Structural Design of Highway

Second Semester

Third Stage

Lecture1

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Rigid Pavements

For all conventional rigid pavement types, a concrete slab is usually poured directly on a subgrade, base, or subbase. The base or subbase could be a bonded or un-bonded material that provides adequate support and drainage.

Materials used in Rigid Pavements

The Portland cement concrete commonly used for rigid pavements consists of Portland cement, coarse aggregate, fine aggregate, and water. Steel reinforcing rods may or may not be used, depending on the type of pavement being constructed.

Reinforcing Steel

Steel reinforcing used in concrete pavements for

- Reduce the amount of cracking that occurs,
- As a load transfer mechanism at joints,
- As a means of tying two slabs together.

Types of steel reinforcement can be classified as follows:

- Steel reinforcement used to control cracking is usually referred to as temperature steel,
- Steel rods used as load transfer mechanisms are known as dowel bars,
- And those used to connect two slabs together are known as tie bars.

A) Temperature Steel

Temperature steel is provided in the form of a bar mat or wire mesh consisting of longitudinal and transverse steel wires welded at regular intervals. The mesh usually is placed about 3 in. below the slab surface. The cross-sectional area of the steel provided per foot width of the slab depends on the size and spacing of the steel wires forming the mesh. The amount of steel required depends on the length of the pavement between expansion joints, the maximum stress desired in the concrete pavement, the thickness of the pavement, and the moduli of elasticity of the concrete and steel.

Temperature steel does not prevent cracking of the slab, but it does control the crack widths because the steel acts as a tie holding the edges of the cracks together.

B) Dowel Bars

Dowel bars are used mainly as load-transfer mechanisms across joints. They provide flexural, shearing, and bearing resistance. The dowel bars must be of a much larger diameter than the wires used in temperature steel. Diameters of 1 to 1 1⁄2 in. and lengths of 2 to 3 ft have been used, with the bars usually spaced at 1 ft centers across the width of the slab. At least one end of the bar should be smooth and lubricated to facilitate free expansion.

C) Tie Bars

Tie bars are used to tie two sections of the pavement together, and therefore they should be either deformed bars or should contain hooks to facilitate the bonding of the two sections of the concrete pavement with the bar. These bars are usually much smaller in diameter than the dowel bars and are spaced at larger centers. Typical diameter and spacing for these bars are 3/4 in. and 3 ft, respectively.

Types of Rigid Pavements

There are three conventional types of concrete pavements:

- ✓ jointed plain concrete pavement (JPCP), Figure 1.5a and b,
- ✓ jointed reinforced concrete pavement (JRCP), Figure 1.5c, and
- ✓ Continuously reinforced concrete pavement (CRCP), Figure 1.5d.

All Rigid pavements carry traffic loading through flexural strength of the concrete.

However, they differ in the slab lengths, joint details, and the type and amount of reinforcement they use.

