Introduction to the Design of Slabs On Ground

Phuc Vu, Agricultural Engineer, CNTSC

and

John Van Leeuwen, Structural Engineer, NDCSMC

Objectives

- Upon completion of this presentation, the attendee will be able to:
  - Identify the industry and agency standard codes and references related to concrete design.
  - Understand design loads and critical criteria for the design of NRCS slabs on ground

Concrete Slab on Ground

Design References

NRCS References

- **NRCS**
  - NEH Section 6, Chapter 4 – Reinforced Concrete (Working Stress)
  - TR 67 - Reinforced Concrete Strength Design
  - TR 74, Lateral Earth Pressures
  - NEH 19, Construction Inspection
  - NEM Part 511 – Design
  - NEM Part 536 – Structural Engineering
  - NEM Part 642 – Construction Specifications
    - Chapter 31 – Concrete for Major Structures
  - Various Design Notes and Technical Releases

American Concrete Institute References

- **American Concrete Institute**
  - ACI 223-98   Standard Practice for the Use of
    Shrinkage-Compensation Concrete
  - ACI 224.3R-95 (Reapproved 2008)   Joints in Concrete Construction
  - ACI 302.1R-04 Guide for Concrete Floor and Slab Construction
  - ACI 315 Detailing Manual
  - ACI 318-14 Building Code Requirements for Structural Concrete
  - **ACI 330R-08 Guide for the Design and Construction of Concrete Parking Lots**
  - **ACI 350-06 Code Requirements for Environmental Engineerin Concrete Structures**
  - ACI 350.4R Design Considerations for Environmental Engineering
  - **ACI 360R-10 Guide to Design of Slabs on Ground**
  - ACI SP-2 Manual of Concrete Inspection

Other References

- **National Structural Engineering Design Standards**
  - American Society of Civil Engineers (ASCE)
    - Minimum Design Loads for Buildings and Other Structures, (ASCE 7), (2016 Ed.)
  - International Code Council (ICC)
    - International Building Code (IBC) (2015)

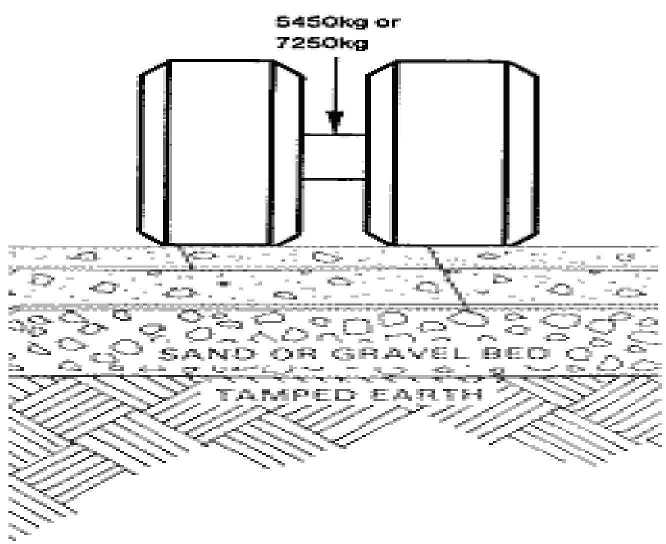
- **Corps of Engineers (USACE) & Naval Facilities Command Unified Facilities Criteria (NAVFAC)**
  - UFC 3-301-01 Structural Engineering
  - EM 1110-1-1904 Settlement Analysis
  - EM 1110-1-1905 Bearing Capacity of Soils
  - EM 1110-2-2104 Strength Design of Reinforced Concrete Hydraulic Structures (New in 2016)

Concrete Slab on Ground

Introduction

Introduction
Slab on Ground Definition

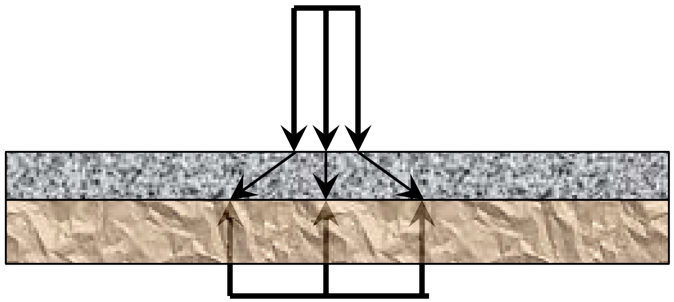
- ACI 360R-10 1.1 defines a slab-on-ground as "a slab, supported by ground, whose main purpose is to support the applied loads by bearing on the ground"
- Doesn't include footings or mat foundations – those should be designed per ACI 318, ACI 350 or other.



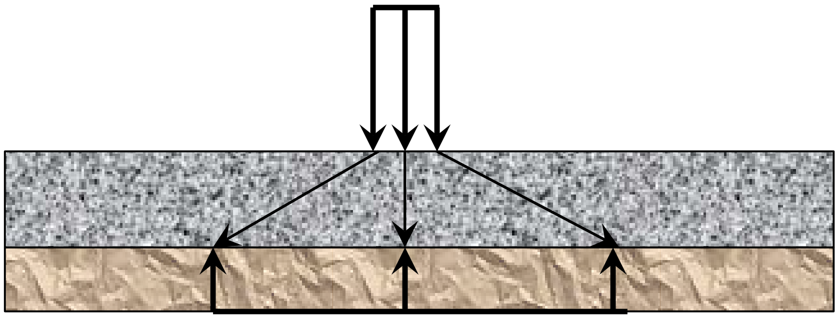
Introduction

- Slabs on grade are PAVEMENTS not generally structural elements
  - Pavements pass loads through compression to the supporting soil
  - If soils deformations are low, there is negligible bending in the slab

For a load applied to a slab:



The slab is stiffer than the soil, so the load is distributed over a larger area of soil



A thicker slab is even stiffer and will distribute the load over an even larger area of soil

Therefore, the thicker the slab, the lower the bending stresses will be in the concrete and thus produce less cracking due to the loading

Introduction

- Slab performance is considered successful if there is little or no cracking - minimal crack width and evenly dispersed
- Slab performance is dependent on a variety of factors:
  - Thickness of slab
  - Joints
  - Mix design
  - Construction and finishing

Introduction

- Thickness required is dependent on a variety of factors:
  - Support Conditions - properties of the subgrade/base material
  - Concrete Mix Design - properties of concrete materials
  - Loading – location, magnitude, and of frequency of loads
  - Factor-of-safety – loading type and stress ratio desired
  - Usage – interior, refrigerated area, coverings required, abrasion expected, levelness/flatness required
  - Use of reinforcement

