R&T UPDATE
Concrete Pavement Research & Technology

OPTIMIZING CONCRETE PAVEMENTS

Concrete pavements are typically designed to be both long-lasting and low maintenance facilities. In order to maximize these benefits, a variety of design features are available, including widened lanes, tied concrete shoulders, doweled joints, high strength concrete, and numerous others. To effectively optimize a pavement design, the cost of each design feature must be carefully considered in terms of the initial cost and the estimated long-term performance benefit.

The majority of highway pavements in the United States are designed using the AASHTO 1993 Design Guide (e.g. 93 Guide). This empirical procedure has a limited number of variables and is only suited to basic analysis of the benefit of performance enhancing features. The Mechanistic-Empirical Design Guide (M-E PDG) is currently being evaluated as the next generation tool for pavement design and analysis. It will permit an engineer to perform a thorough evaluation of various design features.

This R&T Update (first in a series) highlights an overall strategy to economize concrete pavements based on design features using the 93 Guide. Subsequent R&T Updates will focus on more detailed strategies and analyses using the M-E PDG for each design element.

Basis for Comparison

The most straightforward method of determining the benefit of a particular design feature is through the use of established design methodologies. The 93 Guide is used herein to show the effects of several primary design elements on the thickness of concrete pavements.

Numerous pavement evaluation studies have been conducted to establish a relationship between design features and performance including the Long-Term Pavement Performance Studies (LTPP). However, limited data exists for many new and innovative designs and particularly for long-life pavements.

The structural capacity of concrete pavement is influenced by many factors other than loading. Material durability and construction quality are two of the primary considerations influencing short-and long-term pavement performance.

Design Assumptions

Concrete pavement design is based on a series of estimates including support conditions, traffic projections, environmental factors and so on. Table 1 shows baseline values for the analysis herein. The 93 Guide has relatively few variables compared with the M-E PDG and is limited in the number and type of design details that may be analyzed.

The inter-relationship (or sensitivity) of variables is not clearly defined in any of the current design methodologies. In other words, changing one variable has a corresponding effect on many other variables. In order to simplify the analyses herein, a baseline value is defined for each design input and then varied throughout a reasonable range (for highway facilities).

AASHO Road Test, still the basis of design used by many agencies until the Mechanistic-Empirical Design Guide is adopted by AASHTO.

Table 1. Variables used in the AASHTO 1993 Design Analysis.

Variable	Baseline Value	Range of Values
Traffic (18 kip ESAL's	20 Million	5 – 80 million
Reliability	80 percent	50 – 95 percent
Concrete Strength (MR)	550 psi	500 – 700 psi
Concrete Modulus (E)	Correlated to MR	Correlated to MR
Support (Modulus of Subgrade Reaction, k)	150 pci	75 – 500 pci
Drainage	Moderately well-drained (C_d= 1.00	Poorly drained (C_d= 0.70) to very well drained (C_d= 1.20)
Edge Support	Yes (tied PCC shoulders or widened lane)	No (Non-tied PCC or asphalt shoulders
Load Transfer	Dowel Bars	Aggregate Interlock
Initial Serviceability	Present Serviceability Index = 4.5	Present Serviceability Index = 4.0 – 4.8
Terminal Serviceabiity	Present Serviceability Index = 2.5	Present Serviceability Index = 2.5

Slab thickness is perhaps the most significant variable in determining initial pavement cost. However, other factors such as shoulder type and design play a dual role in both feature cost and influencing slab thickness.

The design decisions that most affect the initial cost of concrete pavement include:

- Concrete strength
- Load transfer
- Shoulder type and configuration
- Support layers
- Subsurface drainage
- Reliability

The effect of each of these variables is dependent on many factors and interrelationships with other variables. In this analysis only a single design input value is varied, with the exception of the Concrete's Modulus of Rupture and Modulus of Elasticity, which are related through a standard correlation.

Analysis and Results

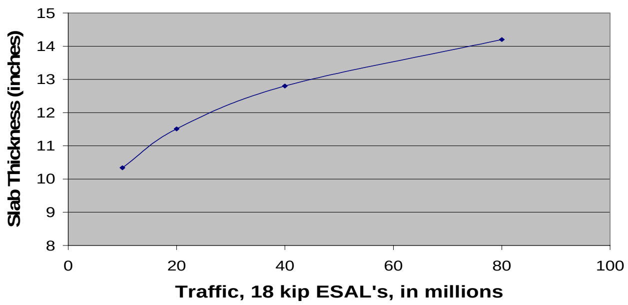
The AASHTO 1993 Design Guide (WINPas software) was used to generate the data shown in the graphs. With the exception of the variable being analyzed, all of the inputs were fixed according to the baseline values shown in Table 1.

