Development of a Thickness Design System for Portland Cement Concrete Pavements

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Mr. R. E. Johnson
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Federal Highway Administration
330 West Broadway
Frankfort, Kentucky 40601

Dear Mr. Johnson:

Subject: Implementation Statement
Kentucky Research Project KYHPR 75-77
Research Report UKTRP 83-5
Development of a Thickness Design
for Portland Cement Pavements

The proposed Kentucky design procedure contained in this report combines the empirical from the original AASHTO design procedure and the Portland Cement Association's procedure with Kentucky's experience.

After the completion of this study, a proposed AASHTO design guide was disseminated. In view of this, it was decided by the Department's engineers that a decision on implementing the Kentucky design procedures should be delayed until a comparison could be made with the new AASHTO design guide. As a result, a comparison is being done as a Quick Response Study, KYHPR 85-108, Subtask 10, COMPARISON OF RIGID PAVEMENT DESIGN METHODS.

Upon completion of the Quick Response Study, a decision will be made as to implementation of the proposed Kentucky design procedures.

Very truly yours,

R. K. Capito, P.E.
State Highway Engineer
Research Report
UKTRP-R3-5

DEVELOPMENT OF A
THICKNESS DESIGN SYSTEM
FOR PORTLAND CEMENT CONCRETE PAVEMENTS

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February 1983
This report covers the merger of criteria used in the Portland Cement Association's and AASHTO's pavement thickness design systems. The combined criteria is coupled with the principle of equal work as defined in classical physics to produce thickness design curves for portland cement concrete pavements. The thickness of portland cement concrete varied by approximately 0.15 inches for the same CBR and design EAL when the thickness of crushed-stone base varied from 3 to 6 inches. Therefore, the design thickness of the portland cement concrete is relatively insensitive to changes in thickness of the crushed stone base.
INTRODUCTION

One aspect of pavement design is the selection of the thickness of the pavement and its various components sufficient to support vehicular loadings and to transfer those loadings through successive layers of the pavement --- surface, base, and subgrade --- to the soil on which the pavement rests. If the load is excessive or if the supporting layers are not sufficiently strong, repeated applications of the vehicular loadings will cause rutting and cracking that ultimately lead to a complete structural failure of the pavement. The structural design scheme suggested in this report provides a procedure by which the load-carrying capabilities of a portland cement concrete slab and of the soil upon which the slab rests are not exceeded.

Generally, pavements often are referred to as rigid (portland cement concrete) or flexible (asphaltic concrete), depending upon pavement stiffness relative to the subgrade. This distinction became artificial as the magnitude and frequency of loads became greater and as pavements correspondingly became thicker and stronger.

The primary difference between types of pavements is the manner in which they distribute vehicular loads to the subgrade. A portland cement concrete pavement, because of its high modulus of elasticity for all ranges of temperature, tends to distribute the load over a relatively large area, and a major portion of the structural capacity is provided by the slab itself. As a result, a major factor in the design of portland cement concrete pavements is the structural strength of the concrete. Uniformity of support is also a major factor, but minor variations in subgrade strength have little influence upon the structural capacity of the pavement.

The load-carrying capacity of asphaltic concrete pavements derive from the load-distributing characteristics of a layered system. Such pavements may consist of a series of layers, or a single layer, with the strongest materials typically at or near the surface. The strength of such pavements lies in the buildup of layers to distribute the load over the subgrade. The design thickness of the pavement is influenced appreciably by the strength of the subgrade.

To determine the thickness of a portland cement concrete pavement from design charts and tables, it is necessary to know only the EAL's (equivalent axleloads) and the CBR (strength) of the subgrade. Normally, traffic volumes are estimated in connection with needs studies and in the planning stages for all new routes and for major improvements of existing facilities. Whereas the anticipated volume of traffic is an important consideration in the geometric design of a highway facility, composition of the traffic stream in terms of axle weights and lane distributions is essential to the structural design of pavements. Traffic volumes used for EAL computations should therefore be reconciled with other planning forecasts of
traffic. Even though predictions of traffic volumes may be reasonable, estimates of EAL's are also dependent upon predictions of vehicle types and loadings over the design life.

Computation of EAL's involves estimates of the total number of vehicles during the design life and of multiplying factors for various vehicle types, loading configurations, and loads to convert traffic volumes to EAL's. Ideally, yearly increments of EAL's could be calculated and summed. This approach would permit consideration of anticipated changes in legal weight limits, changes in styles of cargo haulers, and changes in routing.

