State of the Art and Practice in Rigid Pavement Design

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Three types of concrete pavements are commonly used (*1*):

- *Jointed plain concrete pavement (JPCP)* has transverse joints spaced less than about 5 m apart and no reinforcing steel in the slab. JPCP may, however, contain steel dowel bars across transverse joints and steel tiebars across longitudinal joints.
- *Jointed reinforced concrete pavement (JRCP)* has transverse joints spaced about 9 to 12 m apart and contains steel reinforcement in the slab. The steel reinforcement is designed to hold tightly together any transverse cracks that develop in the slab. Dowel bars and tiebars are also used at all transverse and longitudinal joints, respectively.
- *Continuously reinforced concrete pavement (CRCP)* has no regularly spaced transverse joints and contains more steel reinforcement than JRCP. The high steel content influences the development of transverse cracks within an acceptable spacing and serves to hold these transverse cracks tightly together. Transverse reinforcing steel is often used.

According to a 1999 survey, at least 70 percent of the state highway agencies in the United States use JPCP. About 20 percent of the states build JRCP, and about six or seven state highway agencies build CRCP, most notably on high-volume, urban roadways. A few states report that they do not build concrete pavements (*2*).

CONCRETE PAVEMENT DESIGN METHODS

The most widely used procedure for design of concrete pavements is specified in the *Guide for Design of Pavement Structures* published in 1986 and 1993 by the American Association of State Highway and Transportation Officials (AASHTO) (*3*). [Note that the 1993 version differs from the 1986 version only in the overlay design chapter.] A few states use the 1972 American Association of State Highway Officials (AASHO) Interim Guide procedure (*4*), the Portland Cement Association (PCA) procedure (*5*), their own empirical or mechanistic-empirical procedure, or a design catalog.

KEY CONCRETE PAVEMENT THICKNESS DESIGN PARAMETERS

The key input parameters in any concrete pavement design procedure are outlined in the following paragraphs.

Traffic over Design Period

The number of heavy (truck) axle loads anticipated over the design life must be estimated on the basis of current truck traffic weights and volumes along with growth projections. In the AASHTO methodology, the anticipated spectrum of truck axle loads over the design period is expressed in terms of an equivalent number of 18-kip single-axle loads (ESALs), computed using load equivalency factors that relate the damage done by a given axle type and weight to the damage done by this standard axle.

Subgrade

The modulus of subgrade reaction (*k*-value) of the foundation (natural soil and embankment) can be measured by plate bearing tests but is usually estimated from correlations with soil type, soil strength measures such as the California bearing ratio (CBR), or by backcalculation from deflection testing on existing pavements.

Environment

Daily and seasonal variations in temperature and moisture influence the behavior of concrete pavements in many ways, including

- Opening and closing of transverse joints in response to daily and seasonal variation in slab temperature, resulting in fluctuations in joint load transfer capability;
- Upward and downward curling of the slab caused by daily cycling of the temperature gradient through the slab thickness;
- Permanent upward curling of the slab, which in some circumstances may occur during construction, as a result of the dissipation of a large temperature gradient that existed in the concrete while it hardened;
- Upward warping of the slab caused by seasonal variation in the moisture gradient through the slab thickness;
- Erosion of base and foundation materials caused by inadequate drainage of excess water in the pavement structure, primarily from precipitation;
- Freeze-thaw weakening of subgrade soils;
- Freeze-thaw damage to certain types of coarse aggregates in the concrete mix; and
- Corrosion of dowel bars, steel reinforcement, or both, especially in coastal environments and in areas where deicing salts are used in winter.

Although the effects of climate on concrete pavement behavior and performance have been recognized since the time of the earliest concrete pavement design experiments, concrete pavement thickness design practice traditionally has not explicitly considered most of these climatic effects. Several recent field and analytical studies have contributed greatly to better understanding and quantifying these effects so that they may be more adequately considered in thickness design.

Concrete Material Properties

For the purpose of pavement thickness design, concrete is characterized by its flexural strength as well as by its modulus of elasticity. Concrete flexural strength is usually characterized by the 28-day modulus of rupture (*MR*) from third-point loading tests of beams, or it may be estimated from compressive strengths. The corresponding elastic modulus (*E*) can also be measured but is usually estimated from strength data. In addition to its strength and stiffness, the durability of the concrete mix is important to the long-term performance of the pavement.

