.

The exercise of these models offered opportunity to become familiar with their use and the organized factorial studies allowed evaluation of their predictive abilities. In general, the results of the preliminary sensitivity analyses were consistent with the significance assigned to the material properties selected.

CHAPTER 6. SUMMARY OF WORK ACCOMPLISHED AND RECOMMENDATIONS FOR SUBSEQUENT TASKS

The purpose of this chapter is to summarize the work completed in Task A, "Model Selection," and to provide recommendations for accomplishing the remaining work in Tasks B and C of this project.

SUMMARY OF TASK A WORK

Task A has been discussed in detail in the previous chapters of this report. Chapter 2 includes definitions of terms for use in the project and concepts for considering pavement structures and pavement models within the framework of these definitions. Chapter 3 includes results of a detailed study to identify distresses that occur in the various types of pavements and the related material properties that have a significant effect upon these distresses, the distresses of primary significance to be considered subsequently in this project, the material properties which sufficiently effect these distresses to warrant further consideration, and the distresses that are readily controllable through good design. Chapter 4 includes the various pavement response and distress models that were considered for possible use in this project, reviews their capabilities and limitations, and identifies those models selected for use in subsequent studies. Chapter 5 provides the results of preliminary sensitivity analyses utilizing the selected models and other models studied during Task A, but not selected for subsequent use.

The final subtask to complete Task A is the proposed "Plan and Recommendations" for conducting the remainder of the project. These recommendations are provided below.

PROPOSED RESEARCH APPROACH

The various subtasks in Tasks B and C have been discussed previously in Chapter 1 and the proposed research approach for their completion is described below.

Task B, Model Utilization

TABLES 4-3 through 4-7 identify nine initial study factorials to be accomplished utilizing six different distress models and requiring a total of 272 solutions. This factorial of solutions will represent only conventional materials and will be followed by more limited initial factorials for "nonconventional" materials available but not in common use, and by secondary studies of both conventional and nonconventional material properties. The results of these factorials will be analyzed to determine the general effects of specific material properties on specific distresses and the zero maintenance potential for both conventional materials and nonconventional materials. Although an accurate estimate may not be made at this time, it is expected that 550 to 700 solutions will be required to create the data base required to meet the analytical goals for Tasks B and C.

FIGURE 6-1 illustrates the nature of the proposed initial study factorials. For this typical case, a full factorial study is planned including the four environmental zones and low and high levels of the elastic modulus of the portland cement concrete, elastic modulus of the subbase material, and the fatigue life characteristics of the portland cement concrete. That this factorial will provide the effects of the variables on only one specific distress and pavement type. For each type of pavement, there will be from one to three such factorials, each representing a particular distress. There will also be other separate studies such as that required for the evaluation of reduced skid resistance as proposed for flexible pavements in TABLE 4-3.

FIGURE 6-2 provides a flow diagram for study of one specific distress for one specific pavement type and also serves to illustrate the basic research approach proposed. Two specific studies are proposed, one for conventional and one for nonconventional materials. The one for conventional materials will be conducted first and the output from its initial factorial solutions used as background for structuring the initial factorial solutions for nonconventional materials. A specific level of traffic will be selected in terms of 18-kip (80 kN) equivalent single axle loads and a specific set of layer thicknesses will also be used for each pavement type.

The results of the initial solutions will be analyzed and specific secondary factorials established to provide additional data required. The results from initial factorial studies and the subsequent secondary factorial studies will be analyzed to arrive at the zero maintenance potential of specific conventional and nonconventional materials for specific distresses. The study results will also be used for a general analysis of specific material properties to determine their effects on specific distresses. Results will be accumulated for each combination of distress and pavement type considered.

The results of the factorial studies illustrated in FIGURE 6-2 and other studies described above are used as shown in the flow diagram, FIGURE 6-3, for the analysis of specific materials to determine their zero maintenance potential. This will require that the material properties be matched as closely as possible to the input material properties in the analytical studies and the probable levels of distresses predicted. For these levels of distresses, the probable maintenance requirements will be compared with the maintenance goals for zero maintenance pavements to evaluate the zero maintenance potential for specific materials. The results from the individual distress studies will then serve as a data bank for further optimization studies in Task C.

Having provided a brief overview of the proposed research plan, activities from several of the blocks in FIGURES 6-2 and 6-3 will be discussed in more detail below.

	Environmental Zones	Wet-Freeze		Dry-Freeze		Wet-No Freeze		Dry-No Freeze	
	Elastic Modulus of PCC	Low	High	Low	High	Low	High	Low	High
Fatigue Life Potential of PCC	Elastic Modulus of Subbase								
Low	Low	X	X	X	X	X	X	X	X
	High	X	X	X	X	X	X	X	X
High	Low	X	X	X	X	X	X	X	X
	High	X	X	X	X	X	X	X	X

FIGURE 6-1. EXAMPLE OF INITIAL STUDY FACTORIAL FOR A SPECIFIC DISTRESS PAVEMENT TYPE (FATIGUE CRACKING FOR RIGID PAVEMENTS IN THIS CASE).

