Module 3-2

PCC DESIGN PROCEDURES

This module provides a framework for performing, analyzing, and checking PCC pavement designs.

PCC Design Procedures

- PCA Procedure
- AASHTO Procedure
- NCHRP 1-26 Methodology

Recognize the capabilities and limitations of different PCC design procedures

Procedures can be used independently or as checks for designs generated by other procedures.

Each procedure has its own advantages and limitations.

Design catalogs will also be discussed.

PCA Design Procedure

- Mechanistic-empirical procedure
- Originally developed in 1966
- Incorporates new trends in PCC design (tied PCC shoulders, widened lanes, LCB)
- For JPCP, JRCP, and CRCP
- Considers two failure modes:
  - ► Fatigue cracking
  - ► Erosion

Goal is to "find the minimum thickness that will result in the lowest annual cost, as shown by both initial construction costs and future maintenance costs."

PCAPAV, a computerized version of this procedure, is also available.

Cumulative Damage Concept

- **Every load application inflicts a small amount of damage to a pavement.**
- **Repeated loading applications can cause failure of the pavement.**
- **Miner's Fatigue Damage Concept**

$$\text{Damage} = \sum \frac{n}{N}$$

n = Actual number of applications sustained
N = Theoretical number of applications to failure

Remember that these numbers represent allowable and actual load applications of all different vehicle types.

PCA Fatigue Analysis

- **Critical stress occurs at outer slab edge, midway between the transverse joints**
- **Repeated application of less than ultimate loads can lead to midslab cracking**
- **Controlling factor is the ratio of the stress induced by the load (σ) to the PCC modulus of rupture (MR):**

$$\text{Stress Ratio} = SR = \sigma / MR$$

When the stress ratio is kept low (less than 0.45), the number of allowable load applications is considered to be unlimited (see next slide).

PCA Fatigue Models

$$\log N = 11.737 - 12.077\ SR$$

for $SR \geq 0.55$

$$N = [(4.2577 / (SR - 0.4325)]^{3.268}$$

for $0.45 < SR < 0.55$

N = unlimited

for $SR \leq 0.45$

These equations are incorporated into the design nomograph.

PCA Erosion Analysis

- Critical deflections in a jointed pavement occur with a load placed at the slab corner
- Many repetitions of corner loading can cause pumping, erosion, loss of support, voids, corner breaks, and faulting
- PCA researchers investigated the "power" with which an axle pounds the pavement:
  - ➤ Thinner slabs receive a faster load punch, creating greater erosion

Pumping was the principal mode of failure of concrete pavements at the AASHO Road Test.

For jointed PCC pavements, distresses at joints are a more common problem than fatigue cracking.

PCA Erosion Model

$$\log N = 14.524 - 6.777\,(C_1 P - 9.0)^{0.103}$$

where:

P = power

= $268.7\,[p^2 / h]\,k^{-0.73}$

C_1 = subbase adjustment factor

Again, designer does not need to calculate the power factor or the erosion life (N). Both are already incorporated into the design charts.

Truck Placement

- 6 percent of the trucks are assumed to travel at the slab edge
- This assumption is incorporated into stress charts
- High estimate provides some conservatism to the resulting thickness design

The procedure provides only guidelines which may be modified based on local experience.

PCA Thickness Design Procedure

- **Determine inputs (including selection of trial thickness)**
- **Conduct fatigue analysis**
- **Conduct erosion analysis**
- **Revise design as needed**

The PCA procedure can be broken down into these four simple steps.

We'll work through the steps manually, although a computer program (PCAPAV) is available for solving this procedure.

The trial thickness is used in the initial erosion and fatigue analysis (discussed later).

PCC Modulus of Rupture

- **Mean 28-day strength (third-point loading)**
- **MR reduced by 1 standard deviation in design charts (assuming 15% COV)**
- **Effects of strength gain after 28 days incorporated in design charts**

Although third-point loading is recommended, cantilever or center-point loading may also be used. Third-point loading provides a more conservative answer.

Modulus of rupture is reduced by one standard deviation to account for variation in PCC strength.

Slab Support (*k*-value)

- **Determined from plate loading test**
- **Estimated from other soil strength parameters**
- **Presence of base or subbase increases the *k*-value**

Plate loading test is time-consuming and expensive.

Can estimate k-value from CBR, R-value, or soil classification (see figure 3-2.3 on page 3-2.9).

Seasonal variations are ignored and normal summer or fall k-values are used as inputs.

PCA feels that brief periods of weakness are offset by long periods of strength.

Axle Load Data

- Axle load distribution (axle type and load magnitude)
- Expected number of load repetitions over design period
- Load safety factor:
  - 1.2 for high truck volume roadways
  - 1.1 for moderate truck volume roadways
  - 1.0 for low truck volume roadways

The designer must estimate the yearly rate of traffic growth.

