Module 3-1

PCC PAVEMENT RESPONSES

This module describes several methods for analyzing stresses in PCC pavements.

Review instructional objectives (page 3-1.1).

For PCC pavements, stresses correlate better to performance than strains.

Need to Evaluate Slab Stresses

- **Excessive stresses can produce failure**
- **Several "critical locations" in the slab that can control pavement performance**
  - ➤ **Slab edge**
  - ➤ **Slab corner**
- **Design modifications may be warranted if stresses are excessive**
- **Mechanistic-based design procedures directly consider slab stresses**

Must clearly understand the causes and effects of stresses:

- Reduce stresses in pavement
- Enhance pavement performance

Sources of Slab Stresses

- Traffic Load
- Thermal Curling
- Moisture Warping
- Drying Shrinkage
- Temperature Contraction

Combine various stresses to determine the combined stress state in a PCC pavement.

Critical condition exists when stresses are additive.

Stresses are not always directly additive; often multiplied by a correction factor before combining.

Traffic Load Stresses

- **Major source of stresses in pavements**
- **Traffic load creates a bending stress (tensile stress at the bottom of the slab)**
- **Repeated applications can result in fatigue cracking**
- **Critical location is generally along outside slab edge (and/ or at transverse joint for nondoweled pavements)**

Generally most critical when load is placed at slab edge, midway between transverse joints.

- Sometimes at an interior location (but usually reduced through load transfer within slab)
- Sometimes at transverse joints (reduced through dowels or aggregate interlock)
- Sometimes at corners (especially if loss of support is experienced)

There is no evidence that fatigue cracking begins at any location other than slab edge.

Curling Stresses

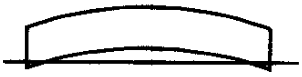
- **Temperature differentials between the top and bottom of the slab**
- **Magnitude depends on slab properties, support conditions, and thermal gradient**
- **Positive (daytime) temperature gradients curl the slab down at the corners**
  - ► **Critical when wheel load at slab edge**
- **Negative (nighttime) temperature gradients curl the slab up at the corners**
  - ► **Critical when wheel load at slab corner**

Often neglected by designers

- Shorter joint spacings reduce curling stresses.
- Reinforcing steel holds cracks tight.
- See top of page 3-1.4.

Yet, cracking was still evident in a nontraffic loop at the AASHO road test surveyed 16 years after construction (especially in the 40 ft slabs).

Thermal Curling



Positive (daytime) curling

Negative (nighttime) curling

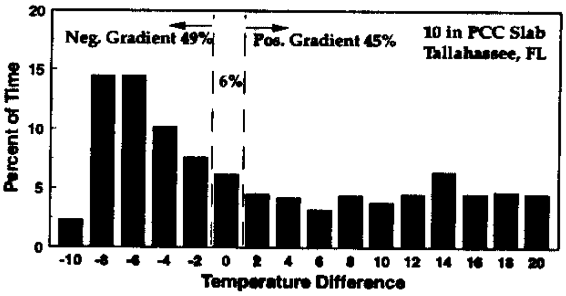
Figure 3-1.1 (page 3-1.3).

Curling stresses can be additive (daytime) or deductive (nighttime).

Daytime stresses are more critical when considering edge stresses and fatigue cracking.

Curling stresses are greater in slabs placed on stabilized materials. Softer materials allows slab to settle, producing increased support.

Curling Frequency



Percentage of time for negative (nighttime) and positive (daytime) gradients is about equal.

However, positive gradients are spread out over a much wider range (0 to 20) than negative (0 to -10).

Other research has shown that the slab has a negative temperature gradient two-thirds of the time.

Warping Stresses

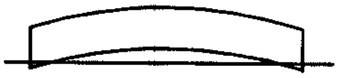
- Caused by differences in moisture content between the top and bottom of the slab
- Greater moisture at top of slab results in downward warping, and vice versa
- Moisture contents through slabs in:
  - Wet climates - fairly constant
  - Dry climates - top is drier than the bottom
- Difficult to measure stresses due to moisture

Moisture stresses are insignificant in most cases.