While it is recognized that the 93 Guide is limited in its ability to assess minor differences pavement performance as a function of many of the design inputs, general trends and the sensitivities of the variables are evident.

Traffic

The primary variable affecting pavement thickness is traffic, expressed in terms of 18,000 pound equivalent single axle loads (18 kip ESALs). Traffic is a site specific input and can't be altered except through additional lanes. The affect of traffic is shown for illustration purposes only.

Figure 1. Traffic Volume versus Slab Thickness



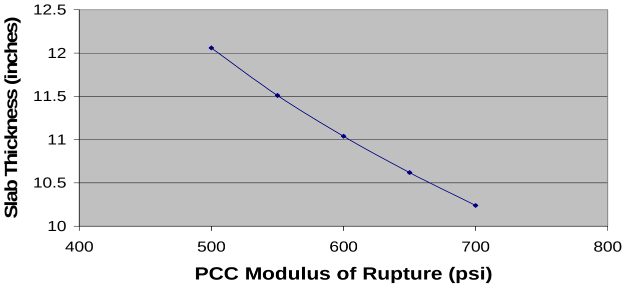
Concrete Strength

Concrete strength for pavements is specified as the modulus of rupture (MR) and is based on a third point flexural loading condition. The elastic modulus (E_{PCC}) of the PCC is positively correlated to MR.

Increased concrete strength results in a decreased slab thickness. Higher strength is typically achieved through increased cement or cementitious materials content, a reduction in the water/cementitious materials ratio, various admixtures, and optimized aggregate gradation. A tradeoff between the increased cost of the higher strength PCC versus a reduction in slab thickness must be addressed.

A key factor in long-term pavement performance is material durability. The 93 Guide does not consider durability aspects which are oftentimes directly related to higher strengths.

Figure 2. PCC Modulus of Rupture versus Slab Thickness



Shoulder Type and Configuration

The type of shoulder has a sizable effect on both the required thickness of pavement for a given level of traffic and the initial cost. The critical factor in determining slab thickness is the level of edge support afforded by the shoulder. Therefore, two broad categories of shoulders exist. The first category assumes that the edge stress is reduced by use of either a concrete shoulder tied to the mainline pavement or a widened lane. The second category of shoulders assumes no reduction in edge stress and includes non-tied concrete shoulders and asphalt shoulders. The cost differential must be considered when selecting a widened lane or tied concrete shoulder versus the reduction in slab thickness. The relationship between reduced slab thickness and edge support is shown in Figure 3.

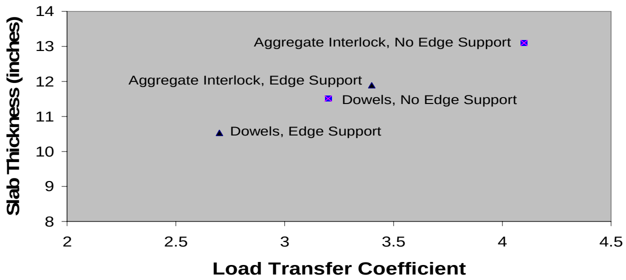
Regardless of type, the shoulder thickness can have a significant impact on the overall initial cost of the pavement. The required thickness of the shoulder depends on the anticipated use; as a temporary diversion lane, a future traffic lane or simply as an emergency parking area. The primary objective is to design the shoulder for the anticipated use and level of traffic and not as a “one size fits all” approach. In many cases the shoulder can be substantially thinner than the mainline pavement and still provide adequate service.

Load Transfer

Load transfer is a very important design aspect of joints for heavily trafficked concrete pavements. The use of dowel bars to maximize long-term load transfer efficiency across the transverse pavement joints and thereby minimize or eliminate faulting is widely accepted. A secondary benefit is that load transfer using dowel bars reduces the required slab thickness as shown in Figure 3.

Although methods exist for determining the required dowel bar diameter and bar spacing, most Agencies use a standard array of bars in which the diameter is correlated to the slab thickness and the bars are uniformly distributed along the transverse joints at 1-foot intervals. The AASHTO 1993 Guide does not specify the impact of dowel bar design and optimization of size and spacing.

Figure 3. Load Transfer/Edge Support versus Slab Thickness



Support Conditions

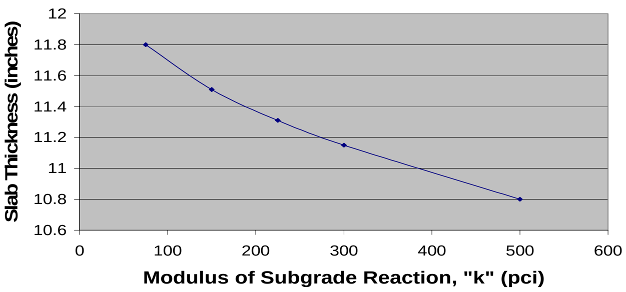
Concrete pavements may be constructed on a wide range of support conditions. The stiffness of the underlying support is not as important to long-term performance as the uniformity of support. The influence of the modulus of subgrade reaction “k” on slab thickness is minimal as shown in Figure 4.