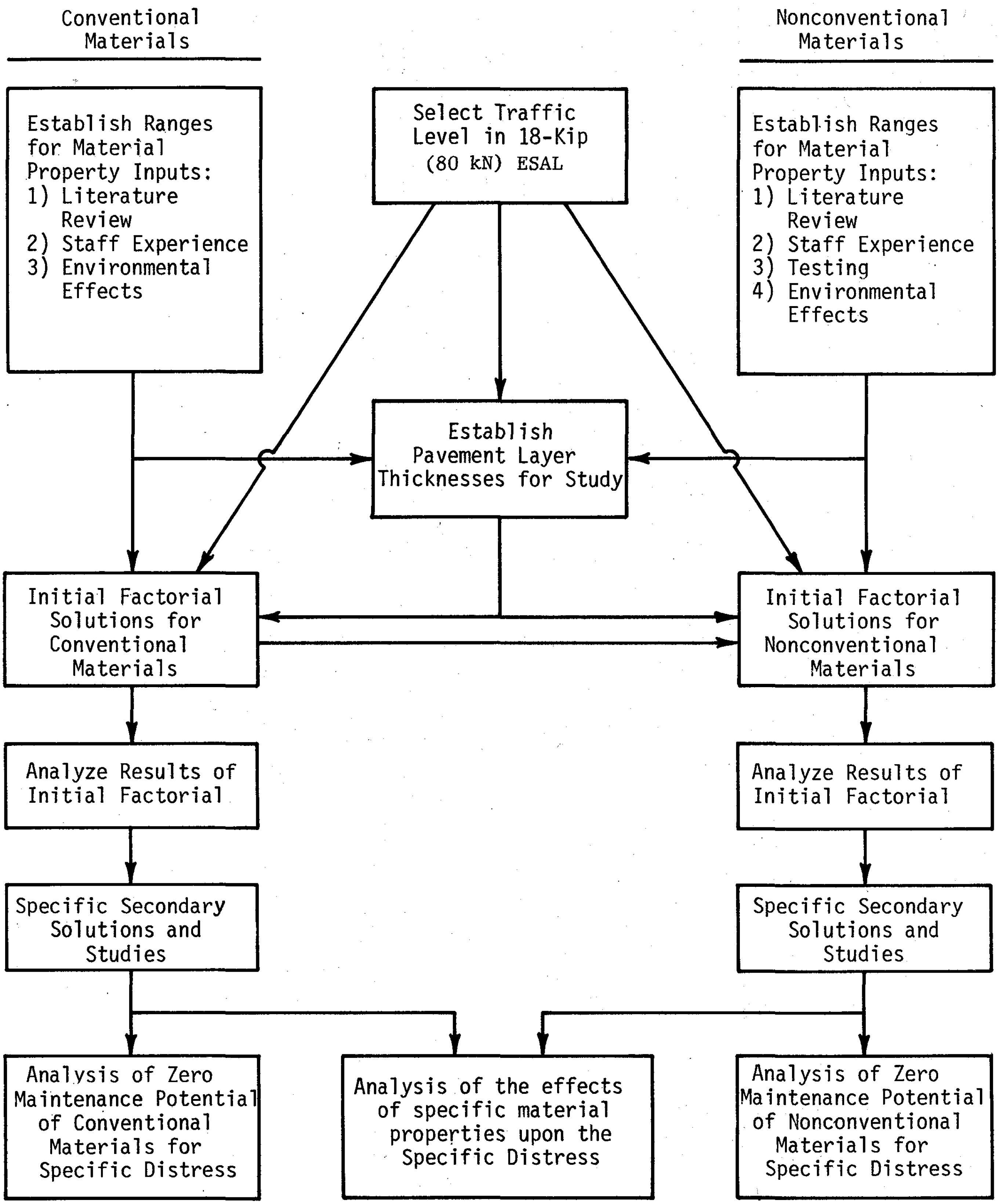


FIGURE 6-2. FLOW DIAGRAM FOR STUDY OF A SPECIFIC DISTRESS AND PAVEMENT TYPE.

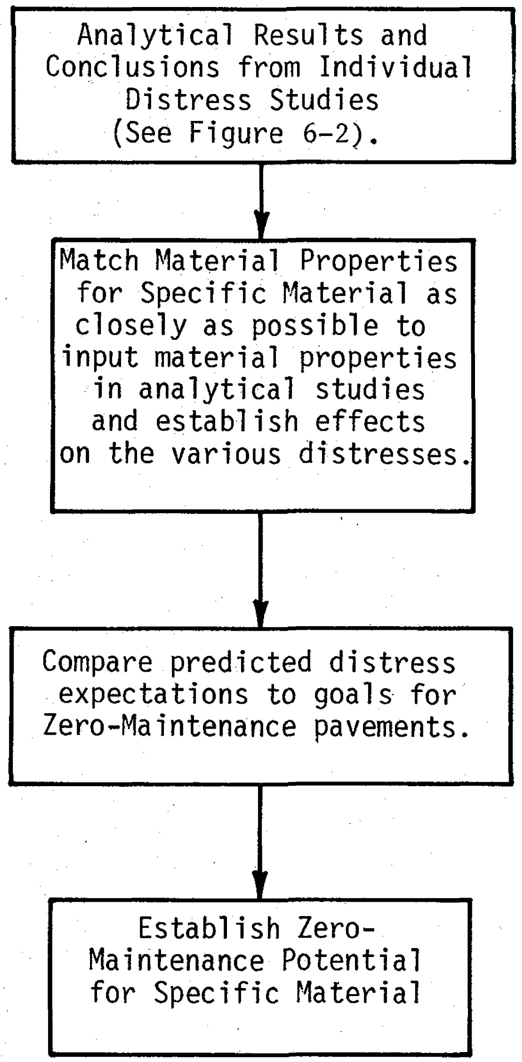


FIGURE 6-3. FLOW DIAGRAM FOR ANALYSIS OF A SPECIFIC MATERIAL TO DETERMINE THE ZERO-MAINTENANCE POTENTIAL.

Establishing Ranges for Material Property Inputs. Because of the interactions between the material properties considered, the results of this study will be greatly affected by the ranges of input values selected for individual material properties. The ranges selected are a function of the variability that may be expected. Two types of variability commonly considered are:

1. The within-project variability associated with variations about the mean magnitudes of material properties within the same pavement section. This variability is primarily due to inadequate quality control during construction and is found in most in service pavements.

2. The between-project variability associated with variability between magnitudes of material properties for different pavement sections or projects. This variability includes differences in design, in material from different sources, in construction equipment and procedures, and in environmental effects on the materials.

The "within-project" and "between-project" variabilities are for this project accompanied by what will be called a "between-materials" variation. This latter variation is a primary reason for considering conventional and nonconventional materials separately. The broad ranges of material input values that might be required to include all available materials could result in invalidation of the results of the factorial studies. Some difficult decisions on ranges of input value will be required and the validity of these decisions will depend heavily upon the project staff experience in using sensitivity analyses and other parametric studies.

The ability to select ranges of material property input values depends upon knowledge of the variation of real material properties under field conditions. The project staff will draw on its experience and literature reviews to establish the ranges for material property input values for conventional materials. For nonconventional materials, this may not suffice.

A detailed study of potential candidates for zero maintenance paving materials has been conducted by Hoff et al (Reference 60[1]) and the results of this study are summarized in TABLES 6-1 and 6-2 for flexible and rigid pavements, respectively. Considerable information on values of material properties appears in this reference, but review of these tables indicates

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[1] Hoff, G.C., L.N. Godwin, K.L. Sancian, A.D. Buck, T.B. Husbands and K. Mather, "Identification of Candidate Zero Maintenance Paving Materials," Report No. FHWA-RD-77-109, U.S. Army Engineer Waterways Experiement Station, May 1977.

TABLE 6-1. COMPARISON OF CHARACTERISTICS OF ASPHALT BASED MATERIALS TO THOSE OF ASPHALT CONCRETE (REFERENCE 60).

Characteristic	Gussasphalt	Asbestos Asphalts	Sulfur Modified Asphalts
Temperature dependency	NC*	NC	NC
Compressive strength	P-G	G	NA
Marshall stability	NA	NC	G
Flexural strength	NA	G	NC
Tensile strength	P-G	G	VG
Dimensional changes	NA	NA	NA
Durability	G	G	NA
Abrasion resistance	G	NA	NA
Toughness	NA	G	NA
Fatigue strength	NA	G	P-G
Dyanmic response	NA	NA	NA
Permeability	G	NC	G
Ease of construction	NC	NC	P
Ease of maintenance	NC	NC	NC
Environmental compatibility	NC	P	P
Availability	P	P	NC
Cost	P	P	P

---

* P = Poor.
NC = No change.
NA = Not available.
G = Good.
VG = Very good.

TABLE 6-2. COMPARISON OF CHARACTERISTICS OF SPECIAL CONCRETES AND RIGID BINDER SYSTEMS TO THOSE OF PORTLAND CEMENT CONCRETE (REFERENCE 60).

	Noncalcareous Inorganic Cements			Polymers in Concrete		
Characteristics	Sulfur Concrete	Sulfur Infiltrated Concrete	Phosphate Cements	Polymer Impregnated Concrete	Polymer-Portland Cement Concrete	Polymer Concrete
Compressive strength	NC*	VG	NC	G-VG	P-NC	G-VG
Flexural strength	NC	NA	NC	G-VG	G	VG
Tensile strength	NA	NA	NC	G-VG	G	G-VG
Modulus of elasticity	NC	G	NC	NC-G	NA	NA
Dimensional changes	P	NA	NC	P-NC	P-NC	P
Durability	P	G	NA	G	VG	G
Abrasion resistance	NA	NA	NC	NC	G	NA
Toughness	NA	NA	NC	NC	G	P-G
Impact resistance	NA	NA	NC	NA	NA	NA
Fatigue strength	NA	NA	NC	NA	NA	NA
Dynamic response	NA	NA	NC	NA	NA	NC
Permeability	VG	VG	NC	VG	P-G	VG
Ease of maintenance	NC	NC	NC	P	NC	NC
Ease of construction	NC	P	P	P	NC	P
Environmental compatibility	P	P	P	P	NC	NA
Availability	NC	NC	P	NC	NC	NC
Cost	NA	NA	P	P	P	P

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* P = Poor.
NC = No change.
NA = Not available.
G = Good.
VG = Very good.

