That bituminous highway and airfield pavements can and should be designed in part to control fatigue distress is no longer questionable. This state-of-the-art paper describes how such a design can be accomplished by means of the phenomenological approach and emphasizes those procedures essential to the prediction of fatigue life. Each element of the design process is presented in terms of a comprehensive flow chart that depicts not only the interrelations among individual elements but also the chronological sequence within which the individual elements are addressed. Critical stresses and strains in the pavement structure can be estimated sufficiently well by means of elastic, multilayered analysis. That analysis is made tractable only by approximating the continuous spectra of traffic loads and physical states of the pavement by means of discrete categories. Failure criteria relating the number of load applications causing failure to the calculated strain level and other variables are used to estimate the fatigue damage caused by 1 application of each traffic load while the pavement is in each physical state. The total accumulation of fatigue damage during the design life is estimated by the hypothesis of the linear summation of cycle ratios (Miner's hypothesis). Failure criteria for use in routine design can probably best be developed from analyses of the performance of in-service pavements. However, methods of structural analysis, materials characterization, and pavement-state categorization must be identical during both development of the criteria and their application to design. Proper selection of the physical-state categories affords an excellent opportunity for realistically recognizing the effects of environmental variables on pavement performance and design.

Fatigue Life Prediction

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The one structural function of a highway or airport pavement is to ensure that stresses repetitively applied to the subgrade by traffic loads are sufficiently small that shear failure and excessive permanent deformation within the subgrade are prevented. At the same time, the structure itself must be so constructed as to prevent internal distress that might ultimately impair the ability of the pavement to carry traffic safely and smoothly. One of several types of internal distress that must be controlled is fatigue, that is, cracking of the bound components of the pavement due to repetitive traffic loading.

The notion that pavement structures can exhibit fatigue distress and that such distress can and should be controlled by judicious design is certainly not new. As early as 1938, Bradbury (3) suggested a design methodology for controlling fatigue distress in portland cement concrete pavements. The central thrust of the current Portland Cement Association design methodology (34) is the control of fatigue cracking through proper thickness selection. Design techniques have also been advanced for controlling fatigue in bituminous pavements. In 1963, Shell made a significant contribution to available technology through the introduction of a design methodology for highway pavements (36). That was followed in 1970 (12) by the development of a design procedure for bituminous airfield pavements. The Kentucky Department of Highways has developed a comprehensive design methodology (8, 9) that, like the Shell procedures, incorporates a concern with fatigue cracking.

The Asphalt Institute has also incorporated means for controlling fatigue distress in its new manual (1) for the design of full-depth asphalt pavements for airfields.

In addition to those methodologies that have immediate applicability to routine design situations (41, 42), there have been several notable research investigations in which the prevention of fatigue cracking has been examined in detail (27, 40). The purpose of this paper is to summarize some of the currently available techniques necessary for fatigue-life estimation in bituminous pavements.

DESIGN APPROACH

The recommended approach for design of bituminous pavements to control fatigue cracking is similar to that for the design of most engineering structures. Basically it is a trial-and-error procedure whereby (a) a trial structure is assumed, (b) the structure is analyzed by estimating the levels of the critical stresses and strains anticipated under in-service loading, (c) the structure is evaluated by comparing the estimated stresses and strains with tolerable levels derived from failure criteria, and (d) modifications are made to the trial structure as necessary, and the process is repeated until a satisfactory design has evolved.

A more detailed representation of the design process as it can be applied to the control of fatigue cracking in bituminous pavements is shown in Figure 1. The process flow is described below.

1. Select the design life in order to enable an estimate of traffic accumulation (Fig. 1, box 24).
2. Select or specify materials to be used in the trial pavement from among those available locally (box 21).
3. Select a trial structural section, that is, the thicknesses of the component layers (box 22).
4. Select the physical states of the pavement structure that are anticipated in service and that are to be used in the design process (box 23). A physical state is that which corresponds to given moisture and temperature profiles or an equivalent representation thereof. If the physical states of the pavement are properly defined, regional effects as influenced by climatic conditions may be properly considered in the design.
5. Estimate the future traffic that is anticipated while the pavement is within each distinct physical state during the entire design life (box 52).
6. Characterize the deformability, that is, the stress-strain response, of the trial materials either by direct laboratory testing (box 41) or by comparisons with prior testing of similar materials (box 33).
7. Estimate the levels of critical stresses or strains or both in the pavement structure that result from the application of each traffic load while the pavement is in each physical state (box 51).
8. Establish simple failure criteria, that is, the number of load applications causing fatigue failure for each of all possible combinations of traffic loads and pavement states (box 50). That is a somewhat complex process and may entail any or all of the following: laboratory fatigue testing of bituminous materials (box 40), comparisons with prior laboratory fatigue testing of similar bituminous materials (box 32), evaluation of failure criteria developed by others (box 31), analysis of the performance of in-service pavements (box 30), and selection of a suitable level of terminal serviceability, that is, definition of failure (box 20).
9. Estimate the accumulation of fatigue damage in the trial pavement (box 60) under the anticipated design loading (box 52) by suitably comparing the estimated history of stress or strain or both (box 51) with the simple failure criteria (box 50).
10. Determine the acceptability and optimality of the trial pavement and, if necessary, modify the materials or structure or both of the trial pavement and iterate (boxes 70 and 71).
11. Examine all other failure modes (box 80).