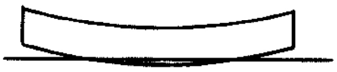
They can be taken into effect by adjusting the thermal gradient.

They are often difficult to quantify.

Moisture Warping



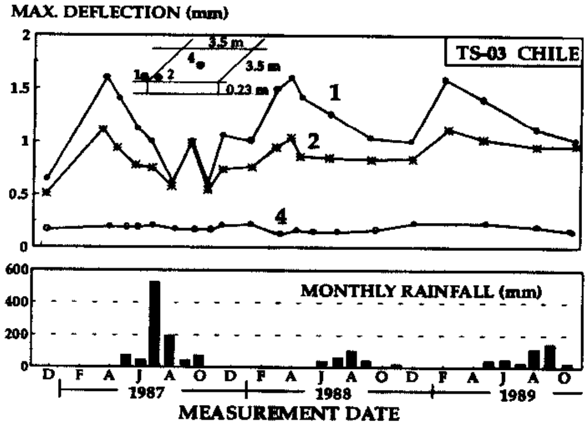
Slab top wetter than slab bottom



Slab bottom wetter than slab top

This is figure 3-1.4 (page 3-1.5), which illustrates the effect of moisture on the slab.

More moisture at the top of the slab caused downward curling, and vice-versa.



Moisture warping data from Chile - Figure 3-1.5 (page 3-1.6).

Corner deflections are highest during the dry periods of the year (slab corners warped upward).

Deflections are lowest after periods of rainfall.

Drying Shrinkage Stresses

- **Loss of moisture in hardened concrete leads to shrinkage of slab**
- **Shrinkage resisted by friction of the base, which induces the development of stresses in the slab**
- **Introduction of joints reduces magnitude of shrinkage stresses**

Varies with: water/cement ratio, cement type, gradation of aggregate, admixtures, wind, temperature, and relative humidity.

Typically, for joint spacings less than 6 m (20 ft), drying shrinkage will have only a minor effect on transverse cracking development.

Drying shrinkage cracks are more evident in CRC pavements.

Temperature Shrinkage Stresses

- **Daily and seasonal temperature changes cause PCC slab to expand/contract**
- **Frictional force between slab and base creates stresses in slab**
- **Magnitude of stress estimated by subgrade drag formula:**

$$\sigma_c = \frac{L \; f \; \gamma_c}{2}$$

Tensile stress increases linearly with joint spacing.

Coefficient of frictional resistance (f) is difficult to estimate accurately.

Subgrade drag formula is Eq. 3-1.2 (page 3-1.8).

Combined Load and Curling Stresses

- Stresses result from traffic loading and climatic forces
- Combined stress state determined by combining environmentally related stresses on load-associated stresses.

Critical condition when curling and loading stresses are additive:

- Slab curled upward and load placed at corner
- Slab curled downward and load placed at an edge or interior location

Calculating Stresses in PCC Pavements

- Westergaard Equations
- Influence Charts
- Zero-Maintenance Equations
- NCHRP 1-26 Equations
- Finite Element Methods

Information required (list on page 3-1.9)
- Material properties
- Environmental information
- Load and traffic data
- Construction data (design details)

Specific stresses of interest depend on location of the load in relation to the slab edges.

Westergaard Equations

- Stress equations for three loading conditions (interior, edge, corner)
- Assumptions:
  - Slab is homogeneous, isotropic elastic solid
  - Shear forces ignored
  - Infinite slab dimensions
  - Winkler foundation
  - Circular contact area for interior and corner; semicircular contact area for edge

Original equations published in 1926.

Last revised by Westergaard in 1948.

Several simplifying assumptions are required, many of which are violated.

Westergaard equations are found on pages 3-1.11 through 3-1.13.