TABLE 6-2. COMPARISON OF CHARACTERISTICS OF SPECIAL CONCRETES AND RIGID BINDER SYSTEMS TO THOSE OF PORTLAND CEMENT CONCRETE (continued)

			Ceramic Materials			Sealants
Characteristic	Expansive Cement Concrete	Fiber Reinforced Concrete	Calcined Bauxite	Prestressed** Concrete	Vacuum Processed Concrete	Internally Sealed Concrete
Compressive strength	NC	NC-G	G*	--	G	NC
Flexural strength	NC	VG	G	--	G	NA
Tensile strength	NC	NC-G	NC	--	G	NA
Modulus of elasticity	NC	NC	NA	--	NA	G
Dimensional changes	NC-G	NC	NC	--	G	NA
Durability	P-NC	NC-G	NC	--	G	NA
Abrasion resistance	NC	G	G	--	VG	NA
Toughness	NC	VG	NA	--	NA	NA
Impact resistance	NC	VG	NA	--	NA	NA
Fatigue strength	NA	G	NA	--	NA	NA
Dynamic response	NC	NC	NA	--	NA	NA
Permeability	G	NC	NC	--	G	G
Ease of maintenance	NC	P	NC	P	NC	NC
Ease of construction	NC	P	NC	P	P	P
Environmental compatibility	NC	NC	NC	NC	NC	NC
Availability	NC	NC	P	NC	P	NC
Cost	NC	P	P	NC	NC	P

** Comparisons not possible.

TABLE 6-3. MATERIAL PROPERTY VALUES NOT AVAILABLE FOR NONCONVENTIONAL MATERIALS (REFERENCE 60).

Material Property	Type of Rigid Material Data Not Available
Tensile Strength	Sulpher Concrete Sulfur Infiltrated Concrete
Modulus of Elasticity	Polymer - PCC Polymer Concrete Vacuum Processed Concrete
Flexural Strength	Sulphur Infiltrated Concrete
Fatigue Relationship	Sulphur Concrete Sulphur Infiltrated Concrete Polymer Impregnated Concrete Polymer - PCC Polymer Concrete Vacuum Processed Concrete
Volume Change (Thermal and Shrinkage)	Sulfur Infiltrated

that much of the information required is not available (See TABLE 6-3 for data reported by Hoff et al as not available). While more material is available for sulphur asphalt, the only known information for the permanent deformation characteristics of this material is a very limited amount in Reference 61[1]. It is very probable that additional data may be obtained from the results of continuing studies on nonconventional materials. However, it is probable that some of the material property inputs necessary for the evaluation of promising nonconventional materials will not be available, especially materials subject to permanent deformation. It is expected that limited testing may be required for such materials and hoped that samples of these materials may be obtained from their developers.

Selecting Traffic Level for Study. One level of traffic will be used for all of the factorial and secondary studies.

This decision was made because:

1. More variables in the study factorials than those shown in TABLES 4-3 through 4-7 would increase the factorials to sizes manageable only through fractional factorial techniques and would tend to detract from the clarity of direct comparisons of the effects of the material properties.
2. Variability in traffic levels are not necessary to the study of material property effects. The traffic level selected will be based on traffic predictions for heavily-trafficked expressways at an appropriate time in the future.

Establishment of Pavement Layer Thicknesses. It is believed that it will be necessary to also establish single pavement thickness designs for each type of pavement for use throughout the factorial. The reasons for this are the same as those cited above for traffic level, but appear on the surface to be more artificial since pavement thickness design is inherently dependent on material properties. However, variation in thicknesses of layers would make direct comparisons of the effects of material properties on the distress more difficult. In developing a set of optimum material properties required to resist all distresses for Task C, it may be necessary to consider additional layer thicknesses in a series of secondary studies.

Analytical Results and Conclusions from Individual Distress Studies. It can be readily seen how the analytical results are accumulated for each distress as shown in FIGURE 6-2. The result will be a body of information representing the utilization of the analytical models. In addition, these

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[1] Lytton, R.L., D. Saylak and D.E. Pickett, "Prediction of Sulphur-Asphalt Pavement Performance with VESYS IIM," Proceedings, Fourth International Conference on the Structural Design of Asphalt Pavements, Vol. I, August 1977.

results must also include output from separate studies identified in TABLES 4-3 through 4-7. As discussed previously, these distresses for which mathematical distress models do not exist will be studied separately and such studies combined with that of the mathematical studies in order to more completely assess the zero maintenance potential of the various materials.

Establishing Zero Maintenance Potential for Specific Materials. Establishment of the zero maintenance potential for a specific material involves a comparison of that material's properties with the properties used in the study factorials to arrive at approximate predictions of distress and the comparison of those predictions to the goals for zero maintenance pavements. To the extent possible, the values of material property inputs selected for initial study factorials will approximate those for specific materials to simplify this evaluation. There should be sufficient information from the hundreds of solutions conducted to allow suitable accuracy in this matching and comparison process. If not, for specific cases, limited additional solutions may be made.

Summary of Research Approach for Task B. The research approach for Task B will involve separate considerations of conventional and nonconventional materials in successive factorial studies to provide a data base for assessing both the zero maintenance potential of various materials and the general effects of the various material properties on distresses. In order to design the factorial studies, detailed studies of ranges of material property input values and some difficult decisions must be made. The results from the Task B studies will provide data for use in the evaluations of the zero maintenance potential for both conventional and nonconventional materials for the various types of pavements and a data base for study of the more general effects of specific material properties on the various distresses. The data used in this analysis will be utilized then in Task C for optimization of material properties.

Task C, Optimization of Material Properties

The several subtasks in Task C have been discussed in Chapter 1. The two specific objectives of this task are the selection of optimum materials properties and their verification. The proposed approaches for accomplishing these two goals are discussed separately below.

Selection of Optimum Materials Properties. The data needed for optimizing the material properties will result from Task B. For efficiency, portions of Tasks B and C will be accomplished concurrently and on an interactive basis. Specifically, analysis of the results from the "initial factorial studies" appearing in FIGURE 6-2 will include optimization studies as a portion of the analysis that will lead to "specific secondary solutions" in the studies. This will mean that Task C will also be partially complete at the time that Task B is completed.

The specific approach proposed for optimization is to increase the magnitudes of material properties that act to reduce distress and to decrease the magnitudes of material properties where increases in these magnitudes appear to increase distress. However, this optimization will require compromise where a change in a material property results in increasing the occurrence of one distress while decreasing occurrence of another. Further, the relative effects of the significant distresses must be considered on a weighted basis as they will not affect ride quality and requirements for maintenance equally. In example, one might optimize the stiffness of a flexible surface such that rutting and fatigue cracking might have an equal probability of occurring. However, serious rutting distress has an immediate effect on ride quality and generates a fairly immediate requirement for maintenance, whereas fatigue cracking does not lead to immediate loss of ride comfort and the secondary distresses affecting ride comfort may be several years in occurring.

After Task B is completed, the information will be available from previous optimization studies as described above and from the secondary distress studies from Task B to perform final optimization and to describe material properties for ideal materials. These ideal material properties will be identified, the compromises leading to their selections discussed, and any other pertinent useful information derived from the studies accumulated.

Verification of Optimum Material Properties. The first cycle to verify the validity of the ideal material properties identified will be conducted using the models selected for this study. If the distresses do not appear to be sufficiently minimized, they can at this time be "fine-tuned" further as described in the previous subsection.