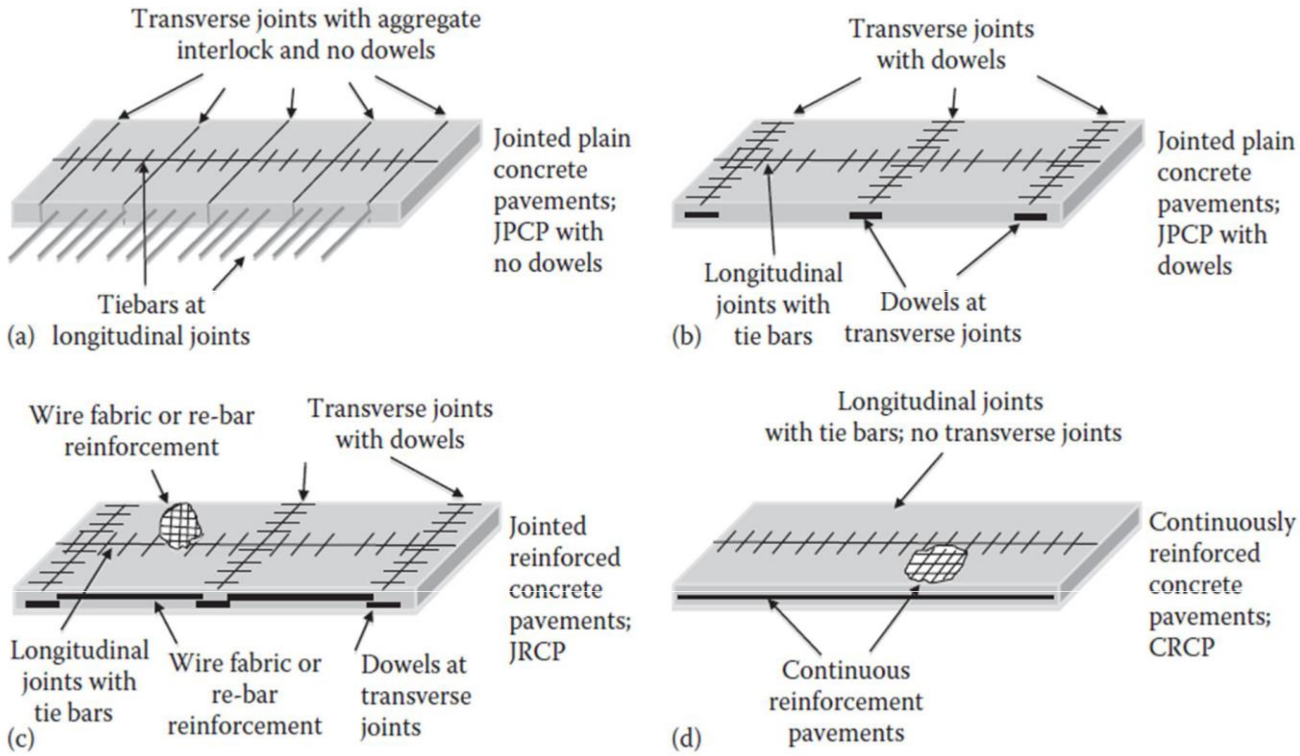


FIGURE 1.5 Jointed plain concrete pavement (JPCP) with tiebars and (a) no dowels, (b) with dowels, (c) jointed reinforced concrete pavements with tiebars and dowels, and (d) continuously reinforced concrete pavements (CRCP). The slab has continuous reinforcement.

A) Jointed Plain Concrete Pavements, JPCP

Jointed plain concrete pavements (JPCP) are the most common type of rigid pavements due to their cost and simplicity. Contraction joints are typically constructed every 12–20 ft apart to control mid-slab cracking. In JPCP, no slab reinforcement is used except for dowel bars placed at transverse joints or tie bars at longitudinal joints. Dowels are used for load transfer across transverse joints and allow the joints to move along the longitudinal axis of the dowel. Conversely, tie bars keep the longitudinal joints held tightly together.

B) Jointed reinforced concrete pavements (JRCP)

Jointed reinforced concrete pavements (JRCP) are similar to JPCP except for the longer slabs and the added light reinforcement in the slab. Joint spacing is typically 25–40 ft, although joint spacing of 100 ft has been used. For the longer slabs and joint spacing, dowels are highly recommended. The steel reinforcement in JRCP is not used for carrying structural loads but to hold the cracks tightly together to preserve shear load transfer across the cracks. The steel is placed near mid-slab depth. This reinforcement is also termed "temperature steel" since its purpose is to hold the cracks caused by temperature stresses tightly together.

C) Continuously reinforced concrete pavements (CRCP)

Continuously reinforced concrete pavements (CRCP) are heavily reinforced concrete slabs with no contraction joints. The amount of reinforcing steel used in the longitudinal direction is typically 0.6%–0.8% of the cross- sectional area of the concrete, with less being used as temperature steel in the transverse direction.