Concrete Slab on Ground

Types of Slabs

Types of Slab Construction

ACI 360 - Design of Slabs on Ground Table 3.1

Table 3.1—General comparison of slab types

Slab type	Advantages	Disadvantages
Unreinforced concrete	• Simple to construct. • Generally is less expensive to install than slabs designed by other methods.	• Requires relatively closely spaced sawcut contraction joints. • More opportunity for slab curl and joint deterioration. • Large number of joints to maintain. • Positive load transfer may be required at joints. • Flatness and levelness may decrease over time.
Reinforced with deformed bars or welded-wire reinforcement sheets for crack-width control	• Reinforcement is used to limits crack width.	• May be more expensive than an unreinforced slab. • Reinforcement can actually increase the number of random cracks, particularly at wider joint spacings. • More opportunity for slab curl and joint deterioration. • Positive load transfer may be required at joints.
Continuously reinforced with deformed bars or welded-wire reinforcement mats	• Sawcut contract joints can be eliminated where sufficient reinforcement is used. • Eliminates sawcut contraction joint maintenance. • Curling is reduced when high amounts of reinforcement are used. • Less changes in flatness and levelness with time.	• Requires relatively high amounts (at least 0.5%) of continuous reinforcement placed near the top of the slab to eliminate joints. • Typically produces numerous, closely spaced, fine cracks (approximately 3 to 6 ft [0.9 to 1.8 m]) throughout slab.
Shrinkage-compensating concrete	• Allows construction joint spacings of 40 to 150 ft (12 to 46 m). • Sawcut contraction joints are normally not required. • Reduces joint maintenance cost due to increased spacing of the joints reducing the total amount of joints. • Negligible curl at the joints. • Increases surface durability and abrasion resistance (ACI 223, Section 2.5.7—Durability).	• Requires reinforcement to develop shrinkage compensation. • Window of finishability is reduced. • Allowance should be made for concrete to expand before drying shrinkage begins. • Construction sequencing of adjacent slab panels should be considered, or joints should be detailed for expansion. • Contractor should have experience with this type of concrete.
Post-tensioned	• Construction spacings 100 to 500 ft (30 to 150 m). • Most shrinkage and flexural cracks can be avoided. • Eliminates sawcut contraction joints and their maintenance. • Negligible slab curl when tendons are draped near joint ends. • Improved long-term flatness and levelness. • Decreased slab thickness or increased flexural strength. • Resilient when overloaded. • Advantages in poor soil conditions.	• More demanding installation. • Contractor should have experience with post-tensioning or employ a consultant with post-tensioning experience. • Inspection essential to ensure proper placement and stressing of tendons. • Uneconomical for small areas. • Need to detail floor penetrations and perimeter for slab movement. • Impact of cutting tendons should be evaluated for post-construction slab penetrations.
Steel fiber-reinforced concrete	• Increased resistance to impact and fatigue loadings when compared to slabs reinforced with bars or mesh. • Simple to construct.	• May require adjustments to standard concrete mixing, placement, and finishing procedures. • Fibers may be exposed on the surface of slab. • Floors subjected to wet conditions may not be suitable for steel fiber because fibers close to the surface and in water-permeable cracks will rust.
Synthetic fiber-reinforced concrete	• Helps reduce plastic shrinkage cracking. • Simple to construct. • Macrosynthetic fibers provide increased resistance to impact and fatigue loadings, similar to steel fibers. • Synthetic fibers do not corrode.	• Microsynthetic fibers do not help in controlling drying shrinkage cracks. • Joint spacing for microsynthetic fiber-reinforced slabs are the same as unreinforced slabs.
Structural slabs reinforced for building code requirements	• Slabs can carry structural loads such as mezzanines. • Reduces or eliminates sawcut contraction joints where sufficient reinforcement is used.	• Slab may have numerous fine or hairline cracks if reinforcement stresses are sufficiently low.

- **Lists slab types and advantages and disadvantages**

Types of Slab Construction

- **Unreinforced concrete slabs**
- **Slabs reinforced for crack width control**
  - Non-prestressed reinforcing
  - Continuously reinforced
- **Slabs reinforced to prevent cracking**
  - Post-tensioned slabs
  - Shrinkage-compensating concrete slabs
  - Steel fiber reinforced
  - Synthetic fiber reinforced
- **Structural slabs (Plain & Reinforced per ACI 318 / 350)**

Types of Slab Construction

- **Unreinforced concrete slabs**
  - May have joints strengthened with dowels.
  - Ref ACI 360-10 Fig. 6.6 for recommended joint spacing
- **Slabs reinforced for crack width control**
  - Steel reinforcement (or fibers) and closely spaced joints
  - Steel selected by T&S control procedures in ACI 318 can lead to excessive crack width if high steel reinf. stresses are allowed.
  - Joint spacing is slightly larger than plain slab
  - Place steel in upper 1/3 or above mid-depth of slab

Types of Slab Construction

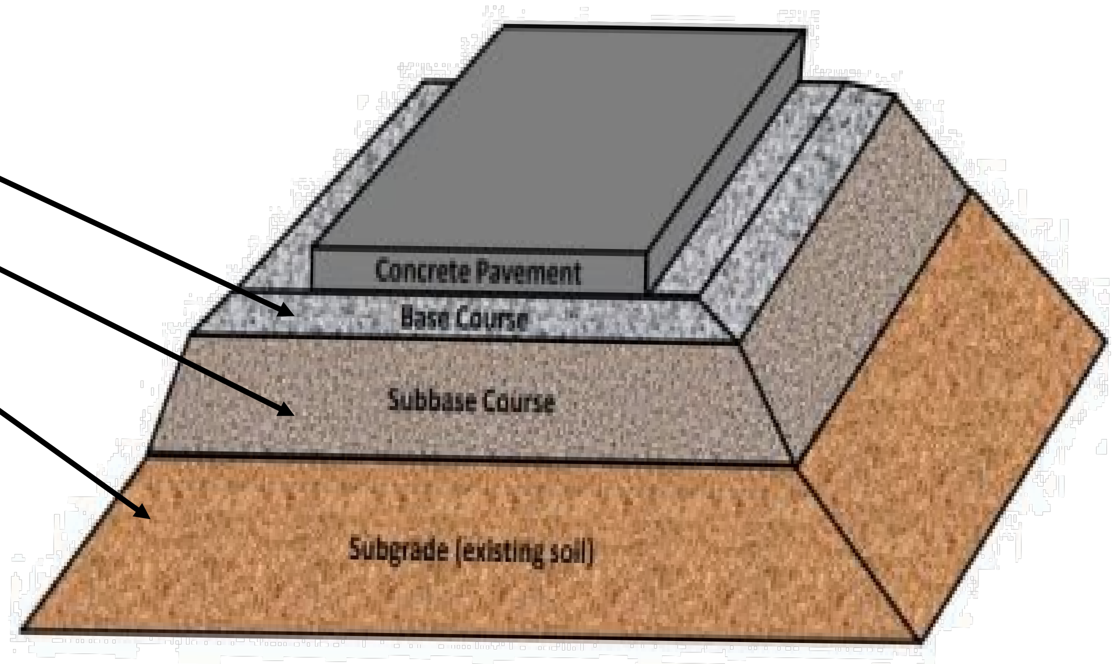
- **Slabs reinforced to prevent cracking**
  - **Post-tensioned slabs**
    - No contraction joints required between construction joints
    - Still requires reinforcing steel to compensate for T&S restraint and applied loads
  - **Shrinkage-compensating concrete slabs**
    - Designed as unreinforced, but reinforcement to offset stresses due to S&T restraint
    - Expansive admixture or Type K cement
    - Larger joint spacing (with expansion joints)
- **Structural slabs (Plain and Reinforced per ACI 318 / 350)**
    - Design allows certain amount of cracking but carries loads
    - May require reinforcement for crack control as well

Concrete Slab on Ground

Soil Support Systems

Soil Support Systems

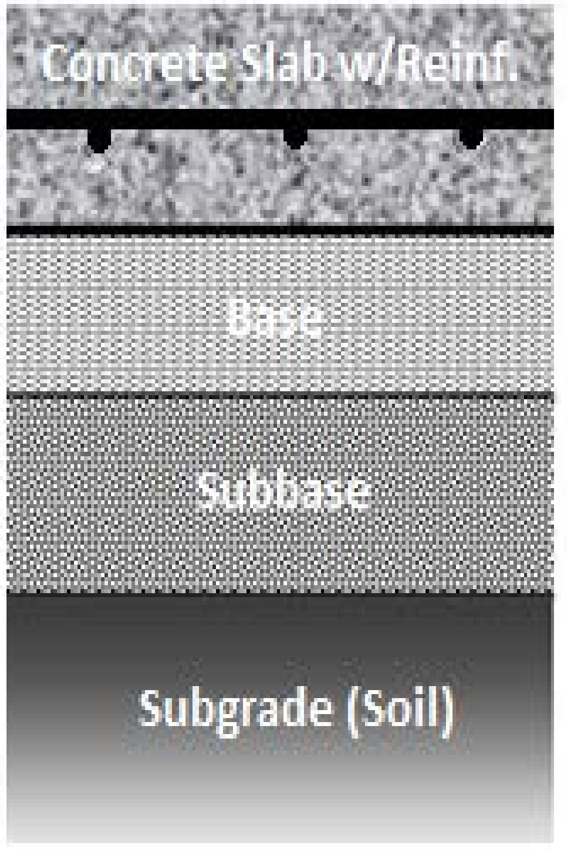
- Concrete slab over a soil support system
- Soil support system consists of:
  - Base
  - Sub-base
  - Sub-grade



- For best design, all base courses should be free draining granular materials

Soil Support Systems

- Base
  - Free draining granular material
  - Crushed rock, gravels, or coarse sands have high strength.
  - Low compressibility, and high permeability
- Sub-base
  - Crushed rock, gravels, sands, select soils, and stabilized soils
  - Can be omitted if high quality subgrade exists
- Sub-grade
  - Native soil, usually compacted