That design process may be viewed by pavement designers as excessively long and complex when it is compared with many of the more conventional procedures. However, after the methodology has been developed, routine designs can be accomplished with ease. Simple charts or nomographs can often be used to depict design relations, and, if desired, laboratory and field testing can be minimized.

DESIGN DETAILS

In many respects, bituminous pavements are extremely complex structures. That is partly due to the extensive influence of the climatic environment on pavement response to traffic loading. The stiffness of the bituminous layers is strongly dependent on pavement temperature. Also the mechanical response of many subgrade soils is influenced by prevailing moisture and temperature conditions. During its life in service, a pavement undergoes continual fluctuation in its temperature and moisture profiles. Analyses of pavement structures, such as those described here, are made tractable only by classifying all environmental conditions into a limited number of discrete categories or states. The subscript j will be used hereinafter to represent the jth physical state of the pavement that corresponds to a particular set of moisture and temperature conditions within the structure.

In a similar way, the continuum of traffic loads is best treated in analyses such as these by all loads being classified into a limited number of discrete categories. For highway vehicles, that classification is normally based on axle type, for example, single or tandem, and on axle load. The subscript i will be used hereinafter to represent a traffic load of the ith type or category.

Analysis of fatigue is based on the concept that each load application induces in the pavement irrecoverable damage and that, under load repetitions, such damage continually accumulates until such time that the pavement fails, that is, is no longer serviceable. In the phenomenological approach to fatigue analysis, damage is represented by a simple fraction (or percentage). The pavement is said to fail in fatigue when the cumulative damage under repetitive loading reaches 1.0 (or 100 percent). Failure may be defined in many ways, such as the point of fatigue-crack initiation or the point at which cracking has progressed to a given extent. In any case, the damage at failure is considered to be complete, that is, 100 percent.

Immediately following are discussions of some of the details of fatigue analysis and design. For clarity of presentation, the discussion proceeds in reverse numerical order with respect to the design sequence shown in Figure 1.

Evaluation and Decision

The evaluation phase consists of fatigue life estimation, that is, estimation of the cumulative damage that is induced in the trial pavement by the loading anticipated during the design life (Fig. 1, box 60). A structurally efficient pavement is one in which the cumulative damage during the design life is estimated to be exactly 1.0. Normally, in analyses of bituminous pavements, no allowance is made for a factor of safety.

Let d_{ij} be the damage induced in the pavement by 1 application of the ith load while the pavement is in the jth physical state. If that particular load is repetitively applied to the pavement in that state until the pavement fails and if N_{ij} represents the number of applications before failure, then d_{ij} can be estimated in the most simple way as follows:

$$d_{ij} = \frac{1}{N_{ij}} \tag{1}$$

Because both the magnitude of traffic loads and the physical state of the pavement continuously vary for in-service pavements, N_{ij} cannot be measured directly. Hence, it is an estimated or a derived quantity that is usually related to the level of applied strain ϵ_{ij}.

The traffic forecast (Fig. 1, box 52) yields an estimation of n_{ij}, the predicted number of applications of load i on the pavement in state j during the design life. The total cumulative damage D predicted during the design life is then

$$D = \sum_j \sum_i d_{ij} n_{ij} = \sum_j \sum_i \frac{n_{ij}}{N_{ij}} \tag{2}$$

[Equation 2 must be slightly modified when it is necessary to consider the transverse distribution of traffic loads across the pavement, that is, the degree of channelization. Such a consideration is thought to be unnecessary for highways but is an absolute necessity for airfield pavements (5, 39)]. Failure occurs if D equals or exceeds 1.0. Equation 2 represents the well-known hypothesis of linear summation of cycle ratios, also called Miner's hypothesis. It is the basis for the current design procedures of the Portland Cement Association (34) and has routinely been used in the design of aircraft structures (15). More important, all current design procedures for bituminous pavements that are based on the phenomenological approach use Miner's hypothesis. A limited laboratory investigation of bituminous materials has indicated the validity of Miner's hypothesis under randomly varied loads when the physical state is held constant (7). Recent laboratory work at the University of Nottingham confirms the validity of that hypothesis when the physical state is varied (43).

Equation 2 is used to estimate the damage anticipated in the trial pavement during the design life. If the damage exceeds one, the pavement is underdesigned, and the trial structure or materials or both must be modified and the process repeated (box 71). If the damage equals one or is slightly less than one, the trial pavement is accepted as a suitable design (box 70). If the damage is considerably less than one, the pavement is overdesigned and modification of the trial structure and iteration are required (box 71).