Truck weights and volumes are especially important.

Joint Load Transfer and Shoulder Type

- Transverse joint load transfer
  - Doweled
  - Nondoweled
- Shoulder Type
  - Tied PCC
  - AC

Load transfer type has a substantial effect on corner deflections.

Tied PCC shoulders also reduce corner deflections.

Fatigue Analysis

- Select trial thickness
- Determine equivalent stress from charts
- Calculate stress ratio factor
- Determine allowable number of repetitions for each axle load class
- Calculate fatigue damage caused by each axle load class (expected/ allowable)
- Sum fatigue damage
  - If < 1, design acceptable for fatigue
  - If > 1, design unacceptable for fatigue

Demonstrate the procedure using the tables and charts in the manual.

The procedure for fatigue analysis is outlined on page 3-2.14.

Erosion Analysis

- Select trial thickness
- Determine erosion factor from charts
- Determine allowable number of repetitions for each axle load class
- Calculate erosion damage caused by each axle load class (expected/allowable)
- Sum erosion damage
  - If < 1, design acceptable for fatigue
  - If > 1, design unacceptable for fatigue

Demonstrate the procedure using the tables and charts in the manual.

Procedure for erosion analysis is outlined on page 3-2.14.

Axle Load, kips	Multiplied by LSF	Expected Reps	Allowable Fat. Reps	Fatigue, percent	Allowable Eros. Reps	Damage, percent
Single - 30	36	6310	27000	23.3	1500000	0.4
28	33.6	14690	77000	19.1	2200000	0.7
26	31.2	30140	230000	13.1	3500000	0.9
24	28.8	64410	1200000	5.4	5900000	1.1
22	26.4	106900	Unlimited	0	11000000	1.0
20	24	235800	Unlimited	0	23000000	1.0
18	21.6	307200	Unlimited	0	64000000	0.5
16	19.2	422500	Unlimited	0	Unlimited	0
14	16.8	586900	Unlimited	0	Unlimited	0
12	14.4	1837000	Unlimited	0	Unlimited	0
Tandem-52	62.4	21320	1100000	1.9	920000	2.3
48	57.6	42870	Unlimited	0	1500000	2.9
44	52.8	124900	Unlimited	0	2500000	5.0
40	48	372900	Unlimited	0	4600000	8.1
36	43.2	885800	Unlimited	0	9500000	9.3
32	38.4	930700	Unlimited	0	24000000	3.9
28	33.6	1656000	Unlimited	0	92000000	1.8
24	28.8	984900	Unlimited	0	Unlimited	0
20	24	1227000	Unlimited	0	Unlimited	0
16	19.2	1356000	Unlimited	0	Unlimited	0
TOTAL				62.8		38.9

See Table 3-2.5 on page 3-2.13.

Fatigue controls the design of light-traffic and medium-traffic doweled pavements.

Erosion controls medium- and heavy-traffic nondoweled and heavy-traffic doweled pavements.

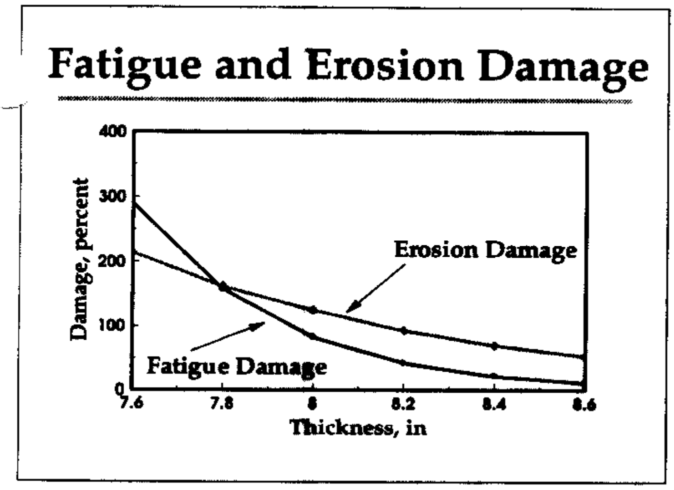
Regardless, both fatigue and erosion analysis should be performed.

PCAPAV solves the procedure more quickly and with greater accuracy.

Sensitivity Analysis of PCA Procedure

- Evaluation of the effect of design inputs on resultant design
- Provides indication of factors that must be carefully determined

Some design inputs will have a much more dramatic effect on the required slab thickness than others.