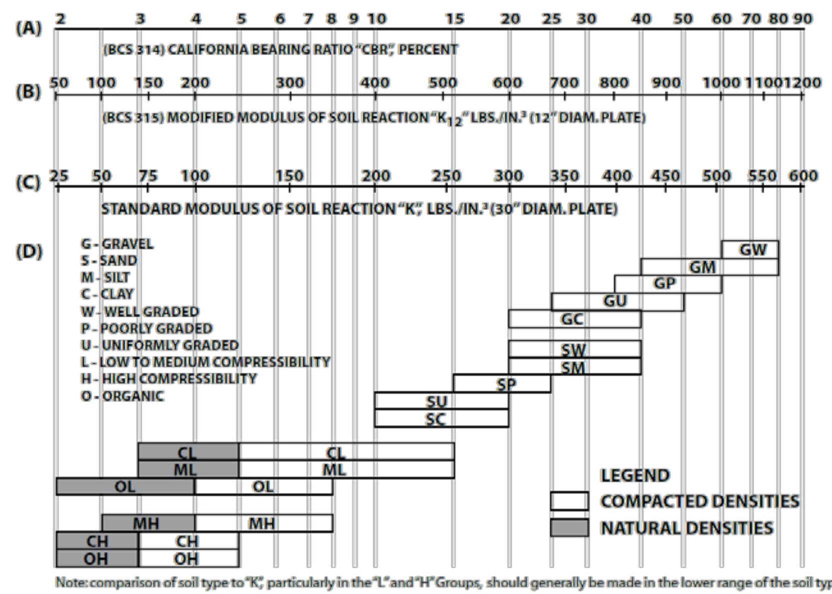


For best design, all base courses should be free draining granular materials

***use $t_{base} = t_{slab}$ as a rule of thumb unless k is small**

Soil Support Systems - Properties

- Assumes rigid slab design
- Modulus of Subgrade Reaction (k)
  - Pressure/Deflection Relationship
  - psi / inch of deflection (psi/in) → pci
- Measurement / Estimation
  - Plate Bearing Test
    - ASTM D1196
  - Charts based on soil types
  - Correlated to CBR, DCP, etc.



Soil Support Systems - Properties

- Improve by adding base course
  - Stable all weather working platform
  - More uniform support
  - Some improvement in k value
- Slab thickness (t_{slab}) not overly sensitive to small changes in k-value (from k_1 to k_2)
  - t_2 / t_1 varies approximately with 4th root of k_1/k_2

or $\longrightarrow$ $t_2 = t_1 \cdot \sqrt[4]{\frac{k_1}{k_2}}$ $\longrightarrow$

- Increasing k from 200 to 300 pci, the t_2/t_1 ratio is 0.90, so a 6" slab would be 5.4" slab
- Increasing k from 100 to 400 pci, the t_2/t_1 ratio is 0.71, so a 6" slab would be 4.25" slab

- Influence of moisture
  - More moisture = lower supporting strength
  - Variations in moisture = variations in support

Modulus of Subgrade Reaction
Addition of a Subbase

Table 2.2—Modulus of subgrade reaction *k*[*]

Subgrade *k* value, pci	Sub-base thickness			
	4 in. (100 mm)	6 in. (150 mm)	9 in. (225 mm)	12 in. (300 mm)
	Granular aggregate subbase			
50	65	75	85	110
100	130	140	160	190
200	220	230	270	320
300	320	330	370	430
	Cement-treated sub-base			
50	170	230	310	390
100	280	400	520	640
200	470	640	830	—
	Other treated sub-base			
50	85	115	170	215
100	175	210	270	325
200	280	315	360	400
300	350	385	420	490

[*]For different subbase applied over different subgrade, psi/in. (Thickness 1984; Airport 1978).
Note: *k* value units can also be expressed as psi/in.

ACI 330

Concrete Slab on Ground

Loading and Factor of Safety

Loading

- Need to know details and geometry of the various loading types anticipated for the slab
- Major Loading Categories
  - Vehicle Wheel (Axle) Loads
  - Concentrated Loads (Rack & Post Loads)
  - Distributed Loads (pallets)
  - Line and Strip Loads
  - Unusual Loads
  - Construction Loads
  - Environmental Effects

Loading

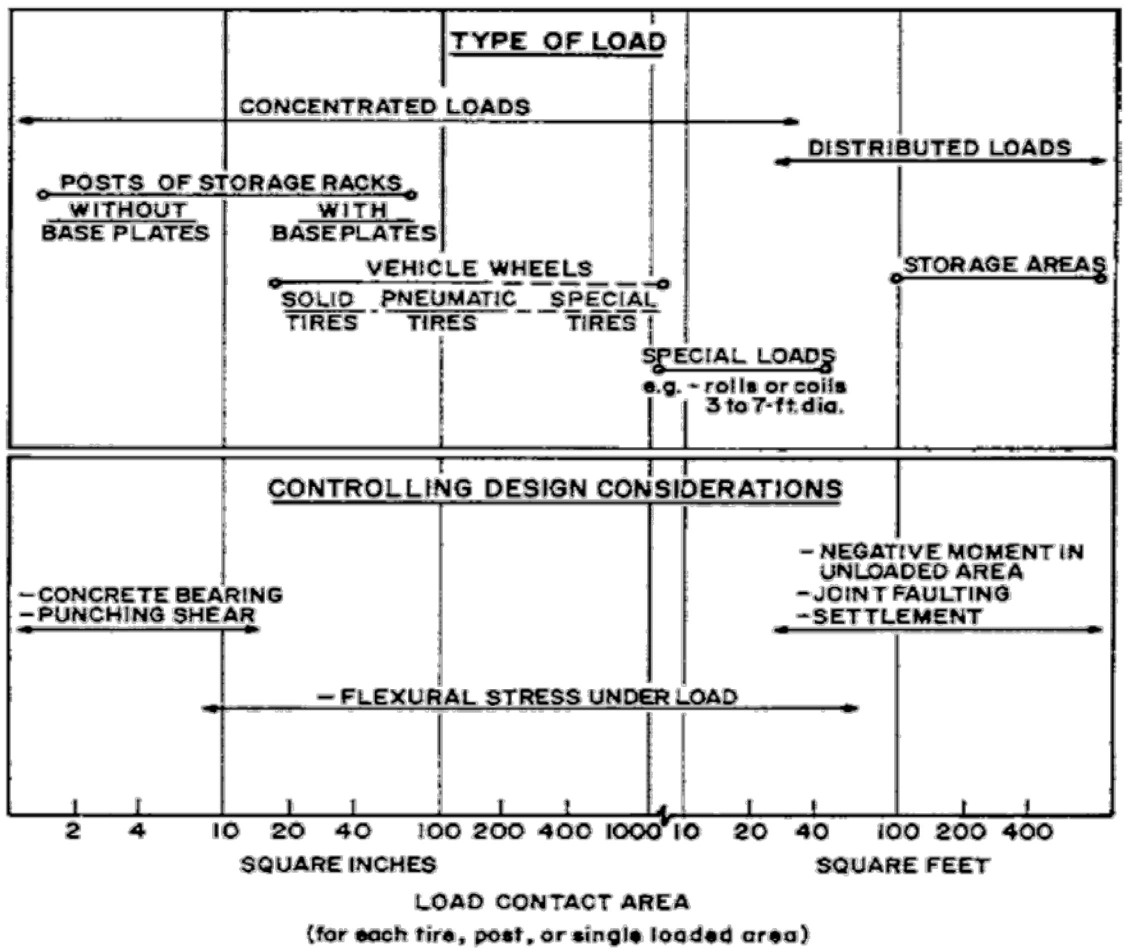


Fig. 5.1—Controlling design considerations for various types of slabs-on-ground loading (Packard 1976). (Note: 1 in.^{2} = 645.2 mm^2; 1 ft^2 = 0.09290 m^2.)