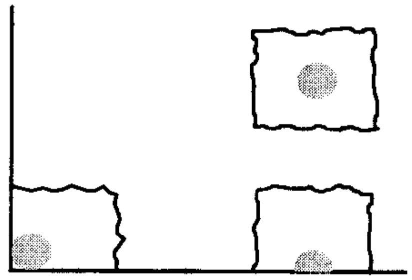
Limitations of Westergaard Theory

- **Only interior, edge, and corner stresses and deformations can be calculated**
- **Shear and frictional forces on slab surface may not be negligible**
- **Winkler foundation extends only to edge**
- **Assumes slab is fully supported**
- **Does not allow for multiple wheel loads**
- **Load transfer between joints and cracks is not considered**

Foundation extends only to slab edge. In reality, support is provided by the surrounding subbase and subgrade.

Neglects voids or discontinuities beneath the slab.

Westergaard Loading Conditions



Interior loading condition

- Wheel load at a considerable distance from the edges (circular)

Edge loading condition

- Wheel load at the edge, but at a considerable distance from the corner (semi-circular)

Corner loading condition

- Wheel load tangent to two perpendicular edges (circular)

Example Westergaard Equations

Edge Loading (semi-circular load)

$$\sigma_e = \frac{3(1+\mu)P}{\pi(3+\mu)h^2}\left[\ln\frac{Eh^3}{100ka_2^4} + 3.84 - \frac{4\mu}{3} + 0.50(1+2\mu)\left(\frac{a_2}{l}\right)\right]$$

Corner Loading

$$\sigma_c = \frac{3P}{h^2}\left[1 - \left(\frac{\sqrt{2}\,a}{l}\right)^{0.6}\right]$$

Equation 3-1.5 (page 3-1.12).

Equation 3-1.9 (page 3-1.13).

Westergaard Curling Stress Equation

Edge Stress

$$\sigma_e = \frac{C\ E\ \alpha_T\ \Delta T}{2}$$

Interior Stress

$$\sigma_i = \frac{E\ \alpha_T\ \Delta T}{2}\left[\frac{C_1 + \mu C_2}{1 - \mu^2}\right]$$

Equation 3-1.11 (page 3-1.13).

Equation 3-1.12 (page 3-1.13).

Overestimates curl stress for short slabs on stiff subgrades.

Underestimates curl stress for short slabs on soft subgrades.

Solutions to Westergaard Equations

- Manual Methods
- Influence Charts
- Computer Programs
  - ➤ WESTER
  - ➤ ERES spreadsheet

Pickett and Ray influence charts seldom used today because of their tedious nature.

Computer programs can quickly and easily solve for stresses and deflections in PCC pavements.

Zero-Maintenance Equations

- Regression equations developed from finite element results for determination of edge stress due to load and curling
- STRT = STRL + R *x* STRC
- ZMAN computer program

Load stress and curl stress are calculated separately, then combined using the equation shown (Eq. 3-1.13 on page 3-1.15).

Load (STRL) and curl (STRC) stresses are not directly additive. R is an adjustment factor that also must be calculated (Eq. 3-1.17 on page 3-1.18).

ZMAN example in Figure 3-1.8 (page 3-1.17)

NCHRP 1-26 Equations

- Uses Westergaard's 1948 edge stress equation (circular load) as basis
- Adjustment factors developed from finite element results to account for stress reductions
- Thermal curling stresses based on Westergaard solution, modified by factor from finite element results

Calibrated Mechanistic Design procedure developed under NCHRP 1-26.

Uses regression models based on finite element theory.

Applies various correction factors to the result obtained from Westergaard's 1948 edge stress result (using equivalent loaded area).

ESAR Concept

- Westergaard equations require single load
- Converts multiple wheel configurations to an equivalent single loaded area that produces the same bending stress with the same applied load and tire pressure
- Conversions equations for:
  - ➤ Dual loading configuration
  - ➤ Tandem axle loading configuration
  - ➤ Tridem axle loading configuration

Multiple wheel loads are converted to a single load of known radius and pressure. New radius is then used in Westergaard's equation.

Figure 3-1.9 (page 3-1.20) shows the various load configurations.