Base

A base course provides a stable platform for construction of the concrete slab, improves the smoothness achieved in the paving of the slab and the drainage of the pavement structure, and protects the foundation from frost penetration. Some types of bases also significantly reduce bending stresses and deflections in the slab and improve load transfer at joints and cracks. The estimated elastic modulus of the base, its erodibility, its potential for friction and bond with the concrete slab, and its drainability are factors considered in characterizing the support to the concrete slab and the quality of subsurface drainage.

Performance Criteria

All pavement thickness design procedures incorporate performance criteria that define the end of the performance life of the pavement. In the AASHTO methodology, the performance criterion is the loss of serviceability (riding comfort), which occurs as a result of accumulated damage caused by traffic load applications. The PCA procedure uses both fatigue cracking and erosion criteria.

Design Reliability

The reliability level or, generally speaking, the safety factor for which a pavement is designed reflects the degree of risk of premature failure that the agency is willing to accept. Facilities of higher functional classes and higher traffic volumes warrant higher safety factors in design. In the AASHTO methodology, this margin of safety is provided by applying a reliability adjustment to the traffic ESAL input. The magnitude of the adjustment is a function of the overall standard deviation associated with the AASHTO model, which reflects (*a*) error associated with estimation of each of the inputs (ESALs, subgrade *k*, concrete strength, serviceability, etc.), (*b*) error associated with the quality of fit of the model to the data on which it is based, and (*c*) replication error (differences in performance of seemingly identical pavement sections under identical conditions). When reliability adjustments are made to the traffic input in this manner, average values should be used for the material inputs (*k*-value, *MR*, *E*); that is, no other safety factors should be applied to any of these inputs.

Before the introduction of reliability concepts in pavement thickness design procedures, the traditional approach to introducing a margin of safety into concrete pavement thickness design was to apply a safety factor to the concrete *MR* (i.e., to reduce the *MR* by a certain amount to add some conservatism to the design). This approach is still used in the PCA procedure.

AASHTO DESIGN METHODOLOGY

The empirical model for the performance of the JPCP and JRCP sections in the main loops of the AASHO Road Test predicts the log of the number of axle load applications (log *W*) as a function of the slab thickness, axle type (single or tandem) and weight, and terminal serviceability. This original model applies only to the designs, traffic conditions, climate, subgrade, and materials of the AASHO Road Test. It has been modified and extended to make possible the estimation of allowable axle load applications to a given terminal serviceability level for conditions of concrete strength, subgrade *k*-value, and concrete *E* different than those of the AASHO Road Test. The AASHTO design methodology has also been extended to accommodate the conversion of mixed axle loads to equivalent 80-kN (18-kip) ESALs through the use of load equivalency factors.

An important aspect of the extended AASHO model is that the loss of serviceability that corresponds to a predicted number of axle load applications does not include any contribution of faulting to pavement roughness because, although the doweled pavements in the AASHO Road Test experienced substantial loss of support, they did not fault. The design loss of serviceability is presumed to be entirely due to slab cracking.

Furthermore, it is an extrapolation of the AASHTO model to apply it to the prediction of performance of undoweled jointed pavements, jointed pavements with stabilized bases, jointed pavements with joint spacings other than those used in the AASHO Road Test, CRCP, or concrete pavements of any type in climates that may produce significantly greater curling and warping stresses than those experienced by the AASHO Road Test sections.

1986-1993 AASHTO GUIDE

The 1986-1993 AASHTO Guide (*3*) incorporates many modifications to the procedures for both concrete and asphalt procedures, although the basic design models for both remained the same as in previous versions. The principal modifications to the AASHTO concrete pavement design methodology in the 1986-1993 procedure are the following:

- Addition of a drainage adjustment factor (C_d), a multiplier of the slab thickness that presumably is less than 1.0 for drainage conditions worse than those in the AASHO Road Test and greater than 1.0 for better drainage conditions;
- Determination of the design *k*-value as a function of the subgrade resilient modulus, depth to a rigid layer, base thickness and elastic modulus, erodibility of the base material, and seasonal variation in soil support;
- Presentation of corner stress adjustment (*J*-factor) values as a function of pavement type (jointed or CRCP), load transfer (doweled or aggregate interlock), and shoulder type (asphalt or tied concrete); and
- A reliability adjustment applied to the design ESAL input instead of using a factor of safety on the modulus of rupture.