Once the ideal material properties have been verified on the models used for this study, they may be checked further with other models to test their consistency in distress reduction. Difficulties in use of other models may be expected since the more unusual material properties, such as the permanent deformation characterizations, may not be defined numerically for the other models. It is expected that the ideal material properties will produce reduced distress predictions for other models in much the same manner that they do for the models selected for this study. Should this not be the case and conflicting optimum material properties result from this verification effort, the anomolies will be evaluated and discussed in detail.

After this verification effort is complete, the new data accumulated will be discussed in detail and the ideal materials redefined, if necessary, and identified in final form.

Final Report. The work for Tasks B and C will be documented in a draft final report and furnished to the Contract Manager in ten copies. This report will include a complete accounting of any material tests conducted, investigative results, conclusions, recommendations for utilizing the information developed, and recommendations for subsequent research. The draft final report will subsequently be developed into a final report incorporating the review comments of the FHWA reviewers. The delivery of this final report will represent the final deliverable for this project.

APPENDIX A. FACTORS AFFECTING MATERIAL PROPERTIES

This appendix contains information that describes the various factors that affect the material properties which impact the occurrence of distress. This extensive set of tables was prepared in order to clearly deliniate and categorize the types of factors that impact distress. In preparation of the summary tables contained in Chapter 3, these Appendix A tables were first prepared and all subsequent tables utilized this information. Each of the tables include the following types of information:

1. Category of distress: Fracture, Distortion or Disintegration,
2. Type of Pavement: Flexible, Rigid, or Composite,
3. Distress: Fatigue Cracking, Low temperature cracking, etc.,
4. Engineering Properties: Elastic Properties, Fatigue constants, etc.,
5. Layer of pavement to which the property applies: asphalt concrete surface, asphalt-treated base, cement-treated base, etc.,
6. Category of factor affecting the material property: environment, material, construction, or traffic, and
7. Factors which affect the material property: temperature, asphalt properties, mixing temperature, magnitude of loads, etc.

These tables were prepared by utilization of the extensive experience of project consultants, the use of References 19, 20, 21, 22, 23, 24, and 25, and the experience of the ARE Inc staff.

The tables have been prepared so that the important factors were considered but not in such detail that every characteristic of each of the factors is enumerated. For example, in Table A-1 for mixture stiffness of the asphalt concrete surface, asphalt characteristic is a factor affecting fatigue cracking. Notice that asphalt characteristics includes all those physical properties of the asphalt cement that affect the mixture stiffness including such items as the source of the crude, temperature susceptability of the asphalt cement, viscosity grading of the asphalt, etc. Therefore, one primary purpose of this table is to include those broad categories of factors that impact the properties affecting the distress. The second primary purpose or objective in preparing the table was to permit the staff to clearly differentiate between properties that affect distress and factors that affect properties. This clear differentiation was helpful in establishing the framework for the definitions of terms and the elements included in the phenomenological models of Chapter 2.

Table A.1 Factors Affecting Material Properties That Affect Distress in Flexible Pavements

	Flexible Pavements	Fatigue Cracking Engineering Properties									
	Fracture	Stiffness						Fatigue Constants			
	Factors Affecting Properties	Asphalt Concrete Surface	Asphalt-Treated Material	Cement-Treated Material	Lime-Treated Material	Untreated Granular Material	Subgrade Soil	Asphalt Concrete Surface	Asphalt-Treated Material	Cement-Treated Material	Lime-Treated Material
Environ.	Temperature	x	x	x	x	x	x	x	x	x	x
	Moisture Content	x	x	x	x	x	x	x	x	x	x
Material	Asphalt Type	x	x					x	x		
	% Asphalt*	x	x					x	x		
	Cement Type			x						x	
	% Cement*			x						x	
	Lime Type				x						x
	% Lime*				x						x
	Aggregate Type#	x	x	x		x		x	x	x	
	Aggregate Gradation#	x	x	x		x		x	x	x	
	Soil Type#			x	x		x			x	x
	Type of Clay Mineral				x						x
	% Clay or Pozzolanic				x						x
	Soil Gradation#			x	x		x			x	x
Construction	Mixing Temperature	x	x					x	x		
	Mixing, % Water			x	x					x	x
	Extent of Mixing			x	x					x	x
	Time of Mixing			x	x					x	x
	Compaction Type	x	x	x	x	x	x	x	x	x	x
	Degree of Compaction	x	x	x	x	x	x	x	x	x	x
	Compaction Temperature	x	x					x	x		
	Compaction, % Water			x	x	x	x			x	x
	Curing, % Water			x	x					x	x
	Curing Temperature			x	x					x	x
	Length of Curing			x	x					x	x
Traffic	Magnitude of Loads	x	x	x	x	x	x	—	—	—	—
	Number of Loads	x	x	x	x	x	x	—	—	—	—
	Solar Radiation	x									
	Time (Age)	x	x		x		x				

Table A.1 Continued

	Flexible Pavements	Low Temperature Cracking Engineering Properties									
	Fracture	Coefficient of Thermal Expansion				Creep Stiffness		Tensile Strength			
	Factors Affecting Properties	Asphalt Concrete Surface	Asphalt-Treated Material	Cement-Treated Material		Asphalt Concrete Surface	Asphalt-Treated Material	Asphalt Concrete Surface	Asphalt-Treated Material		
Environ.	Temperature					x	x	x	x		
	Moisture Content	x	x	x		x	x	x	x		
Material	Asphalt Type	x	x			x	x	x	x		
	% Asphalt*	x	x			x	x	x	x		
	Cement Type										
	% Cement*			x							
	Lime Type										
	% Lime*										
	Aggregate Type#	x	x	x		x	x	x	x		
	Aggregate Gradation#					x	x	x	x		
	Soil Type#			x							
	Type of Clay Mineral			x							
	% Clay			x							
	Soil Gradation#										
Construction	Mixing Temperature					x	x	x	x		
	Mixing, % Water										
	Extent of Mixing										
	Time of Mixing										
	Compaction Type					x	x	x	x		
	Degree of Compaction					x	x	x	x		
	Compaction Temperature					x	x	x	x		
	Compaction, % Water										
	Curing, % Water										
	Curing Temperature										
	Length of Curing										
Traffic	Magnitude of Loads					x	x	x	x		
	Number of Loads										
	Solar Radiation					x		x			
	Time (Age)					x	x	x	x		
	Load Duration					x	x	x	x		

Table A.1 Continued

	Flexible Pavements Fracture Factors Affecting Properties	Slippage Cracking Engineering Properties									
		Tensile Strength		Ductility							
		Asphalt Concrete Surface			Asphalt Concrete Surface						
Environ.	Temperature	x			x						
	Moisture Content	x									
Material	Asphalt Type	x			x						
	% Asphalt*	x			x						
	Cement Type										
	% Cement*										
	Lime Type										
	% Line*										
	Aggregate Type#	x			x						
	Aggregate Gradation#	x			x						
	Soil Type#										
	Type of Clay Mineral										
	% Clay or Pozzolanic										
	Soil Gradation#										
Construction	Mixing Temperature	x			x						
	Mixing, % Water										
	Extent of Mixing										
	Time of Mixing										
	Compaction Type	x									
	Degree of Compaction	x									
	Compaction Temperature	x									
	Compaction, % Water										
	Curing, % Water										
	Curing Temperature										
	Length of Curing										
Traffic	Magnitude of Loads	x									
	Number of Loads	x									
	Solar Radiation	x									
	Time (Age)	x									