Other Stress Adjustments

- Slab size effects
  - ➤ Westergaard assumes infinite slab
- Widened lane/tied shoulder
  - ➤ Results in lower critical edge stress
- Stabilized base layer
  - ➤ Effect of bonded/unbonded conditions
- Calculate Total Stress:

$$\sigma_{Total} = \sigma_{\substack{Load \\ (adj)}} + R \times \sigma_{Curl}$$

Calculation of total combined stress is similar to the method used in the Zero Maintenance design.

The correction factor (R) is calculated using a different equation, however. R equation shown in equation 3-1.33 (page 3-1.26).

Work participants through the example problem beginning on page 3-1.26.

Finite Element Methods

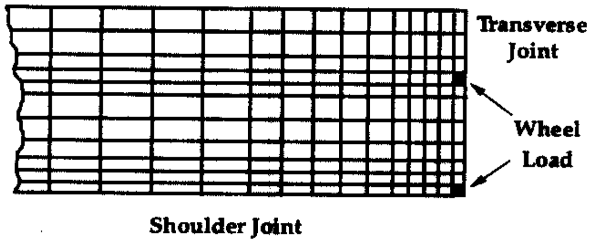
- **Divides slab into discrete "elements," each interconnected with one another**
- **Computes stresses, strains, deflections at any location in the slab**
- **Examples**
  - ► **ILLI-SLAB**
  - ► **JSLAB**
  - ► **KENSLABS**

Most powerful tool for analyzing jointed PCC pavements.

Initial responses calculated and adjusted through iterative process.

Generally, the programs are comparable, although each program has different assumptions and characteristics.

Finite Element Mesh



Finite element mesh must be developed carefully.

- Inadequately sized mesh may produce erroneous results.
- Designers should have a knowledge of finite element concepts before using finite element methods.

Critical Stress Locations

- **For fatigue damage accumulation, critical location is slab edge, midway between transverse joints**
- **Consider both load and curl stresses**

The critical location changes depending on the type of failure/distress being investigated.

Sensitivity of Critical Edge Stress to Design Variables

- Identify effects of design variables (e.g., slab thickness and tied PCC shoulders) on critical edge stress
- Recognize ways that critical edge stress can be reduced

Some slab properties have a much greater effect than others on the resultant edge stress.

Designers should understand the relative effects of various inputs.

Temperature Differential

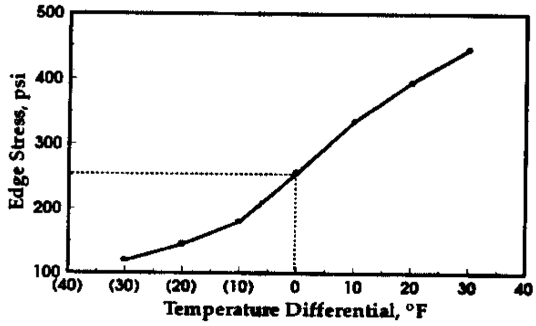


Figure 3-1.11 (page 3-1.31).

Temperature differentials induce curling stresses.

- Positive - additive stress
- Negative - deductive stress

As temperature differential increases, edge stress increases.

Curl stress should not be ignored when analyzing PCC pavements.

Slab Thickness

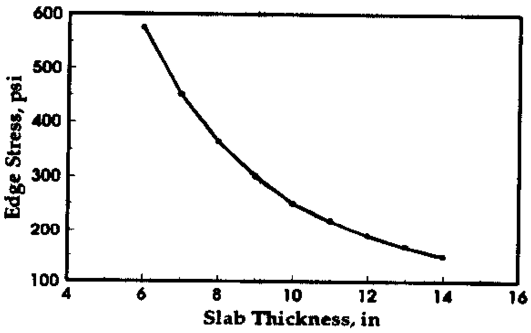


Figure 3-1.12 (page 3-1.31).

As slab thickness increases, edge stress is reduced.