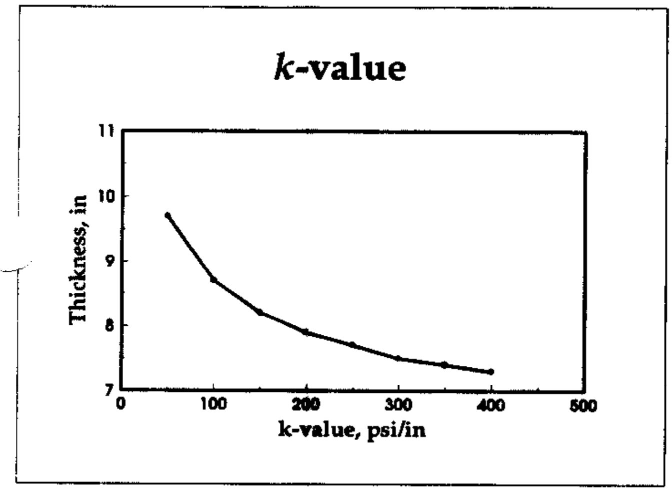
Fatigue and Erosion Damage

Figure 3-2.8 (page 3-2.22).

Fatigue is affected more dramatically with thickness.

Both fatigue and erosion damage decrease with increasing thickness.

Fatigue damage controls initially, then erosion damage controls.

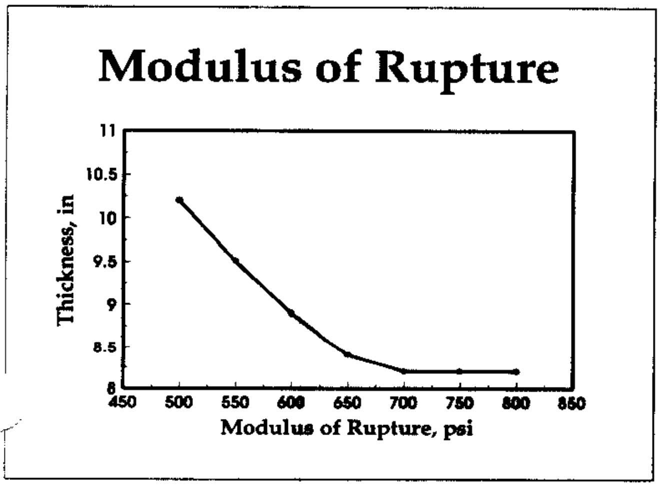


k-value

Figure 3-2.9 (page 3-2.23).

As k-value increases, required design thickness decreases.

Effect is more significant at lower k-values.



Modulus of Rupture

Figure 3-2.10 (page 3-2.23).

PCC modulus of rupture has an enormous effect on the required thickness.

Levels off when erosion analysis begins to control.

ADTT

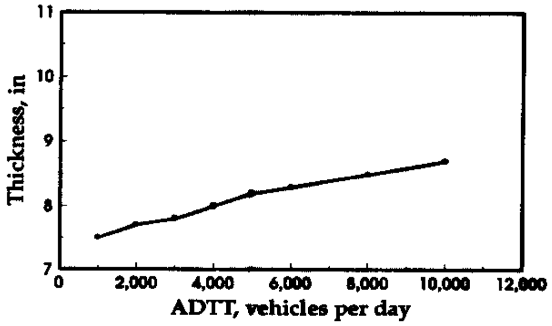


Figure 3-2.11 (page 3-2.24).

Required thickness increases as ADTT increases.

- More pronounced effect at lower levels

As ADTT increases from 5,000 to 10,000 vehicles per day, required thickness increases only by about 0.5 inches.

Load Safety Factor

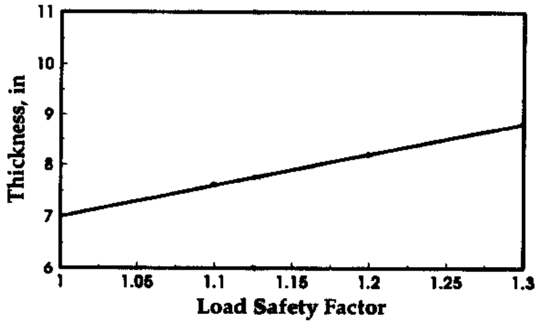


Figure 3-2.12 (page 3-2.24).

Required thickness increases linearly as LSF increases.

Increase in LSF of 0.1 inch leads to a 15 mm (0.6 in) increase in required thickness.

Advantages of PCA Procedure

- Mechanistic-based procedure
- Considers multiple failure modes
  - Fatigue cracking
  - Erosion damage
- Considers load spectra in developing accumulated damage
- Computerized version available

Models joint load transfer alternatives and tied PCC shoulders.

The procedure is relatively simple to use.

Procedure has been used for many years.

Disadvantages of PCA Procedure

- **Some empiricism remains in procedure, limiting applicability**
- **Ignores effects of thermal curling and moisture warping**
- **Ignores effects of drainage**
- **Limited guidance on other design variables (joint spacing, dowels, reinforcement)**

All procedures have some sort of empiricism in order to relate to field performance. This is based on road test data.