ACI 360 - Design of Slabs on Ground Figure 5.1

PCA Load Charts for Design

- **Types of loads included**
  - Axle Loads
  - Post Loads
  - Distributed Loads
- **What is Behind the Charts**
  - Charts developed for interior loading by pneumatic tired wheels
  - Stresses due to edge loading are higher – up to 50% higher
  - Edge loading occurs at joints that do not have load transfer
  - Smooth dowel bar or dowel plates
  - Aggregate interlock decreases when joint opens beyond 0.035 in. (not lost completely)

PCA Load Charts
For Axle Loads

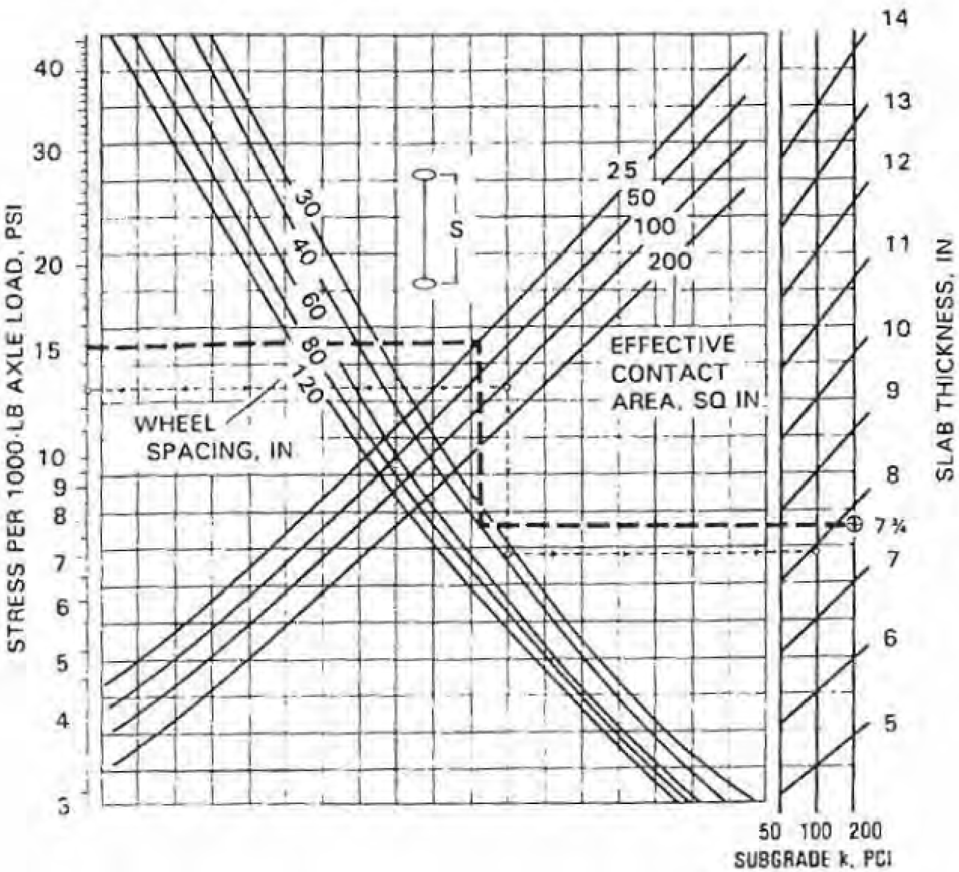


Fig. A1.1—The PCA design chart for axles with single wheels.

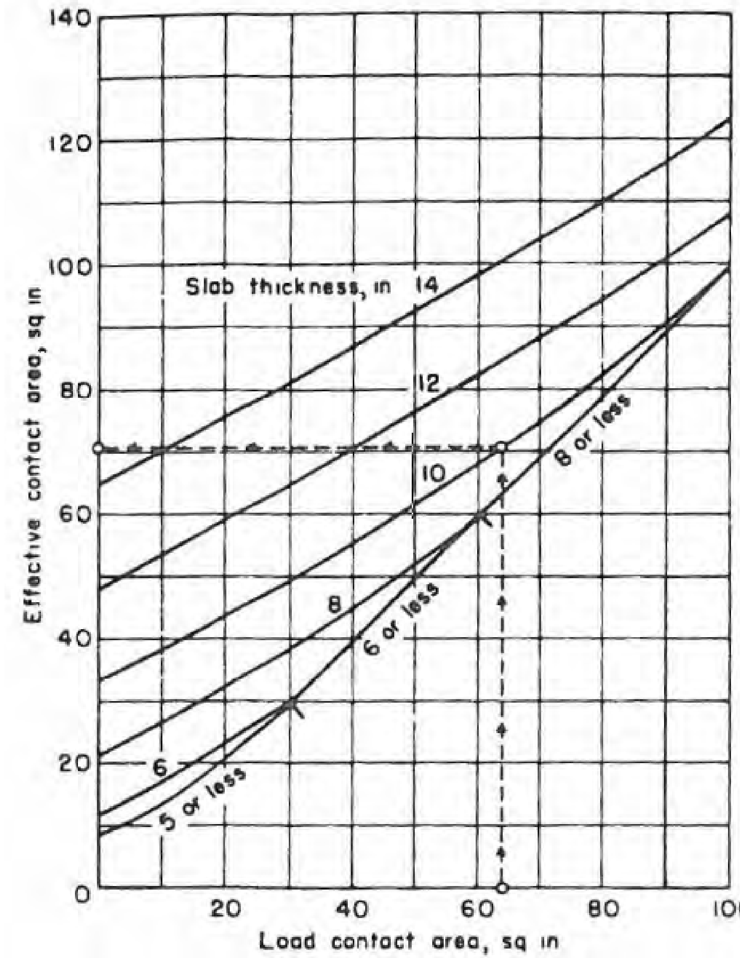


Fig. A1.2—Relationship between load contact area and effective load contact area.

PCA Load Charts
For Post Loads

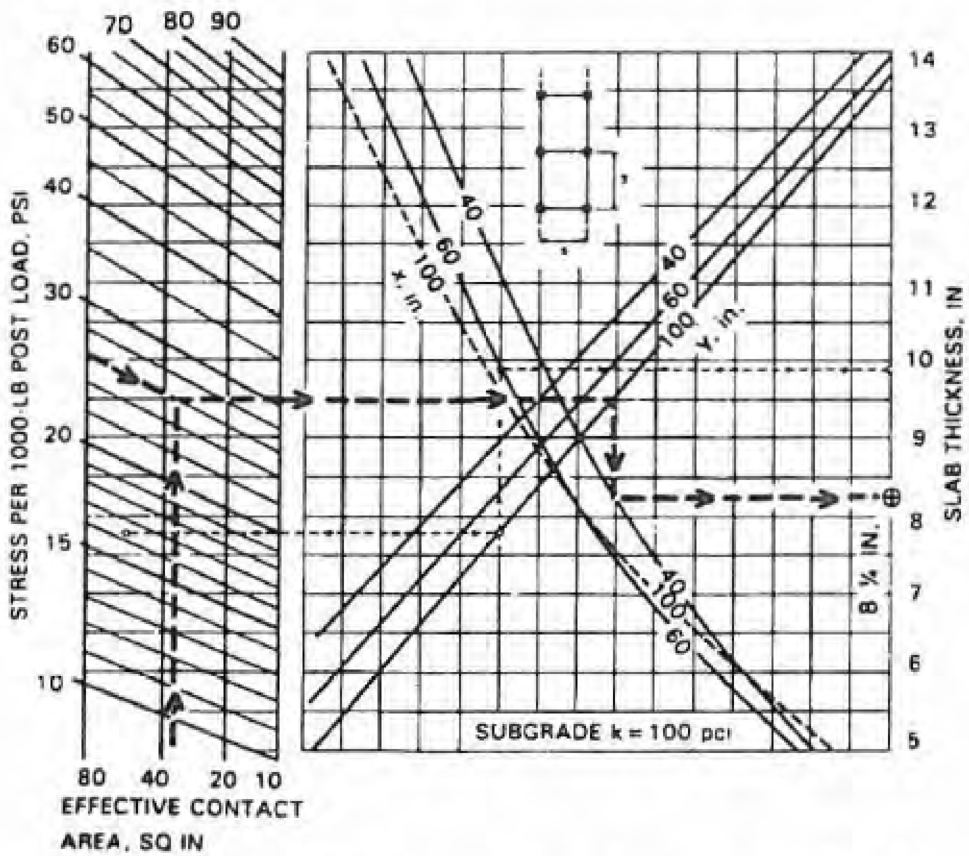


Fig. A1.5—The PCA design chart for post loads where subgrade modulus is 100 pci.