The first set of thickness design curves, for asphaltic concrete pavements, for use in Kentucky (1) was developed in 1948. Extensive laboratory tests of soils were performed using several methods, and the CBR method was chosen as the basis for evaluating soil strength. Performance correlated best with minimum laboratory CBR's. Traffic histories were estimated for the pavements. Those pavements with approximately the same traffic histories were grouped, total pavement thickness was plotted versus CBR, and data points were coded "good" or "bad", depending upon the performance of the pavements. Best-fit curves were drawn to separate the failed from the unfailed. The 1948 curves were based on failure boundaries and performance envelopes.

By 1957, a need to update the 1948 curves and to extend the curves to increased traffic loadings became apparent. Another extensive series of field tests and analyses resulted in the 1959 Kentucky design curves (2). Those curves were in use prior to the AASHO Road Test, were verified by field tests, and had precedence over the AASHO thickness design system that was developed later.

By the mid-1960's, computers had been developed with enough sophistication, speed, and memory capacity to permit the development of the Chevron N-layer program to analyze pavements using elastic theory (3). Using that program, the 1973 Kentucky design curves for asphaltic concrete pavements (4) were prepared. Experience confirmed the design curve for pavements with 1/3 of the thickness being asphaltic concrete and 2/3 being dense-graded aggregate. Based upon elastic theory, thickness curves were created for other proportions. Experimental pavements were designed, constructed, and tested beginning in 1971. Field test data have been matched with theoretical solutions and have confirmed both thickness curves and the method of estimating pavement fatigue caused by traffic loadings.

Design curves and procedures reported in 1981 (5, 6) for asphaltic concrete pavements for application specifically to Kentucky conditions evolved over several decades. Design curves have been refined and updated and correlated with a broad range of field experience and theoretical analyses.

A similar background and history of design guides for portland cement concrete pavements in Kentucky is yet to be developed. Historically, and currently, portland cement concrete pavements have been designed using the Portland
Cement Association's method (7) or the method derived from the AASHO Road Test (8). For many years, it was felt that construction procedures would not permit small increments of thicknesses of portland cement concrete pavements. Thus, comparable designs of portland cement concrete and asphaltic concrete pavements specifically for the Kentucky environment may not have resulted.

Design curves and procedures reported herein have been developed using concepts and analyses similar to those used to produce the asphaltic concrete design curves. Additionally, the analyses have been refined, based on work-strain concepts, and curves presented in this report reflect a first approximation of performance experience of portland cement concrete pavements in Kentucky. Because of the similar bases for development, comparable designs for the two generic types of pavements now can be achieved with confidence.

ELEMENTS OF DESIGN PROCEDURE

SUBGRADE SUPPORT

Several procedures were utilized in a 1948 testing program to evaluate the load-carrying capacity of the subgrade and consisted of plate bearing, North Dakota cone, in-place CBR (California Bearing Ratio), and soaked laboratory CBR tests. The best correlations of pavement performance were with the soaked laboratory CBR (1), which differs from the ASTM method in one aspect. ASTM specifies the sample be soaked for three days (9); the Kentucky method allows soaking until swelling ceases. The soaked CBR was the basis for the 1959 curves (2) and still is the basis for the 1981 curves for asphaltic concrete pavements (5). Correlations have been made with the AASHTO soil support scale (10) and with elastic moduli on the basis of field test data and the Chevron N-layer computer program. A literature review (11, 12) indicated that the elastic modulus of clay soils could be estimated from laboratory tests by

$$E = 1500 \times CBR,$$

in which $CBR =$ value of California Bearing Ratio obtained by the Kentucky procedure and $E =$ elastic modulus of the subgrade.

Research indicates the factor "1500" is reasonably valid for clays, but possibly should be different for sands, gravels, rock, etc. Thus, the factor "1500" may be modified and a new scale fitted, but design thicknesses based upon elastic theory remain valid. Soil at the AASHO Road Test site was assigned a soil support value of 3.0. Samples of the soil were obtained and subjected to the Kentucky CBR test procedure. The equivalent Kentucky CBR was 5.2 (10). The same relationships have been used in the development of
thickness design curves for portland cement concrete pavements.

**CHARACTERISTICS OF PAVING MATERIALS**

**Portland Cement Concrete**

Young's modulus of elasticity for portland cement concrete may vary from 3 to 6 million psi, depending upon quality and type of aggregate, cement content, and water-cement ratio. Analyses were made using the N-layer program in which the modulus was varied over this entire range on increments of 1 million psi. Final design curves were based upon a modulus of elasticity of 4.2 million psi, which is representative of AASHTO conditions (8).

The 1956 Kentucky standard specifications (13) required the minimum expected strength of paving concrete at 28 days to be 3,500 psi in compression and 600 psi for the modulus of rupture. In 1965, the requirement for the modulus of rupture was lowered to 550 psi and then was deleted and only the compressive strength specified in 1976. The requirement for compressive strength has remained at 3,500 psi. For acceptance purposes, compressive strength has been judged as a more routinely reliable test result.