Same thickness required for CRCP and jointed, doweled pavements. This may or may not hold true for actual pavements.

QUESTIONS?

AASHTO Design Procedure

- **Empirical design procedure based on results of AASHO Road Test**
- **Six traffic loops, each containing a range of different pavement designs, subjected to a known truck loads over a 2-year period**
- **Resulting design model relates the number of truck ESAL applications to a loss in pavement serviceability**

The procedure can be used for initial design or as a design check.

It represents the largest database available for pavement design.

This procedure is only discussed briefly for this course; another course is available for AASHTO Design procedure.

AASHO Road Test Conditions

- **Slab thickness ranged from 2.5 to 12. 5 in**
- **Section lengths 120 to 240 ft**
- **Dense-graded sand-gravel subbase**
- **A-6 subgrade (CBR of 2 - 4)**
- **All transverse joints doweled**
- **Slab lengths: 40 ft JRCP; 15 ft JPCP**
- **Northern Illinois climate**
- **Two years of loading (10 million ESALs on heaviest loop)**

A wide range of thicknesses was used.

Test section lengths (*not joint spacings*) were 120 to 240 feet.

These conditions lead directly to some of the limitations in the procedure; only a limited range of materials and design features were represented in the sections.

Evolution of AASHTO Procedure

- 1962 - Original Interim Guide
- 1972 - Interim Guide
- 1981 - Revised Interim Guide (PCC revised only)
- 1986 - New Guide Issued
- 1993 - New Overlay Design Procedure

Several major modifications were made in the rigid pavement design procedures in the 1986 version. These changes were made in an attempt to expand the applicability to different climates, materials and soils across the U.S.

However, no changes were made to the rigid pavement design procedure in 1993.

AASHTO Design Inputs

- Performance Period
- Traffic (ESALs)
- Reliability
- Standard Deviation
- Serviceability
- Effective *k*-value
- PCC Elastic Modulus
- PCC Modulus of Rupture
- Drainage Coefficient
- Load Transfer Coefficient

Discuss each of these inputs briefly. A description of the inputs begins on page 3-2.29.

- Reliability - table 3-2.15 (page 3-2.30)
- Standard deviation - generally 0.39
- Serviceability - initial was 4.5 at Road Test, terminal generally from 2.5 to 3.0
- k-value - effective value, account for seasonal effects and loss of support
- Elastic modulus - 28-day
- Modulus of rupture - 28-day, third-point loading
- Drainage coefficient - accounts for effect of drainage on performance (table 3-2.18)
- Load transfer - table 3-2.19

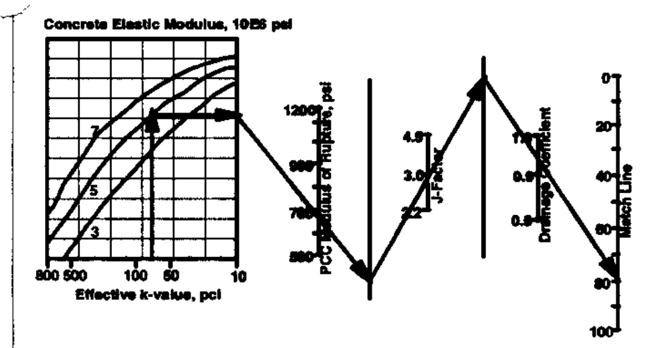
AASHTO Thickness Design Computation

- Manual Solution
- Nomographs
- Computer Program (DARWin)

Manual solution is quite tedious.

Nomographs are simplified but less precise.

Computerized approach allows easy consideration of all design factors and provides precise solutions.



Work through nomograph.

Figure 3-2.13 (page 3-2.35).

Design chart for rigid pavements using mean input values (Segment 1).

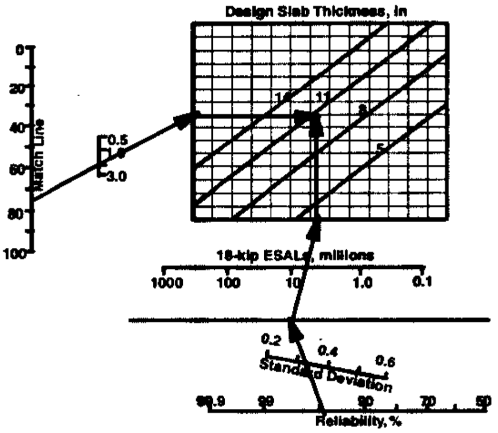


Figure 3-2.13 (page 3-2.36).

Design chart for rigid pavements using mean input values (Segment 2).