Analysis

The purpose of the evaluation phase is simply to estimate how much fatigue damage is expected to accumulate in the trial pavement during the design life. Input to that evaluation is generated in the analysis routines and consists simply of the volumes of traffic anticipated during the design life, n_{ij}, and estimates of the number of repetitions of each traffic load that would cause fatigue failure if that load were repetitively applied in the absence of other loads, N_{ij}. The usual procedure for estimating N_{ij} is (a) establish a failure criterion that relates the number of repetitions to failure N with some critical strain ϵ induced in the pavement and perhaps with other variables such as temperature, (b) estimate the critical strains ϵ_{ij} in the pavement induced by various loads under different physical states by means of analytical simulation, and (c) determine N_{ij} by combining the output of the 2 prior analyses. That procedure is summarized in subsequent sections after a brief discussion of traffic estimation.

Future Traffic (Box 52)

Obtaining an estimate of n_{ij} can be tedious and time-consuming, but it is one of the most critical portions of the fatigue-design process. Detailed procedures are described elsewhere (44), and it is only necessary here to emphasize a few relevant points.

Design is usually based on conditions at a critical location on a highway or airfield. For multilane highways, that is normally the outside lane that carries larger volumes of damaging truck traffic. There may also be a significant difference in the direction of travel along a particular route. Thus, detailed information is necessary on lane and directional distributions of the highway traffic. For airfields, the critical location is most frequently a taxiway servicing the most heavily used runways. In any case, the estimate must be based only on that volume and character of traffic traversing the critical or design location.

Design for fatigue can be accomplished equally well by treating the basic loading patterns directly or by expressing the relative destructive effects of different loads

and configurations in terms of repetitive equivalency factors. Considerable effort, both empirical and theoretical, has been directed to the establishment of applicable load equivalency factors for highways (6, 21, 29, 37) and airports (5, 39). Expressing the destructive effects of a wide spectrum of traffic loads in terms of equivalent repetitions of a standard or base load greatly simplifies the analytical process (box 51) and enables simplified presentation of design relations in a conventional manner.

It is important to recognize that traffic estimates must be related to the physical states of the pavement. If the physical state is represented by average annual conditions, that is a simple task. However, if other more precise representations of the physical states are used, then typical monthly and perhaps even daily fluctuations in traffic volumes must be recognized (27).

Care must be taken to avoid a priori assumptions as to the potential significance of certain traffic loads, for example, the steering axles of trucks and the nose gears of aircraft. For identical loads, a steering axle (single tires) has been found to be approximately 3 times more destructive in fatigue than a conventional single axle (dual tires) (6). Although the total loads on steering axles are usually smaller than those on other axles, steering axles can potentially contribute in a significant way to the total accumulation of fatigue damage.

Procedures for estimating n_{ij} are no different from those required in many current design methodologies with the exception that the volumes may need to be classified according to the physical states of the pavement. Other traffic information may be required, however, including items such as speed, tire inflation pressures, and average distances separating various tires and axles.

Computation of Critical Strains (Box 51)

After the traffic loads, that is, the categories designated by i, have been identified, it is necessary to estimate the critical strains ϵ_{ij} in the pavement. Those strains are combined with the failure criterion (box 50) to obtain estimates of N_{ij}, the remaining set of unknowns in Eq. 2.

Critical Strain

Under conditions of constant air-void and asphalt contents, the determinant of fatigue failure is the maximum principal tensile strain (32). When the bituminous-bound layer of a pavement behaves as a structural slab and is of sufficient thickness, that strain occurs at the underside of the bound layer. Therefore, for normal pavements, the critical strain for fatigue design is the maximum principal tensile strain at the bottom of the bound layer.

Method of Structural Analysis

Methods for the structural analysis of layered systems are described elsewhere (45). The simplest of those, in which the pavement is represented by a linearly elastic, multilayered structure of semi-infinite extent, has been found to reasonably approximate the behavior of bituminous pavements (16) and is readily available in the form of computer software (33, 38) or graphical representation (18, 31). To compute the maximum principal tensile strain in the bound layer requires that each layer of the pavement be characterized by its thickness, modulus of elasticity, and Poisson's ratio.

A structure consisting of bituminous surface and base courses, unbound granular base, and subgrade is usually characterized as a 3-layer system. If there is a thermal gradient in the bound layers, the average temperature is used to derive a suitable modulus of elasticity to represent the composite behavior of the bound layers. Likewise, average moduli may be used to represent the behavior of the base and subgrade layers. A more refined analysis is made possible by representing that same structure by more than 3 layers. That results in a more accurate estimation of stresses and strains at the cost of added analytical complexity. For purposes of routine design, a 3-layer representation is thought to be sufficiently accurate.