For thickness design purposes, modulus of rupture is of greater significance; therefore, a relationship between compressive strengths and thickness design strengths (modulus of rupture) is important.

The Portland Cement Association suggests that the modulus of rupture is approximately eight to ten times the square root of a concrete's compressive strength (14). For a compressive strength of 3,500 psi, the modulus of rupture would range from 473 to 592 psi. Another relationship indicates that the modulus of rupture is equal to the 0.79th power of the compressive strength. On that basis, the modulus of rupture would be 630 psi for concrete having a compressive strength of 3,500 psi. Still another relationship shows the modulus of rupture to be about 15 percent of the compressive strength (15). Derucher and Heins suggest the modulus of rupture to be 16 percent for 3,000-psi concrete and 14 percent for 4,000-psi concrete (16).

Inasmuch as quality concrete continues to gain strength with time, it may be advocated that the 90-day modulus of rupture should be used for pavement thickness determinations. Figure 1 illustrates the increase in the strengths of paving concretes at the Road Test with aging (17). It is noted that the ultimate flexural strength was approximately 800 psi. The ratio of 90-day strength to 28-day strength is approximately 1.10 to 1.14. For 28-day compressive strengths of 3,500 psi, the 90-day modulus of rupture would range from 496 to 632 psi. It is noted from Figure 1 that the 28-day compressive strengths at the Road Test were approximately 4,500 psi. Current practice for the design of portland cement concrete pavements indicates the modulus of rupture to range from 600 to 750 psi (18).

It has been suggested that the modulus of rupture of concrete can be approximated by dividing the modulus of
Figure 1. Increase in Compressive and Flexural Strengths with Time for AASHO Road Test Pavement Concrete.
elasticity by a factor varying from 6170 to 6535 (19). For a modulus of elasticity of 4.2 million psi, the modulus of rupture would range from 643 to 681 psi. It has been reported (20) that the coefficient of variation of the modulus of rupture for most concrete paving projects is approximately 10 to 15 percent. Using this variation, the modulus of rupture could range from 547 to 783 psi.

Figure 2 illustrates relationships between tensile strain at the bottom of a portland cement concrete pavement and repetitions of 18-kip load equivalencies for various combinations of pavement thicknesses and moduli of rupture. Stresses and strains under an 18-kip single axleload on various thicknesses of portland cement concrete slabs were obtained using the Chevron N-layer program. For a given modulus of rupture, stresses for respective pavement thicknesses were converted to stress ratios, which, when coupled with the "Present Curve" in Figure 3 (Portland Cement Association's criterion), yield the respective number of load repetitions. Data from Figure 4 (discussed later in this report) for 5-, 6.5-, 8-, and 9.5-inch pavements at the Road Test were transferred to Figure 2. Average numbers of repetitions associated with the above pavement thicknesses were calculated. (The 9.5-inch pavement had only one data point and was eliminated for this analysis.) The average modulus of rupture was calculated for each pavement thickness, and the values were 675, 615, and 575 psi, respectively.

The use of a modulus of rupture of approximately 600 psi would seem to be reasonable, but probably conservative. There is little evidence of fatigue in portland cement concrete pavement slabs in Kentucky. There are no indications of "punch-outs" and only a few sites of longitudinal cracking in wheelpaths. Most deterioration has been observed at joints, and that involves a different mode of failure. Serviceability ratings of portland cement concrete pavements may be more indicative of conditions at joints than of slab conditions. The rationality of using a modulus of rupture of approximately 600 psi is dependent upon the use of 3,500-psi paving concrete. It is likely that higher-quality concrete is obtained on most construction projects. However, it seems that designs should be based on the more conservative quality of concrete called for in the specifications. This does mean, though, that the pavement performs during a significant portion of its life at strengths greater than the design value. This condition is paralleled in the design of asphaltic concrete pavements with the minimum laboratory CBR of the subgrade. The use of such "minimum" design parameters introduce an unknown "factor of safety." This factor of safety for asphaltic concrete pavements has been minimized in part by the correlation of pavement performance with minimum laboratory CBR. The correlation of the performance of portland cement concrete pavements with modulus of rupture of the concrete is still to be documented. As will be discussed later; the use of a modulus of rupture of 600 psi seems to allow the merger of the Portland Cement
Figure 2. Relationships between Tensile Strain and Repetitions of 18-kip Equivalent Axleloads for Combinations of Moduli of Rupture and Thicknesses of Portland Cement Concrete Pavements.

