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MINIMIZING PREMATURE CRACKING IN ASPHALTIC CONCRETE PAVEMENT

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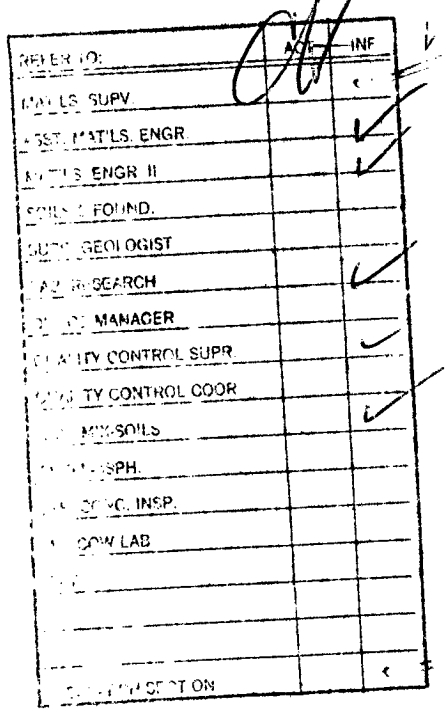

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT 195

MINIMIZING PREMATURE CRACKING IN ASPHALTIC CONCRETE PAVEMENT

F. N. FINN, K. NAIR, AND J. M. HILLIARD
MATERIALS RESEARCH AND DEVELOPMENT
OAKLAND, CALIFORNIA

RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

AREAS OF INTEREST:

- PAVEMENT DESIGN
- PAVEMENT PERFORMANCE
- BITUMINOUS MATERIALS AND MIXES
- CONSTRUCTION
- MINERAL AGGREGATES

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. 1978

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the National Academy of Sciences, or the program sponsors.

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FOREWORD

By Staff
Transportation
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Considerable research effort has been and continues to be directed toward development of mechanistic procedures for asphaltic pavement design to reduce cracking and improve over-all performance. This report contains recommendations for materials specifications, mix design, structural materials selection, and construction requirements that are intended to reduce the possibility of premature fatigue and low-temperature cracking of asphaltic pavements. Suggestions are also included for minimizing reflection cracking. Individual highway agencies should evaluate the recommendations against current practice, implement changes that are judged to be adequately verified in the report, and implement other recommendations on a trial basis for future observations. The report will be of special interest and value to pavement designers, materials engineers, asphalt technologists, and researchers working in the asphaltic pavement field.

Cracking of the surface course is generally considered to be the most significant manifestation of asphaltic concrete pavement distress. Many factors, such as asphalt properties, mix design, construction procedures, aggregate properties, subgrade support, environmental conditions, and traffic loading, influence the ability of a pavement to resist cracking. Premature cracking (that cracking occurring at an early life or after less accumulated traffic than anticipated during design) often results in large expenditures of funds to maintain the intended level of serviceability. The objectives of this project were to (1) recommend suitable materials specifications, paving mix design criteria, and construction requirements that will result in the ability to design and construct asphaltic concrete pavements to carry design traffic with a minimum of premature cracking and (2) develop a program for verification of the recommendations. A major constraint applied to the study was the assumption that a valid asphaltic pavement structural design procedure is available. Increasing the structural strength or thickness to improve the reliability of crack-free performance was not considered within the scope of this study.

The Materials Research and Development researchers have prepared a synthesis, included as an appendix of this report, of available literature and field experience concerned with the influence of the many factors on fatigue and low-temperature cracking and reflection cracking of asphaltic pavements. Mechanistic simulations were used to extrapolate beyond the recorded laboratory and field relationships between the various factors and pavement cracking. With this as a basis, specific recommendations were made for minimizing fatigue and low-temperature cracking. The study recommendations dealing with (1) asphalt content and void content of asphaltic concrete, (2) density of untreated aggregate base courses, and (3) subsurface drainage where accumulation of water is a problem, appear to be well documented and suitable for immediate implementation. Trial sections in new construction should be considered by individual

highway agencies to further evaluate other recommendations such as increasing proportion of asphaltic concrete, use of softer asphalt to reduce low-temperature cracking, and various techniques for reducing reflection cracking.

With regard to verification of the recommendations, it was determined that, because of the large number of variables, conventional experimental programs for field verification would be very costly and time consuming. An alternate procedure, using Bayesian analysis methodology, is suggested. Research on the verification phase of the study is under way as NCHRP Project 9-4A, "Bayesian Analysis Methodology for Verifying Recommendations to Minimize Asphalt Pavement Distress."

Appendixes B, C, D, and E are not included in this report but are available on a loan basis from the Program Director, NCHRP, Transportation Research Board, 2101 Constitution Ave., N.W., Washington, D.C. 20418.

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A number of technologists were extremely helpful in providing time to discuss various aspects of the project, specifically: Professor K. George, University of Mississippi; Professor Ralph Haas, University of Waterloo; Ted Hignell, Gulf Oil Canada, Ltd.; George Sherman and members of his staff, California Division of Highways; Tom Stapler, Georgia Department of Transportation; Roger Le Clerc and members of his staff, Washington State Department of Highways; James Shook and Dr. M. Witczak, Asphalt Institute, College Park, Md.; and Professor K. S. Pister, University of California (Berkeley). Also, the various members of the Triaxial Institute cooperated in providing valuable information to members of the project staff.

Professor Carl Monismith, University of California (Berkeley), acted as a consultant to the project and provided considerable guidance, information, and technological input necessary for preparation of the report.

Professor Haresh C. Shah, Stanford University, was responsible for suggesting use of Bayesian statistical decision theory as a means for verification of various recommendations contained in the report. He also provided guidance in preparation of the questionnaire and in analysis of the subjective priors and experimental data used to illustrate the technique for verification as described in Appendix E.

MINIMIZING PREMATURE CRACKING IN ASPHALTIC CONCRETE PAVEMENT

SUMMARY

The objective of this research project was the preparation of a series of recommendations dealing with materials specifications, mix design criteria, structural materials selection, and construction requirements that can be used by the designer to reduce the possibility of premature cracking in asphaltic concrete pavement. The project was also concerned with the review of possible procedures for verification of the recommendations. The principal constraint applied to the preparation of such recommendations is that the development of improved methods of structural design is not one of the techniques to be considered for the prevention of premature cracking. Specifically, the recommendations assume that an acceptable method for structural design is available to the designer and that these design methods provide structural adequacy for the particular traffic, subgrade support, and climate conditions.

The initial task of the project comprised identification of the types of cracking that are reported to (1) occur extensively, (2) reduce pavement serviceability, and (3) require extensive maintenance. Of the cracking identified, specific recommendations are made which, if implemented, should tend to minimize premature fatique cracking, low-temperature cracking, and reflection cracking. Because of a general lack of definitive information, the recommendations for minimizing reflection cracking are somewhat broad.

The following summarizes the project findings, listed by type of cracking; also included are the determinations in regard to the approaches for verification of the project recommendations:

1. *Increasing the proportion of asphaltic concrete will reduce the potential for fatigue cracking.* Analytical studies indicate that increasing the proportion of asphaltic concrete to provide for approximately 50 to 75 percent of the total structural requirements will reduce potential for fatigue cracking. It should be noted that a significant improvement in performance can be achieved by increasing the density of the untreated aggregate base course; therefore, it is important to evaluate this possibility concurrently with the possibility of increasing the proportion of asphaltic concrete. Also, use of cement-treated materials will virtually eliminate the possibility of fatigue cracking in the asphaltic concrete surface, but the problems of reflection cracking from fatigue and shrinkage of the treated base must be considered.

2. *Increasing asphalt content and reducing void content will minimize fatigue cracking.* Research has indicated that increasing the asphalt content will tend to improve fatigue life of asphaltic concrete, but too much asphalt in the surface course can produce an unstable mix and bleeding or flushing, which could lead to rutting problems and slippery-when-wet conditions. The desired objective is mix design requirements that minimize fatigue cracking without incurring other forms of distress.

3. *Conflicting viewpoints exist regarding influence of asphalt consistency on fatigue cracking.* It is apparent from the information available that different recommendations on asphalt consistency could be made, depending on the failure criteria used in analysis.

4. *The maximum realistic density should be specified for untreated aggregate base course.* Analytical studies indicate that the moduli of resilience of untreated aggregates increase with density and decrease with moisture. Maximum attainable density should be based on previous experience or special tests per project. Where appropriate, some positive drainage system should be provided.

5. *Use of cement-treated bases reduces fatigue cracking of asphaltic concrete surface but may increase reflection cracking.*

6. *A softer asphalt should be used if premature low-temperature cracking is being observed.* This type of cracking manifests itself through transverse cracking beginning in the surface of the asphaltic concrete and progressing through the pavement structure. At present, the most viable designer-controlled factor related to low-temperature cracking is the asphalt cement grade.

7. *It is not possible at present to formulate specific recommendations for minimizing reflection cracking.* General techniques currently being used are: (a) increase the ability of overlay to withstand the stresses and strains that cause cracking; (b) place an intermediate stress-relieving layer; (c) prepare the underlying pavement; and (d) overlay with relatively thick layer of asphaltic concrete.

8. *The case history can be useful as a method to verify specific recommendations.* However, in order to obtain the reliability necessary, such investigations will require extensive field and laboratory measurements. Such programs are very expensive and time consuming.

9. *Since conventional experiment designs for field verification of recommendations are indicated, by example, to be too expensive and time consuming for most highway agencies, an alternative procedure incorporating and quantifying the experience of highway engineers is offered as a reasonable procedure for the verification of recommendations.*

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

Asphalt pavements are extremely complex structures or systems whose performance is influenced by a myriad of factors ranging from the nature of traffic (weight and volume) to the whims of the environment (rainfall and temperature). It is the objective of the pavement design process (thickness of layers, materials requirements, and construction specifications) to produce on the roadway a pavement capable of exposure to traffic and the elements that will provide a desirable level of performance.

Cracking of the asphalt surfacing is generally considered to be one of the most significant manifestations of distress in asphalt-surfaced pavements. In December 1970, the Highway Research Board organized a special Workshop at Austin, Texas, dealing with the structural design of asphaltic concrete pavements. The Workshop was sponsored by the Federal Highway Administration in cooperation with the University of Texas. Participants included a cross section of engineers with experience in pavement research, design, construction, and maintenance. As the name implies, the primary goal of the Workshop was to review the current status of structural design and to evaluate and assimilate research findings into future design procedures. One of the important aspects of the Workshop was the emphasis placed on the definition of performance and the need for relating distress to performance.

The Workshop was conducted in both plenary sessions and group discussions with reports from each group. One of the groups was charged with responsibility for discussing distress and pavement performance. The published report (*108*) from this meeting indicated the following:

1. Traffic-(load-) associated cracking should be the first priority concern for research and design engineers.
2. Traffic-associated cracking may, or may not, occur in conjunction with the development of rutting.
3. No definitive procedure has been developed to establish limiting criteria as regards the amount of cracking that can be tolerated before routine maintenance or rehabilitation is required.

Premature cracking of pavements (cracking that occurs early in the life of the pavement and significantly earlier than the design life provided by any specific structural design method) poses a particularly undesirable situation for highway departments: (1) it requires an unanticipated expenditure of funds to protect the initial investment, (2) it imposes an unanticipated inconvenience to the users, and (3) it reduces public confidence in the highway profession, both contracting and contractor groups.

TYPES AND CAUSES OF CRACKING

There are a variety of publications in the technical literature that describe the types of cracks that have been found in asphalt pavements (*106, 113, 116, 231*).

Although not necessarily all inclusive, most pavement cracks can be described according to their geometry, such as (1) longitudinal, (2) transverse, (3) polygon (also alligator and map), and (4) block. In at least three cases, types of cracking are described by the mechanism that causes the occurrence of cracking, such as slippage, shrinkage, and reflection. In at least one instance, cracking is described by its location, such as edge cracking.

The identification of cracks is relatively easy. For example, longitudinal, transverse, polygon (or alligator), and edge cracking are self-descriptive. Reflection cracking over portland cement concrete pavements or soil-cement (defined as any soil-cement combination that meets or exceeds ASTM requirements for freeze-thaw and wet-dry tests) bases can usually be identified by the systematic spacing of the cracking. Slippage cracks are usually crescent shaped; however, the size of the crescent can be so large in some cases as to be hard to define visually. Shrinkage cracking is distinguished by the indications of volume changes that occur regardless of traffic patterns or wheel path areas. Shrinkage cracks in materials below the surface layer can also be observed because of their ability to reflect through the asphaltic concrete.

The ability of engineers to associate the type of cracking with the cause of cracking, by visual examination, can only be described as "fair," and even then a considerable amount of experience is required. Examination of the various types of cracking enumerated in Ref. *106* will indicate in almost every case that there can be more than one and, sometimes, as many as four causes for a particular type of cracking. Testing, of course, will tend to improve the chances of a correct diagnosis; however, even with testing; identification of the cause can be difficult.

Over the years, engineers have been able to categorize cracking under two broad groups: load associated and nonload associated. Hudson and McCullough (*113*) enumerate the types of cracking into these two groups. The principal class of load-associated cracking has been described as fatigue cracking, the phenomenon of fracture under repeated or fluctuating stress having a maximum value less than the tensile strength of the material. Just when such cracking will occur depends on the fatigue properties of the asphaltic concrete and the in-situ load-deformation properties of the pavement section. It is pertinent to note that there are other classes of load-associated cracks (e.g., single excessive load, slippage, lateral movements in fills due to traffic and excessive strains associated with rutting). Reflection cracking can also be considered at least partially load associated.

There are a variety of classes of nonload-associated cracks. For example, fill subsidence, expansion (swell) of foundation materials, construction joints, shrinkage of various elements of the pavement structure, and low-temperature cracking of the asphaltic concrete. Again, reflection cracking can be considered at least partially nonload associated.

The importance of each class of cracking mentioned can probably vary in accordance with the adequacy of the structural design procedure, types of materials to be used in construction, methods of construction, and environment (temperature, rainfall, frost penetration). According to the discussions and reports at the Austin Workshop (*108*), there was some consensus that fatigue cracking, low-temperature cracking, and reflection cracking were highly significant and were of considerable interest and concern to highway engineers. This is not to say that the other types of cracking do not occur or are not important. However, for purposes of this investigation, the emphasis has been placed on these three types of cracking (fatigue, low-temperature, and reflection).

Causes associated with cracking in asphalt pavements are many and varied, depending to some extent on the type of cracking. Probably the most common associations are made with: (1) structural design, (2) asphalt properties, (3) asphaltic concrete mix design, (4) construction procedures, (5) aggregate properties, (6) asphalt and aggregate durability, (7) foundation support, (8) condition of underlying pavement (overlays), (9) temperature, (10) drainage (or lack of drainage), and (11) traffic.

It is pertinent to note that cracking in asphalt pavements does not occur simultaneously throughout the limits of a given project. A normal experience would be to initially observe cracks in isolated, randomly located areas throughout the limits of construction. With time, traffic, and continued exposure to the environment, the situation will usually progress to some stage at which it is determined that some type of maintenance is required (*163*). Because of the empirical nature (correlations from observed field performance) associated with the development of structural design procedures, materials requirements, and construction specifications, unexpected or premature cracking due to random variations is usually controlled at some acceptable level. However, it probably should be expected that a certain number of projects (some irreducible minimum) may not perform as well as expected. The additional cost of increasing the structural design, materials requirements, etc., for all designs would probably exceed the cost of maintenance and rehabilitation in these unusual

and unexpected circumstances. The recommendations developed from the reports associated with this investigation are directed at minimizing cracking without specifying unusual and extravagant procedures.

Research during the last 10 yr has developed a series of hypotheses as regards the role of structural design, materials, and construction to pavement performance. It is this research that will be relied upon to provide some solution to the problem of minimizing or controlling cracking. The recommendations contained herein represent an effort to extract from the research those findings that are considered practical to apply and, if followed, should minimize the potential for the types of cracking to be discussed.

OBJECTIVES

The over-all objective of this project is the determination of suitable materials specifications, paving mix design criteria, and construction requirements that will result in the ability to design and construct asphaltic concrete pavements to carry design traffic with a minimum of premature cracking. The specific objectives for this investigation are:

1. To identify, evaluate, and synthesize into a form usable by highway departments, the available information from recent and current research and field experience pertaining to the minimizing of premature cracking in asphaltic concrete pavements.
2. To recommend tentative criteria for material specifications, mix design, and construction requirements for asphaltic concrete pavements.
3. To prepare a research plan to verify or modify the recommendations developed using the approach proposed in this study.
4. To conduct a case history study for verification of the recommendations to the extent possible within the limitations of project time and funds.

A major constraint applied to the study was the assumption that a valid thickness design procedure was available to the design engineer. In other words, of the decisions available to the designer to improve the reliability of crack-free performance, increasing the structural section (thickness) is not considered within the scope of this project.

The decisions considered to be designer-controlled are generally in the areas of materials requirements, mix design (treated materials), and the relative proportion and types of materials to be used in the structural elements (layers). This latter item requires some clarification.

Current thickness design procedures almost universally provide for substitution among structural materials in order to meet a specific structural design requirement. Therefore, within a specific structural design requirement (e.g., structural number, gravel equivalency, etc.), the decision as to what material to use is left to the designer. The choice will usually involve reliability of performance and cost, which should include any user costs associated with maintenance or rehabilitation.

To a lesser extent, the project investigators have placed certain limits or constraints on the type of recommendations that can be made. Specifically, considerable effort has been made to try to deal with the various factors (material properties, construction capabilities, etc.) the way they are and not the way they might be. For example, consider the case for asphalt recommendations. The designer must deal with asphalts as they are currently being produced by various suppliers in accordance with specifications issued by AASHTO and ASTM, sometimes with modifications by highway departments.

It should be recognized that a complete design system relates materials specifications, mix design, construction procedures, environment, traffic, and pavement geometry (structural design) to performance. These concepts are presented in Figure 1, which is a schematic representation of the pavement design system. Cracking has been recognized as a manifestation of pavement distress, and the development of recommendations for minimizing cracking is an integral part of the development of a satisfactory and practical procedure for the design of asphaltic concrete pavements. However, in the context of the total design, the recommendations developed for minimizing cracking should also be evaluated with respect to their effect on other measures of distress (e.g., distortion, rutting, and disintegration).

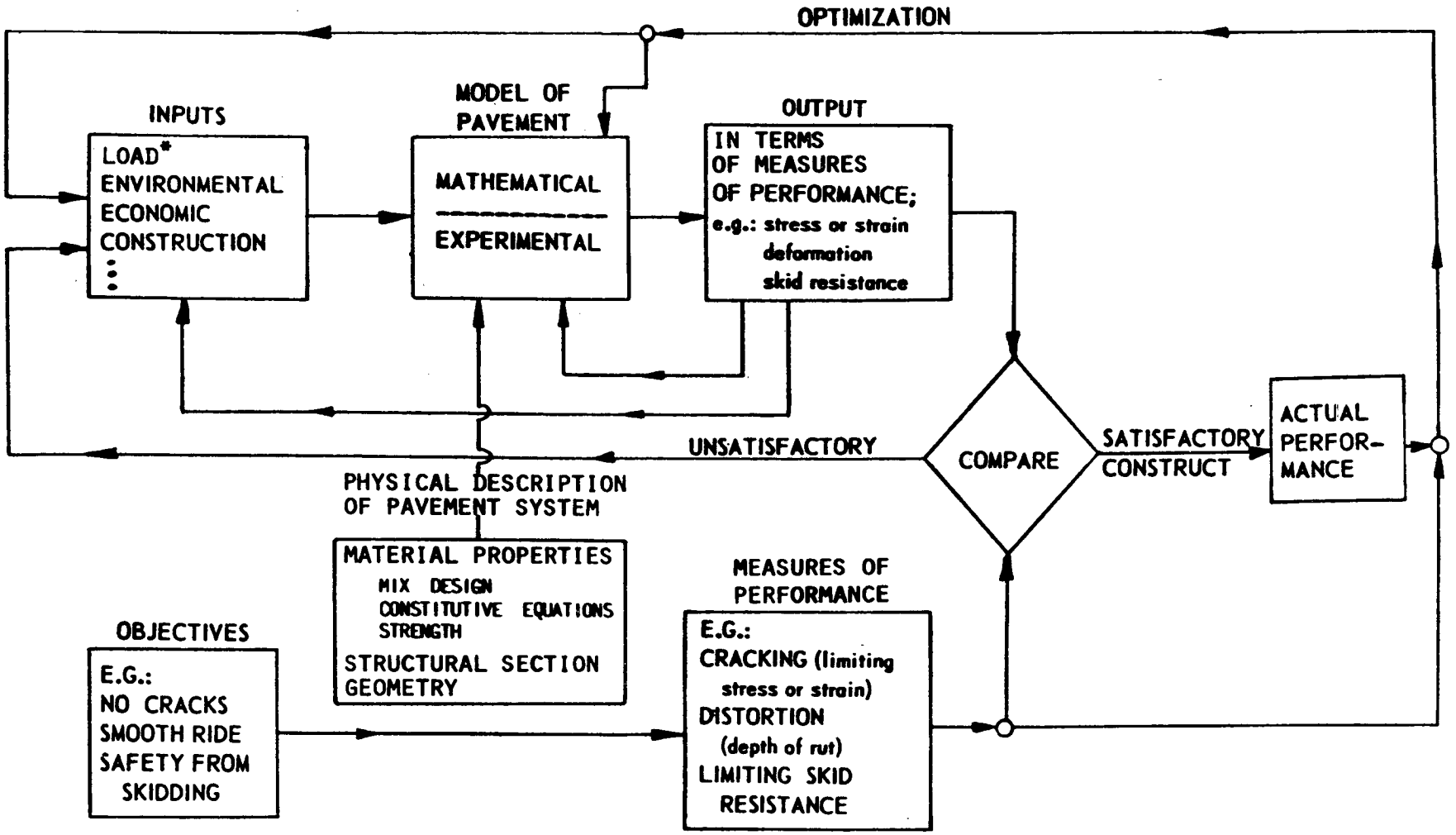
RESEARCH APPROACH

The approach used in this study is shown in Figure 2. The initial requirement was to identify the types of cracking that (1) occur extensively, (2) reduce pavement serviceability, and (3) are expensive to maintain or rehabilitate. A fourth consideration was availability of observational and/or analytical information that could be used to formulate designer-controlled recommendations. Of the many types of cracking that do occur, three have been included (fatigue, low-temperature, and reflection), which meet the foregoing requirements. On the basis of reports and discussions at the Austin Workshop, fatigue cracking is considered most significant.

The next step suggested by Figure 2 is to develop mechanisms associated with various types of cracking. In this usage, "mechanisms" are defined as those processes, physical or chemical, which cause the occurrence of a specific type of cracking. For example, fatigue cracking is caused by the multiple application of wheel loads to an asphalt pavement system.

In order to be able to study cracking, it is necessary to identify a deterministic response variable that is related to a failure theory. For fatigue cracking, for example, it has been shown that the response variables could be pavement deflection or strain in the asphaltic concrete (*51, 52, 115, 165, 169*).

Once the mechanism, response variables, and failure criteria have been developed, the next step is to identify the designer-controlled variables. Published information based on field and laboratory experience, analytical studies, and personal interviews with experienced engineers were used to establish the relative influence of various designer-controlled variables on cracking. Computer simulations relating a structural analyses of layered systems to fatigue properties of asphaltic concrete were used to explore rapidly the potential significance of designer-controlled variables on fatigue life of asphalt pavements.



*One can use the same system considering only one class of input, holding all others fixed; The objectives would have to be formulated accordingly.

NOTES;
1. It should be recognized that the pavement system is embedded in a larger system.
2. The formulation of the objective is a difficult and essential first step.
3. It is usually necessary to have more than one measure of performance and the system is required to satisfy them concurrently.
4. It should be recognized that all components of the system can be considered as functions of time.

Figure 1. Schematic representation of pavement design system.