The moduli of some materials, most notably unbound granular bases, has been found to depend on the level of applied stress. Unfortunately, the level of applied stress is unknown before the analysis. To consider such a situation, one may use an iterative solution of the multilayered elastic system (26). Such a refinement is highly desirable for research, investigative, and developmental purposes but may be of lesser consequence for routine design procedures.

Critical tensile strains ϵ_{ij} must be computed for a relatively large number of traffic loads i when applied to the trial pavement under a relatively large number of physical states j. That can lead to a formidable number of computations. The burden can be eased substantially by the use of repetitive load equivalency factors that make it necessary to compute only those strains resulting from the standard or base load. Another means for expediting the computations is to make extensive use of interpolation techniques (5). Finally, regression techniques may be used to expand a limited number of computed strains to a much more extensive set. Witczak quite successfully used such a technique in his analysis of 2-layered, airfield structures (39).

Traffic Loading

Readily available computer solutions of the elastic, multilayer system employ a tire load that has a circular contact area and a uniform contact pressure and is applied in a direction normal to the pavement surface. The contact pressure is most often assumed to equal the hot, tire-inflation pressure. Impact loading is seldom considered in the design.

Multiple tires in close geometrical proximity can be accurately represented in the analysis. However, a common practice is to approximate the effects of multiple tires through the use of an equivalent single tire. That and similar procedures can lead to erroneous results (6) and should not be used without independent validation.

Establishment of Failure Criterion (Box 50)

The failure criterion is simply a relation between the maximum principal tensile strain ϵ in the bound layers of the pavement and the number of applications N of that particular strain level causing failure by fatigue. (The failure criterion describes the situation that would result if only one strain level were repetitively applied until the pavement failed and if the physical state of the pavement did not change during that load history. Multiple strain levels, caused by varying loads and varying physical states, are analyzed by means of Miner's hypothesis.) All investigators have assumed that the ϵ-N relation is linear on a log-log plot. Such a linear relation has been verified repeatedly from laboratory testing (24).

The failure criterion can be established in at least 4 different ways: from theoretical analysis of existing design curves; from an analysis of the performance of in-service pavements, particularly road tests operated under rigid control (box 30); from laboratory fatigue testing (box 40); and from a combination of the procedures given above.

Failure Criterion From Existing Design Curves

Existing design curves, in which the destructive effects of traffic are represented by equivalent axle loads, offer one means for establishing a failure criterion. The design curves are examined to determine one or more pavement sections that are considered adequate for each of several equivalent axle loads. The tensile strains imposed by the standard or base load in those representative structures are then estimated by elastic, multilayered theory. Average environmental conditions in the region for which the design curves are applicable are used to establish representative elastic parameters for the materials in the sections. The computed tensile strains are finally related to the number of load applications to establish the failure criterion. A failure criterion recently proposed by Deen et al. (8, 9) was derived in part from an analysis of existing design curves.

That method for establishing a failure criterion is particularly attractive because of its inherent simplicity and the fact that it results in designs that are fully compatible with an established history of design and performance experience. At the same time, there are several noteworthy drawbacks. First, the failure criterion can be applied with confidence only in geographical areas that have climatic conditions similar to those of the region for which the original design curves were applied. Second, a one-physical-state representation of the structure must be used in the design process. That presents difficulties if the seasonal and daily variations in future traffic volumes are anticipated to deviate significantly from average, region-wide patterns. Third, and most important, that method requires that the original design curves be based solely on the control of failure by fatigue. Most existing design curves consider all distress mechanisms simultaneously. They can be used properly only if conditions can be isolated in which fatigue is the predominant distress mode. Finally, designs that would incorporate new and different types of bituminous mixtures cannot be examined with such a criterion.

Failure Criterion From In-Service Pavements

In-service pavements for which detailed records of traffic and performance have been accumulated offer perhaps the best current base for establishing a failure criterion. Accelerated road tests are particularly useful because of their extensive data base and the controlled nature of those experiments. Accuracy can be improved by laboratory or field testing to determine the elastic parameters of the materials. In addition, analyses can be limited to those test sections known to have failed by fatigue, thereby ensuring that the failure criterion is relevant to the distress mechanism of interest.

If an average annual characterization of the physical state of the pavement is to be used, the analysis proceeds much as before. For a single pavement state, Miner's hypothesis requires that, at failure,

$$\sum_i \frac{n_i}{N_i} = 1 \tag{3}$$

The conventional form of the failure criterion relates N_i to ϵ_i as follows:

$$N_i = k_1 \epsilon_i^{k_2} \tag{4}$$

Combining Eqs. 3 and 4 results in the following equality:

$$\sum_i \frac{n_i}{k_1 \epsilon_i^{k_2}} = 1 \tag{5}$$

For each test section of the road test, n_i is known from the history of load applications, ϵ_i can be computed by elastic, multilayered theory, and the elastic parameters are evaluated under average environmental conditions. (Often only 1 type and magnitude of load is applied to each test section. Equation 5 thus becomes $n = k_1 \epsilon^{k_2}$.) An equation similar to Eq. 5 is, therefore, available for each test section. That set of equations can be solved for the unknowns k_1 and k_2 to complete the derivation of the failure criterion.