Table A.1 Continued

	Flexible Pavements	Permanent Deformation (rutting) Engineering Properties									
		Stiffness						Creep Comp.		Alpha & Gnu	
	Distortion Factors Affecting Properties	Asphalt Concrete Surface	Asphalt-Treated Material	Cement-Treated Material	Lime-Treated Material	Untreated Granular Material	Subgrade Soil	Asphalt Concrete Surface	Asphalt-Treated Material	Asphalt Concrete Surface	Asphalt-Treated Materials
Environ.	Temperature	x	x	x	x	x		x	x	x	x
	Moisture Content	x	x	x	x	x		x	x		
Material	Asphalt Type	x	x					x	x	x	x
	% Asphalt*	x	x					x	x	x	x
	Cement Type			x							
	% Cement*			x							
	Lime Type				x						
	% Lime*				x						
	Aggregate Type#	x	x			x		x	x	x	x
	Aggregate Gradation#	x	x			x		x	x	x	x
	Soil Type#			x	x		x				
	Type of Clay Mineral				x						
	% Clay or Pozzolanic				x						
	Soil Gradation#			x	x		x				
Construction	Mixing Temperature	x	x					x	x	x	x
	Mixing, % Water			x	x						
	Extent of Mixing			x	x						
	Time of Mixing			x	x						
	Compaction Type	x	x	x	x	x	x	x	x	x	x
	Degree of Compaction	x	x	x	x	x	x	x	x	x	x
	Compaction Temperature	x	x					x	x	x	x
	Compaction, % Water			x	x	x	x				
	Curing, % Water			x	x						
	During Temperature			x	x						
	Length of Curing			x	x						
Traffic	Magnitude of Loads	x	x	x	x	x	x	x	x	x	x
	Number of Loads	x	x	x	x	x	x	x	x	x	x
	Solar Radiation	x						x			
	Time (Age)	x	x		x		x	x	x		
	Type of Stress	x	x							x	x

Table A.1 Continued

	Flexible Pavements Distortion Factors Affecting Properties	Shoving Engineering Properties									
		Permanent Deform. Characteristics				Stability		Modulus of Elasticity			
		Asphalt Concrete Surface	Asphalt-Treated Material	Untreated Granular Material	Subgrade Soil	Asphalt Concrete Surface		Asphalt Concrete Surface	Asphalt-Treated Material		
Environ.	Temperature	x	x			x		x	x		
	Moisture Content	x	x	x	x	x		x	x		
Material	Asphalt Type	x	x			x		x	x		
	% Asphalt*	x	x			x		x	x		
	Cement Type										
	% Cement*										
	Lime Type										
	% Lime*										
	Aggregate Type#	x	x	x		x		x	x		
	Aggregate Gradation#	x	x	x		x		x	x		
	Soil Type#				x						
	Type of Clay Mineral/Fines			x							
	% Clay			x							
	Soil Gradation#				x						
Construction	Mixing Temperature							x	x		
	Mixing, % Water										
	Extent of Mixing										
	Time of Mixing										
	Compaction Type	x	x	x	x	x		x	x		
	Degree of Compaction	x	x	x	x	x		x	x		
	Compaction Temperature							x	x		
	Compaction, % Water			x	x						
	Curing, % Water										
	Curing Temperature										
	Length of Curing										
Traffic	Magnitude of Loads							x	x		
	Number of Loads							x	x		
	Solar Radiation							x	x		
	Time (Age)							x	x		
	Type of Stress	x	x					x	x		

Table A.1 Continued

	Flexible Pavements	Large, relative, vertical differential displacements Engineering Properties									
	Distortion	Volume Change Cons. Dens.			Characteristics Swelling			Frost Susceptibility			
	Factors Affecting Properties		Subgrade Soil			Subgrade Soil			Subgrade Soil		
Environ.	Temperature								x		
	Moisture Content		x			x			x		
Material	Asphalt Type										
	% Asphalt*										
	Cement Type										
	% Cement*										
	Lime Type										
	% Lime*										
	Aggregate Type#										
	Aggregate Gradation#										
	Soil Type#		x						x		
	Type of Clay Mineral					x					
	% Clay or Pozzolanic					x					
	Soil Gradation#		x								
Construction	Mixing Temperature										
	Mixing, % Water										
	Extent of Mixing										
	Time of Mixing										
	Compaction Type		x			x					
	Degree of Compaction		x			x					
	Compaction, Temperature		x			x					
	Compaction, % Water										
	Curing, % Water										
	Curing Temperature										
	Length of Curing										
Traffic	Magnitude of Loads										
	Number of Loads										
	Solar Radiation										
	Time (Age)										

Table A.1 Continued

	Flexible Pavements	Raveling Engineering Properties					Stripping Engineering Properties				
		Tensile Strength					Tensile Strength				
	Disintegration Factors Affecting Properties			Asphalt Concrete Surface				Asphalt Concrete Surface	Asphalt-Treated Material		
Environ.	Temperature			x							
	Moisture Content							x	x		
Material	Asphalt Type			x				x	x		
	% Asphalt*			x				x	x		
	Cement Type										
	% Cement*										
	Lime Type										
	% Lime*										
	Aggregate Type#			x				x	x		
	Aggregate Gradation#										
	Aggregate Surface Coating			x							
	Type of Clay Mineral										
	% Clay or Pozzolanic										
	Soil Gradation#										
Construction	Mixing Temperature			x				x	x		
	Mixing, % Water							x	x		
	Extent of Mixing										
	Time of Mixing										
	Compaction Type										
	Degree of Compaction							x	x		
	Compaction Temperature			x				x	x		
	Compaction, % Water										
	Curing, % Water										
	Curing Temperature										
	Length of Curing										
Traffic	Magnitude of Loads (type of traffic)			x							
	Number of Loads (traffic vol)			x							
	Solar Radiation			x							
	Time (Age)			x							

Table A.2 Factors Affecting Material Properties that affect Distress in Rigid Pavements

	Rigid Pavements	Fatigue Cracking Engineering Properties									
	Fracture	Elastic Properties						Fatigue Constants			
	Factors Affecting Properties	Portland Cement Concrete	Asphalt-Treated Material	Cement-Treated Material	Lime-Treated Material	Untreated Granular Material	Subgrade Soil	Portland Cement Concrete	Asphalt-Treated Material	Cement-Treated Material	Lime-Treated Material
Environ.	Temperature		x	x	x	x	x		x	x	x
	Moisture Content	x	x	x	x	x	x	x	x	x	x
Material	Asphalt Type		x						x		
	% Asphalt*		x						x		
	Cement Type	x		x				x		x	
	% Cement* (content)	x		x				x		x	
	Lime Type				x						x
	% Lime*				x						x
	Aggregate/Soil Type	x	x	x	x	x	x	x	x	x	x
	Aggregate/Soil Gradation	x	x	x	x	x	x	x	x	x	x
	Water/Cement Ratio	x						x			
	Type of Clay Mineral				x						x
	% Clay or Pozzolanic				x						x
	Volume of Aggregate or Paste	x						x			
Construction	Mixing Temperature		x						x		
	Mixing, % Water			x	x					x	x
	Extent of Mixing			x	x					x	x
	Time of Mixing			x	x					x	x
	Compaction/Vibration Type		x	x	x	x	x		x	x	x
	Degree of Compaction/Vibration		x	x	x	x	x		x	x	x
	Compaction Temperature		x						x		
	Compaction, % Water			x	x	x	x			x	x
	Curing, % Water	x		x	x			x		x	x
	Curing Temperature	x		x	x			x		x	x
	Length of Curing	x		x	x			x		x	x
Traffic	Magnitude of Loads	x	x	x	x	x					
	Stress-Strength Ratio							x			
	Number of Loads	x	x	x	x	x					
	Time (Age)										