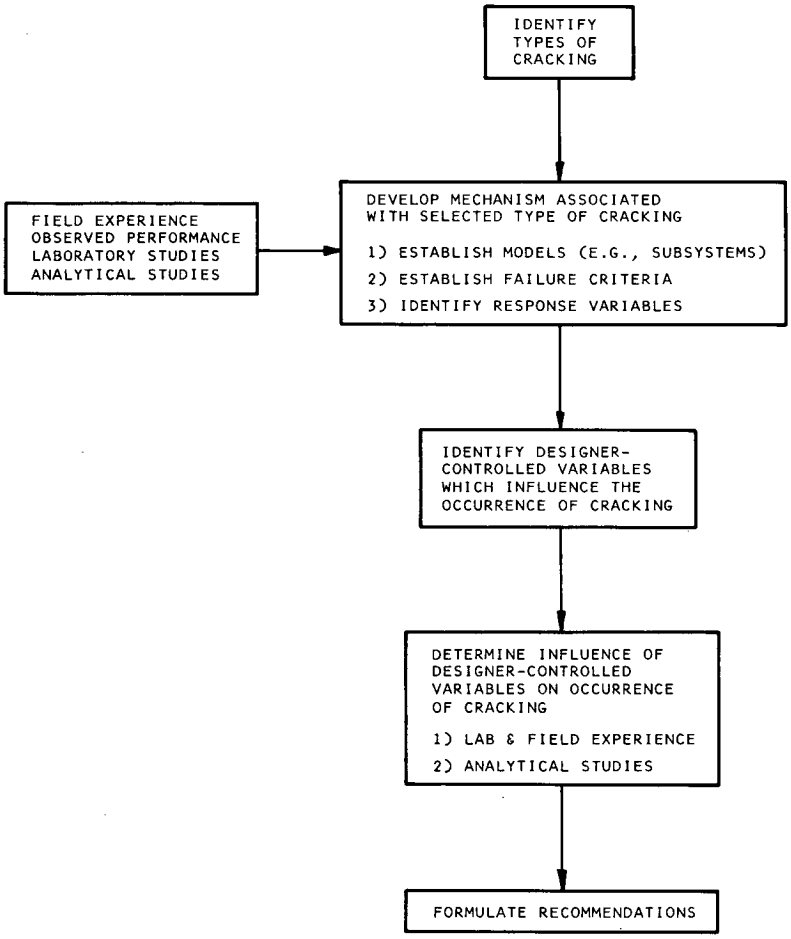


Figure 2. Procedures in formulating recommendations to minimize cracking.

It is recognized that a degree of variability is associated with the factors contributing to the initiation, propagation, and accumulation of pavement damage. Therefore, in order to consider this variability theoretically, it is necessary to treat the problem stochastically. Analytical models that are based on various postulated mechanisms used to predict damage should be probabilistic. However, at the present time, it was felt that such models have not been sufficiently developed to provide a basis for formulating recommendations to minimize cracking. Techniques that recognize the probability of fatigue cracking are referred to in the research literature (*163, 170, 185*).

Appendix A of this report provides a general review of the state-of-the-knowledge regarding the modes of distress covered by this investigation. Details pertinent to the summary provided in Appendix A can be found in the references compiled for this study.

CHAPTER TWO

FINDINGS AND RECOMMENDATIONS

This chapter presents specific designer-controlled recommendations, which, if implemented, should tend to minimize the occurrence of fatigue cracking, low-temperature cracking, and reflection cracking. The recommendations were formulated on the basis of published information, discussion with experienced engineers, and analytical studies. Because of a general lack of definitive information, the recommendations for reflection cracking are necessarily somewhat broad.

FINDINGS

The basic concept in formulating recommendations to minimize cracking, as indicated in Figure 2, is to examine the influence of various designer-controlled variables on the occurrence of cracking based on (1) laboratory and field experience and (2) analytical studies. The application of this concept is illustrated schematically for fatigue cracking in Figure 3.

In following the observational approach, observations of performance, measurement of response variables, and recognition of the stochastic nature of material properties and pavement response are significant parameters. For example, both the AASHO (*104*) and WASHO Road Tests (*102*) indicated that the condition of the foundation soil influenced the deflection significantly. It was also observed that deflection and cracking were associated. Hence, by observation, some association can be made between the properties of the foundation material and occurrence of cracking, and this association can apparently be related to deflection. In both cases, occurrence of cracking and deflection, there is a certain amount of dispersion in the data that requires some kind of statistical interpretation.

In following the analytical approach for fatigue cracking only, the fatigue subsystem (*71*) is modeled analytically and combinations of realistic ranges of structural sections, mechanical properties of the foundation materials and structural elements, and fatigue properties are studied with respect to their influence on fatigue life. Knowing the relationship between designer-controlled variables and mechanical and fatigue properties, it is possible to examine the influence of designer-controlled variables on fatigue life.

The following recommendations are based on information reported in Appendix A together with additional pertinent information included herein.

RECOMMENDATIONS

Minimize Fatigue Cracking

Recommendations to minimize fatigue cracking are based on the assumption that the designer can control the following parameters: (1) composition of structural section, (2) asphalt consistency, (3) asphalt content, (4) air voids and aggregate characteristics in asphaltic concrete, (5) in-place properties of untreated aggregates, (6) in-place properties of cement-treated materials, and (7) the in-place properties of foundation soils. Items 2, 3, 4, and 6 are associated with mix design of asphaltic concrete and cement-treated materials, and items 4, 5, 6, and 7 are associated with construction requirements.

Composition of Structural Section

Analytical studies have indicated that increasing the proportion of asphaltic concrete in the structural section will reduce the potential for fatigue cracking. There is no clear indication of an optimum amount of asphaltic concrete to use; however, if this technique is used, there is some suggestion from the analytical studies that an optimum amount of asphaltic concrete would be approximately 50 to 75 percent.

It should be noted that a significant improvement in performance also can be achieved by increasing the density of the untreated aggregate as will be recommended in a subsequent section. It is, therefore, important to evaluate this possibility along with the possibility of increasing the amount of asphaltic concrete.

Also, the use of cement-treated materials will virtually eliminate the possibility of fatigue cracking in the asphaltic concrete. However, in considering this alternative, the designer must consider the problems of fatigue and shrinkage in the treated materials.

Asphalt Consistency

The influence of asphalt consistency on fatigue cracking is discussed and evaluated in Appendix A.

It is apparent from the reported information that different recommendations could be made depending on the failure criteria used. Table 1 summarizes the recommendations made by the engineers assigned to this investigation. It is believed that, in consideration of various types of distress, these recommendations are reasonable without tending to be extreme. In the event that temperatures can range from less than 10 F to more than 90 F, consideration should be given to the extremes of temperature and the types of cracking observed to be of greatest concern. For example, if normal daily minimum temperatures range from 0 F to normal daily maximum temperatures of 95 F and low-temperature cracking is prevalent, the cold climate recommendations should be used.

Asphalt Content

The research has indicated that increasing the asphalt content will tend to improve fatigue properties of asphaltic concrete. However, too much asphalt can produce an unstable mix or a mix that flushes asphalt leading to a slippery condition. The objective of the designer is to specify mix-design requirements that tend to minimize fatigue cracking without incurring other forms of distress.

Table 2 summarizes designer-controlled recommendations that are believed to provide criteria that will allow for inclusion of a maximum amount of asphalt in both the surface and base-course layers by controlling three factors: (1) stability, (2) voids in the mineral aggregate, and (3) voids in the total mix.

Air Voids and Aggregate Characteristics in Asphaltic Concrete

Recommendations for the allowable voids criteria to be specified for the mix design are given in Table 2. It is equally important for the designer to stipulate void requirements for construction. Table 3 provides recommendations for construction specifications. These recommendations attempt to recognize the risk involved in obtaining lower than desired voids in the surface layer by taking into account the usual dispersion characteristics associated with the placing and compaction of asphaltic concrete.

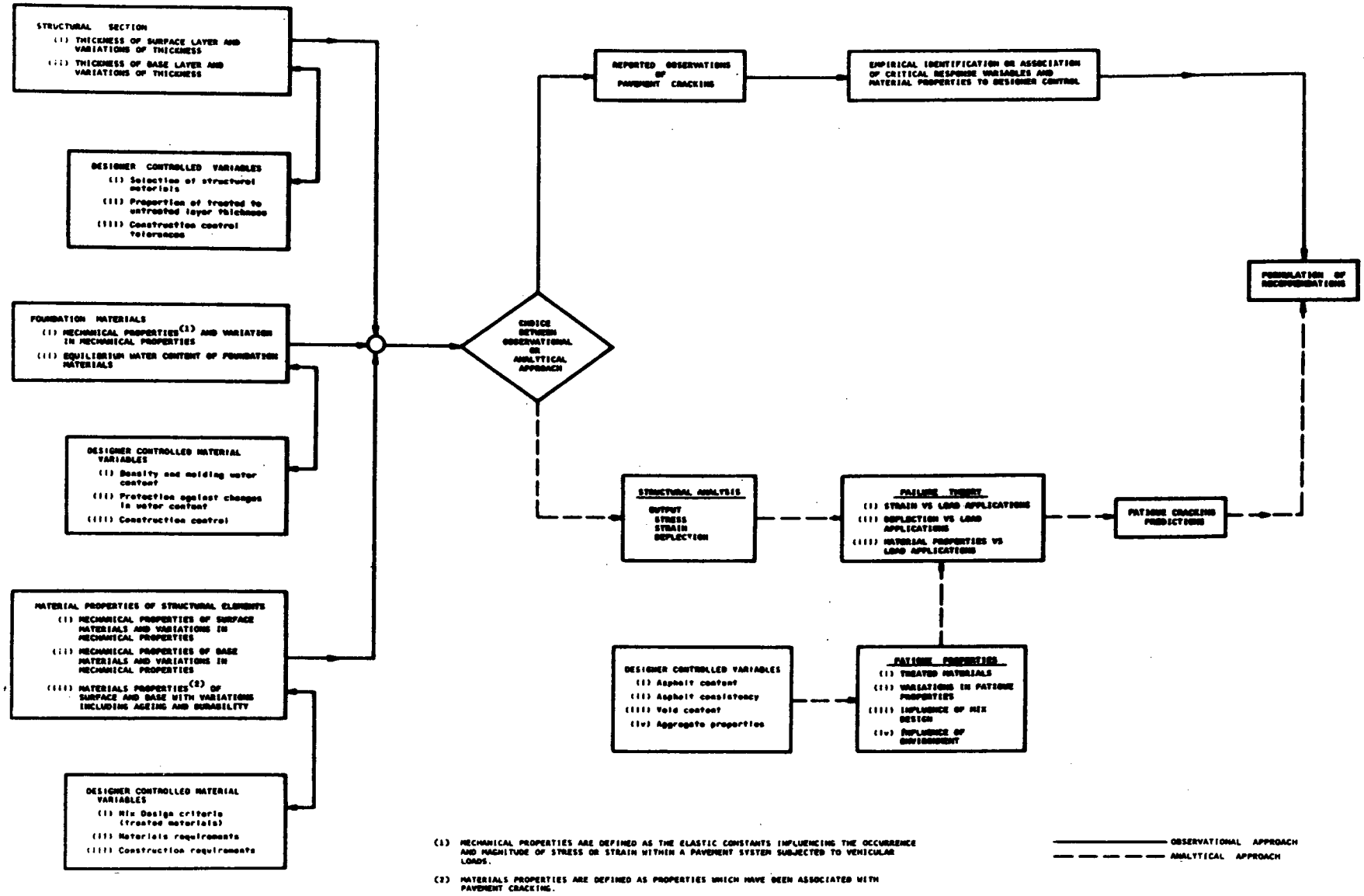


Figure 3. Methodology for formulation of recommendations to minimize fatigue cracking of asphaltic concrete.

Information is limited regarding the influence of aggregate characteristics (gradation, type, shape, and texture) on the fatigue properties of asphaltic concrete. For this reason, no specific recommendations are made regarding this portion of the asphaltic concrete system. However, research has at least suggested some factors that the designer can consider:

1. Gap-graded mixes may exhibit improved fatigue properties compared to dense-graded mixes (*170*).
2. Increasing the maximum size of the aggregate, for a dense-graded mix, may increase the stiffness of the asphaltic concrete (*128*).
3. Increasing filler content up to a filler-bitumen ratio of not more than 2.0 (by weight) will increase the stiffness of asphaltic concrete (*65, 67, 185*).
4. Pretreated aggregates with 1 to 2 percent of slurry lime will stabilize the stiffness properties of asphaltic concrete when subjected to high humidity environments and thereby reduce the annual cumulative damage (*144, 199*).
5. Using angular, crushed aggregates may improve the fatigue properties of asphaltic concrete when compared to elongated shaped aggregate (*67, 147*).

Untreated Aggregates

Table 4 summarizes recommendations for untreated aggregates. Two major considerations are involved in these recommendations. First, if the untreated aggregates become wet, the foundation materials are likely to increase in water content; and second, increasing the density of untreated aggregates will increase the modulus of resilience.

In the event that subsurface drainage has been provided and that high densities (100 percent of AASHO method T180) or higher have been achieved, it is recommended that a treated base be used.

Cement-Treated Bases

Table 5 summarizes recommendations for cement-treated bases. Some question can be raised regarding the inclusion of both compressive strength and ASTM freeze-thaw, wet-dry requirements. In the event that data indicate that testing for one set of criteria (e.g., compressive strength) will provide a mixture that will meet the requirements of the other criteria (e.g., freeze-thaw, wet-dry), it would be logical to eliminate the second set of criteria. However, assuming that premature fatigue cracking is occurring in the cement-treated materials and reflecting through the asphaltic concrete, it is recommended that both criteria be satisfied.

Foundation Materials

Recommendations for foundation materials are given in Table 6. The emphasis in the design phase is to protect the foundation soils from obtaining a high equilibrium water content. The construction requirements attempt to create a soil structure in fine-grained clay soils that will maximize the in-place resilient modulus.

TABLE 1
RECOMMENDATIONS FOR SELECTION OF ASPHALT CEMENT

Thickness of Asphalt Concrete, in.	Climate	Asphalt Cement Grade		Western States[4]
		AASHO M20	AASHO M226	
≤3	Cold[1] Moderate[2] Hot[3]	200-300 85-100 85-100	AC - 5 AC - 10 AC - 10	AR-1000 AR-4000 AR-4000
4-6	Cold Moderate Hot	120-150 60-70 60-70	AC - 5 AC - 20 AC - 20	AR-2000 AR-4000 AR-8000
>7	Cold Moderate Hot	120-150 60-70 40-50	AC - 5 AC - 20 AC - 40	AR-2000 AR-8000 AR-16,000

[1]Normal minimum daily temperature* of 10F or less; for extremely low temperatures special studies are recommended.
[2]Normal maximum daily temperature* of 90F or less.
[3]Normal maximum daily temperature* greater than 90F.
[4]As reported in Western Construction, October, 1972.

*As per U. S. Weather Bureau climatological reports.

Minimize Low-Temperature Cracking

For purposes of this report, it has been postulated that the designer-controlled variables that are associated with low-temperature cracking are primarily concerned with asphalt properties and the proportion or thickness of asphaltic concrete that can be incorporated into the structural design. Figure 4 illustrates a simplified approach to low-temperature evaluations and designs.

By comparing the results obtained in the upper portion of Figure 4 with limiting criteria as represented by the lower part of the figure, the designer can decide if modifications are necessary in the selection of the asphalt or the amount of asphaltic concrete to be included in the design.

Four alternative design approaches to low-temperature cracking have been reported as follows:

1. Specifications for asphalt cement; that is, penetration at 77 F and viscosity at 140 F or 275 F.
2. Stiffness values of asphalt cement or asphaltic concrete that do not exceed limiting criteria for a particular temperature regime.
3. Temperature at which fracture will occur compared to expected low temperature for construction site.
4. Cracking frequency predictions based on empirical correlations for specific constructions compared with tolerable amount of cracking for particular highway functions.

Approaches 1 and 2 have the advantage in that they are most convenient for the designer, because they can easily be incorporated into specifications. However, approaches

TABLE 2

RECOMMENDATIONS FOR MIX DESIGN OF ASPHALTIC CONCRETE[1]

Stability	Void in Mineral Aggregate Based on Maximum Sized Aggregate, Percent			Total Voids In Mix[4]
	1/2 inch max.	3/4 inch max.	1-1/2 inch max.	
No change from current practice for upper 6 inches of asphalt concrete.	15	14	12	3 to 6
Reduce stability in lower layers according to traffic but tentatively not less than 30 by Hveem stability[2] or 500 lbs by Marshall stability.[3]	15	14	12	2 to 5

[1]For conventional dense-graded mixes - local experience to be used for special mix types such as sand-asphalt, open-graded, or asphalt emulsion mixes.

[2]ASTM Designation D1560, Resistance to Deformation and Cohesion of Bituminous Mixtures by means of Hveem Apparatus.

[3]ASTM Designation D1556, Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus.

[4]ASTM Designation D2041-64T or AASHO Designation T209-64 Maximum Specific Gravity of Bituminous Paving Mixtures (or equivalent).

3 and 4 can be written into end result type specifications if sufficient motivation exists. Approaches 1, 2, and 3 can be categorized as "Go" or "No-Go"—in other words, either thermal cracks will occur or will not occur. Approach 4 allows a certain amount of cracking compatible with the service requirements.

At the present time, the single most viable designer-controlled recommendation deals with the grade of asphalt cement. This is illustrated by Figure 22 (Appen. A). Critical temperatures for low-temperature cracking will usually be below — 10 F. As shown in this figure, if the design temperature was — 25 F. the choice of asphalt could range from 85- to 100-penetration asphalt to a 150- to 200-penetration asphalt, depending on the temperature susceptibility of the asphalt. Obviously, local agencies will need to explore their own needs for the specific grade to use, and the technology is available at least for a first try. Table 1 provides reasonable recommendations for asphalt grades considering low-temperature cracking. In all probability, some experimentation may be necessary to determine if such soft grades are actually necessary in thick or full-depth asphalt construction.

McLeod (*158*) has offered limiting stiffness requirements for asphaltic concrete under anticipated field conditions, as given in Table 11 (Appen. A). These low-temperature moduli are determined on the basis of McLeod's procedure for estimating stiffness as described in Appendix B.

Procedures for predicting cracking temperatures are described in Appendix C. Specifications could be prepared such that the mix requirements would stipulate that low-temperature cracking would not be expected according to these procedures for the design temperature. Thus, the maximum allowable temperature at which cracking would occur could be a part of the special provisions for each project.

Cracking frequency can be estimated according to the nomograph in Figure 23 (Appen. A). Haas (*87*) has suggested that some allowable number of temperature cracks can be tolerated, depending on the class of roadway and volume of traffic.

Specifications could be written such that the stiffness of the asphalt cement, at the design temperature, would not

TABLE 3

RECOMMENDATIONS FOR MAXIMUM AIR VOIDS REQUIREMENTS TO BE INCLUDED IN CONSTRUCTION SPECIFICATIONS

Asphalt Concrete Layer	Light Traffic	Moderate to Heavy Traffic
Surface, inches (1½ - 2)	8	7
Base	7	6

Note: 1. Determined from cores in accordance with ASTM Designation D2041-64T or AASHO Designation T209-64.
2. Construction specifications should be written such that not more than 15 percent of the areas would be expected to have air voids exceeding the specified amount. If the specifications are based on average air voids, the construction specification requirements noted in Table 3 should be reduced by one percentage point each.
3. Light traffic is defined as 10 equivalent daily 18 kip single axle loads. Moderate to heavy traffic refers to equivalent daily 18 kip single axle loads in excess of 10.

TABLE 5

RECOMMENDATIONS TO MINIMIZE CRACKING IN CEMENT-TREATED BASES

Designer Controlled Activity	Designer Controlled Recommendations
Design	1. Extend cement treated layer at least one foot into shoulder zone. 2. Minimum design thickness of 0.5 feet. 3. Protection of foundation material against exposure to free water by providing subsurface drainage or membrane protection. 4. Minimum thickness of asphalt concrete surface of 0.25 feet.
Materials Specification	1. Use Type II cement. 2. Cement treated materials should be capable of meeting ASTM, wet-dry and freeze-thaw criteria. 3. Limitation on clay content (approximately 10 to 15 percent depending on clay mineralogy).
Mix Design	1. Cement content sufficient to meet wet-dry and freeze-thaw criteria (see also - materials specification). 2. Sufficient cement content to provide 500 to 750 psi compressive strength after 7 day cure at density expected in 95 percent of area. 3. Additional cement requirement to compensate for non-uniform mixing (suggested increase of 1/2 percent).
Construction	1. Mixing and compaction completed within 2 hours after water added to cement-aggregate mixture. 2. Minimum density compatible with mix design (suggested minimum of 95% of AASHO T180 or equivalent). 3. Layer thickness no less than 0.05 ft. thinner than design section. 4. Provision for adequate curing.

TABLE 4

RECOMMENDATIONS TO MINIMIZE FATIGUE CRACKING IN ASPHALTIC CONCRETE DUE TO PROPERTIES OF THE UNTREATED AGGREGATE

Designer Controlled Activity	Designer Controlled Recommendations
DESIGN	Under conditions where saturation or near saturation can occur, some positive drainage system should be provided to eliminate the accumulation of water in the aggregate.
CONSTRUCTION	Resilient modulus is increased by increasing density; designer should specify the maximum density possible based on past experience or on special test projects.

TABLE 6

RECOMMENDATIONS TO MINIMIZE FATIGUE CRACKING DUE TO PROPERTIES OF FOUNDATION MATERIAL

Designer Controlled Activity	Designer Controlled Recommendations
Design	1. Use treated base. 2. Use untreated base with membrane for moisture protection. 3. Shoulders designed with protected surface for 8 ft and adequate transverse slope. 4. Provide subsurface drainage in cuts or side slope fills when subsurface exploration or experience indicates presence of water.
Construction	1. Compaction water content not to exceed optimum for respective compactive effort.[1] 2. Use highest laboratory compactive effort compatible with field experience.[1]

[1]For highly expansive foundation materials compact to lower densities at higher water contents; redesign structural sections to recognize potential reduction in strength.

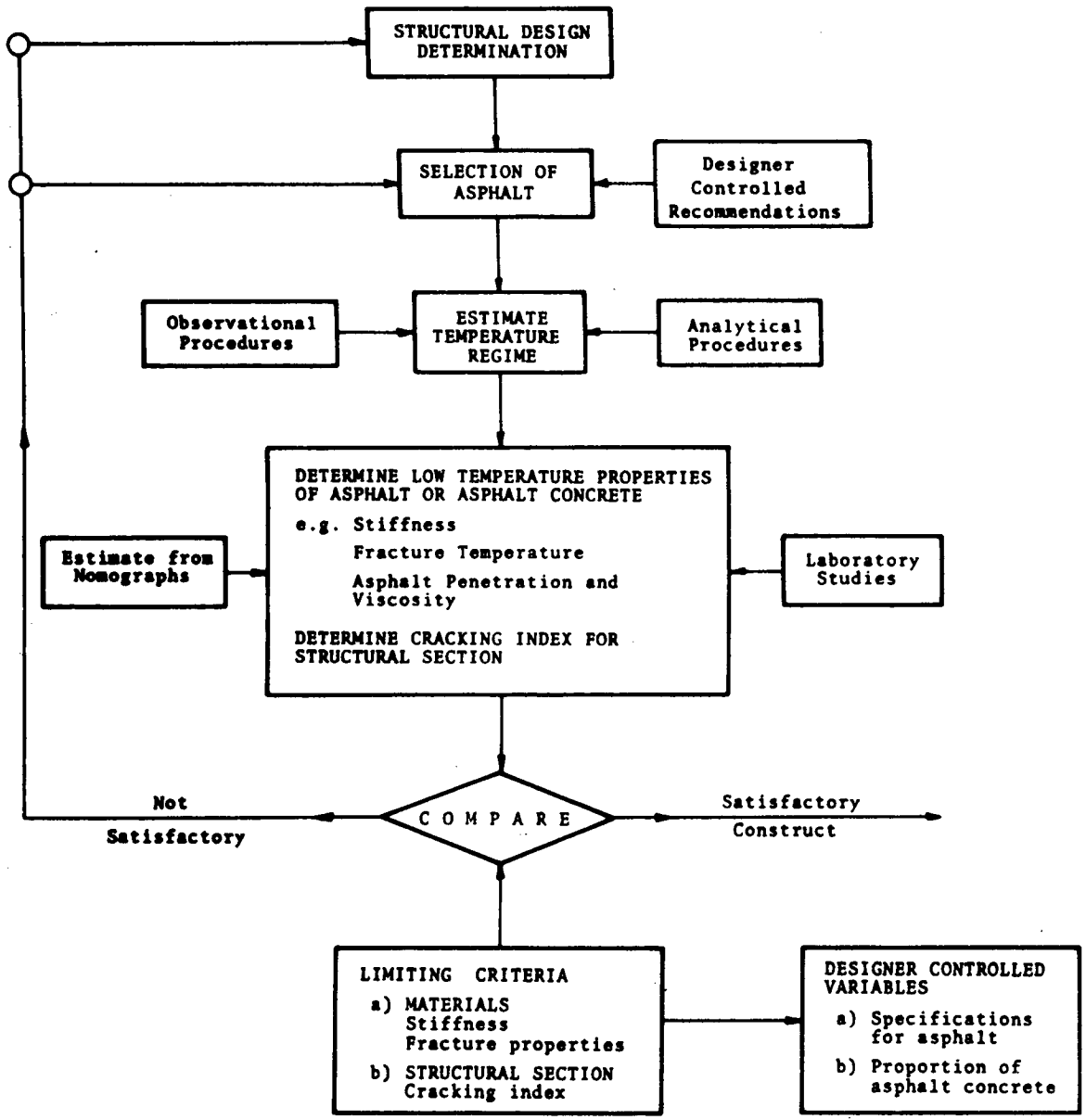


Figure 4. Simplified low-temperature analysis procedure.

exceed a specified amount compatible with limiting the number of transverse cracks for a particular design section. Verification of the nomograph would be necessary by any agency planning to implement such a procedure.