More pronounced effect at lower values of slab thickness.

k-value

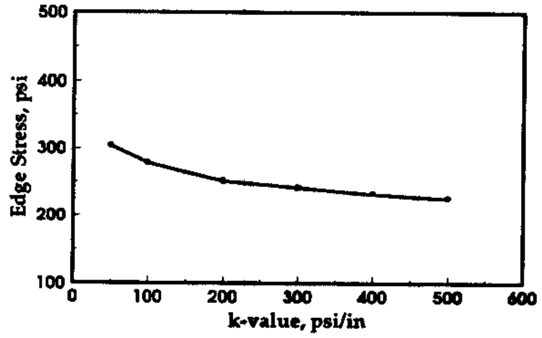


Figure 3-1.13 (page 3-1.32).

Edge stress is fairly insensitive to k-value.

There is some reduction in edge stress as k-value increases (up until about 250 psi/in.).

Elastic Modulus

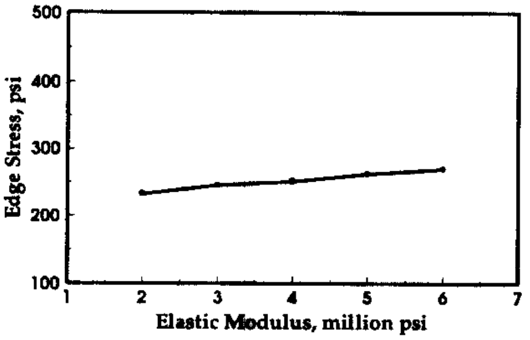


Figure 3-1.14 (page 3-1.32).

Elastic modulus has very little effect on edge stress.

Slab Length

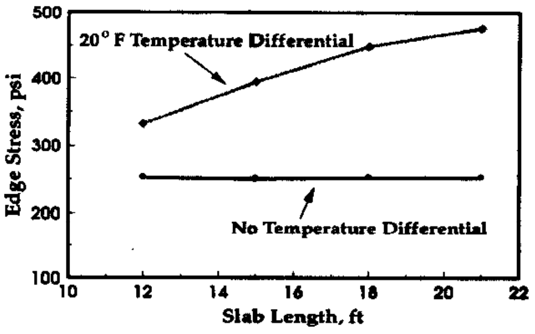


Figure 3-1.15 (page 3-1.34).

Slab length has a large effect on curl stresses.

Therefore, when temperature differential is 0, edge stress does not change with slab length.

However, edge stress increases by a large amount with increased slab length when temperature differential is 20.

Tied PCC Load Transfer

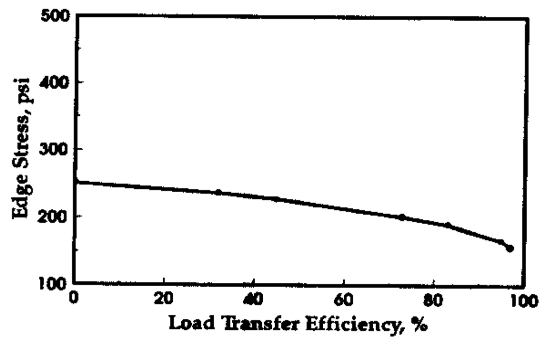


Figure 3-1.16 (page 3-1.33)

Edge stress is reduced with increased load transfer efficiency.

More pronounced reduction in edge stress once load transfer efficiency exceeds 75%.

Dowel Bearing Stresses

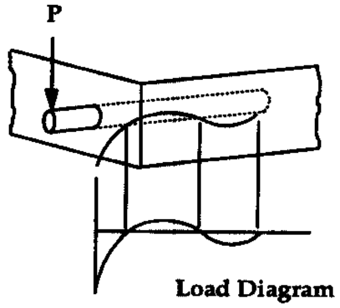
- Long-term effectiveness of dowel bars depends largely on magnitude of bearing stress exerted by dowel
- Excessive dowel bearing stresses can lead to fracture of the concrete, dowel "socketing," poor load transfer, and excessive faulting
- Dowel bearing stresses can be calculated using pioneering work done by Friberg

Dowels bars transfer load across the joint, thus reducing stresses, deflections, and faulting.

Size and spacing of dowels are governed by the bearing stress between the dowel and the concrete.

Although maximum bearing stress exerted by dowels on concrete is a critical aspect of design, it is often overlooked.