Table A.2 Continued

	Rigid Pavements Fracture Factors Affecting Properties	LOW TEMPERATURE									
		Tensile Strength		Coef. Thermal Expansion			Thermal Cond.		Thermal Diffusivity		
		Portland Cement Concrete			Portland Cement Concrete		Portland Cement Concrete			Portland Cement Concrete	
Environ.	Temperature										
	Moisture Content	x			x		x			x	
Material	Asphalt Type										
	% Asphalt*										
	Cement Type	x			x		x			x	
	% Cement* (content)	x									
	Lime Type										
	% Lime*										
	Aggregate/Type	x			x		x			x	
	Aggregate/Gradation	x									
	Water-Cement Ratio	x			x		x			x	
	Type of Clay Mineral										
	% Clay or Pozzolanic										
	Volume of Aggregate or Paste	x			x		x			x	
Construction	Mixing Temperature										
	Mixing, % Water										
	Extent of Mixing										
	Time of Mixing										
	Compaction/Vibration Type										
	Degree of Compaction/Vibration										
	Compaction Temperature										
	Compaction, % Water										
	Curing, % Water	x									
	Curing Temperature	x									
	Length of Curing	x									
Traffic	Magnitude of Loads	x									
	Stress-Strength Ratio										
	Number of Loads	x									
	Time (Age)										

Table A.2 Continued

	Rigid Pavements	Shrinkage Cracking Engineering Properties						Plastic Shrinkage Cracking Engineering Properties				
		Tensile Strength		Shrinkage Characteristics				Plastic Shrinkage Characteristics				
	Fracture Factors Affecting Properties	Portland Cement Concrete			Portland Cement Concrete			Portland Cement Concrete				
Environ.	Relative Humidity				x			x				
	Temperature							x				
	Moisture Content	x			x							
Material	Asphalt Type											
	% Asphalt*											
	Cement Type	x			x			x				
	% Cement* (content)	x						x				
	Lime Type											
	% Lime*							x				
	Aggregate/Soil Type	x			x			x				
	Aggregate/Soil Gradation	x						x				
	Water/Cement Ratio	x			x			x				
	Type of Clay Mineral											
	% Clay or Pozzolanic											
	Volume of Aggregate or Paste	x			x			x				
Construction	Mixing Temperature											
	Mixing, % Water											
	Extent of Mixing											
	Time of Mixing											
	Compaction/Vibration Type											
	Degree of Compaction/Vibration											
	Compaction Temperature							x				
	Compaction, % Water							x				
	Curing, % Water	x						x				
	Curing Temperature	x						x				
	Length of Curing	x										
Traffic	Magnitude of Loads	x										
	Stress-Strength Ratio											
	Number of Loads	x										
	Time (Age)											

Table A.2 Continued

	Rigid Pavements Fracture Factors Affecting Properties	D-Cracking Engineering Properties									
		Tensile Strength of Paste			Permeability of Paste			Pore Char. of Paste		Aggregate Char.	
			Portland Cement Concrete			Portland Cement Concrete		Portland Cement Concrete		Portland Cement Concrete	
Environ.	Temperature										
	Moisture Content		x								
Material	Asphalt Type										
	% Asphalt*										
	Cement Type		x			x		x			
	% Cement* (content)										
	Lime Type										
	Air Entrainment							x			
	Aggregate/Type		x?							x	
	Aggregate/Soil Gradation										
	Water-Cement Ratio		x			x		x			
	Type of Clay Mineral										
	% Clay or Pozzolanic										
	Volume of Aggregate or Paste		x?								
Construction	Mixing Temperature										
	Mixing, % Water										
	Extent of Mixing							x			
	Time of Mixing										
	Compaction/Vibration Type										
	Degree of Compaction/Vibration										
	Compaction Temperature										
	Compaction, % Water										
	Curing, % Water		x					x			
	Curing Temperature		x					x			
	Length of Curing		x			x		x			
Traffic	Magnitude of Loads										
	Stress-Strength Ratio										
	Number of Loads										
	Time (Age)										

Table A.2 Continued

	Rigid Pavements Fracture Factory Affecting Properties	Blowups Engineering Properties									
		Coef. of Thermal Expansion				Mod. of Elasticity					
			Portland Cement Concrete				Portland Cement Concrete				
Environ.	Temperature										
	Moisture Content		x				x				
Material	Asphalt Type										
	% Asphalt*										
	Cement Type		x				x				
	% Cement* (content)						x				
	Lime Type										
	% Lime*										
	Aggregate/Type		x				x				
	Aggregate/Soil Gradation						x				
	Water/Cement Ratio		x				x				
	Type of Clay Mineral										
	% Clay or Pozzolanic										
	Volume of Aggregate or Paste		x				x				
Construction	Mixing Temperature										
	Mixing, % Water										
	Extent of Mixing										
	Time of Mixing										
	Compaction/Vibration Type										
	Degree of Compaction/Vibration										
	Compaction Temperature										
	Compaction, % Water										
	Curing, % Water						x				
	Curing Temperature						x				
	Length of Curing						x				
Traffic	Magnitude of Loads						x				
	Stress-Strength Ratio										
	Number of Loads						x				
	Time (Age)										

Table A.2 Continued

	Rigid Pavements	Joint Faulting Engineering Properties									
	Distortion	Modulus of Elasticity		Pumping Characteristics				Tensile Strength			
	Factors Affecting Properties	Portland Cement Concrete			Untreated Granular Material	Subgrade Soil		Subgrade Soil	Asphalt-Treated Material	Cement-Treated Material	Lime-Treated Material
Environ.	Temperature										
	Moisture Content	x							x	x	x
Material	Asphalt Type								x		
	% Asphalt*								x		
	Cement Type	x								x	
	% Cement* (content)	x								x	
	Lime Type										x
	% Lime*										x
	Aggregate/Soil Type	x			x	x		x	x	x	x
	Aggregate/Soil Gradation	x			x	x		x	x?	x?	x?
	Water/Cement Ratio	x									
	Type of Clay Mineral							x			x
	% Clay or Pozzolanic							x			x
	Volume of Aggregate or Paste	x									
Construction	Mixing Temperature								x		
	Mixing, % Water										
	Extent of Mixing									x	
	Time of Mixing										
	Compaction/Vibration Type							x	x	x	x
	Degree of Compaction/Vibration							x	x	x	x
	Compaction Temperature								x		
	Compaction, % Water							x			
	Curing, % Water	x								x	x
	Curing Temperature	x								x	x
	Length of Curing	x								x	x
Traffice	Magnitude of Loads	x									
	Stress-Strength Ratio										
	Number of Loads	x									
	Time (Age)										

Table A.2 Continued

	Rigid Pavements	Faulting - Heave Engineering Properties					Consolidation-Swell Engineering Properties					
	Distortion	Volume Change Characteristics					Volume Change Characteristics			Frost Susceptibility		
	Factors Affecting Properties		Untreated Granular Material	Subgrade Soil				Subgrade Soil			Subgrade Soil	
Environ.	Temperature										x	
	Moisture Content		x	x				x			x	
Material	Asphalt Type											
	% Asphalt*											
	Cement Type											
	% Cement* (content)											
	Lime Type											
	% Lime*											
	Aggregate/Soil Type		x	x				x			x	
	Aggregate/Soil Gradation		x	x				x				
	Water/Cement Ratio											
	Type of Clay Mineral							x				
	Type of Fines		x					x				
	Volume of Aggregate or Paste											
Construction	Mixing Temperature											
	Mixing, % Water											
	Extent of Mixing											
	Time of Mixing											
	Compaction/Vibration Type		x	x				x				
	Degree of Compaction/Vibration		x	x				x				
	Compaction Temperature											
	Compaction, % Water		x	x				x				
	Curing, % Water											
	Curing Temperature											
	Length of Curing											
Traffic	Magnitude of Loads											
	Stress-Strength Ratio											
	Number of Loads											
	Time (Age)											