Joints in Rigid Pavements

Different types of joints are placed in concrete pavements to limit the stresses induced by temperature changes and to facilitate proper bonding of two adjacent sections of pavement. These joints can be divided into four basic categories:

- Expansion joints
- Contraction joints
- Hinge joints
- Construction joints

A) Expansion Joints

When concrete pavement is subjected to an increase in temperature, it will expand, resulting in an increase in length of the slab. When the temperature is sufficiently high, the slab may buckle or "blow up" if it is sufficiently long and if no provision is made to accommodate the increased length. Therefore, expansion joints are usually placed transversely, at regular intervals, to provide adequate space for the slab to expand.

These joints are placed across the full width of the slab. They must create a distinct break throughout the depth of the slab. The joint space is filled with a compressible filler material that permits the slab to expand. Filler materials can be cork, rubber, bituminous materials, or bituminous fabrics. The load-transfer mechanism is usually a smooth dowel bar that is lubricated on one side. An expansion cap usually also is installed, as shown in Figure, to provide a space for the dowel to occupy during expansion.

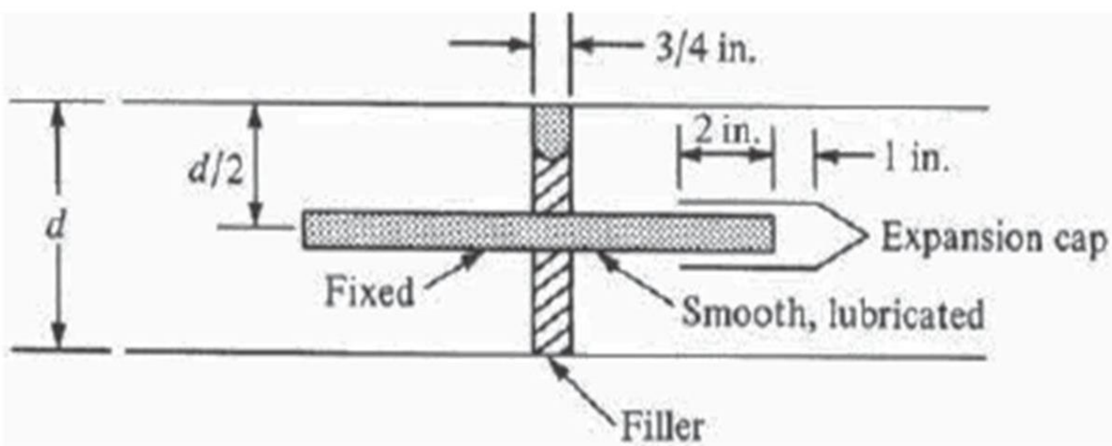


Figure 1: Typical Expansion Joint

B) Contraction Joints

When concrete pavement is subjected to a decrease in temperature, the slab will contract if it is free to move. Prevention of this contraction movement will induce tensile stresses in the concrete pavement. Contraction joints therefore are placed transversely at regular intervals across the width of the pavement to release some of the tensile stresses that are so induced. It may be necessary in some cases to install a load-transfer mechanism in the form of a dowel bar.