Figure 3. Portland Cement Association's Relationship between the Ratio of Working Stress to Modulus of Rupture and Repetitions of 18-kip Equivalent Axleloads to Failure.
Association's criterion and the experience of the AASHO Road Test.

Dense-Graded Aggregate

Kentucky is blessed with high-quality limestone and sandstone aggregates that may be crushed to produce a dense-graded product with very low void contents. Dense-graded aggregate has a very low tensile strength, attributable to a small amount of cementation.

The 1968 analyses of asphaltic concrete pavements assigned one modulus value to the dense-graded aggregate without regard to CBR values. Later analyses were made allowing the modulus of the dense-graded aggregate to vary as a function of the moduli of elasticity of the confining layers. Figure 5 (21) illustrates the relationship of dense-graded aggregate modulus as a function of the asphaltic concrete and subgrade moduli (CBR). Figure 6 illustrates a similar concept and relationship, but in terms of the modulus of elasticity of the portland cement concrete slab.

Design curves presented in this report assume the portland cement concrete slab is placed on a high-quality dense-graded aggregate subbase that is 6 inches thick. If designs for pavement systems incorporating other thicknesses of subbase are desired, different design curves would be required.

TRAFFIC STREAM

The traffic on a pavement is a composite of many styles and sizes of vehicles carrying a wide range of loads. Pavements fatigue under loading, whether the load is legal or not. Ignoring the existence of illegal loads results in underdesigned pavements and contributes to "premature failure."

Axle configurations and the load thereon greatly alter the rate of accumulation of fatigue by the pavement system (17). Adding axles to a given vehicle may, or may not, reduce the fatigue of the pavement. A controlling factor is the suspension system for that configuration. One that can distribute the load equally to all axles of the configuration will reduce the fatigue damage to a minimum for that number of axles. So-called "drop axles" have a high probability of causing an uneven distribution of load among the axles in the closely spaced group. If the axle is lowered so almost no load or a large portion of the load is carried by that axle, then the damage caused by the axle group will be severe compared to the equal-loading situation.

The axle configuration is significant in inducing fatigue damage caused by the total load on that vehicle. The number of tires on an axle also causes a variation in fatigue damage. Two single wide tires will cause more damage that four regular tires (22).

Through the years, the size as well as the number of trucks on the highways have been increasing. Development of the interstate system generated more traffic than was
Figure 4. Relationship between Thickness of Portland Cement Concrete Pavements and Repetitions of 18-kip Equivalent Axleloads (Using 1981 Kentucky Load Equivalency Factors) Using AASHO Road Test Data from Appendix A of Reference 17.

Figure 5. Relationship between the Modulus of the Subgrade and the Modulus of the Granular Base for Asphaltic Concrete Pavements.

Figure 6. Relationship between the Modulus of the Subgrade and the Modulus of the Granular Base for Portland Cement Concrete Pavements.
dreamed possible. Increasing the legal load limits greatly increases the rate of fatigue damage.

Traffic Stream Parameters
Traffic volumes may be estimated in a number of ways. Each is dependent upon the type of data base available for analysis. Loads to be supported by a pavement system are related not only to the volume of vehicles but also are dependent upon the distribution of various types of vehicles (and their associated weights). As with traffic volumes, estimates of the proportions of various vehicle types in the traffic stream can be obtained in a number of ways. The distribution of traffic among the various lanes of a multilane facility also is required. Again, these distributions can be obtained in a number of ways.

Axleloadings
An important attribute in determining the equivalent axleloads is the damage or load equivalency factors associated with individual axleloads or with various vehicle types. The load equivalency is a measure of damage to the pavement relative to the damage caused by an 18-kip axleload (Equivalency Factor = 1.0).

ANALYSIS OF AXLELOADINGS
Analysis of fatigue data for flexible pavements (22) showed that the equation used to develop thickness design nomographs was a best-fit regression. The same technique was used to investigate the fatigue data for rigid pavements (17). The regression equation and standard deviation were calculated for the relationship between the thickness of portland cement concrete pavements and equivalent 18-kip axleloads (Figure 4) using 1981 Kentucky load equivalency factors from Table 1 (6). The line representing the best-fit regression plus 1.2816 standard deviations (so as to include 95 percent of the data points) is also indicated in Figure 4. Note that an approximate thickness of 9.2 inches is required at 8 million EAL's (for the mean plus 1.2816 standard deviations). This is in reasonably close agreement with design (but not necessarily performance) experience in Kentucky.