The foregoing procedures are general recommendations that can be implemented by a designer agency. In each case, some evaluations and testing will be required. Specific recommendations, except as given in Table 1, are not currently feasible because most investigations to date have concentrated on the methodology of crack occurrence. It would be desirable to include a recommendation for temperature susceptibility. However, this does not appear practical, at the present time, without the possibility of rejecting asphalts that should be accepted. From Figure 22 (Appen. A), a table showing design temperature, aged penetration, and penetration index (P.I.) could be developed. McLeod (*158*) has presented a similar type of chart; however, the recommendations are not the same. Both may be satisfactory; and, for the present, the designer could use either one as a beginning point.

Minimize Reflection Cracking

On the basis of the current state of knowledge regarding methods for minimizing premature reflection cracking, it is not possible to formulate specific and definitive recommendations. However, some possibilities that are considered as reasonable considerations for the designer are included in Table 7.

Some explanation of the recommendations referring to modifying the asphalt and asphalt mix properties is required. There is very little specific information to which

TABLE 7

RECOMMENDATIONS FOR PROCEDURES TO MINIMIZE REFLECTION CRACKING IN ASPHALTIC CONCRETE OVERLAYS ON PORTLAND CEMENT CONCRETE PAVEMENTS

Condition of Underlying Surface	Designer Controlled Recommendations
Essentially sound- some rocking slabs and faulted joints with minor cracking.	1. Repair or replace expansion joint sealant. 2. Subseal with asphalt or pressure grout with portland cement mortar as required. 3. Place bond breaker, e.g., stone dust, membrane at joints and cracks. 4. Construct asphalt treated aggregate cushion course minimum 4 inches thick with 3 to 4 inch leveling and surface layers. *5. Modify properties of asphalt concrete. a. Use of fillers such as asbestos or carbon black which increase strain at bread and reduce temperature susceptibility. b. Use of asphalt modifiers such as rubber which increase strain at break and reduce temperature susceptibility.
Moderately cracked - rocking slabs and faulted joints	1. Repair or replace expansion joint sealant. 2. Subseal with asphalt or pressure grout with portland cement mortar as required. 3. Seat by heavy rolling with hammering as necessary to initiate cracking. 4. Construct asphalt treated aggregate cushion course minimum 4 inches thick with 3 to 4 inches leveling and surface layers. 5. See Item 5 under "Essentially Sound" category. 6. Use stress relieving materials
Badly Broken	1. Seat by heavy rolling with hammering as necessary to initiate cracking. 2. Construct asphalt treated aggregate cushion course minimum 4 inches thick with 3 to 4 inches wearing course. 3. See Item 5 under "Essentially Sound" category.

*Have not been documented by field experience - would require further investigation but appear to be reasonable.

one can refer, that documents these recommendations. However, it has been concluded that both horizontal and vertical movements cause reflection cracking. The recommendations are predicated on the assumption that increasing the adequacy of the mix to sustain strain without rupture will reduce the potential for reflecting cracking. Some work with the modifiers referred to in Table 7 has been reported in the literature (*99, 196, 197, 198, 199*).

Implementation

At least three approaches for implementation of the recommendations could be considered as follows:

1. Evaluate the recommendations, as contained herein, against current department practices. If some changes are indicated, they can be made without further verification. Observations of performance would be necessary in order to determine the effect of designer changes on the occurrence of cracking.

2. Initiate field experiments to verify, modify, or expand the recommendations contained herein.

3. Initiate a verification investigation based on the recommendations contained in Chapter Four of this report.

It is unlikely that many agencies would initiate changes without some type of verification, except possibly in three cases, where recommendations would be generally accepted

by experienced highway engineers: (1) reducing voids in the asphaltic concrete, (2) increasing density of untreated aggregates, and (3) providing subsurface drainage in those areas where the accumulation of water is known to be a problem.

The most efficient means of verifying recommendations would be a combination of items 1 and 3 enumerated earlier in this section. Techniques for doing this will be described in Chapter Four.

CHAPTER THREE

INTERPRETATION AND VERIFICATION OF RECOMMENDATIONS

The generally accepted approach to verification has been to design experimental test sections based on factorial analysis from classical statistics and to monitor performance under controlled conditions. An alternate approach has been to verify an analytical model by using case histories and, then, to use this model as a generalized procedure to identify the significant designer-controlled variables that influence the distress present in a pavement. The feasibility of these two approaches to verifying the recommendations presented in Chapter Two is discussed in the subsequent sections. Also included is a discussion of an approach that represents a new philosophy, which uses the cumulative experience of engineers working in the areas of design, evaluation, construction, and maintenance of pavements.

CURRENTLY USED APPROACHES TO VERIFICATION

Factorial Experiment Design Approach

This is a rational and useful approach to take when not too many variables are involved or when the number of replicates (approximately 10 to 30) can be included economically in the data acquisition phase.

In essence, the cost of experimentation and the information that can be obtained for the cost must be evaluated and a proper trade-off obtained. In the present study, the number of designer-controlled variables, the variety of loading and environmental conditions, the cost of the experiment, and the elapsed time before any definitive results can be obtained suggest that the classical approach may be impractical. In order to recognize this, it is sufficient to note that the AASHO Road Test considered only two variables, the structural section and the load, and each variable was considered at several levels (e.g., three levels each of surface, base, and subbase for each load). Therefore, the experiment involved two variables with several levels of each variable.

Originally, it was thought that the plan for verification would involve an experiment design utilizing classical statistical techniques. However, further study has indicated that such an approach would not be feasible. The major difficulty concerns the required size and the associated cost of the field experimental program. To illustrate this problem, two examples will be considered: (1) design of an experiment that includes the major variables that influence the occurrence of fatigue cracking as stated in Chapter Two and (2) design of an experiment that considers only a limited number (i.e., the more significant of the designer-controlled variables).

Experiment Design for All Variables

In order to consider the designer-controlled variables, the experiment should include as a minimum the following: asphalt consistency—3 levels; asphalt content—3 levels; void content—3 levels; asphalt temperature susceptibility—2 levels; structural composition—3 levels; properties of untreated aggregate—2 levels; properties of foundation material—2 levels; and subsurface drainage—2 levels.

A factorial experiment to evaluate these eight variables with the number of levels indicated would require 1,296 test sections, not including replication to evaluate the reliability and statistical properties of the data. This is clearly not a practical approach to the problem. One modification in the experiment design could be made by reducing the number of levels for each variable to two, which would reduce the size of the experiment to 256. Without any replicates, this is still considered impractical. Furthermore, it should be recognized that these variables have to be considered within the context of different environmental loading conditions. This further increases the scope of the experimental program.

Experiment Design for a Limited Number of Variables

It is reasonable to assume that two of the most significant designer-controlled variables with respect to the occurrence of premature cracking are asphalt consistency and the in-situ void content of the asphaltic concrete. Two variables at three levels would require only nine sections, still without replications. An experiment of this kind involving a limited number of variables requires that all of the remaining variables be held constant. An experiment with nine test sections for two variables might not be considered unreasonable; however, as previously mentioned, this experiment contains no replications.

Pavement cracking measurements are never precisely reproducible from pavement-to-pavement; therefore, depending on the size of the experimental error, the experiment must be repeated in order to draw valid conclusions. Replicates provide information regarding the type of distribution to be used in representing the measurements, the statistical properties required to make certain statistical tests necessary for the evaluation of the data, and the determination of confidence levels associated with the conclusions obtained from the data. According to information in the textbook by Cochran and Cox on "Experimental Designs," the number of replicates necessary for fatigue cracking could vary from 9 to 30 for an 80 percent probability of obtaining a significant result at the 5 percent level. The exact number would depend on the true difference due to experimental effects, the value of the standard error, the minimum desirable level of the difference to be detected, and the assigned probability level. Even this number assumes the independence of the experimental variables. Thus, the minimum size of the field experiment required to obtain sufficient replications for two variables is 81; again, an impractical recommendation. Some replicates could potentially be deleted if prior information was available as to the statistical properties of the field results. However, at the present time, such information does not appear to be available in the literature. Obviously, smaller experiments can be, and have been, conducted. It is contended that one of the reasons that most test projects do not have the expected influence on design decisions is the lack of replicate tests.

The smallest possible experiment would involve only one variable. For example, if only asphalt consistency was to be evaluated, three sections (three levels) would be required for each replicate. There is very little data available to suggest either what type of distribution (normal, Poisson) would be obtained for any given level of asphalt consistency or what the probability density function would be for each level of asphalt consistency. In the absence of such information, the minimum number of replicates would be difficult to estimate. Ten replicates would not be unreasonable for initial experiments; as information is accumulated, it is probable that the number of replicates could be reduced. Thus, even for this simple case, the experiment would require some 30 sections in order to provide sufficient information for a valid analysis. Again, it is important to recognize the necessity of considering different environmental and loading conditions and structural sections, which would greatly increase the size of the experiment. For example, the influence of asphalt consistency may depend on the thickness of the asphaltic concrete, an interaction not included in the experiment just described.

A significant disadvantage in using data from restricted field projects is that such data are likely to be rejected if they do not fit the previous experience of the engineer. He has to make a choice because he has no method available for combining these new data with his prior experience. Experienced engineers, in general, will not accept the results of experimental data from isolated field projects unless they are in agreement with their subjective "feel" for the problem.

Case History Approach Using Analytical Simulation

This approach can be considered as an attempt at reducing the scope of the experiment as determined by factorial design. The basic concept in this approach is to develop an analytical model to simulate the occurrence of cracking. This model is then verified using case histories. If the model is judged adequate, the model can be used to indicate the influence of certain variables on the occurrence of premature cracking. In this approach, the recommendations can be verified indirectly through the verification of the model.

It should be realized that the model is verified in a limited sense in that it is the final output; that is, prediction of cracking that is compared with performance. To verify the effect of each variable in the model would require data from a number of case histories of the same order of magnitude as in the factorial experiment design discussed earlier. However, the claimed advantage for an analytical model is its ability to extrapolate; thus, a complete verification would not be considered necessary.

In recognition of these limitations, verification of the fatigue model was attempted using the Morro Bay Project, which concerns a four-lane divided highway located on U.S. Route 1 north of San Luis Obispo, Calif. Details of the verification are provided in Appendix D. This verification is based on a single case history and can only be considered as an indication of the applicability of the model. Actual and predicted performance were not in complete agreement; however, the performance trends were similar. It was concluded in this particular case that the fatigue model was considered to be a reasonable representation of actual physical behavior and could be used to predict the occurrence of cracking under this particular mode of distress.

Two cases involving the performance of projects on the Interstate System in Georgia were also studied using the analytical model. Both of these investigations could only indicate probable causes of distress and provide some preliminary ideas as to what steps the designer may take to avoid the occurrence of premature cracking. Further investigations will be required before definitive recommendations can be formulated. Therefore, none of the recommendations made in Chapter Two could be entirely verified at this stage. Details of these case history studies are also provided in Appendix D.

One case history with low-temperature cracking was studied. The model did not include the detailed structural analysis that was used in the fatigue model. A model (Appen. C) for predicting fracture temperature based primarily on material properties as influenced by temperature was used. As with the previous case studies, this investigation provided only an indication of possible causes of distress and what steps the designer may consider in reducing distress. The recommendations presented in Chapter Two could not be verified directly. Details of this study are discussed in Appendix D.

Summary

The previously discussed two approaches utilize specially designed experiments to verify the recommendations pro-

posed in Chapter Two. The use of analytical procedures to reduce the scope of field experiments is also suggested.

The major shortcomings of the foregoing approaches are (1) the excessive cost and scope of the experimental program to reach any definitive conclusion and (2) the inability to consider the conflict that can arise between field-test results and the subjective "feel" of engineers based on experience.

On the basis of the discussion presented in the previous pages, it was evident that the two approaches thought to be most useful do not represent a feasible approach for the verification of the recommendations in Chapter Two. This does not imply the exclusion of special test sections to verify specific recommendations; it does imply that some method must be found to reduce the size of the experiment. It was, therefore, considered necessary to find an alternate approach to the problem of verification which did not have the shortcomings discussed earlier. The general concepts of such an approach are discussed in the next section.

GENERAL CONCEPTS OF A NEW APPROACH

The approach proposed here for verification and updating of recommendations represents a new philosophy, which uses the cumulative experience of engineers working in the areas of the design, evaluation, construction, and maintenance of pavements together with laboratory data, data from special test sections, and analytical studies. The most important feature of this approach is that it can utilize information from all of these sources and place them in a consistent and compatible format for use by the practicing highway engineer. Research and field experience can be brought together to assist in solving the problem.

The methodology for such an approach is based on Bayesian decision statistics. By using this approach, it is possible to extract the past experience of engineers in a meaningful statistical format similar to data obtained from experiments. New experience gained from observation of field performance or test data can be combined with previous experience using Bayes' formula to arrive at posterior information. Such an approach, while new in the highway field, is well established for decision-making in other fields and areas of transportation engineering (e.g., Ref. *209*).

The general methodology is presented in simplified form in Figure 5. The key concepts in the proposed approach are based on the following:

1. The recommendations presented in Chapter Two were based on a "partial" state of knowledge and necessarily limited to the published information. The recommendations were formulated without the inclusion of a great deal of the experience that has been gained in the performance of the highways systems because this experience resides in the subjective evaluation of experienced engineers. It is believed that only a small percentage of this information has been published.

2. To verify these recommendations, a "more complete" state of knowledge should be developed. It is proposed to verify and update the recommendations in the context of a more complete state of knowledge. This will be done by extracting the subjective information from experienced engineers and combining it with the available published information.

3. The state of knowledge developed in item 2 will be updated periodically as new information becomes available.

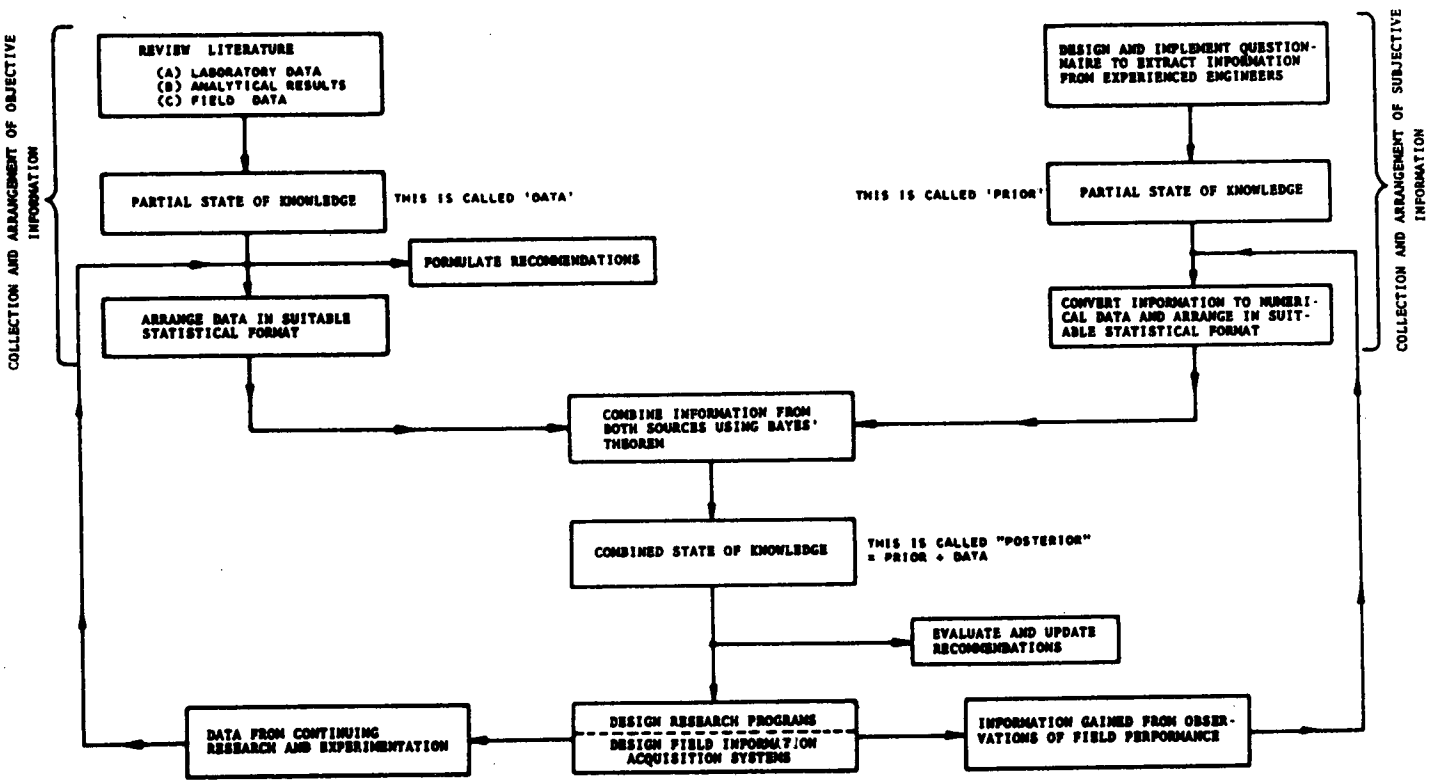


Figure 5. General methodology for combining subjective and objective information to represent current state of knowledge.

This new information will come from laboratory and analytical research and observations of performance. In this context, the existing highway system can be considered as a large-scale experiment. The methodology will provide a rational method for designing feedback systems, and more significantly, provide a means for including the information (experience) being developed into the design process. This does not preclude designing special test sections to verify certain specific recommendations. However, in general, such special test sections should only be considered in the context of the total experience on a particular problem. The methodology will also assist in suggesting directions for future research.

Advantages of Suggested Approach

1. Information from all sources can be used in a rational and consistent manner for developing and verifying recommendations to minimize premature cracking. Research, analysis, and practical field experience can be brought together to contribute to the solution of the problem.
2. The scope of cost of the special field experiments is greatly reduced.
3. The experience of practicing engineers, which is the greatest collection of valuable information on the performance of pavements under a variety of conditions, can be used in the development of design recommendations. This will increase the likelihood of acceptance of the results obtained through the proposed methodology by the practicing engineer.
4. Data and subjective evaluations can be combined in a theoretically sound and consistent manner.
5. The methodology provides a means for updating information as new information becomes available.
6. It provides a basis for designing performance monitoring and information feedback system.

Research Plan

The research plan to verify the recommendations based on the approach suggested is best described in the context of implementing the general methodology. The methodology and plan are described in a series of steps and, in general, follow the flow diagram shown in Figure 5. Theoretical aspects of the methodology are omitted in this discussion but are included in Appendix E.

Step 1—Identify and Rank Those Factors That Have a Significant Influence on the Occurrence of Each Type of Cracking

On the basis of the information presented in Chapter Two, a list of those factors that are considered to have a significant influence on each type of cracking would be prepared. This list would be circulated to experienced engineers who would be asked to rank the factors in order of importance and add any that had been omitted from the list. In selecting the engineers, emphasis would be placed on design and materials engineers from state highway departments, inasmuch as the opinions of researchers have already been considered in the context of published information. It is also planned to include adequate representation of the major climatic zones in the United States.

Step 2—"Extract" the Subjective Information of Experienced Individuals on the Influence of the Significant Variables on the Various Types of Cracking

This requires (1) designing a suitable questionnaire, (2) implementing the questionnaire, and (3) arranging the data in suitable statistical format.

Designing the Questionnaire. The questionnaire is prepared to extract (1) range, mean, and coefficient of variation of each variable; and (2) information regarding the influence of the independent variables on the dependent variable (e.g., fatigue cracking). In formulating the questionnaire, attention must be paid to the background and training of the individuals who will be asked to respond to the questionnaire. In some cases, it will be necessary to go through a number of iterations before a satisfactory questionnaire is designed.

Implementing the Questionnaire. Individuals with experience in the field under study would have to be located. As in Step 1, emphasis will be placed on materials and design engineers from state highway departments and will cover the major climatic subdivisions of the United States. It is planned to implement the questionnaire on a personal basis (interview). Using the interview process has three significant advantages: (1) it permits an explanation of the basic philosophy of the method, (2) it provides an opportunity to explain statistical concepts to individuals when necessary, and (3) it provides an opportunity to explain questions that are stated in terms that are outside the usual thought process of the interviewed individuals. It is also important to recognize that the personal explanation and individual participation will greatly increase the acceptability of the results of such research into practice.

Arrangement of Data. On the basis of an examination of the data and discussions with experienced engineers, a relationship (equation) between the dependent variables (e.g., fatigue life) and the independent variables will be postulated. The subjective information will be equated to experimental data based on techniques of information theory. This requires equating the experience of the engineers to a certain number of experiments. Details of how this might be done are provided in the example presented in Appendix E.

Step 3—Assembling Objective Information

Objective information both in the form of laboratory and field data will be assembled. The relationship developed between the dependent and independent variables in Step 2 is used to analyze the data. The results are placed in the same form as the information obtained from implementing the questionnaire. In some cases, if substantial published data are available, Step 3 may be conducted prior to Step 2 and the relationship between dependent and independent variables is postulated on the basis of objective data. This was the case in the illustrative example presented in Appendix E.

Step 4—Combining Information to Develop State of Knowledge

The information obtained in Steps 2 and 3 will be combined to develop the state of knowledge. This is done using Bayes' formula. The theoretical basis for doing this and a practical example are presented in Appendix E.

Step 5—Evaluation of Recommendations

Using the updated relationship developed in Step 4, sensitivity studies will be conducted to evaluate the relative influence of various factors on the occurrence of cracking. The recommendations that have been made in Chapter Two can now be evaluated using the sensitivity studies conducted on the basis of a more complete state of knowledge as developed in Step 4.

Step 6—Continued Evaluation and Modification of Recommendations

In the classical approach, this would require a factorial design of experiments. In the proposed approach, a single set of experiments is unlikely to have any significant effect on the cumulative experience of engineers as determined in Step 4. Therefore, continuing evaluation will be based on incorporating the results of continuing research and the experience that is being gained by engineers on the basis of the performance of the highway system to update the existing state of knowledge. In this context, this step will consist of designing feedback and information-gathering systems and detailing the procedure for combining information as it becomes available with the previously available information to obtain a new state of knowledge.

It is envisioned at this time that the total data-gathering process will include three sources of information: subjective priors, feedback, and special test sections, as follows:

1. Subjective priors—The fastest way to obtain some verification of recommendations or to expand on recommendations is through the quantification of engineering experience as has been discussed and is illustrated in the sample in Appendix E. By this procedure, a great amount of data can be generated over a relatively short time. There are limitations regarding this procedure. Probably, the most significant one is that engineers who are interviewed can best speak with confidence only about their personal experience, which itself is limited to "what is" and not so much about "what might be." For example, if one is interested in exploring recommendations regarding the use of thick asphalt layers, it may develop that field engineers have very little experience with this type of design. Nevertheless, experienced engineers can be asked to extrapolate on their experience if the weighting assigned to such experience is modified and the confidence is reduced.

2. Feedback system—To supplement, reinforce, or negate recommendations, a field feedback system will be required. Three aspects are required for this system: (a) the development of a model for statistical analysis, (b) the field quantification of the input variables required by the regression model, and (c) the field evaluation of pavement performance. The model will initially be developed from information obtained from the subjective priors. The field measurements and information necessary to quantify or modify the model would be obtained from new and existing constructions in the highway system. Selections would be based on the following:

a. Four levels of environment: hot and wet, hot and dry, cold and wet, cold and dry.
b. Three levels of traffic: light, medium, and heavy as generally defined by The Asphalt Institute.
c. Three levels of foundation material properties.
d. Two levels of thickness of the asphalt layer: less than 50 percent or more than 50 percent of the structural section.

The number of dependent variables cannot be determined until subjective priors have been obtained. However, it can be assumed that at least eight variables, enumerated previously, could be evaluated. As an initial recommendation, it is suggested that at least 10 projects in each category of traffic and foundation properties be included from each environment, a grand total of 360 sections. Such a feedback system would require time to develop and implement. However, such a system is feasible and does not require special construction. It does require special measurements of both the dependent and independent variables. The data obtained from the feedback system would be evaluated initially without being combined with the subjective priors. A comparison of the two sources of data will provide information between subjective and objective data. Eventually the feedback data would be pooled with all data previously acquired for a revised analysis.

3. Test sections—If the information from Phases 1 and 2 is sufficiently definitive, implementation can be initiated without further delay. However, in the event that further documentation is considered necessary, a series of field-test sections can be programmed.