Improved accuracy can be achieved if due recognition is given to the varying nature of the physical states of the pavement during the test. In this case, Miner's hypothesis at failure is

$$\sum_j \sum_i \frac{n_{ij}}{N_{ij}} = 1 \tag{6}$$

The failure criterion must incorporate the effect of the stiffness of the bituminous mixture on the ϵ-N relation. The generalized form of such a criterion as used by Witczak (39) is

$$N_{ij} = k_1 \epsilon_{ij}^{k_2} E_j^{k_3} \tag{7}$$

in which E_j is the modulus of elasticity of the bituminous mixture when the pavement is in the jth physical state. Constants k_1, k_2, and k_3 can be evaluated by Eqs. 6 and 7 being combined as follows:

$$\sum_j \sum_i \frac{n_{ij}}{k_1 \epsilon_{ij}^{k_2} E_j^{k_3}} = 1 \tag{8}$$

Again n_{ij} is known from the loading history on the test section, and ϵ_{ij} is estimated by elastic, multilayered theory. Evaluation of the resulting set of equations yields suitable estimates of k_1, k_2, and k_3.

The primary disadvantage of a failure criterion so derived is that it is applicable only to the type of bituminous mixture employed in the road test. The failure criterion used by Witczak (39) and developed by Kingham (20) was based on analyses of AASHO Road Test data.

Failure Criterion From Fatigue Testing

A failure criterion can be readily developed from laboratory fatigue testing of the bituminous mixture. Monismith and McLean (27) are among those successfully using such an approach. Test specimens are subjected to repeated flexing until failure, and the ϵ-N relation is determined directly. Laboratory testing is the best way in which the behavior of new and different bituminous mixtures can be accounted for. However, there are several serious obstacles to the use of laboratory-derived failure criteria in routine design. Several of these are noted below.

1. One of the major difficulties is that of defining failure in the laboratory in such a way as to be compatible with failure as defined for the in-service pavement. Brown and Pell (4) suggest that in-service pavement life (applications to failure for a given strain level) is of the order of 20 times the life of a test specimen in the laboratory. Thus, perhaps the best that can currently be achieved with laboratory-derived failure criteria is to obtain an estimate of crack initiation in the in-service pavement. Few techniques are available for quantitatively estimating the progression of cracking in a pavement or for considering varying levels of terminal serviceability.

2. Laboratory fatigue specimens are conventionally subjected to either of 2 types of repetitive loading: controlled-stress or controlled-strain, depending on whether stress (load) or strain (deflection) is controlled during testing. Unfortunately, the number of load applications to failure is extremely dependent on the type of test. It has been hypothesized that in-service pavements are subjected to a type of loading intermediate between those 2 types and that controlled-stress and controlled-strain loadings merely represent end points of an infinite spectrum of possible modes of loading (24). In the absence of suitable means for defining and applying intermediate modes, the problem of which form of laboratory testing to use in design procedures will continue to exist. [Pell (43) gives a discussion of the effect of test type and design recommendations.]

3. Laboratory testing requires selection of a frequency of loading, which is greater than that normally encountered by a pavement in service, and, for pulsating loads, a load duration. Those as well as other laboratory loading variables significantly affect the number of applications to failure. The possibility that rest periods can beneficially alter fatigue response is another variable complicating use of laboratory-derived failure criteria (2, 35).

4. There are certain simplifications in the multilayered, elastic analyses that can cause a departure of predicted from actual pavement response. One of those is that theoretical analysis normally assumes the pavement to have unlimited lateral dimen-

sions and allows no lateral variation in material properties. Barksdale and Hicks (45) discuss an expanded, 2-dimensional, finite-element analysis that can approximate those effects. Complexities in the application of such an analysis probably outweigh any advantages that might accrue by virtue of its use in routine design. Thus, for example, no means are available for readily treating pavement edge support or differential subgrade moisture conditions. Failure criteria derived from in-service pavements would seem intuitively to account for those and other such discrepancies between theory and practicality.

5. Most analyses of highway pavements assume perfect tracking of vehicles; that is, they do not treat the transverse or lateral distribution of vehicle placement. That simplifying assumption may lead to erroneous results if laboratory fatigue criteria are used.

Summary

The most critical component of the fatigue design methodology is establishment of a failure criterion. Unfortunately, no universally acceptable means for establishing such a criterion has been developed. Possibly a combination of methods that uses laboratory testing to establish the behavior of individual mixtures together with analyses of in-service pavements to establish an appropriate definition of failure will evolve as the optimal technique.