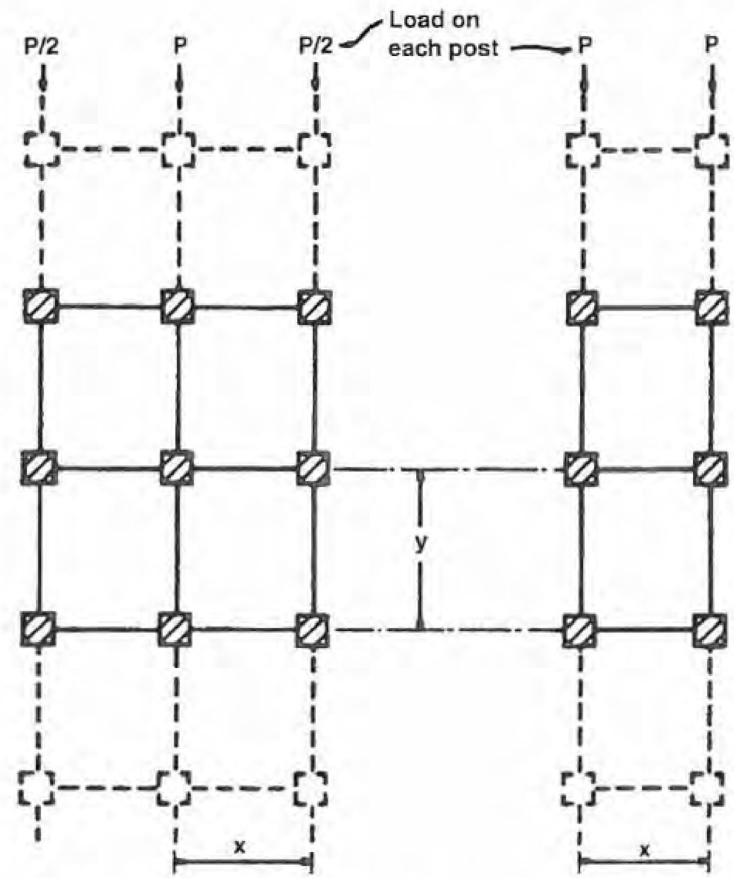


Fig. A1.4—Post configurations and loads.

Factor of Safety

- **Unique serviceability requirements compared to other structural elements:**
  - Minimize cracking and curling
  - Increase surface durability
  - Optimize joint locations & types for joint stability (differential deflection)
  - Maximize long-term flatness and levelness
- **Designer selects the factor of safety (SF) to minimize serviceability failure based on consequences:**
  - Lost productivity
  - Lost beneficial use
  - Costs for repairing areas in an active facility

Factor of Safety

- ## Factor of Safety for Design
  - ACI 360-10 Table 5.2
  - Commonly used factors of safety, SF for various loadings
  - Most range from 1.7 to 2.0, but some loading conditions use factors as low as 1.4.
  - Values do not provide for impact type loading and are no guarantee to prevent cracking due to drying shrinkage

Table 5.2—Factors of safety used in design of various types of loading

Load type	Commonly used factors of safety	Occasionally used factors of safety
Moving wheel loads	1.7 to 2.0	1.4 to 2.0 and greater
Concentrated (rack and post) loads	1.7 to 2.0	Higher under special circumstances
Uniform loads	1.7 to 2.0	1.4 is lower limit
Line and strip loads	1.7	2.0 is conservative upper limit*
Construction loads	1.4 to 2.0	—

*Follow appropriate building code requirements when considering a line load to be a structural load due to building function.

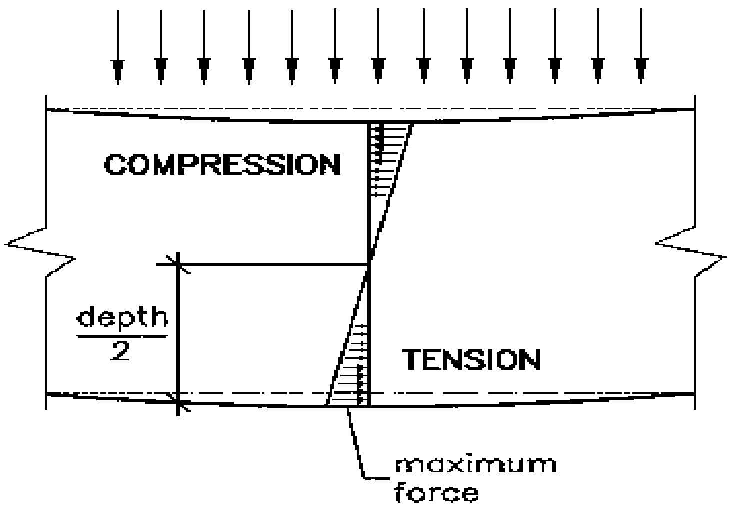
ACI 360 - Design of Slabs on Ground Table 5.2

- ## Fatigue Strength
  - ACI 360-10 Table 5.3
  - Moving vehicles subject a SOG to the effects of fatigue
  - Increasing the factor of safety (SF) reduces the stress ratios (SR) and can allow for a longer service life (lower stress = more cycles)
  - For stress ratios, SR < 0.45, concrete can be subjected to unlimited load repetitions (PCA 2001).

Concrete Working Stress

$$\text{Working Stress} = \text{WS} = \frac{\text{MOR}}{\text{SF X JF}}$$

- **MOR = Modulus of Rupture (flexural strength)**
  - 6 to 12 f'_c typically use $9\sqrt{f'_c}$ TR 67 uses $7\sqrt{f'_c}$
- **JF = Joint Factor**
  - 1.0 where load transfer provided at joints
  - 1.6 where load transfer not reliable
  - in between, at discretion of designer



- **SR = Stress Ratio**
  - Applied Stress / Developed Strength
  - Inverse of Safety Factor → 1 / SF
  - SF 2.0 = SR 0.50 (50%)
- **Example**: Assume MOR is 493 psi (f'_c=4,000 psi) and SF of 1.7
  - Allowable Stress = 493/1.7 = 290 psi
  - Equivalent Stress Ratio = 1/SF = 0.588

Concrete Slab on Ground

Cracking

Factors in Cracking

- Concrete Tensile Strength (Loading & Joints)
  - Overstress
  - Fatigue
- Volume Change - Shrinkage/Expansion/Thermal
  - Linear
  - Curling / Warping
- Restraint Conditions
  - Slab / Subbase Friction
  - Slab Penetrations

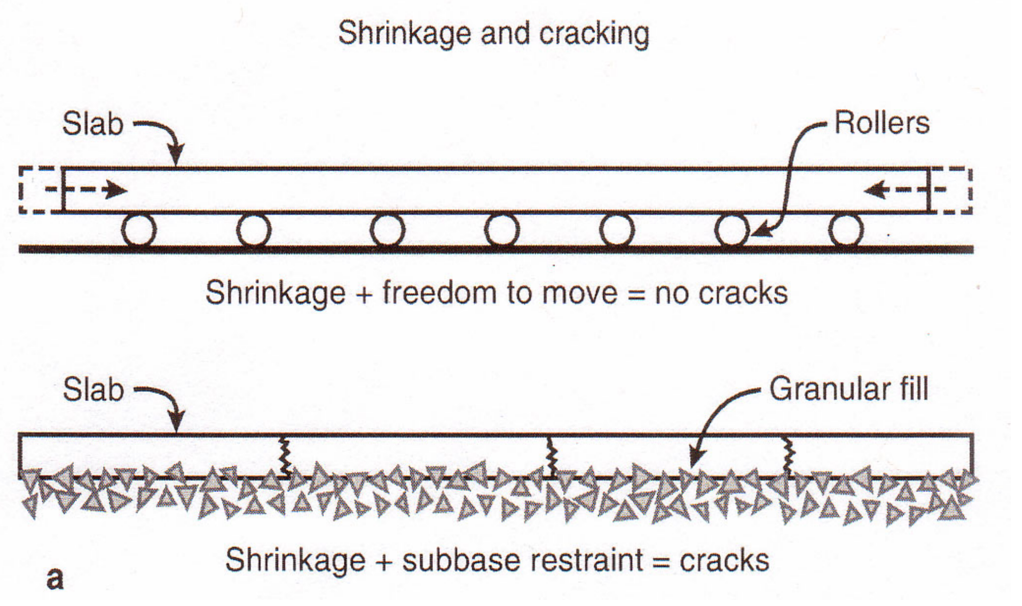


Fig. 15-10, PCA

Factors in Cracking

- **2 Main Categories of Crack Occurrences**
  - **Cracking in Plastic Concrete**
    - Plastic Shrinkage Cracking
    - Settlement Cracking
  - **Cracking in Hardened Concrete**
    - Drying Shrinkage
    - Thermal Stresses
    - Chemical Reaction
    - Weathering
    - Corrosion of Reinforcement
    - Poor Construction Practices
    - Construction Overloads
    - Design and Detailing Errors
    - External Loading (Design and Overload)