Sensitivity Analysis of AASHTO Procedure

- **Provides indication of factors that must be carefully determined**
- **Sensitive Factors:**
  - ➤ **Traffic (ESALs)**
  - ➤ **Serviceability**
  - ➤ **Modulus of Rupture**
  - ➤ **Load Transfer Coefficient**
  - ➤ **Drainage Coefficient**

Some design inputs have a greater effect on the required slab thickness than others.

A sensitivity analysis will illustrate the effect that an input has on the design.

Review the sensitive plots (figures 3-2.15 to 3-2.20).

The effect of certain factors varies depending on other design conditions; a sensitivity analysis should be conducted for each particular design.

Advantages of AASHTO Procedure

- **Straightforward, easy-to-use procedure**
- **High "comfort level" due to its long history of use in highway agencies**
- **Addresses many of the critical areas of concrete pavement design**
- **Computerized version available**

The procedure is widely used and well understood. It is currently used by many State highway agencies.

Takes into account factors such as reliability, load transfer, and drainage.

The inputs can be selected to fit an agency's needs.

Disadvantages of AASHTO Procedure

- **Empirical procedure limited to specific conditions of AASHO Road Test**
  - ► **Climate**
  - ► **Subgrade**
  - ► **Joint design**
- **Not clear on the effect of the various enhancements that have been added over the years**

Lack of guidance on some inputs, such as loss of support and drainage factors, is a major limitation.

Limitations of general use of a design procedure that was developed from very specific conditions over a short period of time.

QUESTIONS?

NCHRP 1-26

- **Methodology for designing PCC pavements**
- **Mechanistic-empirical procedure**
- **Did not develop new pavement design technologies, but rather made use of best available mechanistic-empirical technology**
- **Methodology structured so that highway agencies can tailor it to their specific conditions using local models and calibrations**

Calibrated Mechanistic Structural Analysis Procedures for Pavements

This approach may appear in future versions of the AASHTO Design Guide

Performance is influenced by a number of factors that cannot be precisely modeled by mechanistic methods. Therefore, it is necessary to calibrate the models with observations of performance (i.e., empirical correlation). Thus, the procedure is referred to as mechanistic-empirical.

Design Methodology

- Determine design inputs (including slab thickness)
- Compute key slab responses for use in distress models (e.g., edge stress)
- Analyze design using selected mechanistic-based models (e.g., cracking, faulting)
- Modify design as appropriate to reduce distresses to acceptable levels

Look at critical distresses:

- How much cracking?
- What degree of pumping?

Design Inputs

- PCC properties
- Slab properties
- Subbase type and characterization
- Subgrade support
- Environmental data
- Design traffic

All inputs required for distress models are needed

Each design input is described subsequently in more detail.

PCC Properties

- Modulus of rupture
  - ► Mean 28-day strength (ASTM C 78)
  - ► Third-point loading
- Elastic modulus
  - ► Estimate from strength parameters
- Poisson's ratio
  - ► Use 0.15 as standard input

Third-point loading provides a more conservative answer than cantilever or center-point loading, and is generally preferred.

Slab Properties

- Slab thickness
- Slab dimensions
  - ► Slab length
  - ► Slab width
- Load transfer design
  - ► Dowels
  - ► Aggregate interlock

First, assume a slab thickness an joint spacing. Then, the procedure checks the design to see if it is adequate.

Adjust thickness and joint spacing until distresses meet certain minimum criteria.

Subbase Type and Characterization

- Subbase type
  - ► Stabilized (cement-treated, asphalt-treated)
  - ► Nonstabilized
  - ► Open-graded
- Characterization
  - ► Use *k*-value of natural subgrade
  - ► Stabilized base will reduce load-related stresses in overlying slab, but may reduce or increase environmental stresses, depending upon bonding condition

Specific properties (elastic modulus and Poisson's ratio) are required for stabilized bases.

The effect of a nonstabilized layer on required thickness is insignificant.

Open-graded materials may be stabilized or nonstabilized.

Subgrade Support

- Modeled as a Winkler foundation
- Characterized by *k*-value

The model uses a slab on a dense liquid (Winkler) foundation, which uses buoyancy forces.

Recommend the use of k-value of the natural subgrade; do not increase k-value for effect of base layers.

Environmental Data

- Temperature differentials through slab
  - ► Determined using climatic models (e.g., CMS) or from tables in NCHRP report
  - ► Relative frequency that slab is subjected to discrete temperature differentials
- Average yearly maximum and minimum temperatures
- Freezing Index

Temperature differential:

- Temperature at top of slab minus the temperature at bottom of slab
- Positive = daytime
- Negative = nighttime
- Figure 3-2.21 (page 3-2.46) shows a histogram of temperature differentials (similar data available for 13 cities across the U.S.)