Step 7—Research on Special Problems

As has been pointed out, there is the case when, because of new materials, of new methods of construction, or of other factors, there is very limited prior experience. In such cases, people may be asked to extrapolate on the basis of their previous experience. However, to rely on this extrapolation alone can be very misleading. Therefore, in some cases, it will be necessary to conduct laboratory research, carry out analytical studies, and implement special field experiments. The key requirement in the proposed methodology is the ability to collect and combine data (measurements) and subjective information. The theoretical basis for doing this is discussed in Appendix E.

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

The premature cracking of asphaltic concrete pavements is a continuing problem and often results in large expenditures of money to maintain a necessary level of pavement serviceability. The over-all objective of this project is to formulate recommendations for the determination of suitable materials specifications, paving mix design criteria, and construction requirements that will result in the ability to design and construct asphaltic concrete pavements to carry design traffic with a minimum of premature cracking. This over-all objective is intended to be accomplished in two or more phases. Phase I, the preparation of recommendations, is satisfied by this report. Phase II would be satisfied by the implementation of procedures outlined in Chapter Three for the verification and evaluation of the recommendations and by the initiation of a feedback system aimed at obtaining pertinent information for further verification at a national level. If necessary, Phase III would be the construction of special test sections, as required, to obtain information not resolved by Phase II.

It is acknowledged that considerable research effort is being directed toward the development of more rational procedures for pavement design, utilizing the measured values of the significant basic properties of materials used in road construction, which will be applicable to all locations, environments, and traffic loadings. It should also be recognized that implementation of currently available research results provides prospects for some improvement in the performance of new asphaltic concrete pavements. The conclusions and recommended research should be considered in the foregoing context.

CONCLUSIONS

On the basis of the findings on Phase I of the investigation, the following conclusions are drawn:

1. Field, laboratory, and analytical procedures have provided the basis for formulating a series of recommendations to minimize fatigue and low-temperature cracking in asphalt pavements. Specific recommendations to minimize premature cracking are presented in Chapter Two.

2. It is necessary to develop a method for verifying the proposed recommendations and updating the recommendations as additional information becomes available.

3. Field experiments, if adequately designed, using classical statistical design techniques to verify or develop information on pavement cracking are too expensive and time consuming for the immediate needs of the designer.

4. A new approach to verify recommendations and to develop information as a basis for continuous updating of recommendations has been formulated. This approach combines subjective engineering experience with available data. It offers an opportunity to expand on the current state of knowledge as generally contained in the research literature. The approach is presented in Chapter Three. This procedure would be faster and less expensive than experimental design based on classical statistics.

5. Asphalt properties are the major determinant of low-temperature cracking. Methodology is available to evaluate the role of material properties and to write end result specifications to minimize such cracking. Agencies should be encouraged to implement such methodologies to determine if cracking can be minimized in the field and for preparation of simple guidelines in selecting asphalt cement.

6. Accumulation of performance information from the field is required in order to continually update knowledge of factors influencing the performance of asphalt pavements.

7. Specific or nonconflicting engineering criteria are lacking regarding the influence of the following factors on pavement cracking:

a. Drainage—A consensus of engineering information is available to support the contention that subsurface drainage is desirable for pavement structures. However, there is a very limited amount of quantitative information available to define the sensitivity of pavement cracking to drainage.
b. Asphalt consistency—A difference of distress criteria exists regarding the role of asphalt cement consistency on the fatigue cracking of asphalt type pavements.
c. Reflection cracking—Little specific information is available to help formulate recommendations to minimize reflection cracking.

RECOMMENDED RESEARCH

Three areas of research are recommended for Phase II of this investigation as follows:

1. The major recommendation for future research is to implement the research plan described in Chapter Three and Appendix E. This will provide:

a. Development of the detailed methodology and implementation procedures for using the Bayesian decision statistics approach for verifying and updating recommendations as outlined in Chapter Three and Appendix E. Implementation procedures will be geared primarily towards state highway departments.
b. Formulation of updated recommendations on minimizing premature cracking obtained through the implementation of (a).
c. Recommendations for pavement feedback system useful in the determination of factors that are significant for minimizing cracking. The information to be obtained from the feedback system should be delineated in accordance with the findings in (a) and (b).

d. Recommendations for case studies to obtain objective information necessary for the verification of data and subjective information obtained in (b) and (c).

2. Undertake to develop criteria to minimize reflection cracking for portland cement concrete pavements, soil-cement bases, and fatigue or low-temperature cracking in asphalt pavements.

3. Published research findings indicate conflicting recommendations as regards the role of asphalt consistency on fatigue cracking of thick asphaltic concrete layers incorporated in "real" pavements. Investigations should be undertaken to resolve these differences. A research plan involving Bayesian statistics and interviews, and an in-depth evaluation of published research and case studies, where possible, would be necessary.

4. In the area of materials research, it is recommended that research be initiated for the purpose of developing new binders that would be capable of sustaining high strains at failure and that would also have adequate load distribution properties. Modified asphalt cement systems would be a logical starting point, considering available material and construction capabilities. Materials with such properties would be especially useful to minimize reflection cracking.

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APPENDIX A

SYNTHESIS OF LITERATURE AND FIELD EXPERIENCE

This appendix provides information pertinent to the state of knowledge regarding the occurrence of fatigue cracking, low-temperature cracking, and reflection cracking. The primary sources of information for this synthesis are research and field experiences that have been reported in technical publications. It is not possible to describe in full the total of the information; further details can be found in the references to this report. Designer-controlled variables are also discussed as considered pertinent to this evaluation.

FATIGUE CRACKING

Fatigue cracking is defined herein as a mode of distress resulting from the repeated application of traffic-induced stresses. When such cracks are visible, it is generally assumed that a significant reduction in load distribution takes place and permanent deformation at the surface will often occur.

Summary of NCHRP Report 39

NCHRP Report 39, issued in 1967, contains a considerable amount of information on fatigue properties of asphaltic concrete. It is appropriate to summarize some of the material reported at that time, which is still applicable, as a point of beginning for this investigation of fatigue cracking.

Mechanisms of Fatigue Failure

Both laboratory and field investigations have indicated that cumulative damage occurs in asphaltic concrete under repeated loads.

Failure Criteria

1. It has been found that a linear relationship exists between the log of stress, σ, or strain, ϵ, and the log of the number of load repetitions, N, to failure. The failure criteria can therefore be expressed as:

$$\log (\sigma \text{ or } \epsilon) = a + b \log N \qquad \text{(A-1)}$$

2. It has been found that the mode of testing (i.e., stress-controlled or strain-controlled) influences the results. Constants a and b are dependent on whether a stress-controlled or strain-controlled test is utilized as well as on the properties of the asphalt mix. Controlled-stress tests indicate increased fatigue life with increased stiffness of the asphaltic concrete. Controlled-strain tests indicate a decrease in fatigue life with increased stiffness. Stiffness has been defined by the relationship

$$S\ (t, T) = \sigma/\epsilon \qquad \text{(A-2)}$$

where S = stiffness, in psi or N/m^2; σ = axial stress; ϵ = axial strain; t = time of loading; and T = temperature.

3. Deacon and Monismith (*52*) have proposed a linear summation of cycle ratios criterion for accumulating fatigue damage due to mixed loading. The procedure depends on the applicability of Miner's hypothesis to laboratory fatigue test results. In effect, this concept says that the damage accumulated in fatigue is independent of the order in which a range of loads is applied. Thus, the damage due to the application of a single load is represented by

$$D_i = \frac{1}{N_i} \qquad \text{(A-3)}$$

where D_i = damage due to single stress application i, and N_i = fatigue life in simple loading at stress condition i; and fatigue failure occurs when

$$\sum_{i=1}^{i} \frac{n_i}{N_i} = 1 \qquad \text{(A-4)}$$

where n_i = number of applications at stress condition i.

4. Fatigue properties as measured in the laboratory exhibit considerable variability, and methods of testing and interpretation must take this into account.

5. Rate of loading will have some effect on fatigue behavior, at least when tested above 30 applications per minute.

6. Load duration affects fatigue behavior; longer duration reduces fatigue life.

Response Variables

1. Both tensile stress and tensile strain have been suggested as the response variable that controls the occurrence of fatigue.

2. Limiting surface deflection has also been suggested as a means of controlling fatigue cracking.

Effect of Designer-Controlled Variables

1. Aggregate gradation—The relationship between aggregate gradation and fatigue performance has not been definitely determined. Nijboer (*174*) has suggested that a minimum ratio (volume basis) between filler (minus No. 200 sieve) and asphalt (F/B < 1.0) will result in longer fatigue life in sheet asphalt mixes. Monismith (*165*) has compared an open-graded mix (100 percent passing ⅜ in., 0 percent passing No. 50 sieve) with a dense-graded mix (100 percent passing ½ in., 9 percent passing No. 200 sieve) in constant stress and found the dense-graded mix to have better fatigue properties. It appears that gradation is important only as it influences the volume concentration of aggregate and the stiffness modulus.

2. Surface texture—Jimenez et al. (*67*) have indicated that a rough-surface-textured material is superior to a smooth-surface-textured aggregate and that an optimum asphalt content is associated with each surface type. Monismith's (*165*) data have tended to support the

superiority of rougher (crushed granite) surface textured material; however, he found no optimum asphalt content, rather a continuous improvement in fatigue properties with asphalt contents up to 7 percent in a well-graded (¾-in. maximum size) aggregate.

3. Asphalt content—On the basis of laboratory test results, higher asphalt contents have generally resulted in better fatigue properties, particularly when using a rough-surface-textured aggregate.

4. Asphalt consistency—This has long been considered to be a significant material property influencing the performance of asphaltic concrete surfacing. *NCHRP Report 39* summarized what then (1967) appeared to be a general consensus of the paving profession regarding the role of asphalt to pavement performance. Specifically, it was indicated that a prime factor contributing to the satisfactory performance of asphaltic concrete was the in-service consistency of the asphalt cement. Investigators had indicated that acceptable performance could be related to such material properties as (a) penetration, (b) softening point, (c) viscosity, (d) ductility, or (e) some combination of these. In general, the asphalt that hardens most was considered the least desirable. However, laboratory studies of fatigue and resistance to effects of water had indicated that some advantage was potentially possible with the use of high viscosity asphalt.

With this background of information, it is the purpose of the subsequent sections of this appendix to bring the information up to date regarding the fatigue properties and, where possible, to quantify the effect various designer-controlled variables have on fatigue cracking. The information will also be extended to include the role of base layers (treated and untreated) and the possible influence of the foundation or roadbed materials (*106*).

Response Variables for Fatigue Cracking

Response variables (determinants) for fatigue of asphaltic concrete have been described in the literature (*13, 14, 31, 51, 54, 59, 68, 71, 73, 102, 104, 115, 118, 130, 131, 133, 169, 170, 184, 205, 214*) as (1) deflection, (2) radius of curvature, and (3) stress or strain in the asphaltic concrete.

From a strictly theoretical standpoint, it should only be necessary to relate fatigue cracking to the mechanical state (stress, strain, or deflection) in a pavement system. However, recognizing the practical nature of this study in that many practitioners consider certain aspects of the state of material components, specifically asphalt consistency, to be a determinant for fatigue cracking, some attention has been given to this material property.

An effort was made in the investigation to select from among the foregoing determinants of distress those which (1) have been shown to relate to fatigue cracking and (2) have workable distress criteria that can be used to study the probable occurrence of cracking. Thus, from among the four items enumerated, three were selected for use in the formulation of recommendations as follows: (1) total pavement deflection, (2) maximum tensile strain in the asphaltic concrete, and (3) the physical properties of the asphalt cement. The specific distress criteria used for the interpretation by the analytical approach were as follows:

1. Deflection—The Asphalt Institute's criteria as described in the Institute's Research Report 69-3 (*5*).

2. Tensile strain—Strain criteria have been recommended by four agencies as follows:
   a. The Asphalt Institute by Kingham (*131*).
   b. The University of California by Monismith et al. (*170*).
   c. Royal Dutch Shell by Heukelom and Klomp (*93*).
   d. Kentucky Department of Highways by Deen, Southgate, and Havens (*53*).

Investigation indicated that the criteria of the Kentucky Department of Highways and that of Heukelom and Klomp were similar, and, hence, numerical determinations indicative of qualitative effects are based on published criteria of Heukelom and Klomp only. Each of the strain criteria referred to claims some correlation with field performance as will be found in the respective references. The work of Kingham and of Deen et al. is dependent almost exclusively on field performances and computer simulation in the development of failure criteria. On the other hand, the work of Monismith et al. and Heukelom and Klomp is dependent on laboratory studies supported by correlations with field observations.

Figure 6 illustrates the fatigue properties of asphaltic concrete as depicted by the studies of Monismith et al. Figure 7 shows a comparison with the Kingham criteria, Figure 8 with Heukelom and Klomp, and Figure 9 with Deen et al. It is apparent from these figures that a quantitative difference exists regarding the predicted fatigue properties of asphaltic concrete. In a qualitative sense, the criteria are quite similar.

From observational data, there is some indication that as asphalts harden (usually understood to mean a reduction in penetration or ductility or increase in viscosity), the tendency for fatigue cracking increases (*67*). The general acceptance of such conclusions is somewhat clouded because (1) field studies have concentrated on cracked pavements without giving equal attention to noncracked pavements (how many noncracked pavements contain low penetration asphalts?) and (2) field studies have generally applied to pavements with 2 to 5 in. of asphaltic concrete surfacing.

The Zaca-Wigmore project (*251*) in California is one of the more significant field investigations to study the role of asphalt on the performance of the pavement. On the basis of information obtained from this project, a critical penetration of 30 and viscosity of 20 megapoises at 77 F were indicated as critical values.

Sisko et al. (*210, 211*) have summarized studies of asphalt properties compared with pavement performance. Among their conclusions were the following: (1) asphalt roads can be constructed in which the asphalt rheological properties do not change appreciably over long periods of time; such roads appear to be less susceptible to cracking and not necessarily susceptible to plastic deformation; and (2) large increases, induced by aging, in the hardness of the asphalt binder are associated with road cracking. Although not specifically discussed by Sisko, the 77 F penetration of asphalts in those pavements with significant cracking ranged from 14 to 27 with an average of 21. The 60 F viscosity for cracked pavements ranged from 95 to

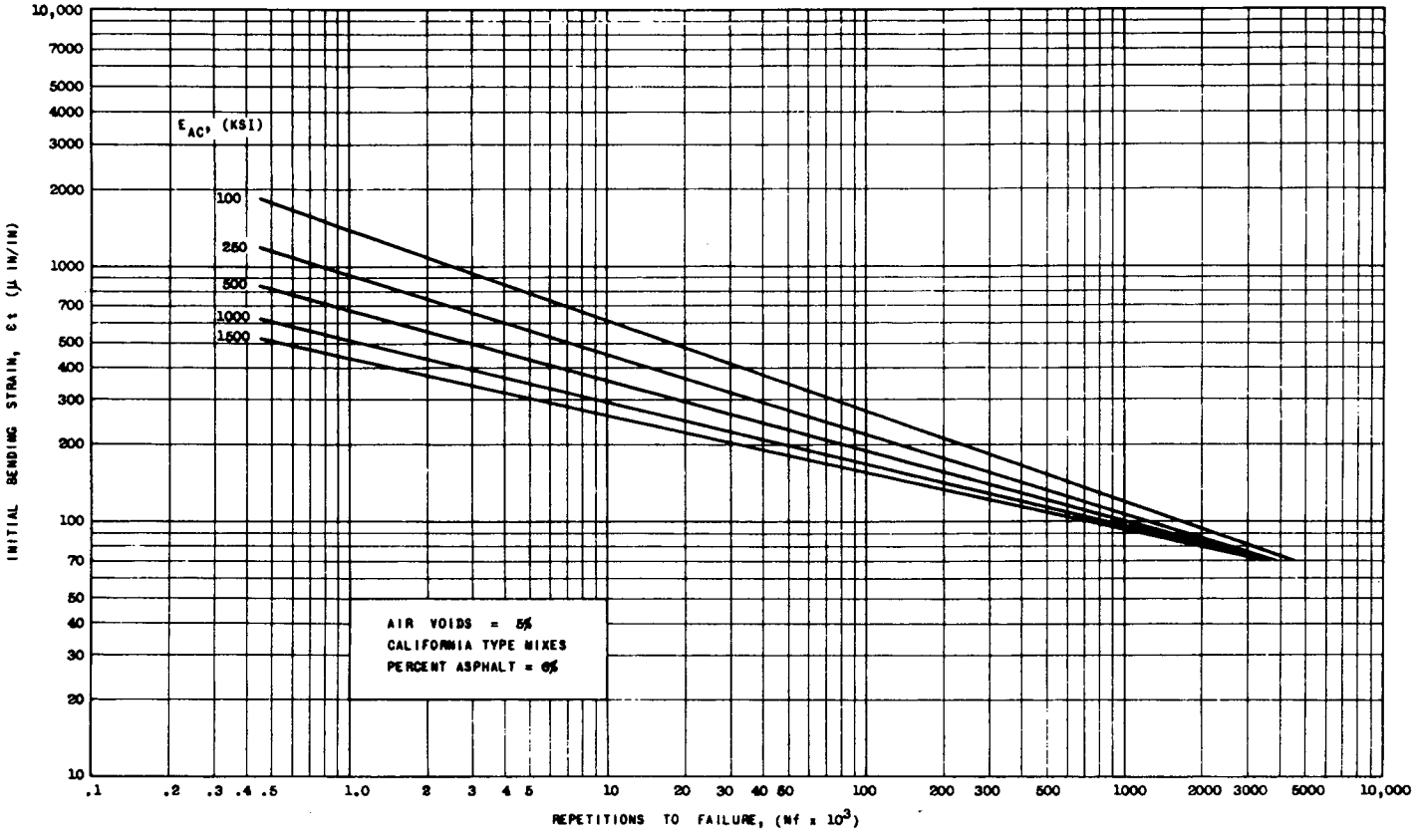

Figure 6. Fatigue properties of asphaltic concrete as proposed by Monismith et al. at Univ. of California.

292 megapoises with an average of 151 megapoises. For pavement with only slight or no cracking, the penetration ranged from 26 to 52 with an average of 37. The 60 F viscosity for noncracked pavements ranged from 28 to 197 with an average of 88 megapoises.

Combining the Zaca-Wigmore results with the Sisko data would suggest that the critical penetration value is between 20 and 30 penetration and a critical viscosity at 60 F of less than 100 megapoises. These limits are admittedly tenuous and require more documentation.

It is pertinent to note that asphalt viscosity can influence the mechanical state in the pavement induced by wheel loads by influencing the stiffness of the asphaltic concrete layer. The higher the asphalt viscosity (lower penetration), the higher will be the stiffness. Data reported by Monismith et al. (*170*) and by Vallerga et al. (*232*) indicate that the stiffness values using 60- to 70- or 85- to 100-penetration asphalt were not significantly different; however, use of 40- to 50-penetration asphalt will definitely increase the stiffness modulus. Nomographs of Van der Poel (*67*) indicate that the consistency of the recovered asphalt (penetration and softening point) will influence the stiffness of the asphalt.

Designer-Controlled Variables

The next several sections of this appendix deal with the influence of various designer-controlled variables on fatigue cracking. Evaluations and designer-controlled recommendations will be found in Chapter Three.

Structural Section

Through analysis by computer simulation of a range of structural sections designed for light, medium, and heavy traffic on poor, fair, and good foundation materials, it was possible to study the influence of the proportion of asphaltic concrete on fatigue cracking. The layer coefficients used in this evaluation were based on the procedures of the Illinois Division of Highways for a Marshall stability of 1200 lb and provided a 1:2.5 substitution of asphaltic concrete for untreated aggregate.

The investigation has indicated that one of the most positive designer-controlled actions is to increase the proportion of asphaltic concrete in the structural section. Such changes do not modify the basic structural design; they may increase the initial cost but not the total cost indicators if user costs are included in such determinations.

Figures 10 and 11 illustrate the influence of increasing the proportion of asphaltic concrete within the structural design on fatigue damage. The damage factor for this figure was obtained by use of the computer simulation technique. The step-wise procedure is as follows:

1. Obtain structural number according to most recent AASHO Interim Design Guides.

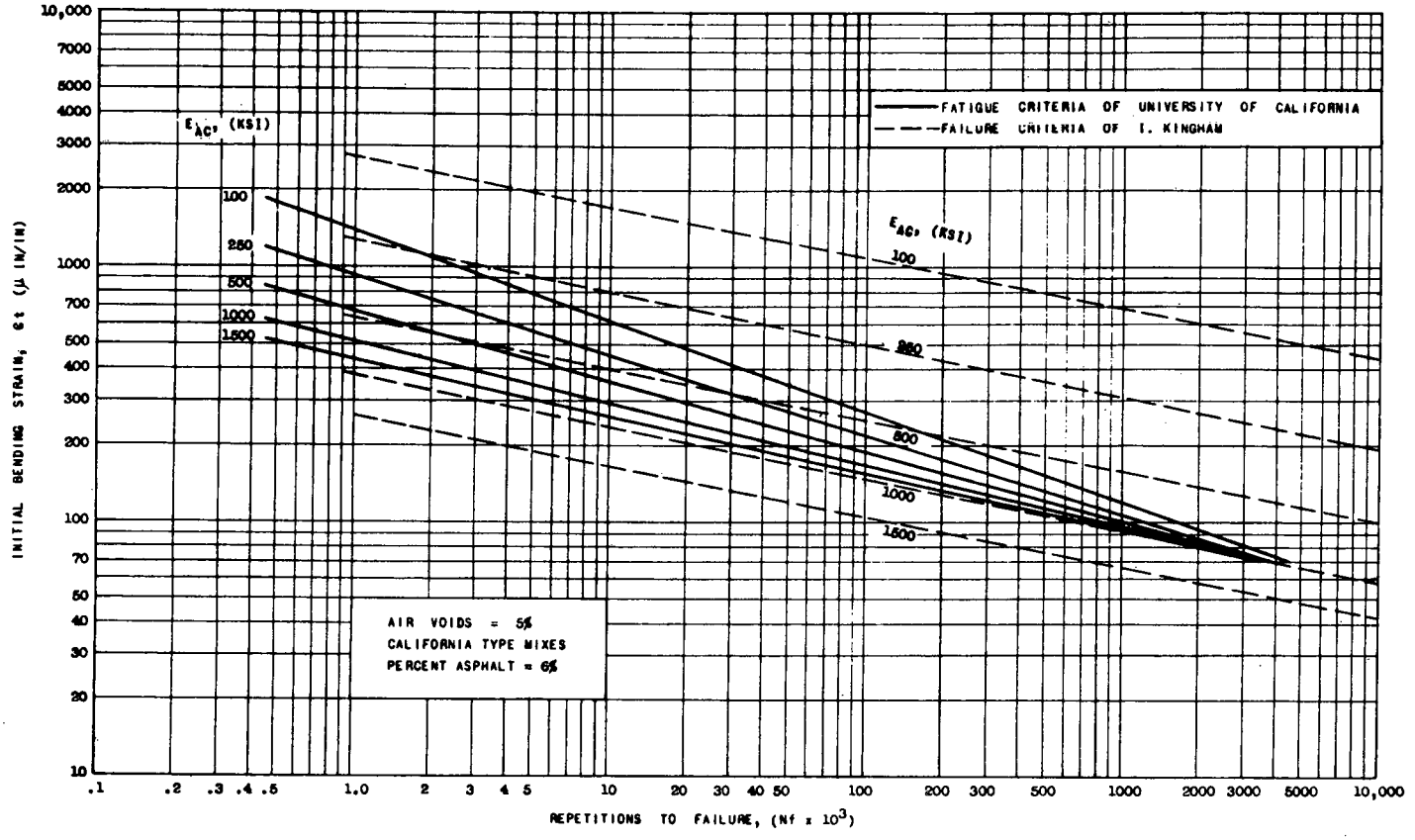

Figure 7. Failure criteria developed by Kingham with Univ. of California fatigue criteria provided for comparison.

2. Assume realistic material properties for structural analysis; that is, elastic constants for each pavement element including foundation material.

3. By use of layer coefficients, determine thickness combinations necessary to satisfy structural number requirements with thin, thick, and full-depth asphalt sections.

4. Calculate maximum tensile strain in asphaltic concrete or total pavement deflection for each case.

5. Obtain damage estimates based on fatigue criteria, such as shown in Figures 6, 7, and 8 or from Ref. 5.

For these examples a range of elastic moduli (stiffness) was used for the asphaltic concrete, and it was assumed that one-third of the traffic would be applied during each period. The damage factor is the unit damage per 9-kip dual-tired wheel load. For example, a damage factor of 0.01×10^{-4} indicates that each load application reduces the time to fatigue cracking by $1/10^6$ or the 18-kip axle load traffic capacity is 10^6 repetitions. Figures 10 and 11 suggest that the full-depth asphaltic concrete section is the best to minimize fatigue cracking regardless of the distress criteria used.