At the same time, numerous failure criteria have been established and used by individual investigators. Some of those are shown in Figure 2. The ϵ-N relation is dependent on the modulus of elasticity of the bound materials [the one exception is that used by Brown and Pell (4)], and a smaller number of applications of a given strain level can be tolerated when the mixture has a higher modulus such as during periods of low temperature. Each of the criteria shown in Figure 2 may be adequate in the situation for which it was derived. At the same time, none has universal applicability. They are simply available to be subjected to the test of time as they are applied to the future design of in-service pavements.

Finally, a specific failure criterion can be applied with confidence only if methods used in derivation of that criterion are similar to those used in the design process. That means that methods for characterizing materials, methods for calculating the response of the pavement structure to load, and methods for classifying the physical states of the structure must not be allowed to vary. That caveat is especially important when one uses a failure criterion developed by other investigators. It also casts serious doubts on the practice of using a 1-state pavement representation (average annual conditions) and failure criteria derived from laboratory testing. There is simply no justification for assuming that damage will accumulate under the 1-state simplification in the same manner as it actually accumulates under the varying temperature and moisture conditions of the in-service environment.

Application

The purpose of the analysis phase is to generate estimates of n_{ij} (the number of applications of each traffic load anticipated during the design life while the pavement is in the jth state) and N_{ij} (the number of applications of each traffic load that would cause fatigue failure in the pavement if that load were repetitively applied in the absence of other loads while the pavement is in the jth state). Analyses of existing and projected traffic data yield estimates of n_{ij}. Strains ϵ_{ij} induced in the pavement by the traffic loads are first determined before N_{ij} is estimated. Those strains together with the failure criterion (ϵ-N relation) are used to estimate N_{ij}.

Testing

The analytical routines require, as input, knowledge of the elastic parameters (modulus of elasticity and Poisson's ratio) associated with each material in the pavement structure. In addition, knowledge of the fatigue behavior of the bituminous mixture

Figure 1. Design process.

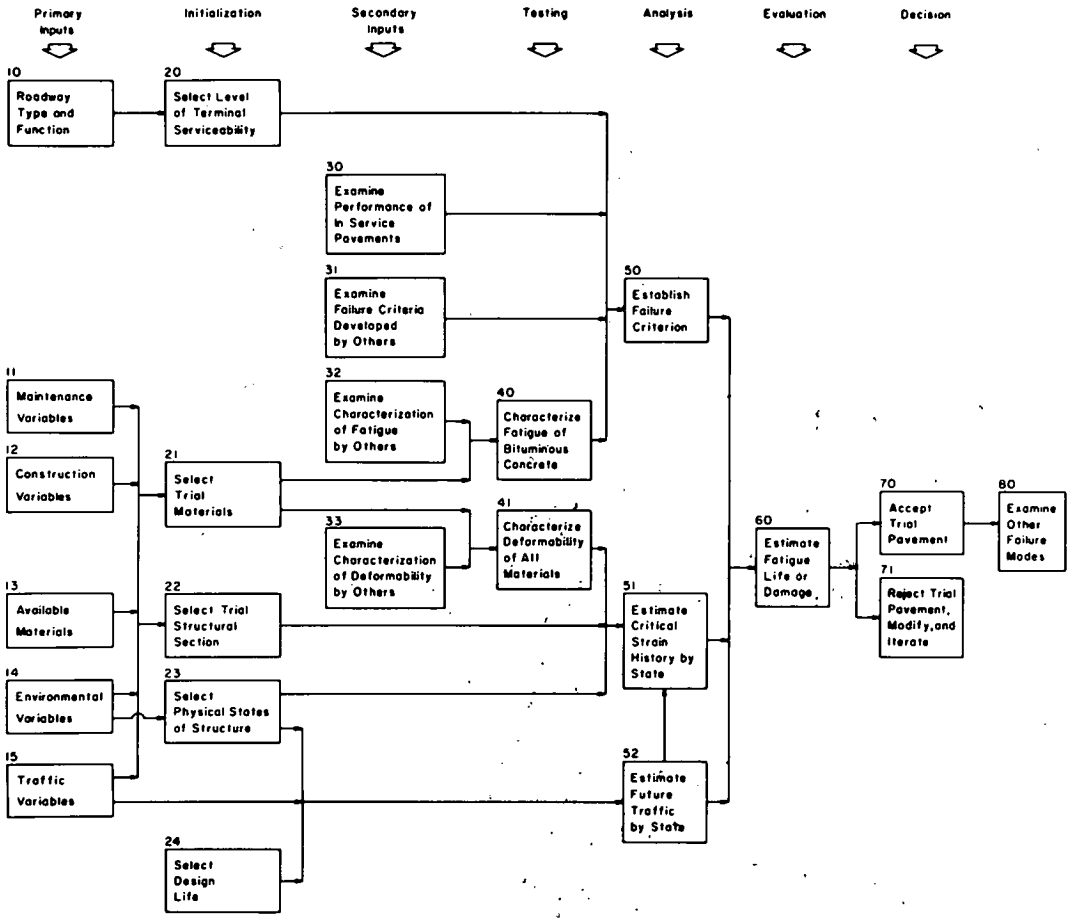
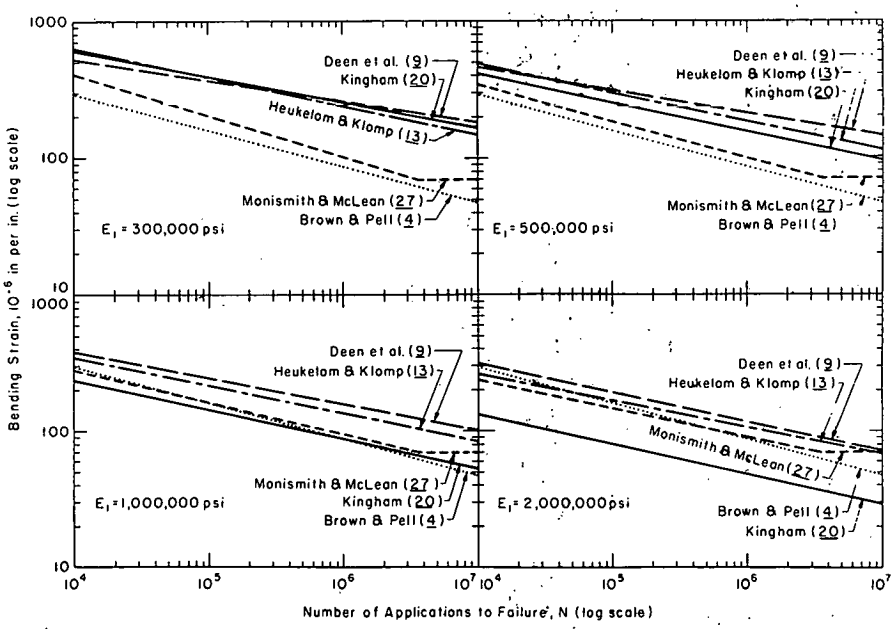