Thermal curling stresses are incorporate into the procedure, but moisture warping stresses are ignored.

Traffic Data

- Truck traffic load spectra
  - ► Axle type
  - ► Axle load
  - ► Expected number of repetitions
- Estimated ESAL applications over design period
  - ► Conversion of load spectra data using equivalency factors

There are different LEFs for each different distress type.

LEFs developed at AASHO Road Test are based on serviceability only, and are not the same as LEFs developed for different distress types.

The preferred (more accurate) method is direct input of load spectra data. The ESAL concept is empirical and often disputed. However, the use of load spectra data is mechanistic but also more rigorous.

Computation of Slab Responses

- Edge stress
  - ► Determine ESAR for multiple loaded areas (e.g., dual tires, tandem axles)
  - ► Uses Westergaard's 1948 stress equation
  - ► Corrected for slab size, widened lane, tied shoulders, and stabilized base
  - ► Curling stresses added to edge stress
- Dowel bearing stress
- Corner deflection

Finite element method is most accurate, but also the most complex model for analyzing pavement responses. Therefore, regression equations were developed based on ILLI-SLAB results (discussed in Module 3-1).

These equations can be used to easily solve for stresses, and user does not have to be familiar with finite element methods.

Computer program ILLICON solves these equations.

Analysis of Design

- **Suitable distress models selected**
  - ► **Transverse Cracking**
    - → **Edge stress computation**
    - → **Fatigue model**
  - ► **Pumping**
  - ► **Joint spalling**
  - ► **Faulting**
    - → **Bearing stress computation**
- **Selected design inputs used in distress models to predict performance**

Transfer functions (performance prediction models) correlate mechanistic pavement responses to specific distresses.

Only the fatigue and faulting models are incorporated into ILLICON.

Transverse Cracking

- **Fatigue Model**

$$\log N = -1.7136\,R + 4.284 \qquad \textit{for } R > 1.25$$

$$\log N = 2.8127\,R^{-1.2214} \qquad \textit{for } R < 1.25$$

- **Cracking Model**

$$\%\ \text{Cracks} = \frac{1}{0.01 + 0.0713\,[\,2.5949^{-\log FD}\,]}$$

R > 1.25 should lead to failure, theoretically.

However, field and lab results differ (different material strengths over time, support conditions, etc.).

See Figure 3-2.22 (page 3-2.49).

Cracking - FD of 100% translates to 50% slabs cracked (see figure 3-2.23, page 3-2.49).

Joint Faulting

- **Doweled Joints**

$$F_d = ESAL^{0.6}\,[0.00334\,\sigma_{bc}^2 + 60.228\,k^{1.809} - 0.0074\,TS]$$

- **Nondoweled Joints**

$$F_{ud} = ESAL^{0.3057}\,\omega^{0.4088}\,\delta_c^{0.1205}\,[0.2602 - 0.0693\,D - 0.1101\,TS]$$

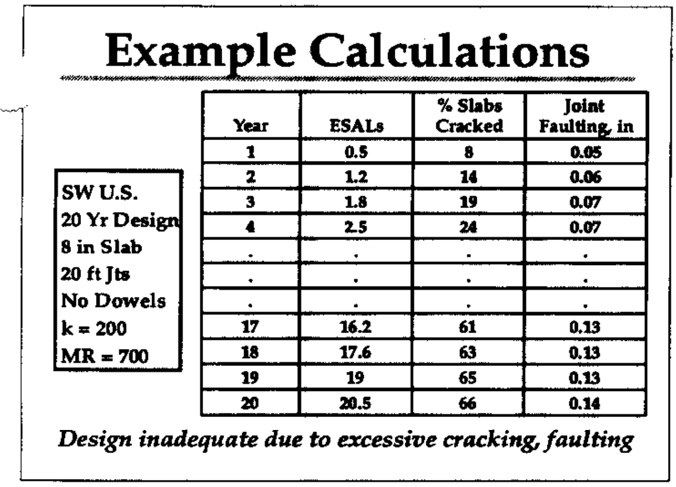
Predicted vs. measured faulting for doweled joints - Figure 3-2.26 (page 3-2.53).

Sensitivity - Figure 3-2.27 (page 3-2.54)

- ESALs and stress have largest effect on joint faulting.

Undoweled joints - Figures 3-2.28 - 3-2.30 (pages 3-2.56 - 3-2.58)

- More scatter in data.
- As joint widens, aggregate interlock is decreased, resulting in greater faulting.