It could be concluded that the layer coefficient of 1:2.5 used in substituting asphaltic concrete is too conservative. This may be true; however, it cannot be proven by the results shown in Figures 10 and 11. The results suggest a conservative value for fatigue but not necessarily for other performance parameters, such as the present serviceability index, rutting, etc.

Properties of Asphaltic Concrete

The influence of five designer-controlled variables on premature cracking was evaluated: (1) asphalt consistency, (2) asphalt content, (3) air voids, (4) aggregate gradation, and (5) aggregate type, shape, and texture.

Asphalt Consistency. In asphalt pavement technology, the role of asphaltic cement is generally considered as a waterproofing agent for the surface layer and to increase the over-all pavement strength by its ability to add cohesion to the asphaltic concrete. The properties of asphalt cement are usually described in terms of consistency, expressed in terms of penetration or viscosity. A relatively flat temperature viscosity relationship below 140 F (60 C) and the ability to remain flexible (durable) throughout the design life of the pavement are considered to be desirable properties. Other factors, particularly chemical composition, are also important in describing and controlling the properties of asphalt cement. At the present time, however, chemical composition has not been directly related to fatigue cracking. Research has indicated that chemical properties are related to durability, which, in turn, influences pavement stiffness, which has been shown to influence fatigue (*233*). However, at the present time no quantitative or qualitative associations have been made among all the factors involved.

For the most part, the only designer-controlled decision, with regard to the asphalt cement, will be to specify the grade of asphalt to be used in the mix design and for

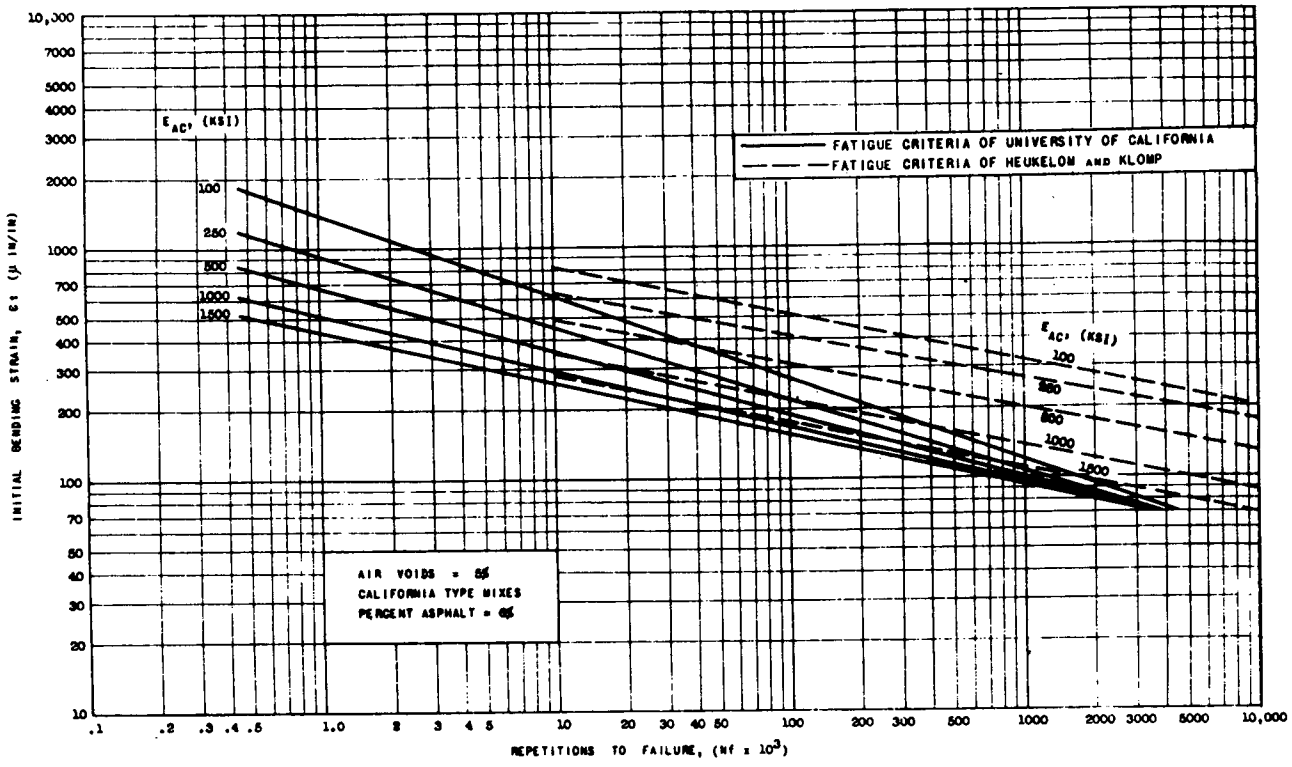

Figure 8. Fatigue criteria developed by Heukelom and Klomp with Univ. of California fatigue criteria provided for comparison.

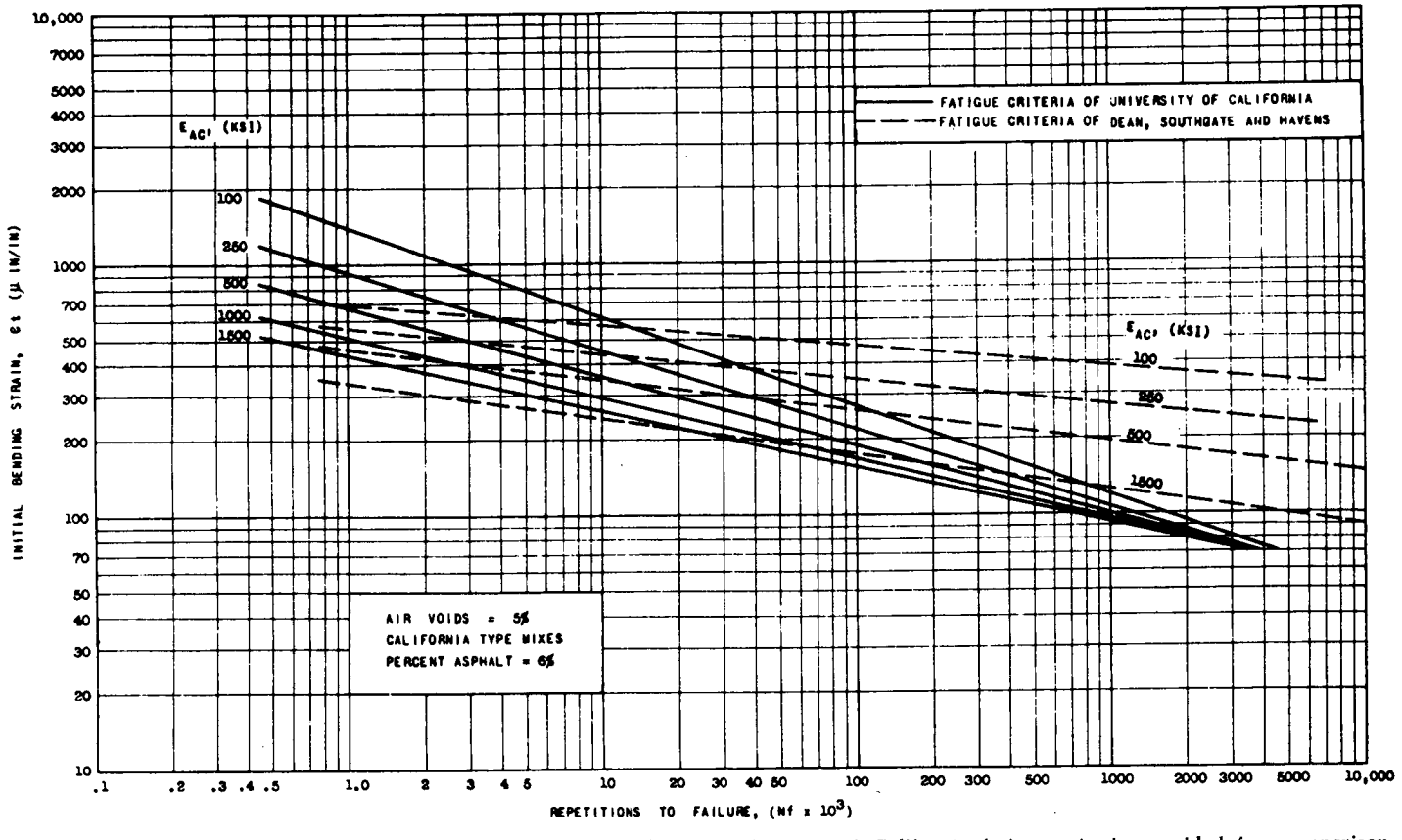

Figure 9. Criteria developed by Kentucky Department of Highways with Univ. of California fatigue criteria provided for comparison.

construction. Considerations of durability, flexibility, and temperature susceptibility are presumably covered by the specifications for each asphalt grade. There is a considerable amount of research necessary in order to be able to obtain asphalts that will retain flexibility for a wide range of temperatures and for long periods of time. In all probability, such an asphalt will require some type of modification, which, in turn, will increase the cost and thus necessitate an extensive benefit-cost study (*196, 198, 199*).

Figures 6 through 9 illustrate the general trend of the influence of asphaltic concrete stiffness on the fatigue properties of asphaltic concrete. As the stiffness increases, the fatigue properties decrease. A search of the literature has not produced any evidence to the contrary. It is postulated that cracks propagate at a slower rate in mixes with lower viscosity asphalts.

One way to evaluate the role of asphalt consistency to fatigue cracking is by means of computer simulation. This technique provides for consideration of structural design as well as asphalt consistency. Figure 12 shows a typical evaluation of the influence of asphaltic concrete stiffness on the damage factor as previously defined. It is clear that a different interpretation would be obtained according to the distress criteria used. The Kingham criteria suggest a preference for softer asphalts, while the criteria of the University of California and of Heukelom and Klomp suggest a preference for harder asphalts. The differences shown in Figure 12 were also found for a range of structural sections subjected to both hot and cold (computer-simulated) temperatures.

At the present time it would appear that the differences cannot be reconciled under this investigation. Reasonable arguments can be made for each position. Some of the factors to be considered are discussed as follows.

First, it must be recognized that each of the criteria suggests that, for a given level of strain, the cycles to failure (fatigue properties) will increase as the stiffness modulus of the asphaltic concrete decreases. In order for the analysis

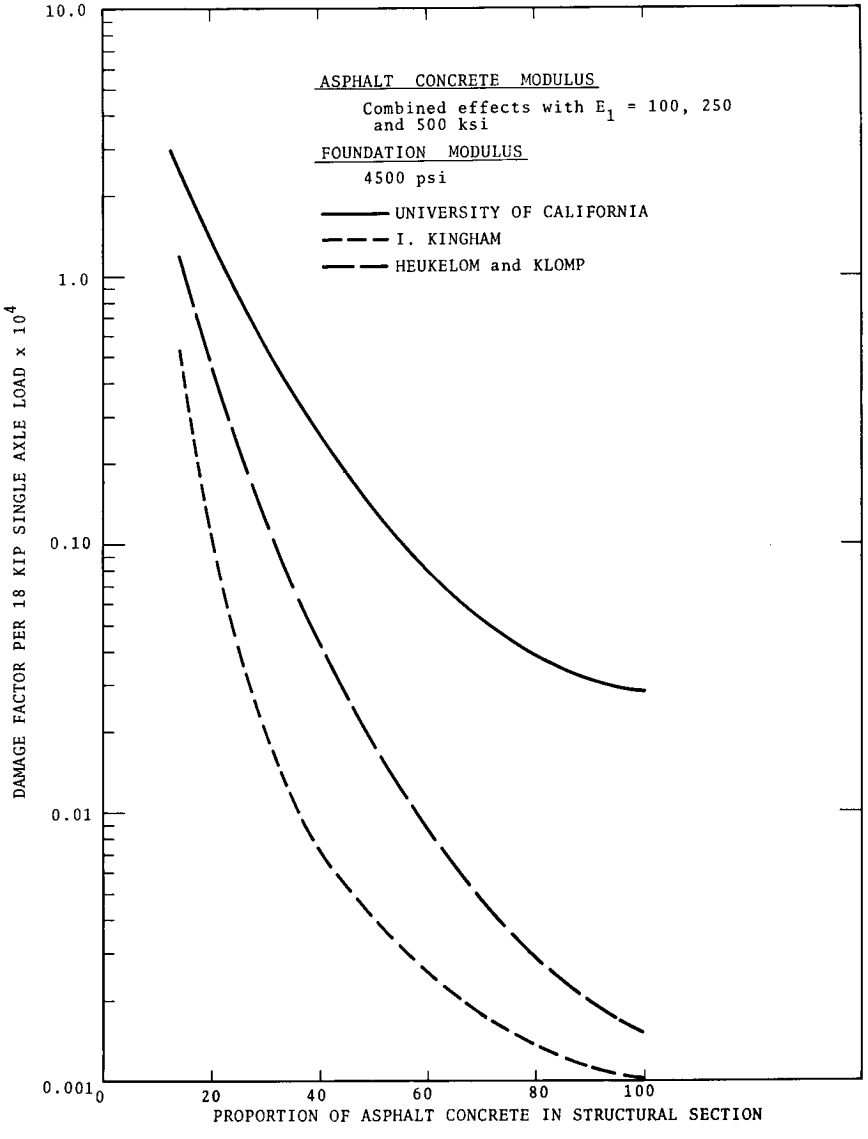

Figure 10. Effect of increasing proportion of asphaltic concrete thickness on fatigue damage factor based on strain criteria.

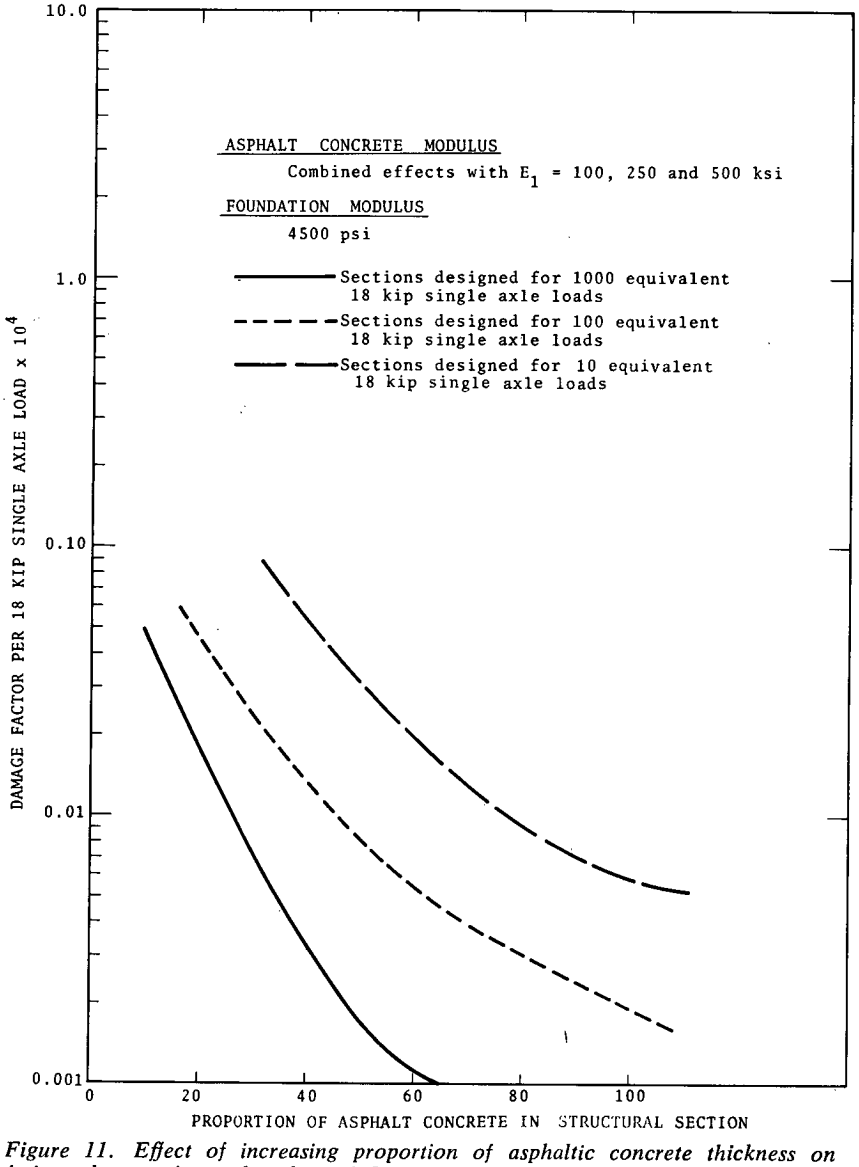

Figure 11. Effect of increasing proportion of asphaltic concrete thickness on fatigue damage factor based on deflection criteria.

to suggest improved performance for stiffer mixes, there would have to be a reduction in the calculated strain value. In effect, in the structural section, the reduction in strain associated with the increased stiffness would need to more than offset the less favorable fatigue properties of the stiffer asphaltic concrete. This would appear to be increasingly possible as the percent or proportion of the asphaltic concrete in the structural section increases.

Second, the use of softer asphalts is recognized to be preferable for thin layers of asphaltic concrete surfacing (*67*).

Third, for the intermediate range in stiffness, damage does not appear to be particularly sensitive to stiffness modulus regardless of the fatigue properties used.

Fourth, the designer must also consider the other forms of distress, such as plastic deformation in hot climates and transverse cracking in the severely cold climates. Plastic deformation would be less likely to occur if high-viscosity asphalts were to be used. Lower viscosity asphalts, with low-temperature susceptibility properties, would be preferred to avoid low-temperature cracking.

Such factors as asphalt stripping and disintegration will also be a consideration; however, in neither case will high-viscosity asphalt pose a problem to performance. For example, resistance to adverse effects of water is apparently improved by the use of higher viscosity asphalts (*203*). By use of commercially available sealing materials, disintegration can be halted or satisfactorily minimized.

In summary, it will be the recommendation of the authors of this report that designers should specify the use of higher viscosity asphalts in moderate and warm climates, but avoid extreme values in all but full-depth asphaltic concrete sections in hot climates. For areas subject to freezing temperatures, it may be necessary to use low-viscosity asphalts if temperature cracking poses a sufficiently serious performance and maintenance problem. Even in this situation a higher viscosity asphalt could be used at depths in excess of 2 in. below the pavement surface.

Asphalt Content. It is generally accepted by paving engineers that asphalt mixes should incorporate as much asphalt binder as possible without reducing the mixture stability below some acceptable limiting value. It is considered that two beneficial effects will occur as the asphaltic content increases: (1) the durability of the asphalt will be enhanced by the resulting increase in asphalt film thickness and by the reduction in the amount of permeable (air) voids, and (2) the flexibility will be increased by the thicker films.

Kasianchuk et al. (*127*) have presented information indicating that for a given aggregate and aggregate gradation, there is an optimum asphalt content for both stiffness and fatigue properties for asphaltic concrete. It is significant to note that the design asphalt content, by the Hveem stabilometer, for mixture stability was approximately 0.8 percent lower than the optimum asphalt content for stiffness and fatigue. It is implicit in this information that as the asphalt content is increased, the void content is also decreased. Thus, the interaction of decreasing voids with increasing asphalt content may be contributing to the development of an optimum asphalt content of about 0.5 to 1.0 percent above that normally found for stability.

Hadley et al. (*88*) have reported on extensive measurements of tensile strength using a split tension procedure. Their results indicated that increasing the asphalt content had a significant influence on increasing the tensile strength.

The conclusion from all of the data presented is that asphalt content will influence the tensile strength, stiffness, and fatigue properties. The indications are that asphalt contents normally obtained by stability design methods (Hveem, Marshall) are below the desirable asphalt content for fatigue regardless of aggregate gradation.

Air Voids. Paving technologists have long considered air voids to be of major importance to the performance of asphaltic concrete. The major factors associated with void content have been (1) stability, (2) permeability, (3) asphalt hardening, and (4) asphalt flushing in the surface.

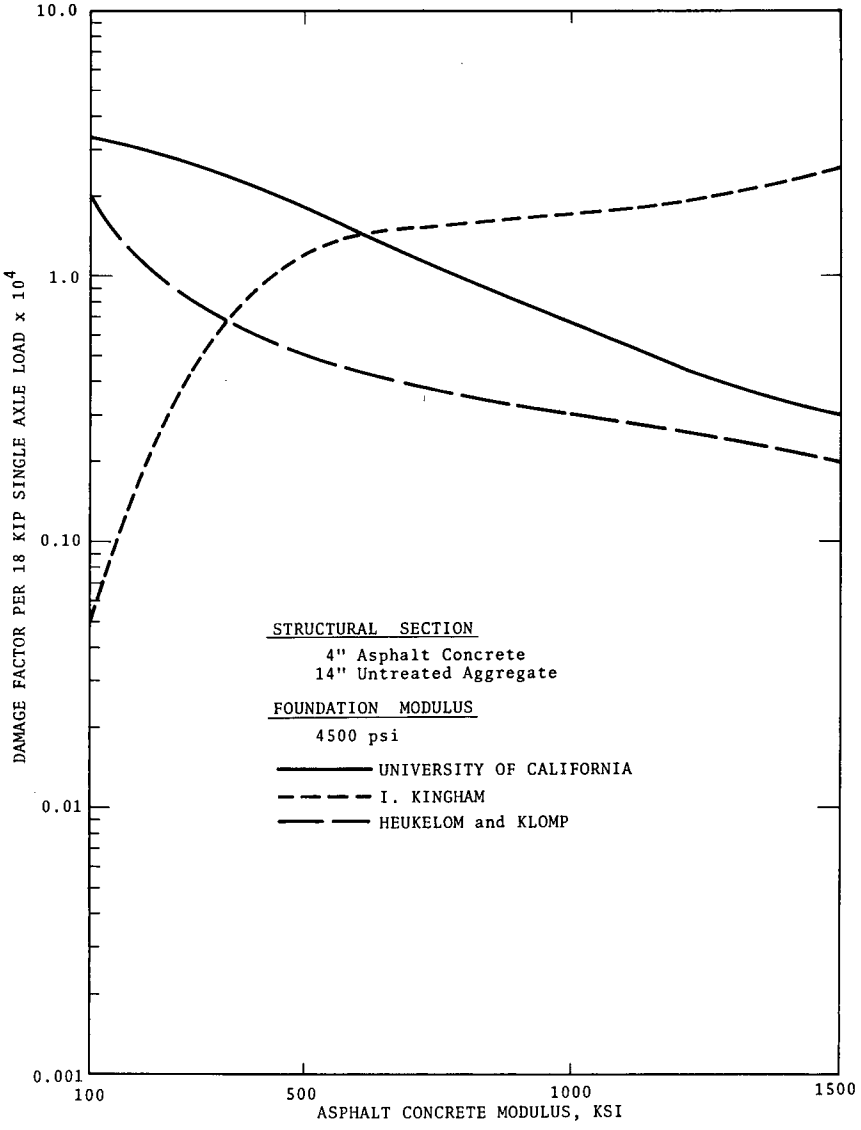

Figure 12. Effect of asphaltic concrete stiffness modulus on fatigue damage factor.

One of the most important effects that air voids have on mix properties is on the hardening rate of asphalt (*157, 233, 251*). For purposes of this investigation, it is important to know the effect that air voids have on asphaltic concrete stiffness and on fatigue properties.

As would be expected, stiffness has been reported to be inversely proportional to air voids (*48, 62, 212*). Shook and Kallas (*212*) have indicated that the dependency is affected by temperature as well as mix properties. Reported research indicates that fatigue properties improve as the air voids in the mix decrease (*61, 185*). Data reported by Epps and by Pell suggest that fatigue properties can be reduced by 30 to 40 percent for each 1 percent increase in air-void content.

Analytical studies, based on the influence that air voids have on asphaltic concrete stiffness and on fatigue properties, can be used to evaluate further the influence of air voids on fatigue cracking. Typical results for a series of constructions are illustrated in Figure 13. From these results it is suggested that a 1 percent increase in field void content would reduce the fatigue life by 30 percent. Although this may not be quantitatively correct in the field, it does emphasize the potential influence of air voids.

Thus, laboratory data and analytical studies point out that air voids will significantly influence fatigue cracking of asphalt pavements. Field studies also indicate the influence of air voids on asphalt aging (*211, 233, 251*). The question must then be asked relative to what air voids should be achieved in the field at the time of construction. The answer would be: as low as possible without causing the asphaltic concrete to flush asphalt and thereby create a skid hazard or cause the mix to become unstable. Although no precise definition is available as to when flushing will occur in pavements, it is not unreasonable to expect some flushing when the air voids drop below 2 percent (based on ASTM Designation D2041 or AASHO T209, maximum specific gravity of bituminous paving mixtures (or equivalent)).