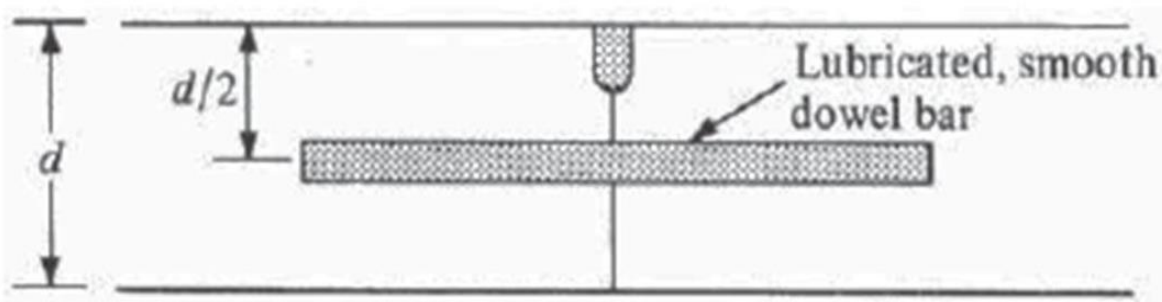


Figure 2: Typical Contraction Joint

C) Hinge Joints

Hinge joints are used mainly to reduce cracking along the center line of highway pavements. Figure shows a typical hinge joint (keyed joint) suitable for single-lane at a-time construction.

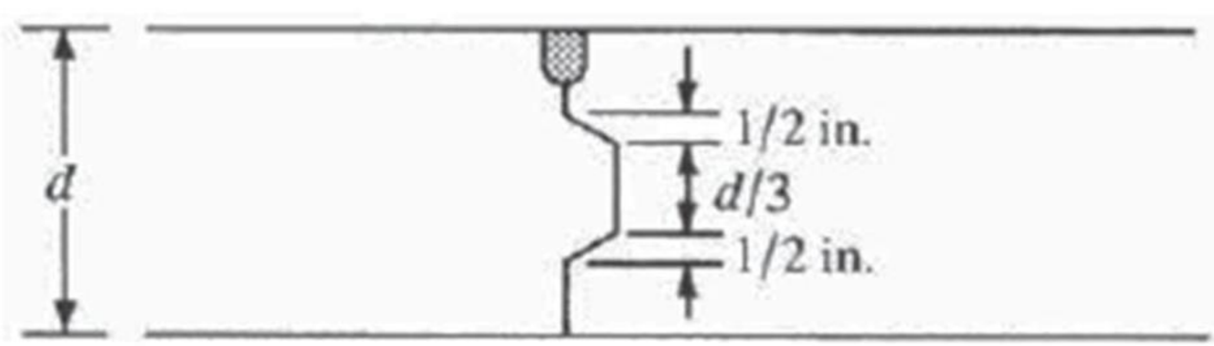


Figure 3: Typical Hinge Joint (Keyed Joint)

D) Construction Joints

Construction joints are placed transversely across the pavement width to provide suitable transition between concrete laid at different times. For example, a construction joint is usually placed at the end of a day's pour to provide suitable bonding with the start of the next day's pour. In some cases, as shown in Figure, a keyed construction joint may also be used in the longitudinal direction.

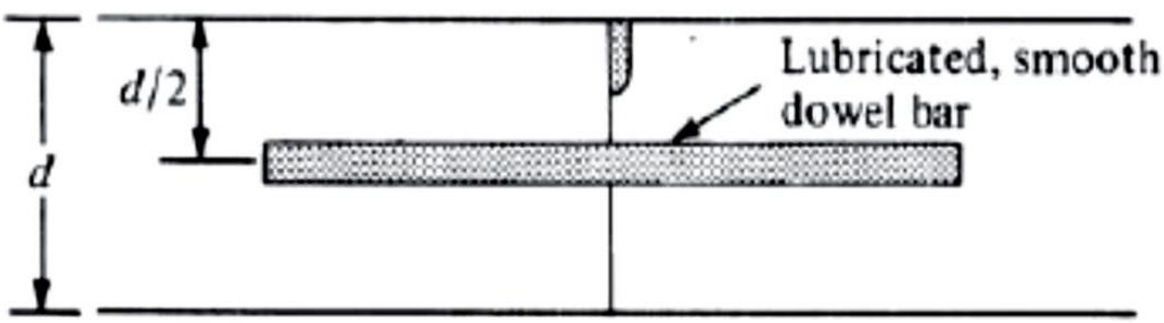


Figure 4: Typical Butt Joint

Pumping Of Rigid Pavements

Pumping is an important phenomenon associated with rigid pavements. Pumping is the discharge of water and subgrade (or subbase) material through joints, cracks, and along the pavement edges. It primarily is caused by the repeated deflection of the pavement slab in the presence of accumulated water beneath it.