1998 SUPPLEMENT TO AASHTO GUIDE

The revised AASHTO design model for concrete pavements presented in the 1998 *Supplement to the AASHTO Guide* (*6*) was developed under NCHRP Project 1-30 (*7*) and field-validated by analysis of the GPS-3, GPS-4, and GPS-5 (JPCP, JRCP, and CRCP) sections in the Long-Term Pavement Performance (LTPP) studies (*8*).

The purpose of the NCHRP Project 1-30 study was to evaluate and improve the AASHTO Guide’s characterization of subgrade and base support. The original AASHO empirical model was calibrated to the springtime gross *k*-value measured in plate load tests on the granular base, whereas the 1986 Guide’s method for determining the design *k*-value was based on a seasonally adjusted annual average *k*-value for the so-called “composite” (subgrade plus base) *k*-value. A key recommendation of the 1-30 study was that, for purposes of concrete pavement design in the existing AASHTO mechanistic-empirical methodology, both the AASHO Road Test subgrade and the subgrade of the project under design should be characterized by the seasonally adjusted annual average static elastic *k*-value. The 1998 AASHTO Supplement presents guidelines for determination of an appropriate design *k*-value on the basis of plate bearing tests, correlations with soil types and properties, CBR, or deflections measured on in-service pavements.

It is recommended in the 1998 AASHTO Supplement that both the beneficial and detrimental effects of a granular or treated base on concrete pavement performance be considered, not in the *k*-value but in the computation of slab stress in response to load as well as temperature and moisture gradients. Using the same process by which the original AASHO Road Test empirical model was extended in 1961, a new AASHTO design model was derived to (*a*) be consistent with the recommended characterization of the design *k*-value and (*b*) consider the effects on stress in the slab of base modulus, base thickness, slab and base friction, joint spacing, edge support, temperature and moisture gradients, and traffic loading. The stress analyses were conducted using a three-dimensional finite element model, which was validated by comparison with stresses (computed from measured strains) in pavements in the AASHO Road Test, the Arlington Road Test, and slab deflections measured in tests conducted by PCA. Regression equations were then developed to relate the computed stresses to the design factors. The three-dimensional finite element model was also used to develop a design check for corner loading for undoweled jointed pavements.

As in the earlier versions of the AASHTO rigid pavement design procedure, the computed slab thickness is that which is required to support the anticipated ESALs to a selected terminal serviceability level, assuming that the serviceability loss is due only to slab cracking. If faulting were to develop on a pavement to such a degree that it contributed significantly to loss of serviceability, the pavement would have been underdesigned; that is, it would have reached terminal serviceability sooner than predicted. The appropriate way to prevent this is not to increase the slab thickness but rather to design the joint load transfer system so that faulting will not develop to the degree that it contributes significantly to loss of serviceability.

PCA METHOD

The PCA's concrete pavement design procedure for roads and streets evaluates a candidate pavement design with respect to two potential failure modes: fatigue and erosion. The procedure was developed using the results of finite element analyses of stresses induced in concrete pavements by joint, edge, and corner loading. The analyses take into consideration the degree of load transfer provided by dowels or aggregate interlock and the degree of edge support provided by a concrete shoulder. The PCA procedure, like the 1986-1993 AASHTO procedure, employs the "composite *k*" concept in which the design *k* is a function of the subgrade soil *k*, base thickness, and base type (granular or cement treated).

The fatigue analysis incorporates the assumption that approximately 6 percent of all truck loads will pass sufficiently close to the slab edge to produce a significant tensile stress. The fatigue model (log of allowable load repetitions versus stress-to-strength ratio) used in the current PCA procedure is the same as that used in the 1966 PCA procedure except for a change to eliminate a discontinuity in the high load repetition range. A factor of safety is introduced in the fatigue analysis by reducing the *MR* by one standard deviation. The erosion analysis quantifies the power (rate of work) with which a slab corner is deflected by a wheel load as a function of the slab thickness, foundation *k*-value, and estimated pressure at the slab-foundation interface. An additional safety factor can be applied to the axle load levels used in the fatigue and erosion analyses to account for the more significant consequences of error in traffic prediction for higher-volume facilities.

For each load level considered, the expected number of load repetitions over the design life is expressed as a percentage of the allowable repetitions of that load level with respect to both fatigue and erosion. An adequate thickness is one for which the sum of the contributions of all axle load levels to fatigue and erosion damage is less than 100 percent.