FATIGUE ANALYSIS

STRAIN ENERGY
The "work" done by a force when its point of application is displaced is the product of that force (parallel to the direction of movement) and the displacement. When work is done on some systems, the internal geometry is altered in such a way that there is a potential to "give back" work when the force is removed, and the system returns to its original configuration. This stored energy is defined as strain energy. Strain energy
<table>
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<th>COEFFICIENTS</th>
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<tr>
<td></td>
<td>a</td>
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<tr>
<td>Two-Tired Single Front Axle</td>
<td>-3.540112</td>
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<tr>
<td>Four-Tired Single Rear Axle</td>
<td>-3.439501</td>
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<tr>
<td>Eight-Tired Tandem Axle</td>
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<tr>
<td>Twelve-Tired Tridem Axle</td>
<td>-2.740987</td>
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\[
\log \left( \text{Load Equivalency Factor} \right) = a + b \log(\text{Load}) + c \left( \log(\text{Load}) \right)^2
\]

Load = Total load (in kips) on axle configuration
per unit volume at a given point in the body is the strain energy density at that point.

If the force acting on a body has varied linearly from zero to \( kx \), its average value is \( kx/2 \), and the work done can be calculated as the product of the average force and its displacement (23):

\[
W = (kx/2) \times x = kx^2/2.
\]

Since this work has not supplied the body with either kinetic energy or gravitational potential energy, and since no work was done against friction, some part of the system must have been supplied with elastic potential energy (or strain energy) \( V \) of

\[
V = kx^2/2.
\]

Under an external wheel load, a pavement is stressed and strained from zero to some maximum values, and a measure of "work" can be expressed as

\[
\text{Work} = (1/2) \text{(stress)} \times \text{(strain)}.
\]

Strain energy density is a function of the Young's modulus of elasticity and Poisson's ratio of the material and the nine strain (or stress) components; however, it is independent of the coordinate system. Stress and strain components, referenced to a local cylindrical coordinate system, for each load can be calculated by the Chevron program (3). The classical equation for strain energy density derived by Sokolnikoff (24) is as follows:

\[
W = \sum \sum \left[ \frac{1}{2} \lambda \varepsilon_{ij} \varepsilon_{ij} + G \varepsilon_{ij} \varepsilon_{ij} \right]
\]

\[
= \frac{1}{2} \lambda \varepsilon^2 + G (\varepsilon_{11}^2 + \varepsilon_{22}^2 + \varepsilon_{33}^2 + 2\varepsilon_{12}^2 + 2\varepsilon_{13}^2 + 2\varepsilon_{23}^2),
\]

in which

- \( W \) = strain energy density, or energy of deformation per unit volume;
- \( \varepsilon_{ij} \) = \( i,j \)th component of the strain tensor;
- \( G = E/[2(1 + \mu)] \), the "modulus of rigidity" or the shear modulus;
- \( E \) = Young's modulus of elasticity;
- \( \mu \) = Poisson's ratio;
- \( \lambda = E /[(1 + \mu)(1 - 2\mu)] \); and
- \( \gamma = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33} \).

Strain energy density may be calculated (24) using stress components from

\[
W = -\mu \theta^2/2E + [(1 + \mu)/2E] (\sigma_{11}^2 + \sigma_{22}^2 + \sigma_{33}^2) +
+ [(1 + \mu)/E] (\sigma_{12}^2 + \sigma_{23}^2 + \sigma_{31}^2),
\]

in which

- \( \theta = \sigma_{11} + \sigma_{22} + \sigma_{33} \) and
\[ \sigma_{ij} = 1, \text{jth component of the stress tensor.} \]

Inspection of Equation 5 shows that the term \( E/[2(1 + \mu) \] is contained by means of the terms \( A \) and \( G \). Also, it is noted that the strain components are squared. Having calculated strain energy density, "work strain" (22) may be obtained from

\[ \varepsilon_w = \left( \frac{2}{E} \right)^{0.5}, \]

in which \( \varepsilon_w \) = work strain.

The associated "work stress" is given by \( E\varepsilon_w \).

Interpretations of Work Strain

Admittedly, work strain is not a true strain because Poisson's ratio has not been eliminated prior to taking the square root; however, it is of the same order of magnitude as any of the strain components. Calculating the work strain is a minor effort since all terms of the equations are either required input to, or calculated output of, the Chevron \( N \)-layer program (3, 25). Work strain is also the composite, or net effect, of all strain components and thus is an indicator of the total strain behavior. There is a direct correlation between a strain component and work strain.

Uses for Work Strain

Some thickness design systems for portland cement concrete pavements are based partially upon tensile strain criteria at the bottom of the concrete slab. The system proposed herein is based upon the concept of "equal work," work strain, and reported laboratory test data wherein measured tensile strains approximated the tangential strain components at the bottom of the concrete slab. The tangential component is generally the largest in magnitude, but the radial component often is nearly as large. Only the tangential component has been utilized because laboratory test data yields one component of tensile strain. The net effect of all components of strain (work strain) can be correlated with any component of strain. Thus, design systems based upon one component of strain may be converted to a design system that utilizes the net effect of all component strains. The load equivalency relationships presented herein are based on work strain. All comments above concerning component strains also apply to component stresses.