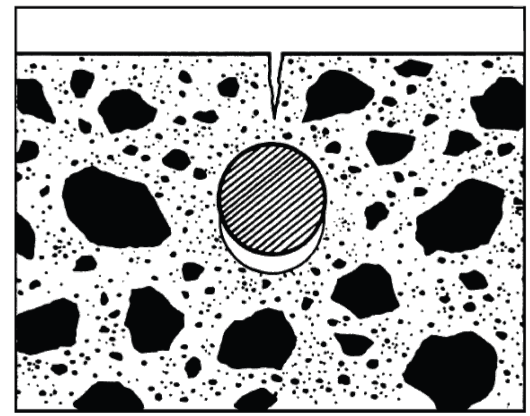


Fig. 1.2—Crack formed due to obstructed settlement (Price 1982).

Shrinkage Cracks - Minimizing

- Shrinkage cracking can be ***minimized*** by
  - Reducing shrinkage characteristics of concrete mix
  - Reducing restraints on the slab
- Shrinkage cracking can be ***controlled*** by
  - Use of joints to “encourage” cracks to appear at predetermined locations
  - Use of reinforcing steel to keep crack widths tight

Shrinkage Cracks - Minimizing

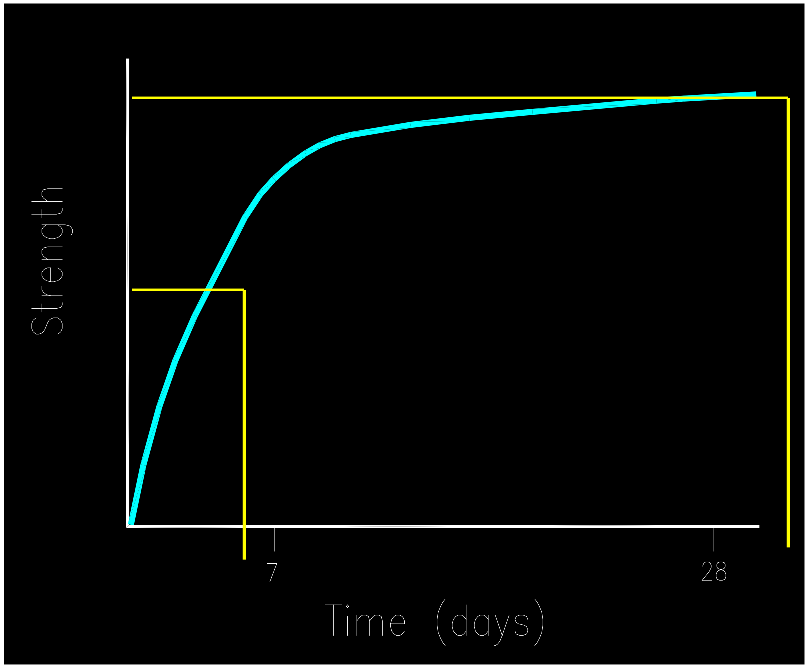
Reducing Shrinkage Through Concrete Mix Design

- Reduce the volume of water in the mix
  - Challenge is to limit amount of water in mix while maintaining workability and finishability without excessive use of water reducers
- Use coarser ground cement
- Use largest sized aggregate permitted by design
- Use shrinkage compensating concrete

Shrinkage Cracks - Minimizing

Reducing Shrinkage Through Concrete Mix Design

- Use of proper curing techniques
  - Keeps water in the concrete until sufficient tensile strength is achieved before shrinkage occurs
  - Allows drying to occur more evenly through the slab thickness



Shrinkage Cracks - Restraint

- **Friction between the slab and ground**
  - As slab shrinks, friction between slab and ground resists the motion, causing tension in the slab
- **Bearing on other features (walls, foundation, drain pipes, columns, etc)**
  - As slab shrinks, friction between slab and object or bearing against object resists the motion, causing tension in the slab
- **Attachment to other features**

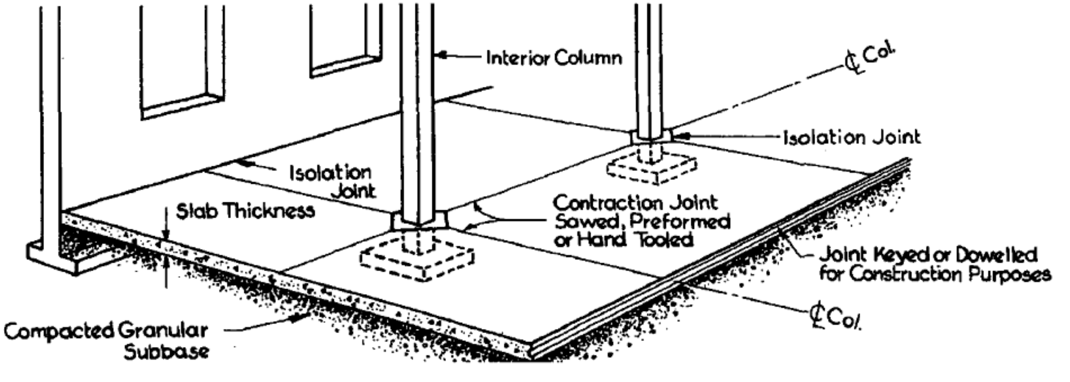


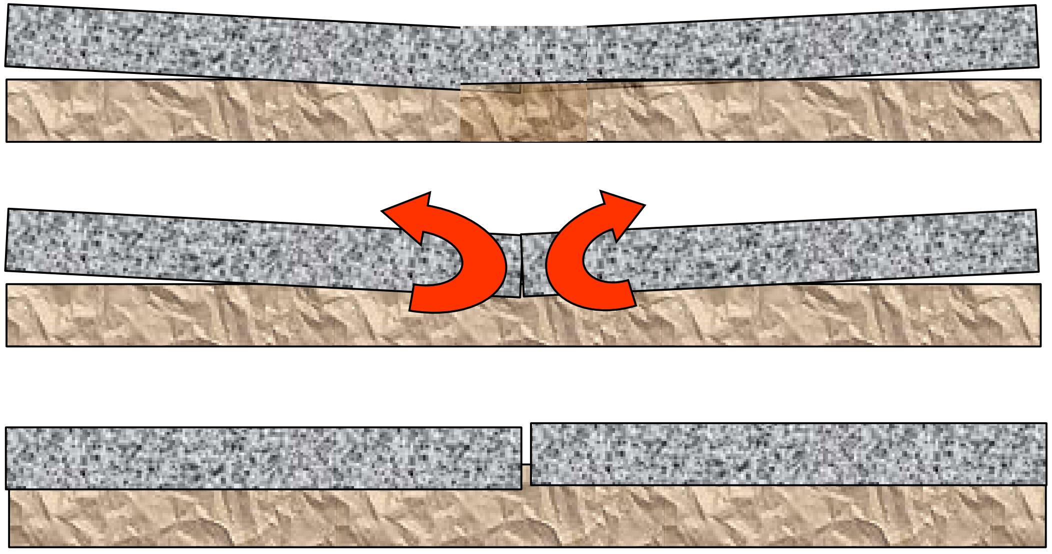
Fig. 5.1—Location and types of joints (ACI 302.1R)

Concrete Slab on Ground

Curling & Warping

Curling/Warping Distress

- Differential shrinkage due to moisture or temperature variations can result in "curling" or "warping" of slab edges
  - Curling: Due to a difference in temperature
  - Warping: Due to a difference in the moisture
- Results in an induced moment in the slab where support is lost
- When the moment equals the cracking moment a crack forms, redistributing the stress
- This can lead to mid panel or slab edge cracks under load or self weight