OTHER METHODS

Other concrete pavement design methods range from empirical adaptations of the AASHTO method to calibration and mechanistic-empirical extension of the AASHTO method and methods that combine mechanistic stress calculation with an empirical fatigue cracking model. Most notable among the mechanistic-empirical methods are the zero-maintenance design procedure (*9*,*10*) and the NCHRP Project 1-26 procedure (*11*,*12*).

DESIGN CATALOGS

A design catalog does not present a thickness design procedure per se but rather a format for recommended thicknesses and other design details. A design catalog for both asphalt and concrete pavements in the United States was developed under NCHRP Project 1-32 (*13*). In addition to slab thicknesses, the NCHRP 1-32 catalog provides guidance on shoulder, joint reinforcement, joint sealant, drainage, and materials design for concrete pavements. Design catalogs have also been developed in several other countries, including Belgium, Germany, and France.

FUTURE DIRECTIONS

Among the efforts currently under way or anticipated to advance the state of the art and practice of rigid pavement design are improvements in and improved understanding of the following areas:

- Mechanistic-empirical design methodology and guidelines, anticipated to eventually be incorporated in a 2002 version of the AASHTO Guide;
- Consideration of climatic effects, such as temperature curling and moisture warping, on concrete pavement behavior;
- Effects of subsurface drainage on concrete pavement performance;
- Influence of aggregate properties on concrete pavement joint and crack formation and behavior;
- Influence of base types and their properties on concrete pavement performance; and
- Methods for design of doweled transverse joints.

REFERENCES

1. Smith, K. D., and K. T. Hall. *Concrete Pavement Design Details and Construction Practice—State of the Art Technical Digest.* FHWA, U.S. Department of Transportation, 1999.
2. *Survey of States' Concrete Pavement Design and Construction Practices*. American Concrete Pavement Association, 1999.
3. *Guide for Design of Pavement Structures*. American Association of State Highway and Transportation Officials, Washington, D.C., 1986 and 1993.

4. *Interim Guide for Design of Pavement Structures*. American Association of State Highway Officials, Washington, D.C., 1972.
5. *Thickness Design for Concrete Highway and Street Pavements*. EB109.01P. Portland Cement Association, Skokie, Ill., 1984.
6. *Supplement to the AASHTO Guide for Design of Pavement Structures, Part II—Rigid Pavement Design and Rigid Pavement Joint Design*. American Association of State Highway and Transportation Officials, Washington, D.C., 1998.
7. Darter, M. I., K. T. Hall, and C. M. Kuo. *NCHRP Report 372: Support Under Portland Cement Concrete Pavements.* TRB, National Research Council, Washington, D.C., 1997.
8. Hall, K. T., M. I. Darter, T. E. Hoerner, and L. Khazanovich. *LTPP Data Analysis Phase I: Validation of Guidelines for k Value Selection and Concrete Pavement Performance Prediction*. Report FHWA-RD-96-168. FHWA, U.S. Department of Transportation, 1997.
9. Darter, M. I. *Design of Zero-Maintenance Plain Jointed Concrete Pavement, Volume 1—Development of Design Procedure.* Report FHWA-RD-77-111. FHWA, U.S. Department of Transportation, 1977.
10. Darter, M. I., and E. J. Barenberg. *Design of Zero-Maintenance Plain Jointed Concrete Pavement, Volume 2—Design Manual.* Report FHWA-RD-77-112. FHWA, U.S. Department of Transportation, 1977.
11. Barenberg, E. J., and M. R. Thompson. *Calibrated Mechanistic Structural Analysis Procedures for Pavements*. NCHRP Project 1-26. TRB, National Research Council, Washington, D.C., 1992.
12. Salsilli, R. A., E. J. Barenberg, and M. I. Darter. Calibrated Mechanistic Design Procedure to Prevent Transverse Cracking of Jointed Plain Concrete Pavements. In *Proc., Fifth International Conference on Concrete Pavement Design and Rehabilitation*, Purdue University, West Lafayette, Ind., 1993.
13. Darter, M. I., H. L. Von Quintus, Y. J. Jiang, E. B. Owusu-Antwi, and B. M. Killingsworth. *Catalog of Recommended Design Features* (CD-ROM). NCHRP Project 1-32. TRB, National Research Council, Washington, D.C., 1997.