EQUIVALENCY FACTORS AND ROAD TEST REPETITIONS OF LOADS

Load equivalency factors were determined, using the 1981 Kentucky load equivalencies, for the various loads applied to the portland cement concrete pavements at the AASHO Road Test. The analyses were based upon output from the Chevron program. Concepts of work strain and work
Stress were incorporated, and the results are shown in Figure 7.

Conventional thickness designs for portland cement concrete pavements on CBR 3 subgrades in Kentucky have been 9 inches for the toll roads and 10 inches for interstate routes. The 18-kip EAL's for comparable asphaltic concrete pavements have been 4 million and 8 million, respectively. From Figure 4, the thicknesses of portland cement concrete slabs using the mean plus 1.2816 standard deviations are approximately 8.4 and 9.2 inches, respectively, but on CBR 5.2 subgrades.

Stress Criterion

Figure 3 illustrates the relationship between working stress, modulus of rupture, and number of repetitions to failure of an 18-kip axleload. The curve labelled "PCA Present Curve" (26) was used in this analysis and was extrapolated to 10 million repetitions.

Fatigue Criteria

Stress-Ratio Fatigue Criterion

The combination of a fixed value for Young's modulus of elasticity, modulus of rupture, and the stress-ratio versus repetitions relationship for the curve labeled "PCA Present Curve" in Figure 3 permits the development of a tensile strain versus repetitions criterion. The exact position of a curve is a function of the specific combination of values for the moduli of rupture and of elasticity.

Analysis of AASHO Road Test Data

The Chevron N-layer computer program (based on elastic theory) was used to analyze data for the portland cement concrete pavements at the AASHO Road Test. All components of stress and strain at the bottom of the concrete slab were combined using superposition principles to calculate an equivalent value of "work stress" and "work strain." Figure 8 illustrates the direct correlation between work strain and the tensile strain component. While the scatter of data is small about the best-fit line, the wide range in values is a function of the different loads and pavement thicknesses evaluated at the AASHO Road Test.

Young's modulus of elasticity for the concrete slab was varied in the analyses from 3 to 6 million psi on 1-million psi increments. Figure 9 illustrates the relationship between work strain and the thickness of a portland cement concrete slab. Each curve in the figure is for a specific CBR subgrade overlain with 6 inches of crushed stone base. Similar figures were prepared for work stress and tensile strain.

Data from Figure 9 were replotted in the form shown in Figure 10 to facilitate interpolations to obtain the relationship for a CBR 5.2 subgrade. Figure 11a combines the interpolated curves for CBR 5.2 from Figure 10 to obtain the curves for a range of moduli of elasticity of the
Figure 7. Concept of Tensile Strain at the Bottom of the Portland Cement Concrete Pavement versus Repetitions of 18-kip Equivalent Axleloads Merging the Portland Cement Association's Stress Ratio and AASHTO Criteria.
Figure 8. Tensile Strain Component versus Work Strain for Portland Cement Concrete Pavements at the AASHO Road Test.
Figure 9. Work Strain versus Thickness of Portland Cement Concrete on 6 Inches of Crushed Stone Base (for specific CBR's and Young's moduli).
Figure 10. Work Strain versus Thickness of Portland Cement Concrete on 6 Inches of Crushed Stone Base (for specific CBR's).
concrete. Figure 11b illustrates the curves for CBR values shown in Figure 9 and for a modulus of elasticity of 4.2 million psi.

**CONCEPT OF EQUAL WORK**

"Work strain" and "work stress" can be substituted for the single component stress and strain to obtain

\[
\text{Work} = \frac{1}{2} (\text{work stress}) (\text{work strain}).
\]

Figures 12, 13, and 14 illustrate the relationships among work stress, work strain, Young's modulus of elasticity, and the product (work) from Equation 8. Note that the lines of equal work are perpendicular to lines of equal moduli of elasticity (see Figure 14). Thus, for a given level of work, strains and stresses vary to maintain a constant value of work. Figures 12 and 13 illustrate the relationships among Young's modulus of elasticity, work stress, and work strain as a function of work given by Equation 8.

The Portland Cement Association's and the AASHTO methods of selecting thicknesses for concrete pavements are based on limiting the tensile strain (or stress) in the slab to some tolerable level. The design method developed by the Portland Cement Association was based upon model and full-scale tests (7). The Arlington Tests were conducted in the 1940's and would be applicable to lower-volume roads in today's highway environment. Conversely, the AASHO Road Test was conducted in the early 1960's and had high volumes of trucks over a relatively few years.