Further load repetitions and deflections of the slab will result in the slurry being ejected to the surface (pumping). Pumping action will then continue, with the result that a relatively large void space is formed underneath the concrete slab. This results in faulting of the joints and eventually the formation of transverse cracks or the breaking of the corners of the slab. Joint faulting and cracking is therefore progressive, since formation of a crack facilitates the pumping action.

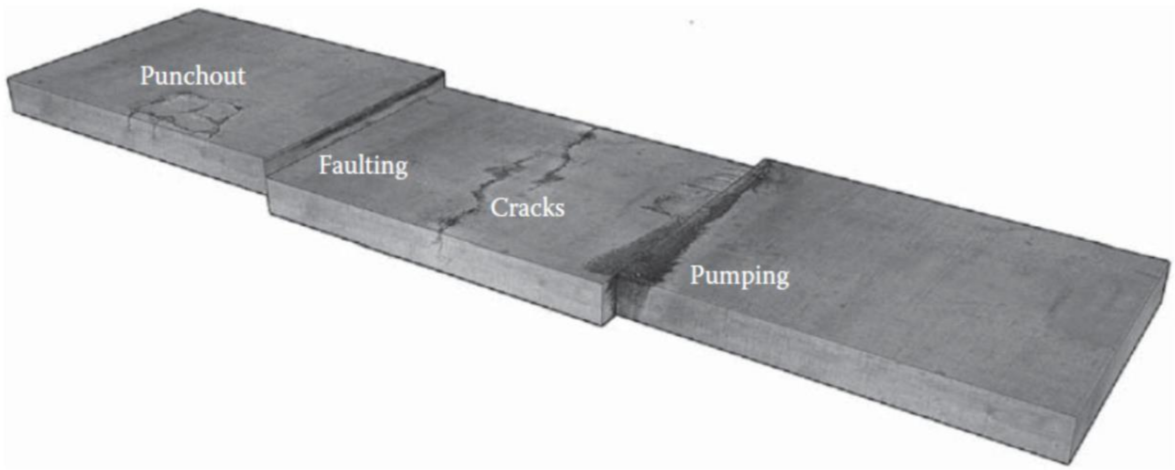
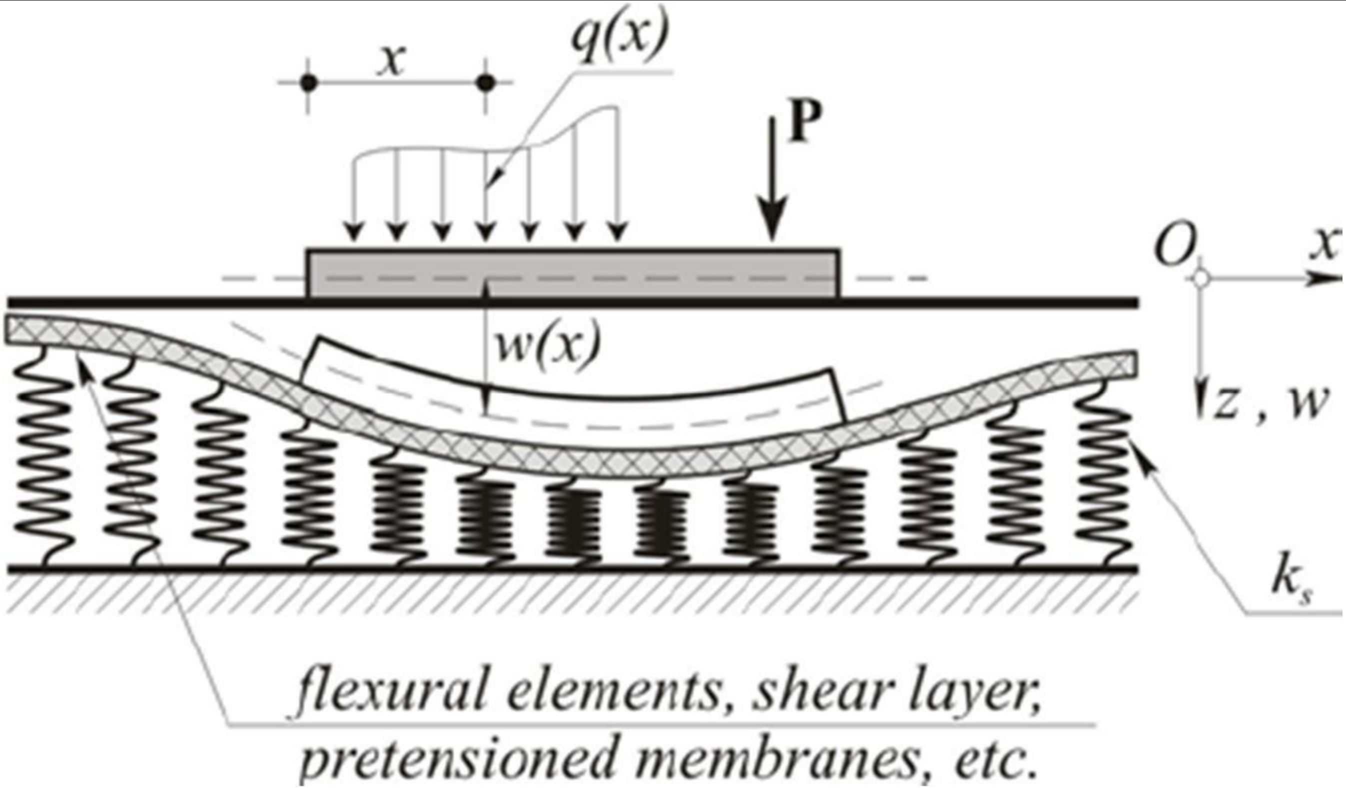