Figure 2. Failure criteria.



under simple laboratory loading conditions may be necessary in the development of a failure criterion. Characterizations of those material responses can, in some instances, be based solely on prior analyses and testing (boxes 32 and 33). [Barksdale and Hicks (45) point out some of the difficulties attendant to the use of deformability characterizations developed by others.] In other instances, such as when new materials are being considered, it may be necessary to evaluate material response by laboratory or field testing.

Detailed procedures for laboratory testing are described elsewhere (43, 45). It is necessary to emphasize, however, that laboratory testing variables, especially those associated with loading, must simulate, to as large a degree as possible, in-service pavement conditions. Nair et al. (28), for example, conclude that asphalt concrete may be characterized as a linear isotropic elastic material for purposes such as fatigue analysis and design. In so doing, however, the elastic parameters must reflect the in-service pavement conditions to adequately account for time of loading, temperature, and stress dependencies.

Physical States

One aspect of the design process shown in Figure 1 deserves additional mention, and that is the selection of the physical states of the structure. The deformability and strength properties of materials within the pavement vary continuously with time in response to environmental factors that alter the moisture and temperature profiles. One approach to that problem is the 1-state representation that uses average, effective, or critical elastic parameters or all of those to analyze structural behavior.

In adopting that approach, Deen et al. (8, 9) found that the average temperature of the bound layers in Kentucky pavements was 64 F. A modulus of elasticity of 480,000 psi, which for the type of mixtures used in Kentucky corresponds with this average temperature, was used in the analytical routines. The subgrade modulus, on the other hand, was a critical modulus evaluated from a soaked laboratory CBR value. That same representation was used both in the development of design relations and in the derivation of a failure criterion largely from an analysis of existing design curves.

Dormon and Metcalf (11) also consider that pavement behavior may be effectively analyzed by means of a 1-state representation. Deformability and strength characterizations of the bituminous layers are based on use of an "effective" temperature, the determination of which requires analysis of the effects on fatigue life of yearly temperature variations for a number of hypothetical pavements. Based on their analysis, a temperature of 50 F was recommended for use in design.

The 1-state representation of in-service pavements is advantageous largely because of its simplicity. No major fault can be found with that procedure as long as the same pavement representation is used both in the analytical routines and in the development of a failure criterion. Difficulties can be anticipated, however, with the use of average parameters if the failure criterion is derived from laboratory fatigue behavior or from evaluations of in-service pavement performance in other geographic regions.