Table A.2 Continued

	Rigid Pavements	Surface Cracking-Deterioration and Scaling Engineering Properties									
	Disintegration	Tensile Strength of Paste				Air Void Char.					
	Factors Affecting Properties		Portland Cement Concrete				Portland Cement Concrete				
Environ.	Temperature										
	Moisture Content		x								
Material	Asphalt Type										
	% Asphalt*										
	Cement Type		x				x				
	% Cement* (content)										
	Lime Type										
	Air Entrainment						x				
	Aggregate/Soil Type		x?								
	Aggregate/Soil Gradation										
	Water/Cement Ratio		x				x				
	Type of Clay Mineral										
	% Clay or Pozzolanic										
	Volume of Aggregate or Paste		x?								
Construction	Mixing Temperature										
	Mixing, % Water										
	Extent of Mixing						x				
	Time of Mixing										
	Finishing Technique						x				
	Degree of Compaction/Vibration										
	Compaction Temperature										
	Compaction, % Water										
	Curing, % Water		x				x				
	Curing Temperature		x				x				
	Length of Curing		x				x				
Traffic	Magnitude of Loads										
	Stress-Strength Ratio										
	Number of Loads										
	Time (Age)										

Table A.2 Continued

	Rigid Pavements Disintegration Factors Affecting Properties	Polishing Engineering Properties									
		Tensile Strength of Paste				Aggregate Hardness					
			Portland Cement Concrete			Portland Cement Concrete					
Environ.	Temperature										
	Moisture Content		x								
Material	Asphalt Type										
	% Asphalt*										
	Cement Type		x								
	% Cement* (content)										
	Lime Type										
	% Lime*										
	Aggregate/Type		x?			x					
	Aggregate/Soil Gradation										
	Water/Cement Ratio		x								
	Type of Clay Mineral										
	% Clay or Pozzolanic										
	Volume of Aggregate or Paste		x?								
Construction	Mixing Temperature										
	Mixing, % Water										
	Extent of Mixing										
	Time of Mixing										
	Compaction/Vibration Type										
	Degree of Compaction/Vibration										
	Compaction Temperature										
	Compaction, % Water										
	Curing, % Water		x								
	Curing Temperature		x								
	Length of Curing		x								
Traffic	Magnitude of Loads										
	Stress-Strength Ratio										
	Number of Loads										
	Time (Age)										

Table A.3 Factors Affecting Material Properties That Affect Distress in Composite Pavements

	Composite Pavements	Fatigue Cracking													
		ENGINEERING PROPERTIES													
		Fatigue Constants					Stiffness Modulus								
	Fracture FACTORS AFFECTING PROPERTIES		Asphalt Concrete Surface	Portland Cement Concrete	Asphalt Treated Materials		Asphalt Concrete Surface	Portland Cement Concrete	Asphalt Treated Materials	Cement Treated Materials	Lime-Treated Materials	Untreated Granular Materials	Subgrade Soil		
Envir.	Temperature		x		x		x		x						
	Moisture		x	x	x		x	x	x	x	x	x	x		
	Freezing Temperature									x	x	x	x		
	Solar Radiation						x								
	Degree of Oxidation														
	Time-Temperature Relationship														
Material	Asphalt Type		x		x		x		x						
	% Asphalt		x		x		x		x						
	Cement Type			x				x		x					
	% Cement									x					
	Lime Type										x				
	% Lime										x				
	Aggregate Type		x	x	x		x	x	x						
	Aggregate Gradation		x	x	x		x	x	x						
	Aggregate Surface Coating														
	Aggregate Moisture Content														
	Soil Type									x	x	x	x		
	Soil Gradation									x	x	x	x		
	Type of Clay														
	% Clay														
	Volume of Aggregate or Paste			x				x							
	Water Cement Ratio			x				x							
Construction	Mixing Temperature		x		x		x		x						
	Mixing, % Water									x	x				
	Extent of Mixing									x	x				
	Time of Mixing									x	x				
	Compaction Type		x		x		x		x	x	x		x		
	Degree of Compaction		x		x		x		x	x	x	x	x		
	Compaction Temperature		x		x		x		x						
	Compaction, % Water									x	x	x	x		
	Curing, % Water			x				x		x	x				
	Curing Temperature			x				x		x	x				
	Length of Curing			x				x		x	x				
Traffic	Magnitude of Loads						x	x	x		x	x	x		
	Types of Stress														
	Stress-Strength Ratio			x											
	Number of Loads						x	x	x		x	x	x		
	Time (age)						x								
	Load Duration														

Table A.3 Continued

COMPOSITE PAVEMENTS		Low Temperature Cracking													
Fracture		ENGINEERING PROPERTIES													
		Tensile Strength			Temperature Suseptibility				Creep Stiffness			Stiffness Modulus			
	FACTORS AFFECTING PROPERTIES	Asphalt Concrete Surface	Asphalt-treated Materials			Asphalt Concrete Surface				Asphalt Concrete Surface		Asphalt Concrete Surface	Portland Cement Surface		
Envir.	Temperature	x	x							x		x			
	Moisture	x	x							x		x	x		
	Freezing Temperature														
	Solar Radiation	x	x							x		x			
	Degree of Oxidation														
	Time-Temperature Relationship														
Material	Asphalt Type	x	x			x				x		x			
	% Asphalt	x	x							x		x			
	Cement Type												x		
	% Cement														
	Lime Type														
	% Lime														
	Aggregate Type	x	x							x		x	x		
	Aggregate Gradation	x	x							x		x	x		
	Aggregate Surface Coating														
	Aggregate Moisture Content														
	Soil Type														
	Soil Gradation														
	Type of Clay														
	% Clay														
	Volume of Aggregate or Paste												x		
	Water Cement Ratio												x		
Construction	Mixing Temperature	x	x							x		x			
	Mixing, % Water														
	Extent of Mixing														
	Time of Mixing														
	Compaction Type	x	x							x		x			
	Degree of Compaction	x	x							x		x			
	Compaction Temperature	x	x							x		x			
	Compaction, % Water														
	Curing, % Water												x		
	Curing Temperature												x		
	Length of Curing												x		
Traffic	Magnitude of Loads	x	x							x		x	x		
	Types of Stress														
	Stress-Strength Ratio														
	Number of Loads	x	x									x	x		
	Time (age)	x	x							x		x			
	Load Duration									x					

Table A.3 Continued

	COMPOSITE PAVEMENTS Fracture FACTORS AFFECTING PROPERTIES	Low Temperature Cracking													
		ENGINEERING PROPERTIES													
		Thermal Diffusivity				Coef.of Thermal Expansion					Thermal Conductivity				
			Asphalt Concrete Surface	Portland Cement Concrete			Asphalt Concrete Surface	Portland Cement Concrete				Asphalt Concrete Surface	Portland Cement Concrete		
Envir.	Temperature														
	Moisture			x			x	x					x		
	Freezing Temperature														
	Solar Radiation														
	Degree of Oxidation														
	Time-Temperature Relationship														
Material	Asphalt Type						x	x							
	% Asphalt						x								
	Cement Type			x									x		
	% Cement														
	Lime Type														
	% Lime														
	Aggregate Type			x			x	x					x		
	Aggregate Gradation														
	Aggregate Surface Coating														
	Aggregate Moisture Content														
	Soil Type														
	Soil Gradation														
	Type of Clay														
	% Clay														
	Volume of Aggregate or Paste			x				x					x		
	Water Cement Ratio			x				x					x		
Construction	Mixing Temperature														
	Mixing, % Water														
	Extent of Mixing														
	Time of Mixing														
	Compaction Type														
	Degree of Compaction														
	Compaction Temperature														
	Compaction, % Water														
	During, % Water														
	Curing Temperature														
	Length of Curing														
Traffic	Magnitude of Loads														
	Types of Stress														
	Stress-Strength Ratio														
	Number of Loads														
	Time (age)														
	Load Duration														