FIGURE 3.2 Major distress conditions considered for design in Portland cement concrete (PCC) pavements.

Theoretical Considerations

A rigid pavement is basically a slab resting on a subgrade or base. The load carrying mechanism is similar to beam action, although a concrete slab is much wider than the beam and should be considered as a plate. Westergaard (1926b) developed stress equations for rigid pavement slabs supported on a Winkler or liquid foundation, which is a conceptual model that considers the foundation as a series of springs. When the slab is loaded vertically down, the springs tend to push back; when the environment-related loads are pulling up on the slab, the springs tend to pull down toward the foundation.



Stresses in Rigid Pavements

If we consider that the pavement slab as a beam on an elastic foundation, then the reactive pressure, p, can be related to the deformation, Δ, through the equation $p = k\Delta$, where k is the modulus of subgrade reaction, which is the ratio of the pressure applied to the subgrade using a loaded area divided by the displacement experienced by that loaded area.

A concrete pavement slab will deform under load. The resistance to deformation due to loading depends upon the characteristics of the foundation and the stiffness or modulus value of the slab.

Westergaard (1927) applied plate theory to a finite PCC slab and supporting foundation and developed the relative stiffness expression "ℓ," which is called the radius of relative stiffness. The radius of relative stiffness expression depends on both slab and foundation properties. The value for ℓ increases with a stiffer concrete, a thicker slab, and a weaker foundation. This term is used in many of the stress and deflection equations derived for rigid pavements by Westergaard and others.