Inspection of Figure 7 indicates that the strain criterion for 10 million repetitions of an 18-kip single axleload would be too low and result in slab thicknesses unreasonably thick using the Portland Cement Association's design method. Conversely, the AASHO criterion would result in slab thicknesses that would be too thin in the lower-volume ranges. For a modulus of elasticity of 4.2 million psi, combined with the mean plus 1.2816 standard deviation line from Figure 8, thicknesses at specific numbers of repetitions were converted to tensile strain using the relationships among tensile strain, thickness, and a CBR of 5.2. Those points fix the relationship for the AASHTO portion of Figure 15. There should be a value of the modulus of rupture that would permit the strain criterion of the Portland Cement Association to become tangent to the AASHTO strain criterion. Furthermore, the literature on the characteristics of concrete discussed previously suggests the value of the modulus of rupture should have a value between 475 and 680 psi. Figures 2 and 15 indicate the modulus of rupture is approximately 600 psi when the two criteria merge into one smooth curve.
Figure 11. Work Strain versus Thickness of Portland Cement Concrete on 6 Inches of Crushed Stone Base.

Figure 12. Relationships among Work, Work Strain, and Young's Modulus of Elasticity.
Figure 13. Relationships among Work Stress, Work, and Young's Modulus of Elasticity.
Figure 14. Relationships among Work Stress, Work Strain, Work, and Young's Modulus of Elasticity.
THICKNESS DESIGN CURVES

DEVELOPMENT OF DESIGN CURVES

Figure 15 provides the criterion relating tensile strain to repetitions of 18-kip single axle loads for a Young's modulus of elasticity of 4.2 million psi and a subgrade CBR of 5.2. Using Figure 15, the tensile strain associated with any specific number of repetitions can be determined. From Figure 8, the corresponding work strain can be obtained. Entering Figure 11b with the work strain, the required thickness of a portland cement concrete slab can be obtained. Plotting those slab thicknesses as a function of the number of repetitions produces a design curve for a subgrade CBR of 5.2. Using Figure 11b and the same value of work strain for the modulus of elasticity permits the development of thickness-repetitions curves for other values of subgrade CBR.

It should be noted that, to this point, the analyses have been based on designs utilizing 6 inches of dense-graded aggregate base under the portland cement concrete slab. Pavement systems having dense-graded aggregate bases of 3, 4, and 5 inches were also analyzed for the same fatigue levels. Increased thicknesses of the portland cement concrete slab ranged from 0.05 to 0.10 inch (low to high EAL's, respectively) when the dense-graded aggregate was decreased from 6 inches to 3 inches. The rigidity of the portland cement concrete slab apparently overshadowed the effects due to decreased base thicknesses (at least in the range of granular-base thicknesses investigated). Thus, the required thicknesses of portland cement concrete slab were averaged for the various thicknesses of dense-graded aggregate base to obtain design curves shown in Figure 16. Figure 16 can be used to determine thickness designs for portland cement concrete pavements using 18-kip EAL's calculated by applying 1981 Kentucky load equivalency factors for asphaltic concrete pavements.

CURRENT DESIGN PRACTICE

Historically, the controlling total thickness of an asphaltic concrete pavement in Kentucky has been 23 inches on a CBR 7 subgrade for 8 million 18-kip EAL's. The 23 inches consists of 7.7 inches of asphaltic concrete over 15.3 inches of dense-graded aggregate. Figures 9, 11b, and 15 were used to determine the design thicknesses for rigid pavements on a CBR 3 subgrade (and 6 inches of dense-graded aggregate) using the 1981 Kentucky load equivalency factors for asphaltic concrete pavements.

The thickness of portland cement concrete pavements for interstate-type highways historically have been taken to be 10 inches over 6 inches of dense-graded aggregate at 8 million 18-kip EAL's calculated using flexible equivalency factors. Figure 16 shows that a CBR 3 subgrade and 8 million EAL's require a 9.9-inch slab. Toll road designs have been associated with 4 million 18-kip repetitions, and the design thickness was taken to be 9 inches of portland
Figure 15. Tensile Strain versus Repetitions of 18-kip Single Axleloads Illustrating the Merging of the Portland Cement Association and AASHTO Design Criteria.
Figure 16. Thickness Design Curves for Portland Cement Concrete Pavements.
cement concrete over 4 inches of dense-graded aggregate. For the CBR 3 curve in Figure 16, the required portland cement concrete pavement would be 8.8 inches on 4 inches of dense-graded aggregate base. Thus, the two designs of the toll roads are very similar.