Table A.3 Continued

	COMPOSITE PAVEMENTS	Slippage Cracking						Reflection Cracking							
		ENGINEERING PROPERTIES						ENGINEERING PROPERTIES							
	Fracture	Tensile Strength						Tensile Strength			Ductility (flexibility)				
	FACTORS AFFECTING PROPERTIES		Asphalt Concrete Surface						Asphalt Concrete Suriace			Asphalt Concrete Surface			
Envir.	Temperature		x						x			x			
	Moisture		x						x						
	Freezing Temperature														
	Solar Radiation		x						x						
	Degree of Oxidation														
	Time-Temperature Relationship														
Material	Asphalt Type		x						x			x			
	% Asphalt		x						x			x			
	Cement Type														
	% Cement														
	Lime Type														
	% Lime														
	Aggregate Type		x						x			x			
	Aggregate Gradation		x						x						
	Aggregate Surface Coating														
	Aggregate Moisture Content														
	Soil Type														
	Soil Gradation														
	Type of Clay														
	% Clay														
	Volume of Aggregate or Paste														
	Water Cement Ratio														
Construction	Mixing Temperature		x						x			x			
	Mixing, % Water														
	Extent of Mixing														
	Time of Mixing														
	Compaction Type		x						x						
	Degree of Compaction		x						x						
	Compaction Temperature		x						x						
	Compaction, % Water														
	Curing, % Water														
	Curing Temperature														
	Length of Curing														
Traffic	Magnitude of Loads		x						x						
	Types of Stress														
	Stress-Strength Ratio														
	Number of Loads		x						x						
	Time (age)		x						x						
	Load Duration														

Table A.3 Continued

	COMPOSITE PAVEMENTS	Rutting													
		ENGINEERING PROPERTIES													
		Modulus			Creep Compliance				Permanent Deformation Characteristics-						
	Distortion FACTORS AFFECTING PROPERTIES		Asphalt Concrete Surface				Asphalt Concrete Surface					Asphalt Concrete Surface			
Envir.	Temperature		x				x					x			
	Moisture		x				x								
	Freezing Temperature														
	Solar Radiation		x												
	Degree of Oxidation														
	Time-Temperature Relationship														
Material	Asphalt Type		x				x					x			
	% Asphalt		x				x					x			
	Cement Type														
	% Cement														
	Lime Type														
	% Lime														
	Aggregate Type		x				x					x			
	Aggregate Gradation		x				x					x			
	Aggregate Surface Coating														
	Aggregate Moisture Content														
	Soil Type														
	Soil Gradation														
	Type of Clay														
	% Clay														
	Volume of Aggregate or Paste														
	Water Cement Ratio														
Construction	Mixing Temperature		x				x					x			
	Mixing, % Water														
	Extent of Mixing														
	Time of Mixing														
	Compaction Type		x				x					x			
	Degree of Compaction		x				x					x			
	Compaction Temperature		x				x					x			
	Compaction, % Water														
	Curing, % Water														
	Curing Temperature														
	Length of Curing														
Traffic	Magnitude of Loads		x				x					x			
	Types of Stress											x			
	Stress-Strength Ratio														
	Number of Loads		x												
	Time (age)		x												
	Load Duration						x					x			

Table A.3 Continued

	COMPOSITE PAVEMENTS Distortion FACTORS AFFECTING PROPERTIES	Large, Relative Vertical Differential Displacement													
		ENGINEERING PROPERTIES													
		Volume Change Characteristics				Frost Susceptibility of the Subgrade									
			Subgrade Soil						Subgrade Soil						
Envir.	Temperature														
	Moisture		x						x						
	Freezing Temperature														
	Solar Radiation														
	Degree of Oxidation														
	Time-Temperature Relationship								x						
Material	Asphalt Type														
	% Asphalt														
	Cement Type														
	% Cement														
	Lime Type														
	% Lime														
	Aggregate Type														
	Aggregate Gradation														
	Aggregate Surface Coating														
	Aggregate Moisture Content														
	Soil Type		x						x						
	Soil Gradation		x												
	Type of Clay		x						x						
	% Clay		x						x						
	Volume of Aggregate or Paste														
	Water Cement Ratio														
Construction	Mixing Temperature														
	Mixing, % Water														
	Extent of Mixing														
	Time of Mixing														
	Compaction Type		x												
	Degree of Compaction		x												
	Compaction Temperature														
	Compaction, % Water		x												
	Curing, % Water														
	Curing Temperature														
	Length of Curing														
Traffic	Magnitude of Loads														
	Types of Stress														
	Stress-Strength Ratio														
	Number of Loads														
	Time (age)														
	Load Duration														

Table A.3 Continued

	COMPOSITE PAVEMENTS Distortion FACTORS AFFECTING PROPERTIES	Shoving													
		ENGINEERING PROPERTIES													
		Permanent Deformation Characteristics						Stability			Stiffness Modulus				
				Asphalt Concrete Surface					Asphalt Concrete Surface			Asphalt Conc& Asphalt Treated Materials			
Envir.	Temperature			x					x			x			
	Moisture			x					x			x			
	Freezing Temperature														
	Solar Radiation											x			
	Degree of Oxidation														
	Time-Temperature Relationship														
Material	Asphalt Type			x					x			x			
	% Asphalt			x					x			x			
	Cement Type														
	% Cement														
	Lime Type														
	% Lime														
	Aggregate Type			x					x			x			
	Aggregate Gradation			x					x			x			
	Aggregate Surface Coating														
	Aggregate Moisture Content														
	Soil Type														
	Soil Gradation														
	Type of Clay														
	% Clay														
	Volume of Aggregate or Paste														
	Water Cement Ratio														
Construction	Mixing Temperature											x			
	Mixing, % Water														
	Extent of Mixing														
	Time of Mixing														
	Compaction Type			x					x			x			
	Degree of Compaction			x					x			x			
	Compaction Temperature											x			
	Compaction, % Water														
	Curing, % Water														
	Curing Temperature														
	Length of Curing														
Traffic	Magnitude of Loads											x			
	Types of Stress			x											
	Stress-Strength Ratio														
	Number of Loads											x			
	Time (age)											x			
	Load Duration														

Table A.3 Continued

	COMPOSITE PAVEMENTS Disintegration FACTORS AFFECTING PROPERTIES	Raveling						Stripping							
		ENGINEERING PROPERTIES						ENGINEERING PROPERTIES							
		Tensile Strength Bonding of Asphalt						Tensile Strength Bond Of Asphalt Amount							
				Asphalt Concrete Surface						Asphalt Concrete Surface					
Environ.	Temperature			x											
	Moisture									x					
	Freezing Temperature														
	Solar Radiation			x											
	Degree of Oxidation			x											
	Time-Temperature Relationship														
Material	Asphalt Type									x					
	% Asphalt			x						x					
	Cement Type														
	% Cement														
	Lime Type														
	% Lime														
	Aggregate Type			x						x					
	Aggregate Gradation														
	Aggregate Surface Coating			x											
	Aggregate Moisture Content									x					
	Soil Type														
	Soil Gradation														
	Type of Clay														
	% Clay														
	Volume of Aggregate or Paste														
	Water Cement Ratio														
Construction	Mixing Temperature														
	Mixing, % Water														
	Extent of Mixing														
	Time of Mixing														
	Compaction Type									x					
	Degree of Compaction									x					
	Compaction Temperature			x											
	Compaction, % Water														
	Curing, % Water														
	Curing Temperature														
	Length of Curing														
Traffic	Magnitude of Loads			x											
	Types of Stress														
	Stress-Strength Ratio														
	Number of Loads			x											
	Time (age)			x											
	Load Duration														

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