$$\ell = \sqrt[4]{\frac{Eh^3}{12\left(1-\mu^2\right)k}}$$

where

ℓ is the radius of relative stiffness, in.; mm

E is the modulus of elasticity of the pavement, psi; MPa

h is the thickness of the pavement, in.; mm

μ is the Poisson's ratio of the PCC, in./in.; mm/mm

k is the modulus of subgrade reaction, pound per cubic inch, pci or MN/m3

STRESSES DUE TO TEMPERATURE CURLING

A concrete slab will undergo volume changes and develop stresses due to changes in temperature and moisture as shown in Figure 3.5. During the day, as the air temperature and sun increase the surface temperature of the concrete slab, the top of the slab will tend to expand relative to the neutral axis and the bottom of the slab will tend to contract as it is insulated by the soil in the base. However, the weight of the slab will prevent it from contraction or expansion, and compressive stresses will be induced in the top layer of the slab, while tensile stresses will be induced in the bottom layer. The opposite will occur at night where the air temperature will be cooler compared to the base of the slab since it is insulated by the base or subgrade. The top of the slab will be cooler compared to the bottom and will tend to contract. The slab weight will prevent the upward curling, and therefore tensile stresses will develop in the top of the slab while compressive stresses will be induced in the bottom of the slab. A similar effect is observed with moisture changes.

Curling stresses are attributed to temperature changes between the top and bottom of the concrete slab.

Warping stresses, on the other hand, are defined as stresses due to moisture changes in the concrete.

These stresses due to curling and warping are usually addressed by joint and steel design of the slab. The maximum total stresses at the interior of the slab, edge, and corner are given by the following equations:

$$\text{Interior stress, } \sigma_t = \frac{E\alpha\Delta t}{2}\left[\frac{C_x + \mu C_y}{1-\mu^2}\right]$$

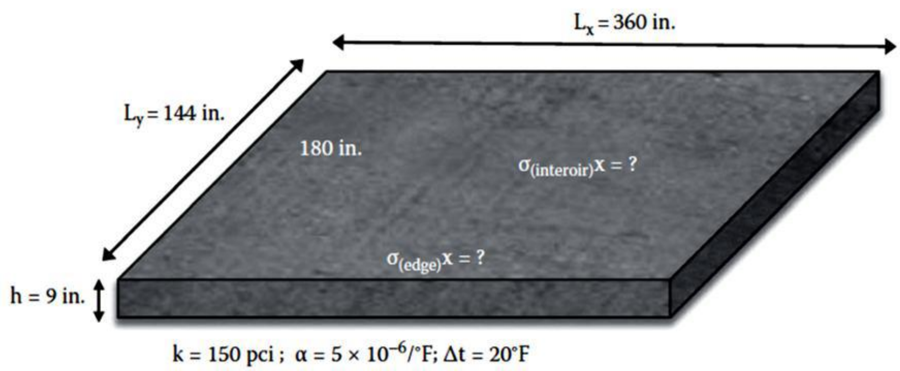
$$\text{Edge stress, } \sigma_t = \frac{CE\alpha\Delta t}{2}$$

where

- E is the modulus of elasticity of concrete
- μ is the Poisson's ratio of concrete
- α is the coefficient of thermal expansion
- $C = C_x$ and C_y are correction factors (after Bradbury 1938) for the finite slab and are dependent on L_x/ℓ and L_y/ℓ
- a is the radius of circular contact area applied at the corner

Example

Consider a concrete slab 30 ft (9.14 m) by 12 ft (3.66 m) and 8 in. (203 mm) thick, subjected to a temperature differential of 20°F (11.1°C). Assuming k = 200 pci (54.2 MN/m3) and α = 5 * 10−6 in./ in./°F (9 * 10−6 mm/mm/°C), E = 4 * 106 psi, μ = 0.15. Determine the maximum curling stress in the interior and at the edge of the slab.



Solution

$$\ell = \sqrt[4]{\frac{Eh^3}{12(1-\mu^2)k}}$$

$$\ell = \sqrt[4]{\frac{4*10^6*9^3}{12(1-0.15^2)150}} = 35.88 \text{ in.} = 911.34 \text{ mm}$$

$L_x/\ell = 10.03$; $L_y/\ell = 4.01$

From Figure 3.6 the values for $C_x = 1.07$ and $C_y = 0.49$.