Unfortunately, the performance of portland cement concrete pavements (as opposed to design experience) in Kentucky has not yet been well documented. The correlation of performance with "design" is further clouded by the introduction years ago of an "impact factor" to increase design loads on portland cement concrete pavements. It may well be that the 10-inch typical interstate design has performed adequately for one and one half to two times the "design" EAL's.

OVERLAY THICKNESS DESIGNS

Thickening design curves in Figure 16 may be used to design portland cement concrete overlays only on rigid pavements. However, this requires a method of evaluating the conditions of the existing rigid pavement and determining the equivalent effective thickness of new (unfatigued) portland cement concrete having a modulus of elasticity of 4.2 million psi. The rigid overlay thickness is the difference between that thickness required to support the future expected traffic and the "behavioral" thickness of the existing pavement.

LIMITATIONS

The design procedures and curves presented in this report are based upon a fatigue criterion applicable to the loading of a rigid slab at its center. Since the Chevron N-layer computer program was used to calculate stresses, strains, and deflections upon which the design curves were based, the design schema assumes the various layers of the pavement system remain in intimate contact. It is further assumed that the stress levels induced in the pavement system are sufficiently low that the various materials perform in an elastic manner. These same assumptions are the basis for the design system for flexible pavements used in Kentucky, as well as the AASHTO systems for both rigid and flexible pavements and the Portland Cement Association design method for rigid pavements.

Because of the nature of a rigid or portland cement concrete pavement, there may be stress concentrations induced within the pavement system that are not properly considered by the above assumptions. Modes of failure other than by fatigue loading also may become significant with regard to the overall performance of portland cement concrete pavements. Increased stresses due to edge loadings, corner loadings, or voids under the slab that have developed for whatever reason are not addressed or included within the design schema. Curling and warping forces are included indirectly only through the long-term fatigue stresses induced by temperature gradients. Failure of the
slab by D-cracking is not normally included in thickness
design procedures. The design of joints, joint spacings,
and load transfer between slabs has not been examined in
this study and thus are not accounted for in the design
schema presented herein.

Thickness design curves presented in this report were
prepared on the basis of calculations using the Chevron
N-layer program with the moduli of elasticity of the various
materials as input parameters. In Kentucky, the load­
carrying capacity of the subgrade has been expressed in
terms of the CBR. The modulus scale on the plot of design
curves was converted to a CBR scale using a correlation
factor between modulus and CBR. It has been noted in the
literature on a number of occasions that this correlation
factor is valid for CBR's only in the range of approximately
3 to 20.

IMPLEMENTATION

Prior to a full-scale implementation of the design
procedures reported in this paper, the AASHTO and PCA design
systems will be investigated and compared. Therefore, the
Kentucky Transportation Cabinet will not implement the
reported design procedures at this time.

FUTURE RESEARCH

A rational method for designing asphaltic concrete
overlays for rigid pavements is needed. The design scheme
should provide designs for portland cement concrete
pavements that might be fragmented into various particle
sizes or left intact. Two construction projects (I 71 in
Gallatin County and I 64 in Shelby County) may provide much
insight into the behavior of fragmented and overlaid
pavements.

Method(s) to evaluate the existing condition and value
of portland cement concrete pavements need to be further
refined. Current research is just beginning to develop
potential methodologies. However, phenomena related to the
behavior of portland cement concrete slabs and joints are
not yet fully understood.

No investigation has been made of the effects of
nonuniform axleload distributions within tandem and tridem
assemblies on portland cement concrete pavements. The
effect of nonuniform loading on asphaltic concrete pavements
was significant, but the impact on portland cement concrete
pavements is not yet evaluated.

A cursory series of tests were made on I 71 to study
the effects of time of day (temperature distribution within
the pavement) upon the behavior of portland cement concrete
slabs. At several joints, Road Rater data revealed that the
slab was resting on the four corners and arching diagonally
across the slab and along the joint. Thus, corner failures
or breaks may be a function of a heavy load in the center of
the slab being supported only by the corners of the slab that rest upon the foundation. This condition needs additional field studies and theoretical analyses to determine whether the thickness design methodology should be predicated on conditions other than center-of-slab loadings.

An analysis of quality-control data for paving concretes might assist in selecting a more definitive value for the modulus of rupture to use in pavement design. The performance of portland cement concrete pavements also should be correlated with the modulus of rupture.

Joints in portland cement concrete pavements introduce special problems and considerations into the design of rigid pavements. The effects of joints on thickness design, both for original construction and for overlays, is not known. The design, construction, performance, and maintenance of joints are subjects for study.

REFERENCES