Curling/Warping Distress

Results of curling/warping distress can lead to:

- Decreased load carrying capacity resulting in additional long term cracking
- Slab rocking as loads move across – joint stability
- Joint spalling (joint filler breakdown)
- Decreased vehicle “rideability”
- Tire or equipment damage
- Floor surface covering/surfacing distress

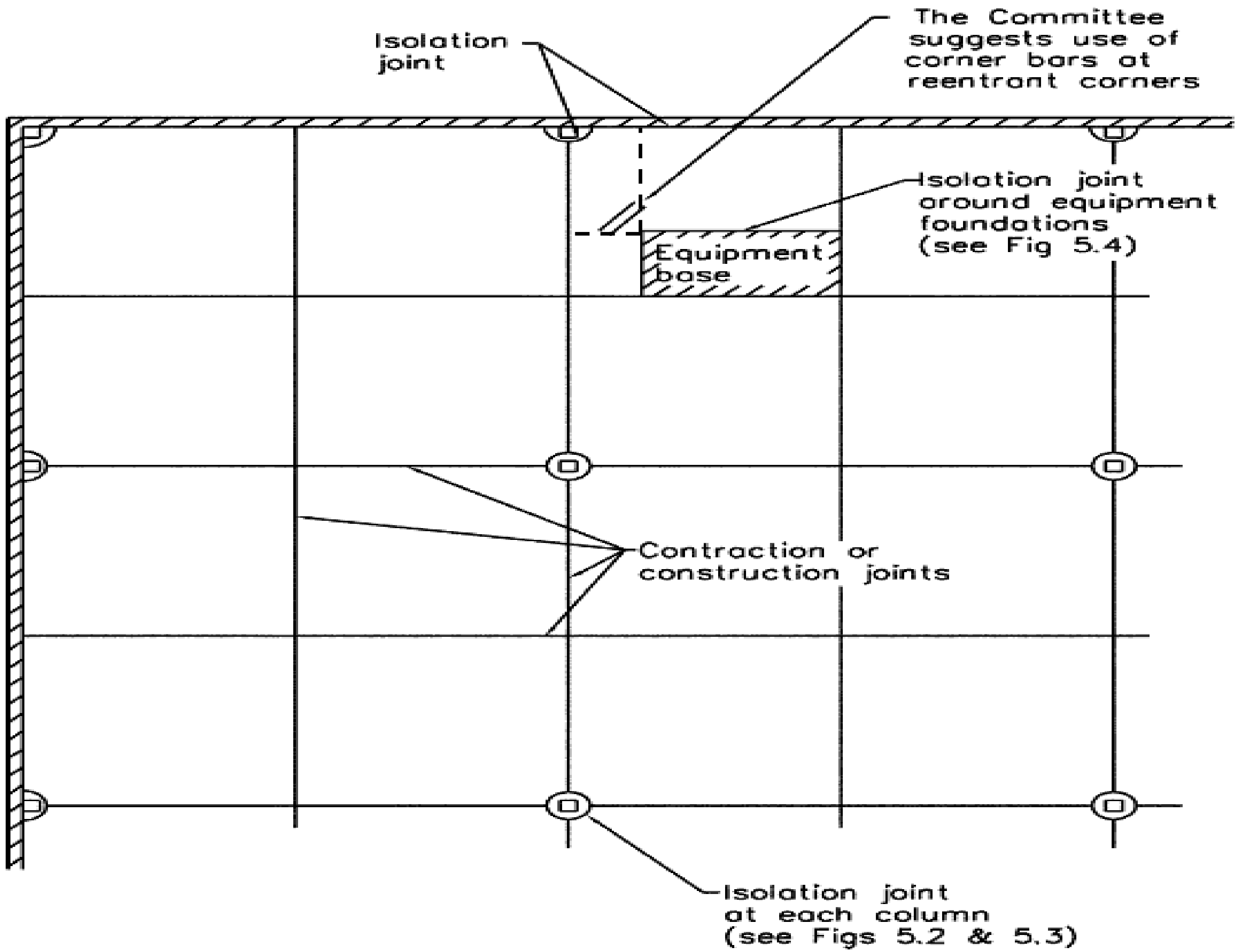
Concrete Slab on Ground

Joints

Joints

- Purpose of Joints
  - To attempt to control the outcome of concrete volume changes (crack locations)
    - Drying shrinkage
    - Temperature changes
  - Provide a designed contact between concrete placements
  - Allow for different movement to occur between adjacent structural components or structures
- Types of Joints
  - Contraction Joints (also called control joints)
  - Construction Joints
  - Isolation Joints / Expansion Joints
- Many variations in guidance – even within ACI

Typical Joint Locations



ACI 360R-10 Fig 6.1 Appropriate Locations for Joints

Contraction Joints

- Spacing typically per ACI 360R-10 Fig. 6-6
- In addition to slab thickness, spacing is influenced by:
  - Design method
  - Shrinkage potential of the concrete
  - Addition of steel reinforcement
  - Base friction and other restraints
  - Environment

- Slab panel Aspect Ratio
  - For unreinforced, reinforced for crack-width control or shrinkage-compensating concrete
  - Maximum of 1.5 to1; 1 to 1 is preferred
  - L- and T-shaped panels should be avoided
- NRCS Specification 31, Section 14