Example Calculations

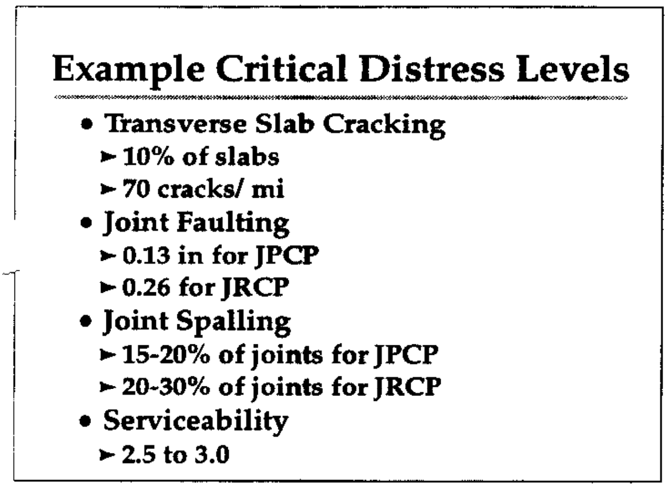
SW U.S.
20 Yr Design
8 in Slab
20 ft Jts
No Dowels
k = 200
MR = 700

Year	ESALs	% Slabs Cracked	Joint Faulting, in
1	0.5	8	0.05
2	1.2	14	0.06
3	1.8	19	0.07
4	2.5	24	0.07
.	.	.	.
.	.	.	.
.	.	.	.
17	16.2	61	0.13
18	17.6	63	0.13
19	19	65	0.13
20	20.5	66	0.14

Design inadequate due to excessive cracking, faulting

This slide illustrates the results from ILLICON.

Design is inadequate, so must change at least one of the design parameters in order to limit distresses.



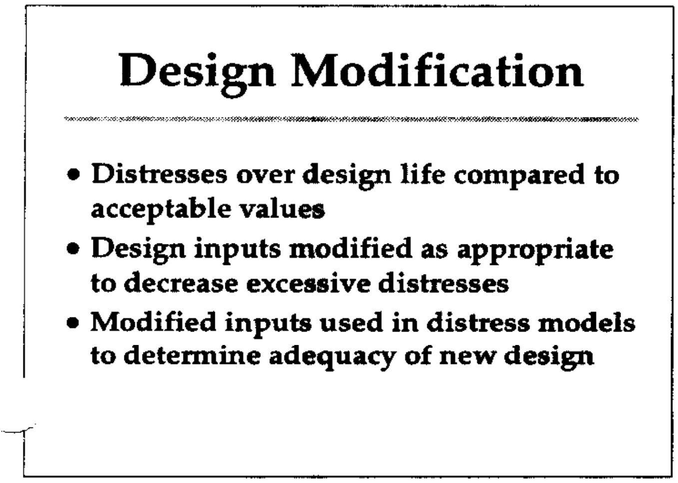
Example Critical Distress Levels

- **Transverse Slab Cracking**
  - **10% of slabs**
  - **70 cracks/ mi**
- **Joint Faulting**
  - **0.13 in for JPCP**
  - **0.26 for JRCP**
- **Joint Spalling**
  - **15-20% of joints for JPCP**
  - **20-30% of joints for JRCP**
- **Serviceability**
  - **2.5 to 3.0**

What level of distress is acceptable?

Each agency can select its own criteria.

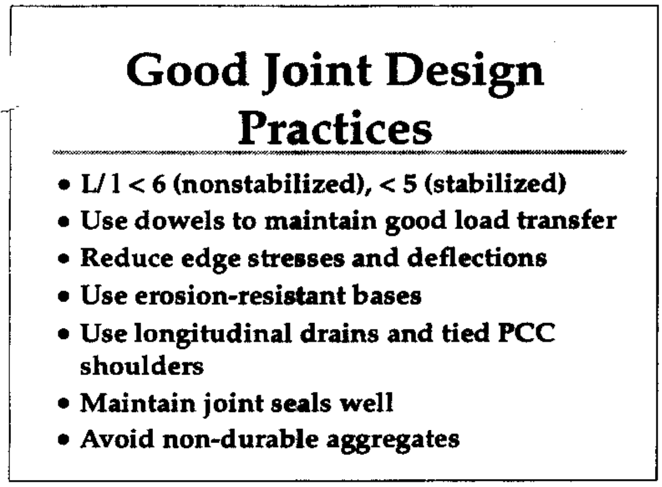
If design is inadequate, modify and check again.



Design Modification

- **Distresses over design life compared to acceptable values**
- **Design inputs modified as appropriate to decrease excessive distresses**
- **Modified inputs used in distress models to determine adequacy of new design**

Continue iterative process until design meets established criteria.