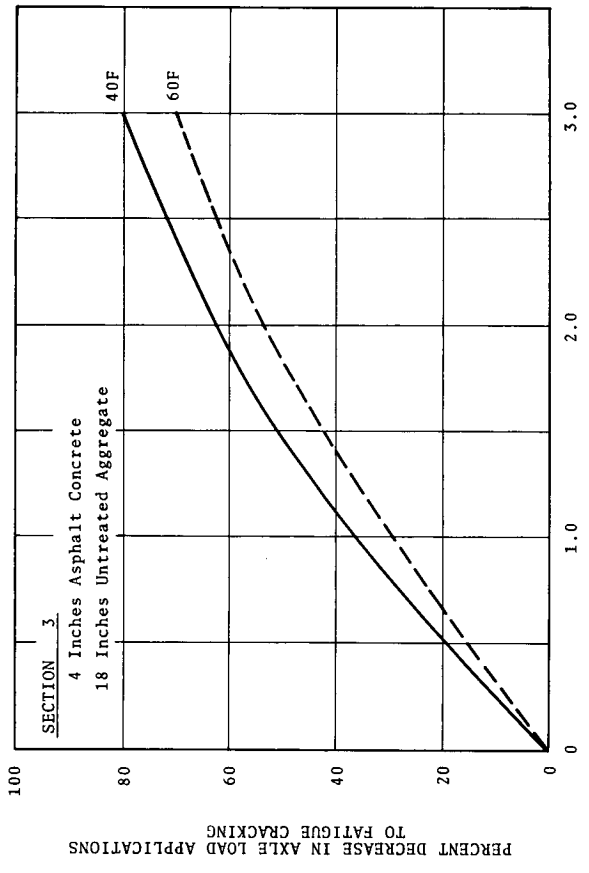

Figure 13. Effect of increase in air voids in asphaltic concrete on fatigue cracking.

When using asphaltic concrete for base (a layer or layers of specified or selected material of designed thickness placed on a subbase or a subgrade to support a surface course (*106*)), there is some indication that lower stability requirements can be tolerated in recognition of reduced temperatures and stresses with depth (*127*).

The ability to achieve low air voids during construction is also important. Recent studies on compaction of asphaltic concrete (*12, 47, 57, 154*) indicate that 5 to 7 percent air voids can be achieved at the time of construction. Other investigations have indicated that the best time to obtain low air voids is at the time of construction rather than depending on traffic (*151, 179, 251*).

Aggregate Gradation. Within the limits of current aggregate gradation requirements as generally specified in the United States, there is no indication of a significant effect on the potential for fatigue cracking (*170, 229*). There is a considerable amount of information regarding aggregate gradation on mix stability as summarized in Ref. *107*. For the most part, aggregate gradation influences the amount of asphalt required for the mix and not so much the physical properties of the mix.

Limited investigations (*128, 158*) indicate that increasing the maximum size of the aggregate will increase the stiffness which, in turn, will allow some reduction in thickness without increasing the strain in the asphaltic concrete.

Fatigue properties of gap-graded mixes (between the No. 4 and No. 30 sieves), as used in England, tend to be improved over dense grading, as typically used in the United States (*170, 185*). Laboratory studies indicate that open-graded mixes exhibit poor fatigue properties (*107*).

Aggregate Type, Shape, and Texture. Research studies are not conclusive regarding the influence of aggregate type, shape, and texture (*107, 170*). Some indications of improved properties with crushed aggregates have been suggested but not extensively pursued (*67*). Maupin (*147*) in a limited investigation has reported that slabby particles (slate) have a significantly shorter fatigue life than a mixture with rounded particles.

Adverse Effects of Water. For many years highway engineers have been concerned with the possible adverse effect of water on asphaltic concrete or asphalt-treated mixes. The principal concern of these engineers has been the potential effects of stripping or displacement of the asphalt films by films of water. From a performance point of view, two consequences of stripping are (1) raveling of the surface of the asphaltic concrete and (2) general loss in stability of the mix resulting in localized pot holes and general degradation of the mix.

Fromm et al. (*75*) have reported on investigations in Ontario, Canada, indicating that pavement cracking can be associated with the loss of structural capacity resulting from stripping of asphalt films from the aggregate. They

reported that stripping, which starts in the lower zone of the asphaltic concrete, appears to be the most serious.

In 1965-1966, the Idaho Department of Highways (*120*) reported on premature pavement distress (cracking) believed to be significantly associated with debonding of the asphalt from the aggregate. Observations indicated that cracking was occurring in the inner and outer wheel paths with no appreciable amount of permanent deformation. Thus, this cracking could be categorized as fatigue cracking that had been accelerated by a loss of strength in the asphaltic concrete layer. In Idaho, as in Canada, stripping was initially noted in the lower zones of the asphaltic concrete.

Fromm et al. (*75*) attempted to study the influence of (1) aggregate type (granite and limestone), (2) asphalt grade (85 to 100 and 150 to 200), (3) high-temperature viscosity (high, medium, and low), (4) crude source (western Canada and Venezuela or Middle East), and (5) the type of base (unprimed granular, primed granular, and old pavements).

These investigators, on the basis of statistical evaluations, reported the following conclusions:

1. Granitic aggregates used in the northern areas of Ontario tended to strip more readily than carbonate aggregates in the southern areas.
2. No significant effects of asphalt source or grade were found.
3. Type of base did have a significant effect. More stripping was observed when bases had been primed or were on old pavements.

Lottman (*144*) has reported on studies to evaluate the sensitivity of asphaltic concrete to the influence of water. To do this, he obtains split tension test (tensile strength) measurements on replicate specimens in which half are thermal cycled (0 F-120 F-0 F) in a vacuum-saturated condition and half are maintained dry prior to testing. The split tension tests are made at 55 F. The ratio of the conditioned specimen strength to the dry strength is identified as the tensile strength ratio (TSR). TSR values range from 0.4 to 1.0, with some suggestion that 0.6 or 0.75 may be a limiting value of the ratio. Lottman reports that TSR increases as the permeable voids decrease. The results indicate that, although a decrease in voids from 7 to 4 percent is significant, the most significant effect takes place between 4 and 2 percent voids. If the mix is not susceptible to the influence of water, the TSR is not affected by the void volume. These studies indicated that lime as a filler was not effective, but that lime-slurry and cationic asphalt additives were effective in improving the TSR.

Schmidt and Graf (*203*) have reported on an investigation of the effect of water on the stiffness modulus of asphaltic concrete. These investigators used a split tension test technique to obtain a diametral resilient modulus (stiffness modulus). Samples were normlaly preconditioned by vacuum saturation and then subjected to four different environmental cycles. The investigation included evaluations of the following factors: water content, asphalt content, asphalt consistency, aggregates, and additives. Figure 14 illustrates the effect of water content on retained strength. It is interesting to note the cyclic pattern of retained strength as a function of wetting and drying of the specimen. Information reported by these investigators indicated that increasing the asphaltic content from 5 percent to 9 percent increased the retained modulus by more than 30 percent.

Figure 15 illustrates the effect of asphalt consistency, suggesting that the reduction in strength can be offset by using a harder grade of asphalt. Commercial additives have a limited effect on improving the strength retention of asphaltic concrete after vacuum saturation, even though they generally improve the coating of aggregate after exposure to water.

Slurry lime with 1 percent and 2 percent residual calcium oxide in the mix caused a definite improvement in retained strength of the asphaltic concrete specimen.

Untreated Aggregate

Shear strength is usually considered by highway engineers as the primary strength requirement of untreated aggregate bases and subbases. Experience has indicated that if these layers are overstressed, it is probable that both rutting and cracking of the asphaltic concrete surface layer will occur regardless of the thickness of the layer and the protection afforded the foundation material. The best example of this was obtained from the special base investigations on the AASHO Road Test. The uncrushed gravel base sections were reported to be ". . . definitely inferior to that of the sections with crushed stone base." Further, when this type material was subjected to 22.5-kip single axles or 40-kip tandem axles, failure (cracking and rutting) occurred early in the test without regard to its thickness.

Therefore, it is pertinent to emphasize the importance of shear strength within the untreated structural elements of the pavement. It is pertinent to note that the shear strength of untreated aggregates increases rapidly as density increases (*222*). The role of these materials in fatigue cracking of asphaltic concrete is to limit the deflection of the pavement or tensile strain in the asphaltic concrete layer.

Several investigations have been conducted to evaluate the influence of untreated aggregates on those material properties that influence the response variables associated with fatigue cracking (*41, 96, 97, 98, 167*). Specifically, such factors as (1) gradation (variations in minus #200 fraction), (2) crushed and partially crushed aggregates, (3) water content, and (4) degree of saturation have been studied. Of these, density and water content can be susceptible to designer control—density by construction specification and water content by requiring subsurface drainage.

Again, computer simulation has been used as a means of estimating the potential role of untreated aggregate on fatigue cracking. In order to model the pavement as a multilayered elastic system, it is necessary to know, or estimate, the elastic constants for untreated aggregates. Investigations by Dehlen (*55, 56*), Hicks (*95, 96, 97, 98*), and Monismith (*169*) have been used to provide information for these material properties. It should be noted that the elastic constant (resilient modulus) used for untreated aggregates has been found to be stress sensitive (i.e., influenced by its stress state in the pavement under load).

The general form of the relationship is given by the following equation:

$$M_R = K\theta^n \qquad \text{(A-5)}$$

where M_R = resilient modulus, $\theta = \sigma_1 + 2\sigma_3$, and K and n = constants, depending on material properties or condition. Examination of the previously referenced literature indicates that most M_R values can be bounded by $M_R = 5000\,\theta^{0.6}$ and $M_R = 2000\,\theta^{0.6}$.

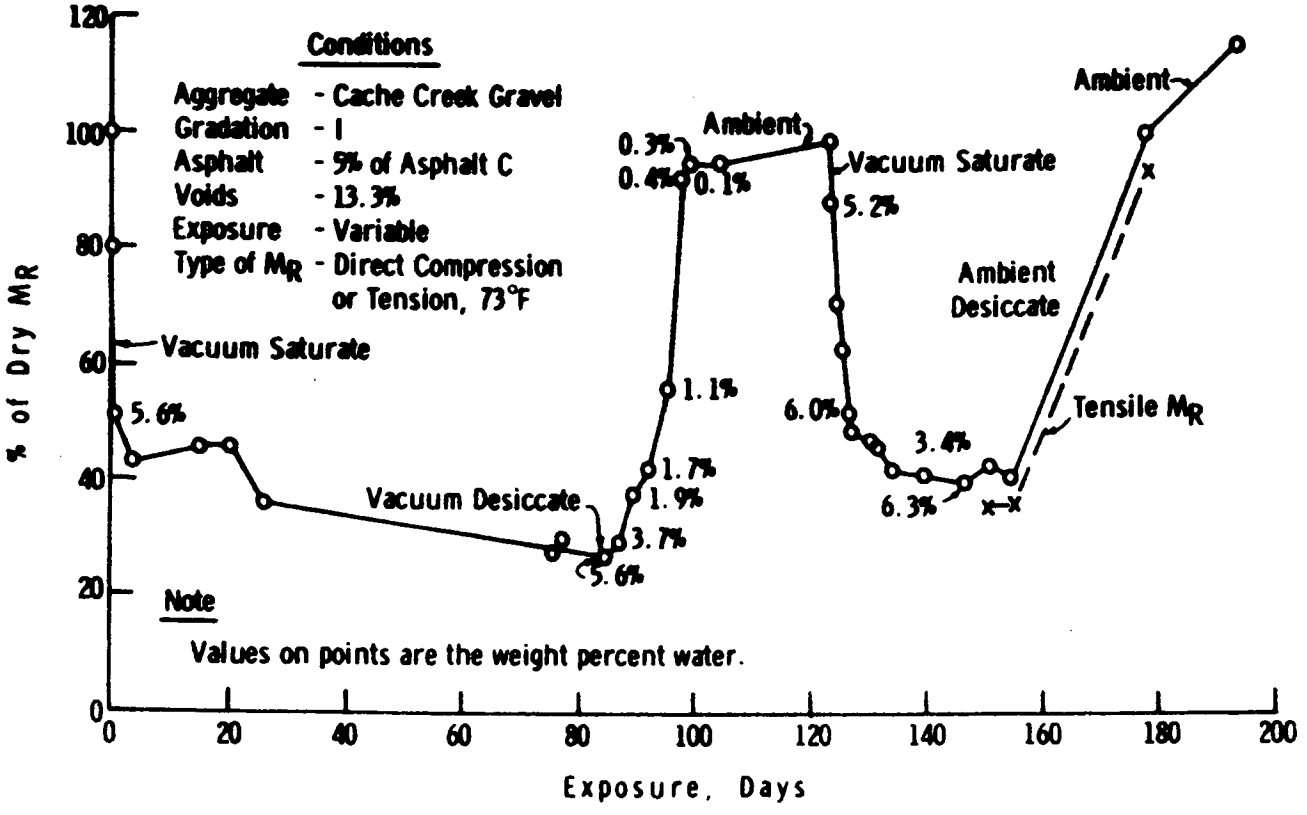

Figure 14. Effect of water content on resilient modulus (after Schmidt and Graf, 203).

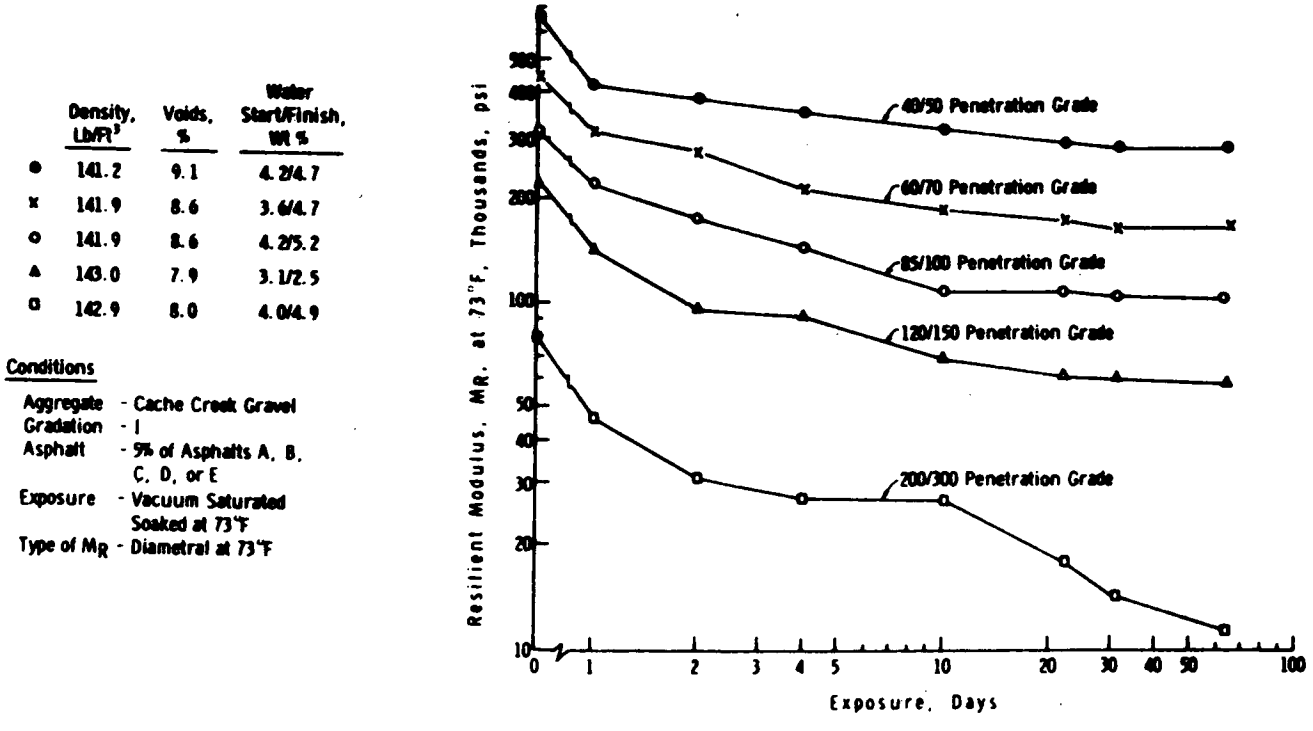

Figure 15. Effect of grade of asphalt on resilient modulus (after Schmidt and Graf, 203).

Figure 16 illustrates the effect of the modulus of the untreated aggregate on the fatigue performance of asphaltic concrete pavement. Several conclusions are suggested by this figure. For example, a significant reduction in the damage factor is associated with untreated aggregates that exhibit the higher modulus, regardless of which one of the fatigue criteria is used. Coffman (*41*) and Hicks (*97, 98*) have indicated that the elastic modulus can be increased by increasing the in-place density and by reducing the degree of saturation. It is worth noting that the substitution of asphaltic concrete is least effective when applying the Kingham criteria with a high-modulus material. Thus, there is some confusion between criteria as to the influence of high-modulus untreated materials; however, there is an indicated consensus regarding the benefits of increasing the proportion of treated materials for low-modulus aggregate.

Table 8 summarizes the results of the structural analysis in terms of the ratio of damage per 18-kip single axle load for the 2000 $\theta^{0.6}$ modulus to the 5000 $\theta^{0.6}$ modulus. In effect, this table indicates the percent damage that would result if the lower moduli material were to be used in lieu of the higher moduli material. For example, assume that the foundation modulus is 4500 psi; the asphaltic concrete thickness represents 25 percent of the structural section; and the temperature conditions are such as to produce stiffness moduli of 100 ksi, 250 ksi, and 500 ksi in the asphaltic concrete. The table provides for three levels of structural design representative of 10, 100, and 1000

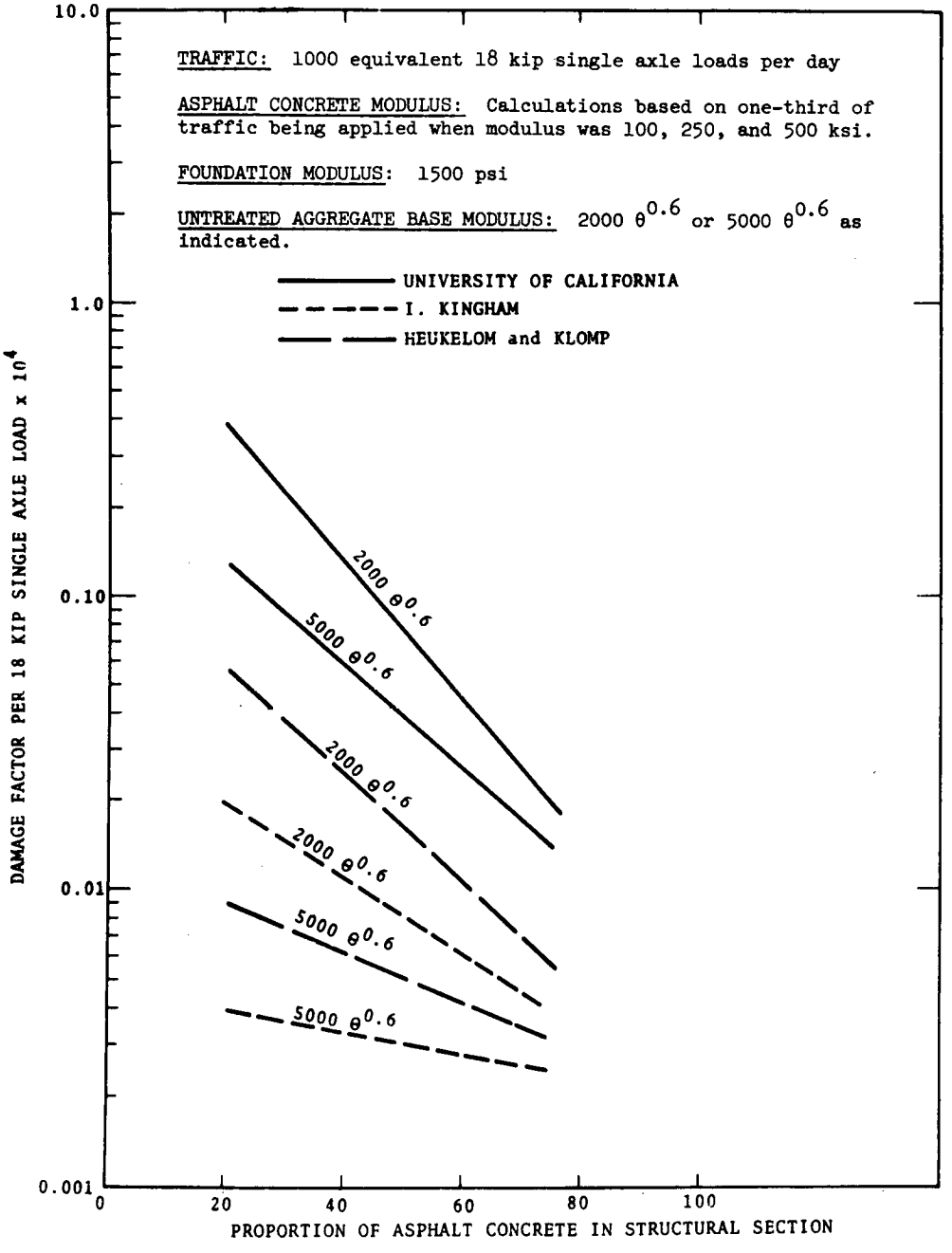

Figure 16. Effect of untreated aggregate modulus on fatigue damage factor based on strain criteria.

TABLE 8

DAMAGE RATIO (%) FOR UNTREATED AGGREGATES WITH RESILIENT MODULI REPRESENTED BY 2000 $\theta^{0.6}$ AND 5000 $\theta^{0.6}$ BASED ON STRAIN CRITERIA OF THE UNIV. OF CALIFORNIA

Structual Section[1]	Asphalt Concrete Modulus, ksi[2]	Percent of Asphalt Concrete[3]	Foundation Modulus, psi 1500	4500	13,500
1	100, 250, 500	25	53	54	--
		50	82	67	--
		75	96	83	--
	500, 1000, 1500	25	50	68	--
		50	77	79	--
		75	87	91	--
2	100, 250, 500	25	69	38	33
		50	83	61	55
		75	91	76	70
	500, 1000, 1500	25	71	60	40
		50	87	80	56
		75	89	86	72
3	100, 250, 500	25	36	44	23
		50	52	59	35
		75	68	76	58
	500, 1000, 1500	25	53	67	29
		50	65	77	53
		75	83	83	74

[1] Structural sections determined for three levels of traffic increasing from 1 to 3.

[2] Includes combined (average) effect with modular values indicated.

[3] Proportion of asphalt concrete to total structural section as a percent.

equivalent 18-kip single axle loads per day. Damage ratio is defined as follows:

$$\text{D.R. } (\%) = \frac{D_{2000}}{D_{5000}} \times 100 \qquad \text{(A-6)}$$

where D_{2000} = average damage per load application for the given conditions when the aggregate modulus is represented by 2000 $\theta^{0.6}$, and D_{5000} = average damage per load application for the given conditions when the aggregate modulus is represented by 5000 $\theta^{0.6}$.

Thus, for the conditions just described and a structural section defined in the second category, the damage ratio is 38 percent. The expected volume of traffic to be accommodated by the 2000 $\theta^{0.6}$ aggregate is 38 percent of that predicted for the 5000 $\theta^{0.6}$ modulus material.

Cement-Treated Bases

Engineers must be concerned with two types of cracking in the asphaltic concrete when using cement-treated bases (cement-treated bases are defined herein as dense-graded granular materials to which cement has been added to improve their performance properties) or soil-cement bases; namely, fatigue and shrinkage cracking of the cement-stabilized materials. Experience indicates that each type of cracking in the cement-treated base will quickly reflect through the asphaltic concrete surface. Fatigue cracking in the asphaltic concrete, per se, would be highly unlikely when cement-stabilized materials are used for the base, because deflections would be low and strain in the asphaltic concrete would be low and relatively insensitive to temperature.

Hveem and Zube (*119*), after an extensive laboratory and field study of cement-treated bases in 1963, reported the following relative to load-associated cracking in cement-treated aggregates:

1. Cracking was significantly reduced when the in-place compressive strength exceeded 500 psi.
2. Compressive strength was increased by increasing the density of the treated layer.
3. Compressive strength was increased by decreasing the time delay before compaction.
4. Field samples indicated that 10 percent of the cores had densities below specification requirements.
5. Compressive strength was influenced by the gradation of the aggregate and amount of crushed material.
6. The compressive strength was affected by both the curing time and the curing temperature.

Hveem and Zube also noted that the presence of clay balls, poor distribution of cement, or the use of alkali aggregate, would reduce the compressive strength of the treated materials.