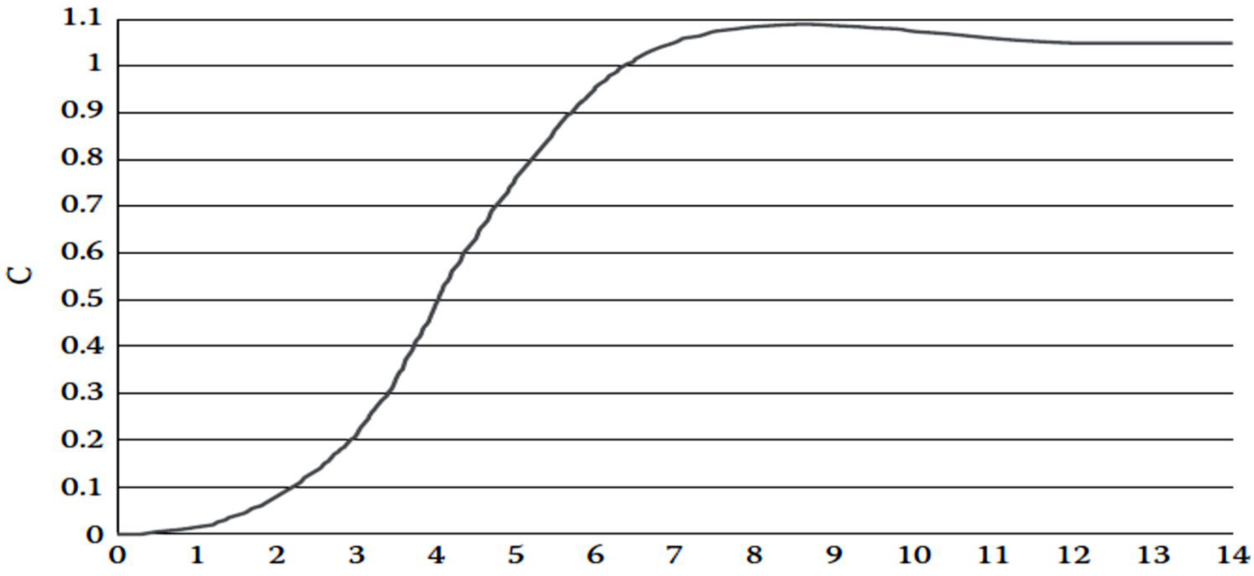
Interior stress x-direction; $\sigma_t = E\alpha\Delta t/2[(C_x + \mu C_y)/(1 - \mu^2)]$

$$\sigma_t = \frac{4*10^6*5*10^{-6}*20}{2}\left[\frac{1.07+0.15*0.49}{1-0.15^2}\right] = 234\ \text{psi} = 1.61\ \text{MPa}$$

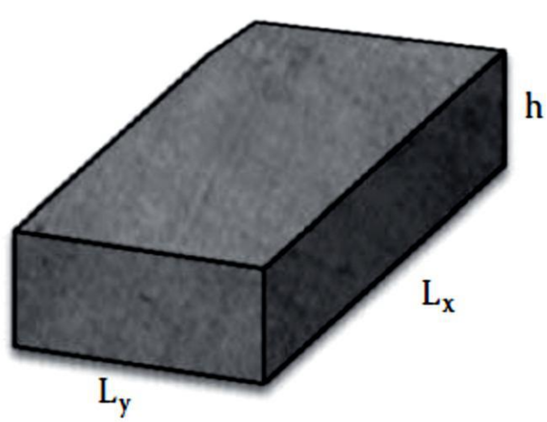
Edge stress x-direction; $\sigma_t = CE\alpha\Delta t/2$

$$\sigma_t = \frac{1.07*4*10^6*5*10^{-6}*20}{2} = 214\ \text{psi} = 1.48\ \text{MPa}$$

Note that both the interior and edge critical stresses are in the x-direction.



(a)



(b)