Good Joint Design Practices

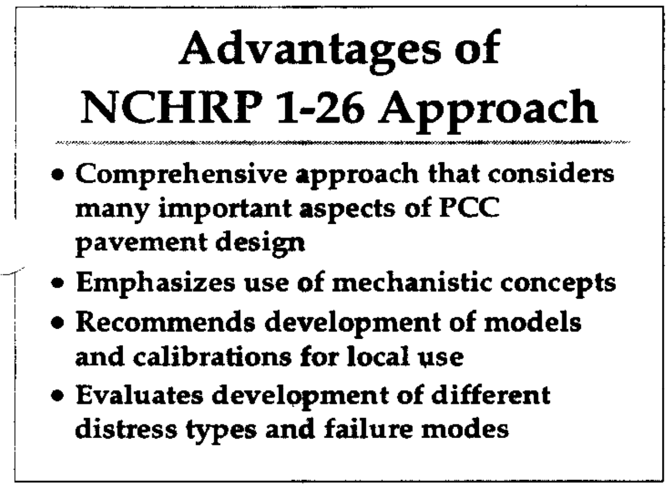
- L/l < 6 (nonstabilized), < 5 (stabilized)
- Use dowels to maintain good load transfer
- Reduce edge stresses and deflections
- Use erosion-resistant bases
- Use longitudinal drains and tied PCC shoulders
- Maintain joint seals well
- Avoid non-durable aggregates

These recommendations are listed on page 3-2.55.

Controlling L/l minimizes potential for transverse cracking due to shrinkage, warping and curling, and traffic loads.

Any reduction in slab stresses and slab deflections will result in improved joint performance.

Erosion-resistant bases, longitudinal drains, and tied PCC shoulders can reduce probability and severity of faulting.



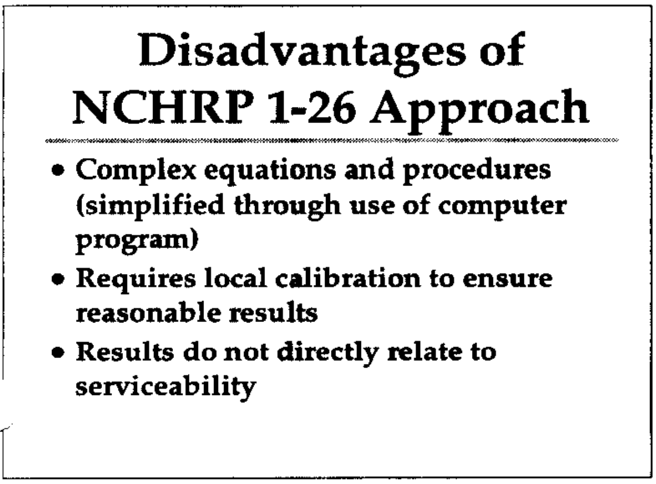
Advantages of NCHRP 1-26 Approach

- Comprehensive approach that considers many important aspects of PCC pavement design
- Emphasizes use of mechanistic concepts
- Recommends development of models and calibrations for local use
- Evaluates development of different distress types and failure modes

Considers curling stresses, which many other procedures neglect.

Considers several important aspects in overall system design.

This approach is a comprehensive, theoretically sound approach to pavement design.



Disadvantages of NCHRP 1-26 Approach

- Complex equations and procedures (simplified through use of computer program)
- Requires local calibration to ensure reasonable results
- Results do not directly relate to serviceability

It is difficult to thoroughly understand and solve the equations. This is made simpler through ILLICON program.

Transfer functions were developed from a specific set of material properties and climatic conditions. Therefore, requires local calibration, but so do other procedures.

Results indirectly affect serviceability.

DESIGN CATALOGS

Design catalogs provide a quick and easy system for pavement design and can be a very valuable tool for designers.

Generally based upon specific key inputs, such as traffic level and k-value.

Widely used in many European and other countries with great success.

Design Catalogs

- Series of similar-performing design options that can be selected for given traffic levels, support conditions, etc.
- Developed from observations of local performance or from multiple runs of design models (e.g., AASHTO) and theoretical analysis
- Easily modified to keep up with current practices and changing conditions

Combine theoretical analysis and engineering and construction experience

Time is spent initially developing catalogs; designs are easier afterwards.

Emphasize the design of the total system, not just thickness. They can simplify the design process without sacrificing comprehensiveness.

Example in Figure 3-2.31 (page 3-2.60).

Summary

- Various design procedures for PCC pavements described
  - ► PCA
  - ► AASHTO
  - ► NCHRP 1-26
  - ► Design Catalogs
- Important to consider alternative design procedures in order to develop reliable, cost-effective design

What if the results from various procedures differ?
- Need to apply engineering judgment
- Use procedure that applies most directly to your own local conditions/materials

Designer should think carefully about all aspects of the design procedure
- Try to understand what is really happening in the pavement <u>system</u>
- Stop thinking of thickness design vs. detail design (each one affects the other).

How do your pavements perform? What are typical failure modes? What are typical performance periods?