The importance of compressive strength was further emphasized in a follow-up investigation made in California

as reported by Zube et al. (*250*) in 1969. The investigation emphasized studies of field performance of 175 projects, which had been in service for periods ranging from 6 to 18 yr.

Table 9 summarizes those factors which the data seemed to suggest were of major significance to the occurrence of cracking. Several factors were indicated to be marginally associated with distress (load), such as pavement drainage, thickness of asphalt concrete, and trimming surface of cement-treated material for leveling purposes after compaction has been completed.

Investigations reported by the Portland Cement Association (*139, 140, 177*) have led to the following findings:

1. The radius of curvature is a good response variable to use in evaluating the fatigue properties of cement-treated materials.
2. Fatigue properties can be estimated from the following equation:

$$\frac{R_c}{R} = aN^{-b} \qquad \text{(A-7)}$$

where R_c = critical radius of curvature, R = curvature developed during fatigue tests, N = number of load repetitions to first visible crack, and a and b = fatigue coefficients.

3. Wheel load, subgrade strength, and thickness of treated layer are major determinants of fatigue damage (*139*).
4. Neither compressive strength nor modulus of rupture was indicated to be significant, provided sufficient cement was added to satisfy the wet-dry and freeze-thaw durability requirements.

Mitchell and Shen (*160*) have also studied fatigue properties of soil-cement mixtures and have presented data indicating that these materials can be analyzed by elastic theory, such as has been used by Monismith et al. (*170*). The tentative indications from these studies suggest that higher modular (10^6 psi) materials would have, over-all, better fatigue properties in a pavement than would relatively lower modulus (10^5 psi) material. Such indications include considerations of reduced thickness of treated materials with increasing modulus.

George (*79*) has reported on the mechanisms associated with shrinkage cracking plus recommended methods to minimize such cracking. Although the materials used by George are primarily in the sand-silt-clay size range, it could be expected that his findings would also apply to gravel-size materials. George indicates that shrinkage is caused by the loss of water, primarily by evaporation or chemical reaction with the cement. He poses three possible mechanisms for shrinkage: (1) capillary tension, (2) liquid absorption, or (3) lattice shrinkage in the clay. Recommendations to minimize shrinkage cracking are as follows:

1. Use a cement content equal to or greater than that specified by freeze-thaw criteria (ASTM D560). (Investigations by Hveem (*119*) would tend to indicate that excessive amounts of cement will increase the amount of shrinkage cracking and, hence, some care needs to be exercised when considering this recommendation by George.)
2. Use Type II cement in preference to Type I cement.
3. Replace 1 to 2 percent of cement with an equal amount of lime.
4. Compact to the highest density possible; specifically, a minimum of 95 to 100 percent of AASHO Method T-180 was recommended.

TABLE 9

FACTORS SIGNIFICANTLY RELATED TO PAVEMENT CRACKING (CEMENT-TREATED BASES)

Traffic Associated (Fatigue)	- Compressive strength
	- Uniformity of mixing
	- Thickness and thickness variations of cement-treated layer
	- Type of cement
	- Width of cement-treated layer
Non-Traffic Associated (Shrinkage)	- Uniformity of mixing
	- Environment[1]
	- Thickness of asphalt concrete
	- Thickness of compacted layer

[1] Coastal areas with mild temperature exhibited less cracking than inland valley areas with high summer temperatures.

5. Adequate membranes or procedures for obtaining good curing conditions are highly desirable. Placement at high ambient temperatures should be discouraged by specifications.
6. Increase the stiffness by increasing the thickness of the treated layer.
7. Designs calling for 7 in. or more of cement-treated base should be compacted in two layers.
8. Compaction water content should not exceed the optimum required to achieve field density.
9. Limit the percent of clay fraction to 15 percent if clay mineral is kaolimite, and 8 percent if clay mineral is montmorillomite.

Asphalt-Treated Bases

Asphalt-treated bases fall in three rather broad categories, as follows: asphaltic concrete, sand asphalt (hot mix), and liquid asphalt, including asphalt emulsions.

Asphaltic concrete bases have been evaluated in accordance with the procedures discussed earlier in this appendix. However, some investigators have suggested modifications in stability criteria that will justify the use of increased asphalt contents (*126, 127*).

Oklahoma (*92*) and Colorado (*44*) have reported on the use of hot-mix sand asphalt construction. Performance has been satisfactory insofar as fatigue cracking is concerned. However, at the present time, there is limited information in the literature to suggest methods for minimizing fatigue cracking. The Asphalt Institute (*4, 8, 9*) has published some mix design criteria.

The use of asphalt emulsions for base treatment is receiving considerable attention as a means of minimizing air pollution associated with construction. Information relative to structural design, mix design, and construction with these materials is needed. References *8, 9, 63, 64, 68, 137, 168, 223* provide some useful information regarding the viability of the use of these materials.

Thickness design methods are generally lacking for asphalt emulsion treated layers. Finn et al. (*68*) and The Asphalt Institute (*10*) have suggested structural design procedures based on layered analysis and field experience. The paper by Finn et al. provides information for selecting the thickness of the base in terms of the elastic modulus of the treated materials.

Lacking specific information regarding fatigue properties of asphalt-treated material, this investigation is based on limiting the deflection of the pavement to a level equivalent to that associated with the untreated aggregate base.

Terrel and Monismith (*223*) have reported on studies to evaluate asphalt-treated base materials including an MC-800 liquid asphalt and SM-K (CMS-2S) emulsified asphalt. One of the significant findings of their investigation was the effect of the type of curing on strength development. Moist or dry curing had little effect on the MC-800 mix, and the modulus was relatively low (160,000 psi) after 90 days. However, for the emulsion, the dry-curing specimens increased the modulus by about tenfold. Thus, good curing (moisture release) conditions must be provided for emulsion stabilization, and toward this end engineers in some western states have been experimenting successfully with open-graded aggregates for stabilized bases and surface layers. Also, recent studies by Terrel and Wang (*224*) indicate that improved curing can be facilitated by adding small amounts of cement to the mix.

Foundation Materials

The term "foundation material" is used to describe the on-site native materials or borrow materials on which the pavement structure is to be constructed. The project was concerned primarily with cohesive type materials, which generally are related to strength and volume change problems. Granular foundation materials would not fall into this category.

Since this phase of the project is related to fatigue cracking of asphaltic concrete, the major emphasis is on properties that tend to influence the strain in the asphaltic concrete or affect the total pavement deflection. Research indicates that the best way to study the role of the foundation materials is to study their elastic properties under conditions representative of a pavement structure (*13, 42, 95, 129, 167, 207*).

Considering designer-controlled variables, it is concluded that only two factors could be controlled; specifically, water content and density. Laboratory research indicates that the water content used during construction will influence the long-term elastic properties of the foundation material (*207*). According to such findings, the most desirable field compaction water content would range from 0 to 2 percent below the optimum laboratory water content required for maximum density. Figure 17 is an illustration of the effect compaction water content has on the elastic properties of the WASHO and AASHO foundation soils. For example, compacting this material wet of optimum has decreased its resilient modulus by approximately one-fourth of its potential maximum. It is recognized that field control of the water content within such limits may be considered impractical. However, for some highly resilient soils, the extra effort may be justified.

Both laboratory and field investigations indicate that, all other conditions being the same, a low equilibrium water content produces the least amount of elastic deformation under moving wheel loads (*102, 207*). Thus, any methods that will protect the foundation material from accumulating water will reduce the potential for fatigue cracking. Two techniques that have been observed to be beneficial in the field are: (1) use of treated bases, and (2) use of membrane seal around exposed portions of pavement structure and side slopes, as illustrated by Figure 18. It is conceivable that if the untreated aggregate were to become partially saturated (degree of saturation significantly higher than required for compaction under field conditions, yet not completely saturated) that the foundation modulus would be reduced. Table 10 projects the reduced fatigue life due to a reduction in foundation modulus for a partially saturated base.

In evaluating the influence of this amount of reduction in fatigue life, it may be well to review the cracking experience from the AASHO Road Test. For example, on the average, Class 2 cracking occurred significantly before the pavement's serviceability (psi) was reduced to a terminal

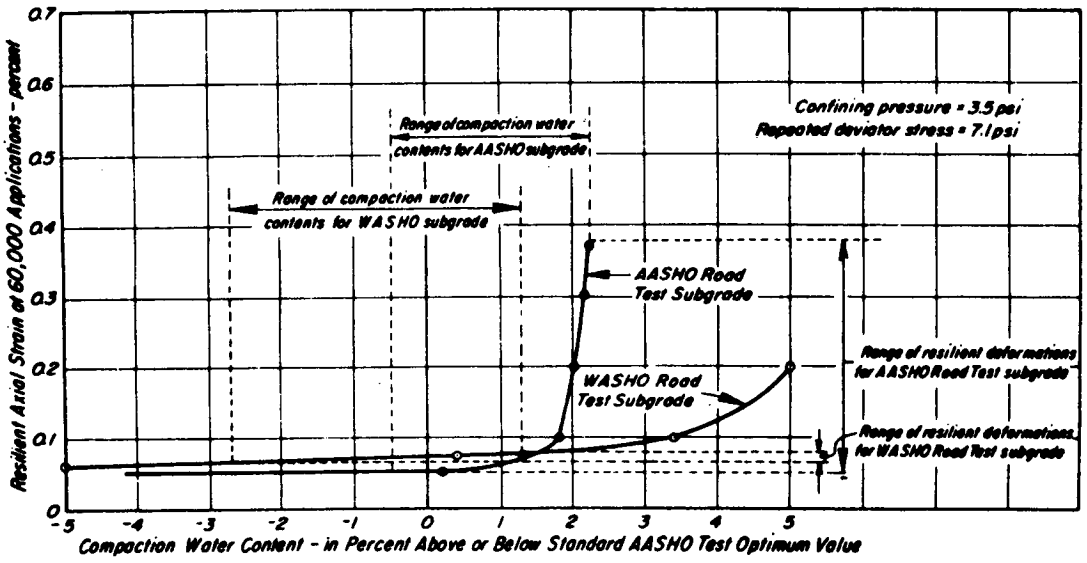

Figure 17. Comparison of resilience characteristics of road test subgrades at field placement conditions (after Seed et al., 207).

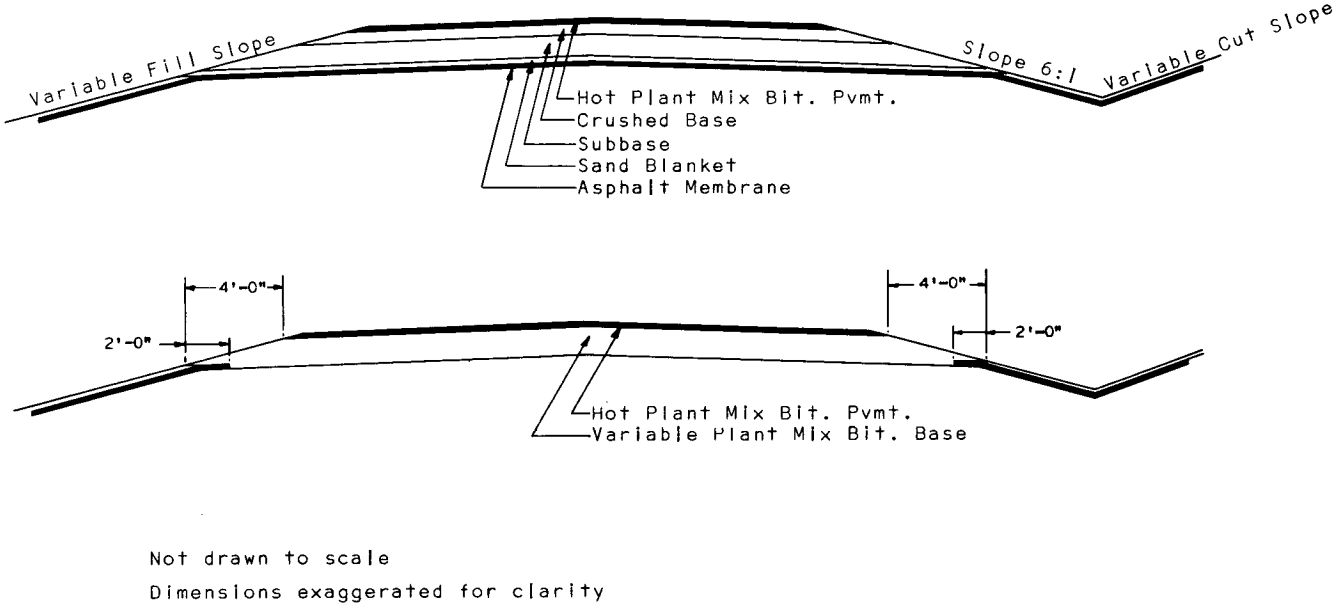

Figure 18. Typical sections showing use of asphalt membranes and asphalt stabilized base for control of expansive soils (after Brakey and Carroll, 23).

value of 2.5. Cracking could occur, according to the AASHO Road Test data, at approximately 60 percent of the traffic required to reduce the psi to 2.5. Thus, a pavement designed for 20 years could easily exhibit cracking after 12 years and still be expected to provide satisfactory over-all performance. It is suggested, by the previous analysis of foundation materials and saturation of aggregates, that this value could be reduced by another 25 or 30 percent to approximately 8 to 9 yr.

LOW-TEMPERATURE CRACKING

Low-temperature cracking manifests itself through transverse cracking in the asphaltic concrete surface layer. Field observations and measurements indicate that the cracking starts in the surface of the asphaltic concrete and can progress through the entire layer (*31, 32, 84*).

Although not necessarily judged as a primary determinant of low-temperature cracking, the freezing index (annual degree days below 32 F) has been used by some Canadian engineers to indicate potential areas for such cracking. Severe conditions have been reported for areas exposed to a freezing index of 1000 and some cracking has been reported in areas with a freezing index of 650. Figure 19 indicates areas of the United States that fall within these critical ranges in which low-temperature cracking can potentially create problems for the highway engineer.

Experience has shown that the initial effect of low-temperature cracking on riding quality may be minor but that the intrusion of water often causes volume change in the subgrade soils (swelling in clays, densification in sands, or frost heave) with adverse effects on the longitudinal profile. Also, the loss of structural integrity at the cracks can result in extension of the initial cracking with spalling in the vicinity of the cracks.

Maintenance and repairs pose a serious problem. Crack filling needs to be repeated on a regular basis and may require annual maintenance. Overlays may be required after 3 to 10 years of service, and reflection cracks usually occur within one year or less after constructing the overlay.

Response Variables for Low-Temperature Cracking

By photographic evidence, McLeod (*157*) has shown that the frequency of transverse cracking was apparently associated with asphalt hardness when identified by original penetration. He indicated, by observation, that the greatest amount of cracking was noted with the harder asphalts. He found some indication that the thickness of asphaltic concrete could influence cracking. At Orangeville, Ontario (freezing index of approximately 1000), he reports that 2-in. pavements with 85- to 100-penetration asphalt were cracked, whereas 5½-in. pavements with the same 85 to 100 asphalt were not cracking. McLeod's data, shown in Figure 20, also produce some information relative to low-temperature (39.2 F) ductility and low-temperature cracking. On a cracking or no cracking basis, it would appear that recovered asphalt ductility at 39.2 F should be greater than 10 cm. Some acceptable asphalts would be rejected on this basis. The use of ductility has not been fully evaluated in the field and requires further study. Some technologists (*94*) believe that ductility and asphalt stiffness are related and that the latter property is preferred because it has additional applications (e.g., predicting cracking temperature).

It is pertinent to note that McLeod (*157*) consistently points out that his data suggest starting with softer asphalts but that this choice in no way decreases the importance of achieving high densities during construction and for obtaining thick asphalt films in the asphaltic concrete. He also indicates that highly absorptive aggregates will have a tendency to produce mixes with thin films of asphalt susceptible to accelerated hardening which, in turn, will increase the possibility for low-temperature cracking.

On the basis of observations from Saskatchewan and Ontario, McLeod was able to show that temperature susceptibility was very important in influencing the number of transverse cracks. In his analysis, McLeod used the penetration index (P.I.) as conceived by Pheiffer and Van Doormaal to evaluate temperature susceptibility. The higher the P.I., the lower the temperature susceptibility (i.e., an asphalt with a P.I. of 0.0 is less temperature susceptible than an asphalt with a P.I. of −1.0). Haas (*81*) has also indicated that consistency (penetration) at 77 F is only part of the influencing parameter and that temperature susceptibility is a major factor.

In 1970, the Canadian Good Roads Association (*32*) offered a summary of the major factors contributing to the behavior of pavements at low temperatures. Their report indicated that, at successively lower temperatures,

TABLE 10

COMBINED EFFECT OF REDUCED FOUNDATION MODULUS AND PARTIALLY SATURATED AGGREGATE

Traffic Classification	Structural Section	PERCENT REDUCTION DUE TO INDICATED REDUCTION IN FOUNDATION MODULUS FOR PARTIALLY SATURATED AGGREGATE					
		1500 to 1000		4500 to 2250		13,500 to 6750	
		Strain[a]	Deflection[a]	Strain	Deflection	Strain	Deflection
Light	4-16	25	<10				
Light	6-11			31	33		
Heavy	4-25					31	40
Heavy	4-14	19	17				
Heavy	8-33			22	17		
Heavy	8-14					31	
Heavy	6-9						(b)

(a) Asphalt concrete modulus of 100 ksi and using University of California criteria for strain in asphalt concrete and Asphalt Institute criteria for pavement deflection.

(b) Deflections below lowest design value of 0.022" and reduction cannot be estimated by Asphalt Institute criteria.

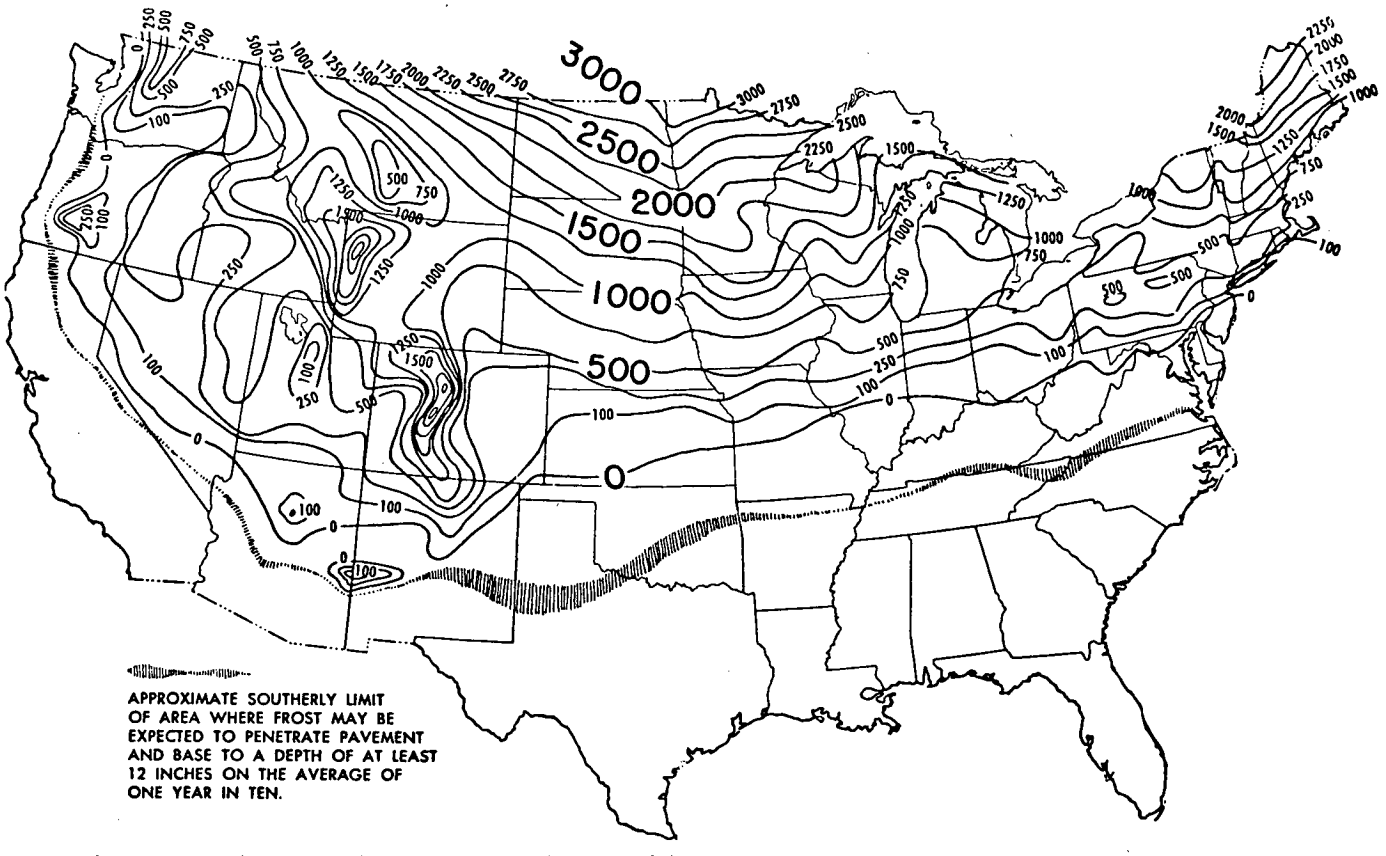

Figure 19. Freezing index map of the United States (after Haas, 87).

(1) the asphalt layer tends to contract but is partially or wholly restrained, and (2) the material becomes stiffer. At some temperature, the tensile strength of the asphaltic concrete layer is exceeded by the tensile stresses induced and fracture occurs. Observations were reported indicating that the asphalt source was the most significant identifiable parameter with the nature of the foundation material being a significant factor. The report also pointed out that a definite relationship existed between pavement age and cracking.

The St. Anne Test Road has been the most comprehensive full-scale project reported in the literature to date (*26, 27, 243*). The experiment contained twenty-nine, 400-ft sections constructed in 1966. It is significant that the high viscosity asphalts used on the project had a lower temperature susceptibility than the low-viscosity asphalts. The conclusions from this investigation included the following:

> From the field observations, the major factors affecting a pavement's cracking tendency are the binder type and grade, low temperature susceptibility and soft grade being beneficial properties.
>
> Subgrade type and structural design have some effect on cracking frequency.
>
> The crucial temperature with respect to the initiation of transverse cracking is the pavement surface temperature, and cracking is primarily initiated at the pavement surface.
>
> For practical purposes, the tendency of a mix to crack at lower temperatures can be indicated by a knowledge of the binder stiffness modulus at low temperatures and long loading times.

Tuckett et al. (*229*) have reported on a laboratory investigation to determine the influence of asphalt viscosity, asphalt content, and absorptive aggregate on the resulting stresses induced by thermal regimes corresponding to those found in actual pavements. Contrary to previously reported results by Hills and Brien (*100*), these investigators found that thermal cracking was influenced by the asphalt content. The most significant indicator of cracking was the interaction between asphalt viscosity and asphalt content. High viscosity at 140 F and low-asphalt content indicated the highest crack potential. However, a high-viscosity asphalt with asphalt contents in excess of those required by Marshall design procedures used by the Utah Department of Highways indicated the lowest crack potential.

Examination of the literature indicates that the technology has been developed that makes it possible to evaluate the factors influencing low-temperature cracking as follows:

1. Methods for estimating the temperature regime in the asphalt layer (*37, 126, 164, 192, 212, 217*).
2. Methods for measuring or estimating stiffness modulus of asphalt or asphaltic concrete (*26, 39, 67, 84, 85, 86, 87, 164*).
3. Methods for measuring or estimating temperature-induced tensile stress (*26, 37, 38, 39, 87, 100, 164*).
4. Methods for measuring or estimating properties (stiff-

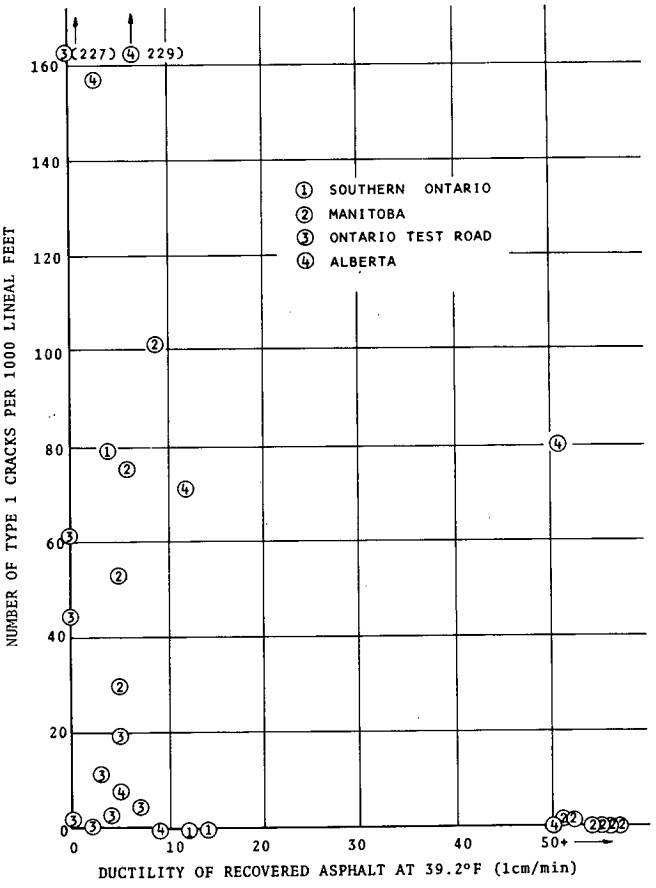

Figure 20. Relationship between low-temperature ductility of recovered asphalt and transverse cracking.

ness, tension) at low temperatures (*26, 27, 32, 37, 87, 94, 100, 164*).