The primary factors influencing the cost of providing uniform and adequate support are subgrade modification, type and thickness of base (stabilized, unstabilized) and subsurface drainage requirements.

Subgrade modification is sometimes required to provide a stable platform during construction. Although not a significant factor in design, expediting construction and the potential for better ride quality can be adequate compensation.

Excessive thickness of granular base materials is generally not warranted and has, in some studies, been shown to be detrimental if over 6-inches thick. Justification for a stabilized base is generally based on improving performance rather than thinning up the pavement. However, the effects of these measures are not adequately reflected in the 93 Guide.

Figure 4. Modulus of Sugrade Reaction "k" versus Slab Thickness



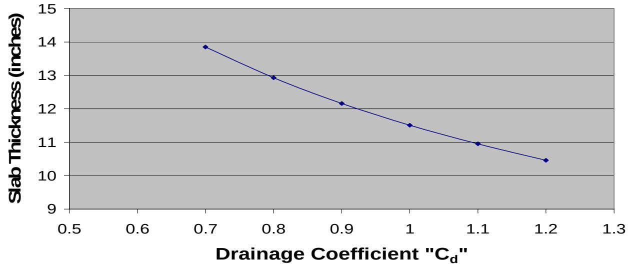
Subsurface Drainage

Subsurface drainage has been specified by a number of states to combat the effects of water infiltrating into the pavement, primarily through unsealed joints and cracks. The National Cooperative Highway Research Program (NCHRP) 1-34 studies have attempted to quantify the benefits of comprehensive drainage systems. The latest study, NCHRP 1-34D will be released soon and will provide specific guidance as to the viability of drainage systems for concrete pavements. Indications are that there is little, if any, enhancement in performance from permeable drainage layers and systems.

Installation of a comprehensive subsurface drainage system includes a drainable base, granular separator layer and/or geotextile fabric, edge drains and redundant outlets. The cost/benefit of these systems has been the subject of much controversy. Subsurface drainage should always be considered on a project by project basis and not as a uniform requirement. The cost savings resulting from elimination of a comprehensive drainage system are substantial.

The 93 Guide doesn't specifically address the issue of subsurface drainage. The drainage coefficient is based on the time the pavement is subject to saturated conditions and the time to drain. If a subsurface drainage system is mandated, the drainage coefficient should have a value of 1.2 to 1.25. The reduction in slab thickness shown in Figure 5 shows a general trend. However, bear in mind that a value of 1.0 is representative of a poorly-draining clay soil from the AASHO Road Test in Ottawa, Illinois. A drainage coefficient of 1.0 is neutral in the analysis and does not change slab thickness.

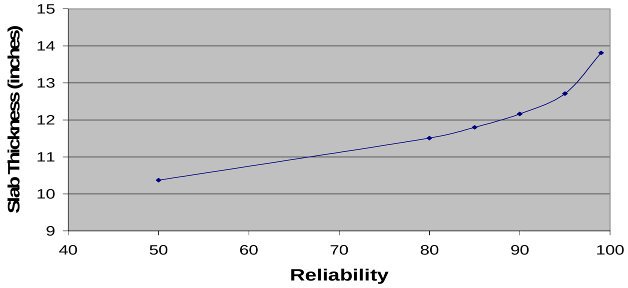
Figure 5. Drainage Coefficient "C_d" versus Slab Thickness



Reliability

Reliability can be viewed in several different ways. Perhaps the most straight forward way is to assume that with a reliability of 90 percent, 90 percent of the pavement will not require rehabilitation prior to reaching the specified terminal serviceability value.
Reliability in the 93 Guide is nonspecific about the mode of pavement failure. As shown in Figure 6, reliability levels exceeding 95 percent have a significant impact on the pavement thickness and their use should be discouraged on the basis of initial cost versus rehabilitation costs.

Figure 6. Reliability versus Slab Thickness



Conclusions

Economizing concrete pavements is not difficult but requires a thorough understanding of the benefits and costs of various design features. The 93 Guide does not lend itself to in-depth analyses of design features, but some ideas can be gained by looking at sensitivity of 93 Guide variables. In the following R&T Update, a similar analysis of variable sensitivity using the most recent version of the M-E PDG will be offered.