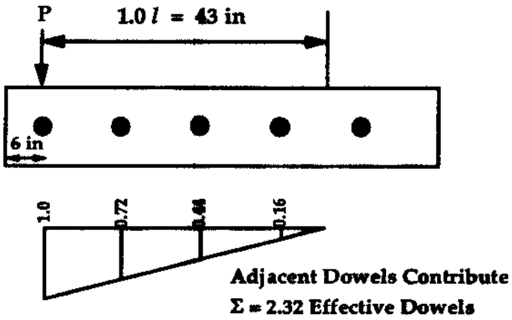
Dowel Bearing Stress



Stress between dowel and concrete generally follows the deflected shape of the dowel.

Maximum stress occurs at joint face.

Dowel Group Action



See figures 3-1.17 and 3-1.18 (page 3-1.36).

The load is transferred through the dowels over the effective length. Dowel directly below the load carries the maximum bearing stress, decreasing to zero over the effective length.

For design, it is generally assumed that 45 percent of the load is transferred to the unloaded slab.

Stresses in Reinforcing Steel

- **Reinforcing steel designed to hold transverse cracks tight, thereby preventing them from deteriorating**
- **Steel content in JRCP often designed using subgrade drag formula**
- **Recent studies indicate that subgrade drag theory often produces inadequate steel contents**

Subgrade drag formula may be used to determine the amount of reinforcing steel needed to hold a crack in JRCP tight (See Eq. 3-1.35, page 3-1.38).

AASHTO Guide provides a nomograph for JRCP reinforcement design (Fig. 3-1.21, page 3-1.39).

Analysis of steel is same whether transverse or longitudinal.

The steel is designed to hold crack tightly without yielding.

Reinforcing Content

- **Subgrade Drag Formula**

$$P_s = \frac{L\ F}{2\ f_s} \times 100$$

- **Modified Subgrade Drag Formula**

$$P_s = \frac{6\ L\ \tau_R}{D\ f_s} \times 100$$

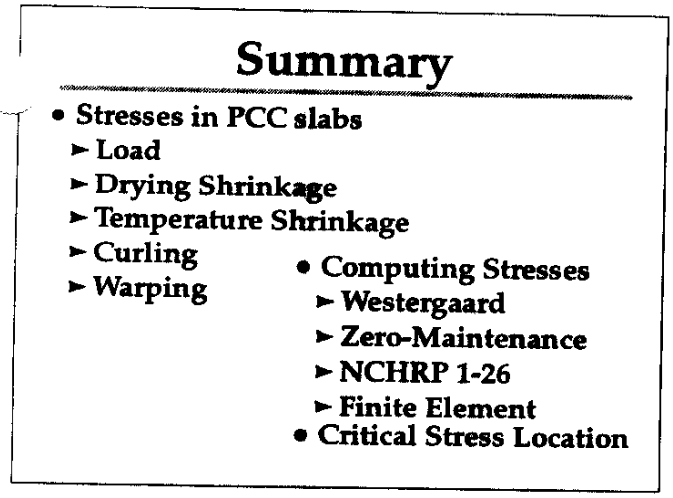
- **JRCP-5 Computer Program**

Ps is determined (area steel/cross-sectional area)
- Convert to area of steel
- Then convert to bar sizes and spacings

Modified subgrade drag formula developed at Texas (Kunt and McCollough).

JRCP-5 regression equations were used to develop computer program PRO1, which predicts short- and long-term steel stress, crack width, and joint opening.

Example problem on page 3-1.42.



Summary

- **Stresses in PCC slabs**
  - **Load**
  - **Drying Shrinkage**
  - **Temperature Shrinkage**
  - **Curling**
  - **Warping**
- **Computing Stresses**
  - **Westergaard**
  - **Zero-Maintenance**
  - **NCHRP 1-26**
  - **Finite Element**
- **Critical Stress Location**

Traffic loadings are the major source of stresses in PCC pavements, but several other stresses contribute to the overall stress.

Several methods are available for estimating stresses. With the advent of the computer, finite element methods have gained in popularity, and have been incorporated into a number of design procedures.

QUESTIONS?