5. Methods for estimating fracture temperature (*26, 27, 32, 37, 87, 94, 100, 164*).

6. Methods for estimating low-temperature cracking frequency (*90*).

7. Methods for defining limiting criteria (*90*).

It must be emphasized that indirect methods for estimating the stiffness modulus are not equal in reliability to direct methods and can produce results that are significantly different. However, as a first approximation, indirect methods are useful and, for this reason, have been summarized by The Asphalt Institute and are reproduced as Appendix B. Methods for estimating fracture temperature are discussed in Appendix C.

Designer-Controlled Variables

For purposes of this report it has been postulated that the designer-controlled variables that relate to minimizing low-temperature cracking are primarily concerned with asphalt properties and the proportion or thickness of asphaltic concrete that can be incorporated into the structural design.

Properties of Asphalt

Laboratory research supported by field observations indicates that asphalt consistency, largely reported in terms of penetration at 77 F, and temperature susceptibility are the major material properties influencing low-temperature cracking. Increasing the asphalt penetration is suggested as the most direct designer-controlled variable for minimizing cracking. However, some care must be exercised to avoid asphalts that are highly temperature susceptible (i.e., could become extremely stiff at low temperatures regardless of the initial penetration).

The St. Anne Test Road confirmed that temperature susceptibility would significantly influence the low-temperature viscosity of asphalt cement. A study (Saskatchewan) in 1963, specified a 150- to 200-penetration grade asphalt (*31*). Subsequent modifications led to the use of AC-4, AC-5, and AC-6 viscosity requirements at 140 F, with minimum and maximum penetration at 77 F. Ontario has used the regular penetration grades 60 to 70, 85 to 100, 150 to 200, and 300 to 400 with a fairly high minimum viscosity at 275 F. In 1967, Alberta started using a viscosity specification (*2*). The grade most commonly used calls for a minimum penetration of 250 at 77 F and a minimum viscosity of 275 poises at 140 F, termed AC-275. The alternate asphalt is an AC-900 with a penetration range of 85 to 120 at 77 F and a viscosity of 900 poises at 140 F. Manitoba used an SC-5 grade of liquid asphalt with a specified viscosity range at 140 F. It should be noted that these criteria are under constant review; however, for those agencies who have modified their specifications, the trend is to the use of higher penetration asphalts at 77 F

and with a relatively low-temperature susceptibility. The temperature susceptibility is controlled by specifying a minimum allowable viscosity at 140 F or 275 F.

Asbestos filler on one project in Canada (*33*) has had a significant effect on low-temperature cracking. Four 1500-ft sections of final surfacing (3 in. thick) with varying amounts of asbestos fibre modification and 120- to 150-penetration asphalt were constructed in 1967. After 3 years, the control (no asbestos) showed 296 cracks; the 1 percent modified mix in the top lift had 176 cracks, the section with 2 percent asbestos-modified mix had 57 cracks, and the section with 3 in. of asbestos-modified mix had only 22 cracks.

Hignell et al. (*99*) have recently reported on the influence of asbestos on temperature susceptibility. A major finding from this investigation indicates that asbestos improves the properties of asphaltic concrete at medium and high temperatures, such that softer asphalts can be used to avoid low-temperature cracking without seriously affecting high-temperature performance.

McLeod (*157*) originally proposed to minimize low-temperature cracking by recommending a minimum penetration of 60 at 77 F and 20 at 32 F on the recovered asphalt. In general, if pavements are exhibiting an excess amount of cracking, he proposed increasing the original penetration and requiring a higher P.I. (lower temperature susceptibility). On the basis of original asphalt properties, he suggested using 150- to 200-penetration asphalts in the milder winter climates of Canada (650-degree days) to 300 to 400 penetration in colder areas. For extreme conditions, he suggested using an SC-3000.

Subsequent to the development of recommendations on penetration, McLeod (*158*) has further examined his data and concluded that cracking will occur when the stiffness of a mix under field conditions exceeds the values given in Table 11. These low-temperature moduli are determined on the bases of McLeod's revision of Pheiffer and Van Doormaal's P.I. chart and of his revision of Heukelom and Klomp's modification of the original Van der Poel stiffness nomograph for asphalt as given in Appendix B. A loading time of 20,000 sections ($10^{4.3}$) or roughly 6 hr is used as the rate at which the pavement is being stressed because of low temperatures.

McLeod (*158*) has translated his stiffness criteria into an asphalt cement selection guide, as shown in Figure 21, for various levels of the penetration index. When using this figure, McLeod recommends selecting a grade of asphalt cement that will avoid low-temperature cracking during the pavement's service life by selecting materials with properties that lie to the right of the diagonal lines for the lowest temperature expected in the upper 2 in. of the pavement.

McLeod recognizes and discusses the need for asphaltic concrete with soft asphalts to provide resistance to plastic deformation during hot weather. He indicates that the need for adequate stability in hot weather will usually dictate the degree to which the asphalt cement can be softened. McLeod argues that asphaltic concrete mixes with soft asphalts are more easily compacted; and, hence, higher density requirements can be specified to achieve comparable stability with mixes made with harder asphalts.

TABLE 11

MAXIMUM MIX STIFFNESSES FOR SELECTING ASPHALT CEMENT GRADE

Min. Temp. at 2 Inch Depth	Stiffness Modulus, S, - psi	
	Cracking Expected	Cracking Eliminated
-40F	1,000,000	500,000
-25F	700,000	300,000
-10F	400,000	200,000
+10F	100,000	50,000

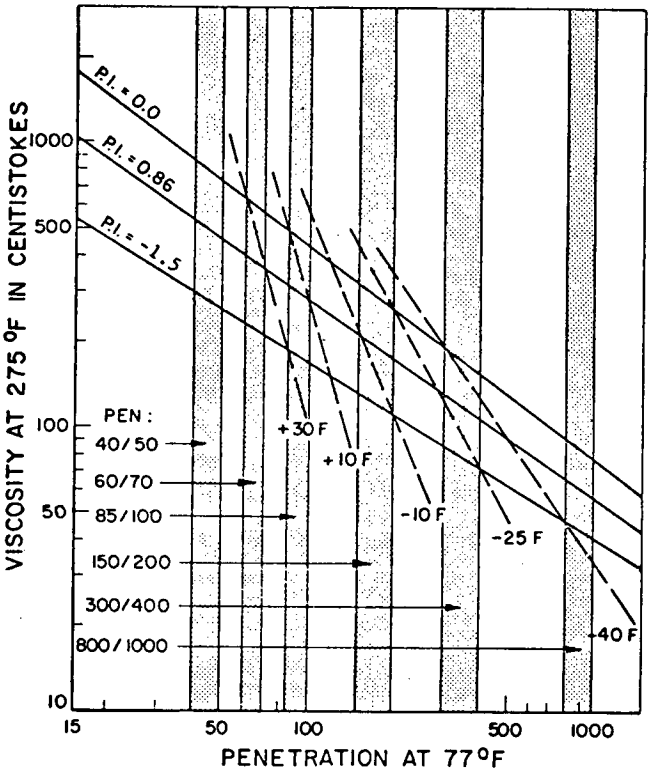

Figure 21. Chart for selecting grades of asphalt cement to avoid low-temperature transverse pavement cracking (after Mc Leod, 157).

Fromm and Phang (*75*) have suggested an asphalt-cement guide, as shown in Figure 22, similar to that of McLeod. The values in Figure 22 are in terms of minimum retained penetration for aged asphalts as simulated by the thin-film oven test.

Structural Section

The second designer-controlled variable is the thickness of the asphaltic concrete. Hajek and Haas (*90*) have developed tentative statistical correlations between thickness of the asphaltic concrete and low-temperature cracking frequency. This relationship is shown in Figure 23. It should be noted that asphalt consistency is the dominant influencing parameter in this figure and that temperature susceptibility is handled by evaluating asphalt stiffness at low temperatures. The cracking index in Figure 23 is defined as the number of full plus one-half of the number of cracks across one lane only of a two-lane highway.

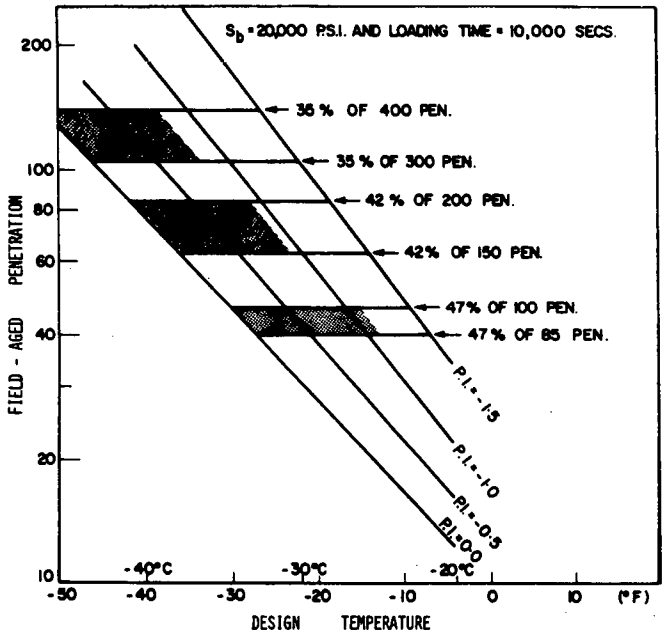

Figure 22. Selecting asphalt cement from design temperature, 1% basis (after Fromm and Phang, 74). Note percentages are for retained penetration after thin-film oven test, D.H.O. specifications.

REFLECTION CRACKING

A description of reflection cracking is contained in *Highway Research Board Spec. Rep. 113,* which states that it is the "cracking of a resurface or overlay above underlying cracks or joints" (*106*). A general definition for reflection cracking is the surface replication of the joints and cracks that are in the underlying layers of the pavement and foundation materials. The general definition would then include the cracking of a surface course of the original pavement due to reflectance of a joint or cracking originating in a base course or subgrade layers.

A considerable amount of field and theoretical experimentation and analysis of the causes and corrective procedures for reflection cracking has occurred over the past quarter century. However, Ref. *111* indicates "there have not been any controlled experimental projects where all these methods have been utilized in a factorial experiment design . . . any comparisons across project lines are only relative."

The importance of preventing or, at least, minimizing reflection cracking cannot be overstated. Prevention will tend to retain the structural integrity of the pavement, preclude water intrusion, and maintain a smooth-riding surface.

Mechanisms and Response Variables for Reflection Cracking

For discussion purposes, it is convenient to describe the mechanisms that cause cracking in terms of traffic- (load-) associated and nontraffic- (nonload-) associated movements. At the present time (1972), a well-developed and generally accepted description of the mechanisms and response variables associated with reflection cracking has not been established. Discussion Group E at the Workshop on Structural Design of Asphalt Concrete Pavement System (*108*) concluded, "Although we can accept that volume changes in an underlying material layer can contribute to the development of reflection cracking, we are uncertain what role is played by repeated traffic loading either in a flexural way or in a relative movement way." At that same workshop, Discussion Group F summarized their session by stating that reflection cracking may in many cases be primarily load associated.

Although considerable field experience and some laboratory work have been published, general solutions to the problem of reflection cracking are only in the early stages of development. A summary of information on reflection cracking is as follows:

1. There are no criteria, such as vertical or horizontal movement, which can be directly applied for the prediction of reflection cracking.
2. Current information and practices are largely developed from empirical studies in the field and laboratory, and many field projects are still inconclusive because of limited time or limited traffic applications.
3. Methods currently in use have generally been effective for limited periods of time, up to 5 yr.
4. No information is available regarding minimizing reflection cracking over cement-treated bases initially surfaced with asphaltic concrete. For the most part, all of the procedures described for controlling reflection cracks over portland cement concrete, except for breaking and seating, could be used.

Designer-Controlled Variables

A number of systems have been devised and tested in full-scale road experiments to discover means to control reflection cracking. These methods generally fall into one of the following classifications:

1. Improve the ability of the asphaltic concrete overlay to withstand or limit the stresses or strains that cause cracking.
2. Place an intermediate stress-relieving layer.
3. Prepare underlying pavement.
4. Overlay with relatively thick layer of asphaltic concrete.

Generally, the methods can be used over either portland cement concrete or asphaltic concrete except where breaking and seating are involved. Also, for asphaltic concrete, one procedure to eliminate reflection cracking would be to eliminate the cause; that is, remove and replace those areas that exhibit cracking.

Increase Flexibility of Asphaltic Concrete

Recognizing that horizontal and vertical movements can cause reflection cracking, one solution would be to provide a more flexible overlay, one that can tolerate high levels of strain without fracture.

Research with fillers, such as short asbestos fibers, limestone dust, or hydrated lime, has been used to modify the flexibility and fatigue properties of asphaltic concrete (*67, 99*). The introduction of synthetic fibers has also been

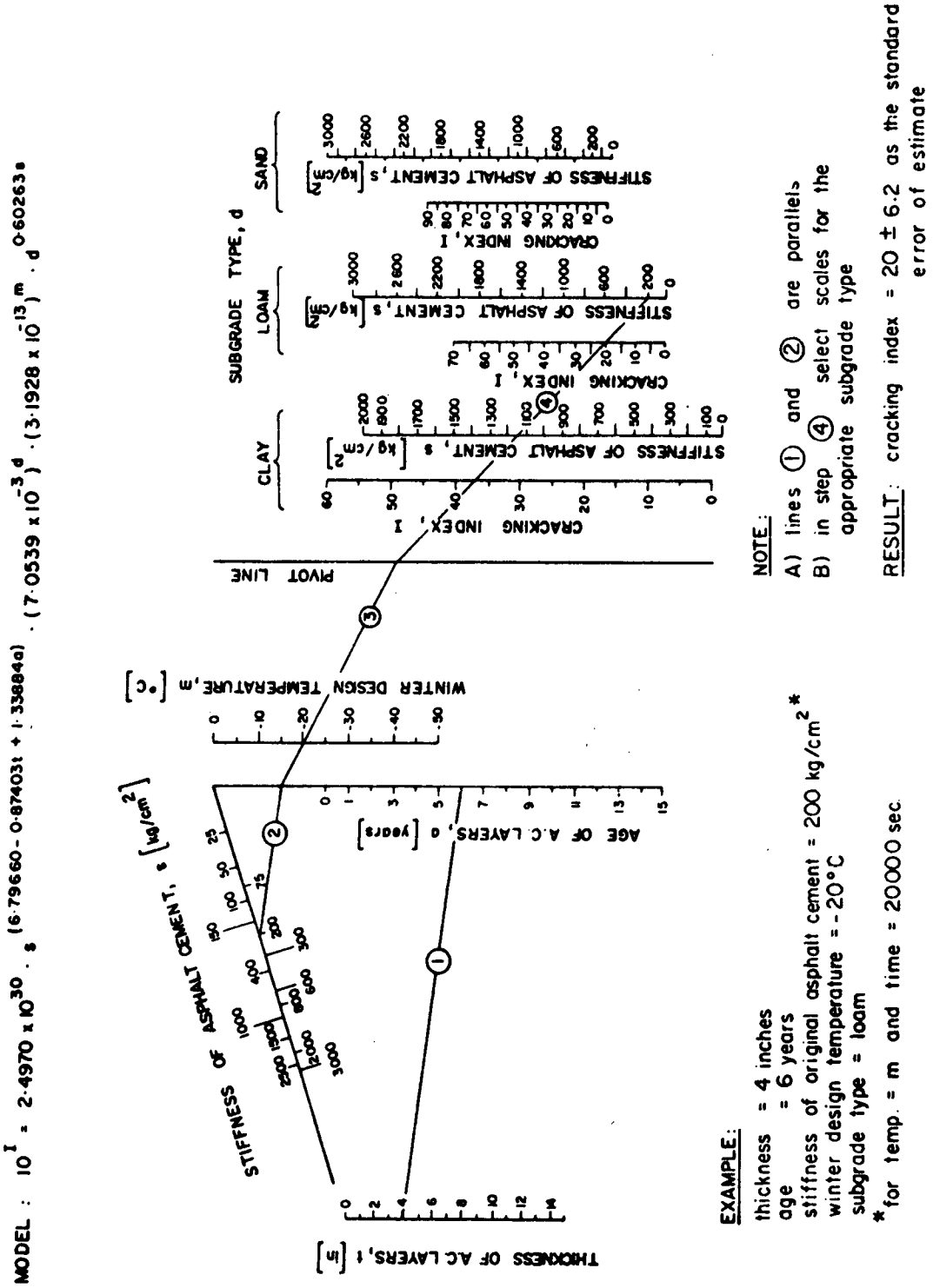

Figure 23. Nomograph for predicting low-temperature cracking frequency of asphalt pavements (after Hajek and Haas, 90).

investigated (*29*). On the basis of limited laboratory data, there would appear to be some merit to the use of fillers of synthetic fibers; however, there are no reports of long-term road experiments to evaluate the field effectiveness of such modifications. The use of rubber in various forms and amounts to increase the extensibility of asphaltic concrete has been investigated (*197*).

A small experiment was conducted by the Road Research Laboratory (*121*) to evaluate the effect of asphalt content with vulcanized rubber crumbs on the performance of thin overlays. The existing two-lane roadway, which carried heavy traffic, consisted of portland cement with an asphalt overlay. The authors concluded that the use of rubberized asphalt in this form had no significant effect on reflection cracking.

The use of rubber in overlay construction was reported for a rehabilitation of a four-lane highway with a pavement consisting of asphaltic concrete over cement-treated base (*35*). The report indicated that the existing cracking in the surfacing was due to reflectance of cracks in the

base. A 2¾-in. overlay was placed in three courses with the leveling and intermediate courses incorporating a 120- to 150-penetration asphalt and the surface course using an 85 to 100 asphalt. In addition, the experimental sections contained an asphalt which had 1.5 percent neoprene added at the refinery. After two years, it was reported that the rate of development of reflection cracking was less in the sections in which neoprene was incorporated into the asphalt. The report mentioned that it was too early to conclude whether total reflection cracking would be reduced over a longer period.

A large number of field installations of wire mesh reinforced overlays have been constructed in the last 25 yr. Reports on these projects are described in numerous publications of the Highway Research Board and the Association of Asphalt Paving Technologists (*22, 25, 28, 36, 46, 80, 83, 136, 220, 227, 228, 248*). There have been cases in which the use of wire mesh has resulted in improved performance over limited periods of time (5 to 7 yr). Again, there is no conclusive evidence in the literature of significant reduction in reflection cracking over extended periods of time.

A thin surface treatment for deteriorating asphaltic concrete has been used on city streets and airfield pavements in Arizona. The binder consists of 20 to 35 percent ground rubber combined with a paving grade asphalt at elevated temperatures. The rubber asphalt mixture is applied at 325 to 460 F and covered with chips in a manner similar to a chip-seal treatment. The resulting ¼- to ⅜-in. surfacing has reportedly reduced the reflection of alligator and block cracking (*152, 153*).

Intermediate Stress-Relieving Layer

The use of an untreated aggregate cushion course has been reported by a few investigators, usually in conjunction with some pretreatment of the existing surface (*17, 46, 217*). Alternatively, the old pavement can be broken up prior to placing the cushion course. A two-lane state highway project in Washington (*218*) consisted of seating the existing portland cement concrete pavement and placing an aggregate blanket with a minimum thickness of 5 in. plus a 4½ in. asphaltic concrete overlay. The report indicated that no reflection cracking occurred after 5 yr. In Michigan (*46*), a 3-mi section of a two-lane state highway was selected for a test of treated, 4-in.-thick cushion courses. The existing pavement was badly cracked with an average slab segment length of 10 ft. The aggregates used varied from coarse-to-fine gradation and were treated with calcium chloride, sodium chloride, and asphalt. A 2½-in. overlay was placed on all sections. Reflection cracking was substantially reduced by the use of cushion courses, and the section that had the asphalt-treated cushion exhibited the lowest percentage of crack reflectance.

Cushion courses can act as drainage blankets and, as such, may require special treatment at the shoulder to preclude trapping water. Total pavement thickness for this type of construction can range from 6½ in. to 11 in. and more (*17, 46*).

To minimize the thickness required in the use of a cushion course as a stress-relieving medium, some agencies have and are experimenting with thinner treatments. A Los Angeles County urban road was used to evaluate the ability of various materials to break the bond between the overlay and the existing pavement in the immediate vicinity of a joint (*241*). The essentially sound existing portland cement concrete pavement, which carried 28,000 veh/day with 36 percent trucks, was effectively subsealed a few years prior. The thin bond-breaking materials, generally 18 in. wide, straddled the transverse joints. The overaly consisted of a variable thickness leveling course, with an 85- to 100-penetration asphalt, and a surface course 2 in. thick, which had a 200- to 300-penetration asphalt. Results varied from immediate reflection cracking in the untreated control sections to no cracking after 4 yr over those joints which had stone dust as the bond breaker. More recently, specially manufactured membranes have been used to break the bond.

Another technique to minimize total thickness is the introduction of a continuous layer of material that serves as a strain-relieving interface. Galloway (*76*) reported on a laboratory experiment with a material consisting of approximately equal parts of ground tread rubber, sand, and residual asphalt in emulsion form used as the strain reliever that can be applied with slurry seal equipment. A road experiment in North Dakota placed asphalt-treated sand, open-graded plant mix seal, slurry seal, and the sand-rubber-asphalt emulsion on test sections prior to the construction of a 3½-in. overlay (*80*). Similar projects are under study in California and Washington, and, possibly, other states or agencies.. Also, proprietary bond-breaking membranes of various types are being offered by suppliers for reduction of reflection cracks.

The Arizona Department of Transportation has reported (*171*) on favorable results with an asphalt-rubber membrane interlayer as a means of preventing reflection cracking. Conclusions after some 6 yr (1971-1976) of experience indicate that the asphalt-rubber interlayer will minimize reflection cracking for both asphalt and PCC construction.

Preparation of Existing Portland Cement Concrete Pavements

Undersealing with asphalt or pressure grouting with a cement mortar will reestablish support with the foundation materials in order to reduce vertical movement at joints (*6, 35, 134*).

Another approach is to put the pavement in full contact with the supporting materials by heavy rolling or various degrees of hammering coupled with heavy rolling. The purpose is to reduce vertical movement and, in cracking the pavement, to reduce horizontal movement by decreasing the slab segment length. Field procedures fall into two broad categories. The pavement may be rolled with minimum hammering, as necessary, to induce cracking resulting in a section with some structural integrity and shorter slab segments. The other procedure involves breaking the slabs into small pieces and using the resulting fragments as a foundation for a new pavement section (*1, 5, 135, 145, 215, 216, 217, 239, 240*).

Overlay with Relatively Thick Layer of Asphaltic Concrete

Stress in an overlay due to movement of the underlying pavement has been reported to be inversely proportional to the thickness of the overlay (*149*). Also, an increase in overlay thickness tends to reduce daily volume change as manifested by horizontal joint movement and perhaps more significantly to reduce slab curling by reducing the temperature differential (*235*). No clear indication has been made regarding the required thickness of overlay to prevent reflection cracking (*83, 135, 215*). The Asphalt Institute (*5*) has suggested a thickness of 4½ in.; other investigators (*178*) have reported up to 10 in.

APPENDIX B

THE ESTIMATION OF STIFFNESS MODULUS OF BITUMINOUS MATERIALS BY INDIRECT METHODS

(See following note.)

APPENDIX C

LOW-TEMPERATURE FRACTURE

(See following note.)

APPENDIX D

CASE HISTORY APPROACH

(See following note.)

APPENDIX E

THEORETICAL BASIS FOR COMBINING DATA AND SUBJECTIVE INFORMATION

(See following note.)

NOTE

Appendixes B, C, D, and E are not published in this report but are reproduced in a supplement, which is available on a loan basis from the Program Director, NCHRP, Transportation Research Board, 2101 Constitution Ave., N.W., Washington, D.C. 20418.

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