Monismith and McLean (27) have employed a more complex and presumably more accurate representation of in-service pavement conditions by defining 288 physical states. Each state is representative of conditions in a typical hour (for example, 1:00 to 2:00 p.m.) during a given month. The 288 states are probably somewhat optimal for using a laboratory-derived failure criterion. The surface modulus varies for each of the 288 hours as a function of the pavement temperature. Theoretical techniques for estimating pavement temperatures are readily available (23, 27). The subgrade modulus can be varied monthly to reflect seasonal changes in subgrade support due, for example, to frozen conditions in the winter months. Witczak (39) has demonstrated how a varying subgrade modulus can be treated. In addition, seasonal and daily variations in traffic volumes can be most effectively handled.

Determination of how best to categorize the physical states of a pavement is a complex task. Some important considerations that affect the choice include

1. The nature of the failure criterion that is to be used,

2. The availability of techniques for estimating the temperature profile within the bound layers (44) and the relation between modulus and temperature,
3. The availability of techniques for estimating the changes in subgrade modulus with season (44),
4. The nature of the anticipated cyclic variation in traffic volumes, and
5. The desire for simplicity.

Fatigue Distress and Pavement Serviceability

The surface manifestation of fatigue distress is patterned cracking. Such cracking combines with surface manifestations of other distress mechanisms such as thermal cracking, distortion, and disintegration to determine the serviceability of the pavement. Hudson et al. (17) have proposed a technique for defining serviceability whereby weighting functions are used to represent the contribution of each distress manifestation to a reduction in pavement serviceability. If that technique were implemented, pavements could be designed to provide any desired level of terminal serviceability.

To implement such a technique from the standpoint of fatigue distress requires the ability to estimate the extent of fatigue cracking. In theory, that would be a simple task if coupling effects among the various distress modes could be justifiably ignored and if a separate fatigue failure criterion were available for each degree of surface cracking. Unfortunately, few failure criteria are currently available that relate to the extent of surface cracking. McCullough et al. (22) have recently demonstrated an ability to estimate cracking index, a measure of the extent of surface cracking, for 2 AASHO Road Test sections as a function of load history. However, future analyses of in-service pavements, such as the AASHO Road Test, should allow the derivation of suitable failure criteria that incorporate the extent of surface cracking. It seems highly improbable that failure criteria incorporating the extent of surface cracking can be developed from phenomenological analyses that use laboratory test data alone. That is further justification for developing failure criteria on the basis of in-service pavement performance rather than on the singular basis of laboratory test data.

CONCLUDING REMARKS

Well-documented methods, based on a blending of analytical skills and empirical evaluations, are currently available for the design of bituminous pavements to control fatigue distress (41, 42). Like other existing design methods, those methods are not perfect and almost certainly will be improved by future modification. Unlike most existing design methods, however, they have the following capabilities:

1. To treat new types of traffic loading for which little or no historical experience exists,
2. To analyze new types of pavement structures such as full-depth construction,
3. To extrapolate from portions of design curves reasonably well-established by extensive empirical validation to portions for which little or no verification has been possible,
4. To examine new materials to ascertain their effects on pavement performance and to seek ways for better use of existing materials,
5. To provide a rational way for explaining regional differences in pavement performance due to climatic variations and to account for those variations in design, and
6. To enable a proper interpretation of the performance of prototype and road-test pavements.

To fully incorporate all of those extended capabilities into the design process requires a degree of sophistication and complexity uncommon to most current design procedures. However, application of the fatigue-design methods discussed here for routine use need be no more difficult or time-consuming than most current design procedures. Laboratory testing, in excess of that normally undertaken, need not be required. Furthermore, use of the computer need not be required because conventional forms of design charts or nomographs can be and have been developed.

Selected techniques for fatigue-life estimation, on which these design methods are based, are summarized here. Elastic, multilayered analysis provides an acceptable means for estimating critical tensile strains in a pavement structure under realistic traffic loads. Those tensile strains have been found to be the basic cause or determinant of fatigue damage. Accumulation of fatigue damage under varying loads and environmental conditions can be effectively estimated by means of Miner's hypothesis. Proper characterization of the physical states of the pavement structure is essential to the development and application of a fatigue-design methodology and is the primary means of accounting for environmental effects. The burden of computations can be eased substantially by use of repetitive load equivalency concepts and regression and interpolation techniques.

Two particularly crucial aspects of fatigue-life estimation are the development of a suitable failure criterion and the evaluation of elastic material properties. For purposes of routine design, failure criteria derived from an analysis of the performance of in-service pavements would appear to be most suitable at this time. Those criteria reflect the effects of both strain level and modulus of elasticity on the number of load applications causing fatigue failure. Similar methods of materials characterization, physical-state representation, and analysis must be employed both in the development of the failure criterion and in its application to design. Elastic material properties can be evaluated either by laboratory testing or by use of previously published and readily available data.

Capabilities exist for estimating future traffic and environmental variables as input to the design process. However, those capabilities are in need of continual extension and refinement. The impact of maintenance and construction variables on pavement performance has not yet been quantitatively assessed.

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