Contraction Joints

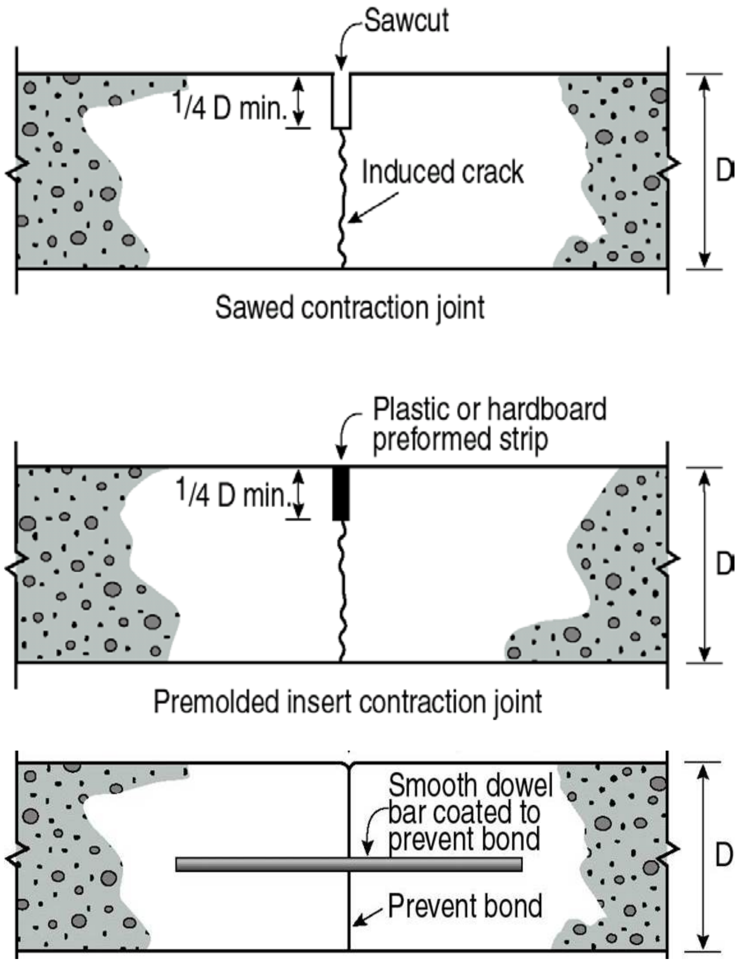


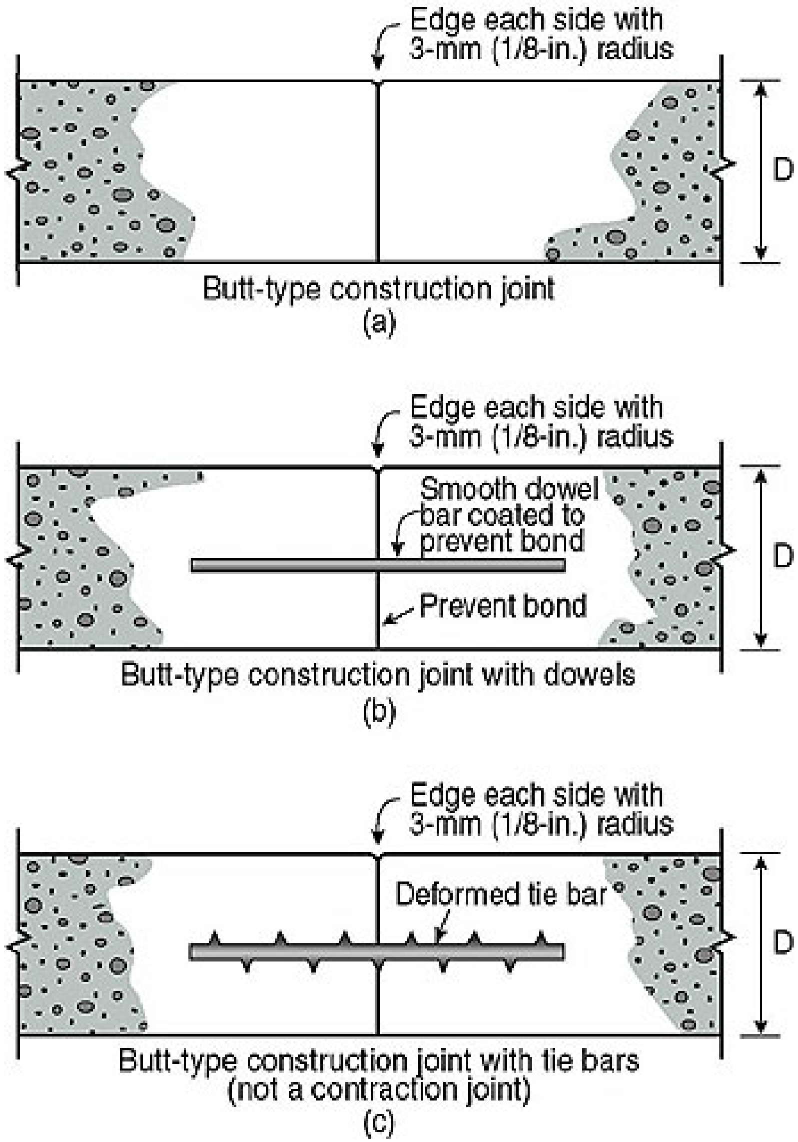
Fig. 11-27, PCA

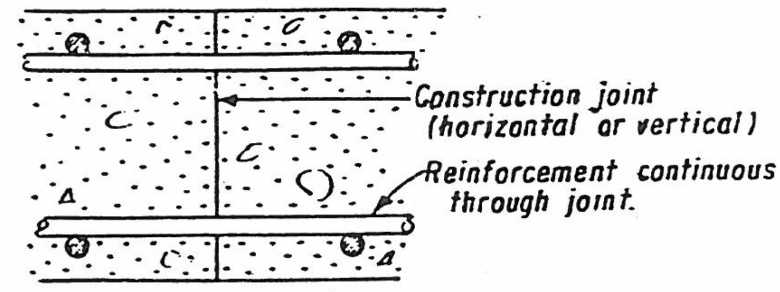
- Saw depth and insertion depth ≥ ¼ D ≤ 1/3 D.
- Joints may also be tooled in before concrete begins to set.

Construction Joints

- Designed stopping place during construction
  - Placed at natural break point in placements and
  - At intervals to limit length or volume of concrete placements
- Unplanned stopping place during construction
  - Weather
  - Construction Problems – forms, material, personnel, delays
- Can be keyed, doweled, or bonded/butt joints
- Typically transfer moment continuity and shear across a joint
- Movement joints can function as construction joints
- Checkerboard placement is not recommended
  - Infill slabs are restrained on all sides
- NRCS Specification 31, Section 13

Construction Joints





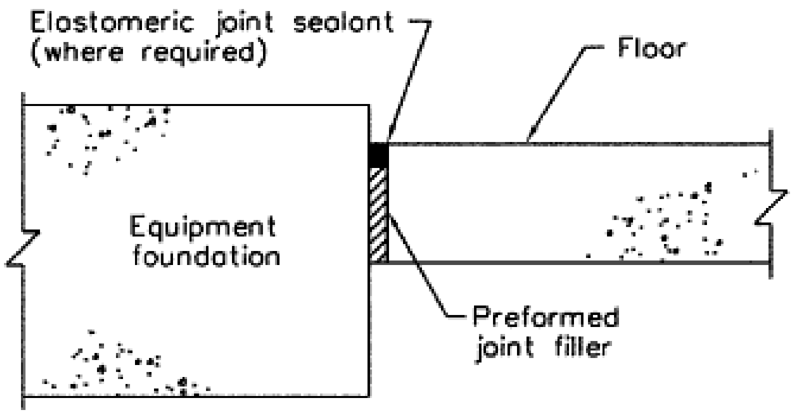
CONSTRUCTION JOINT

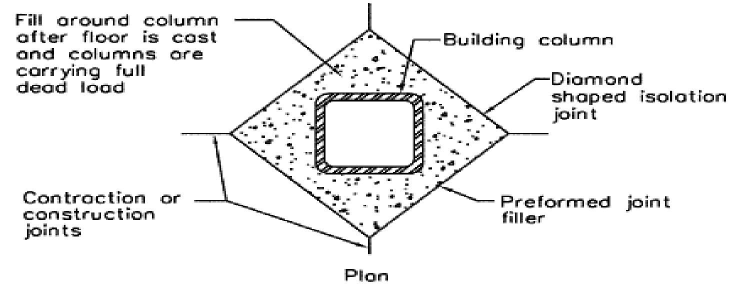
Basic Construction Joints

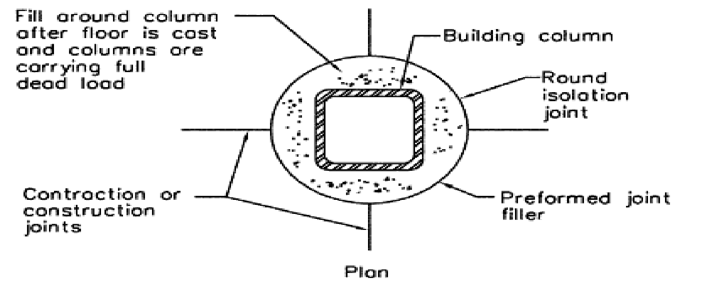
Isolation / Expansion Joints

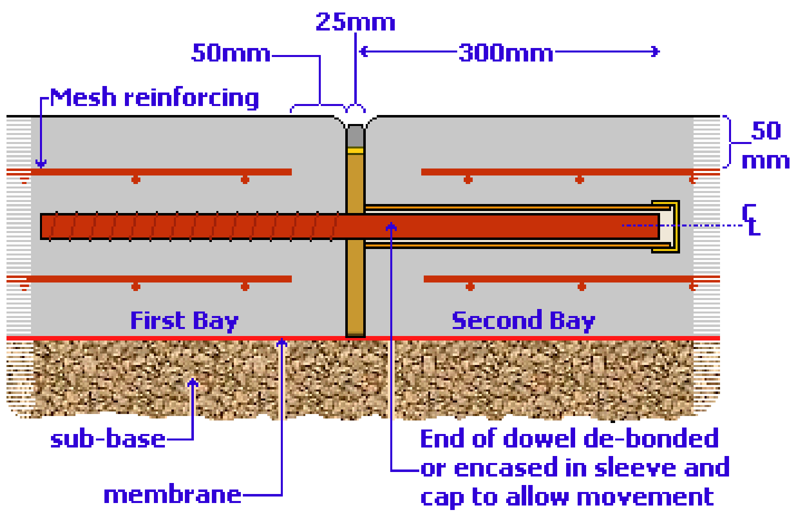
- Used to permit both horizontal and vertical movement between slab and adjoining structures or building elements
  - May act as expansion joints with expansion joint filler
- Used at the junction of floors with walls, columns, footings, and other points of restraint
  - between vibrating equipment and building foundations
  - between column foundations and floating slabs
- Extend full depth of slab and include preformed compressible filler and can also have a joint sealant
- Joint thickness typically ¼” to ½”
- Provide waterstop, where required, for liquid tightness
- NRCS Specification 31, Section 14

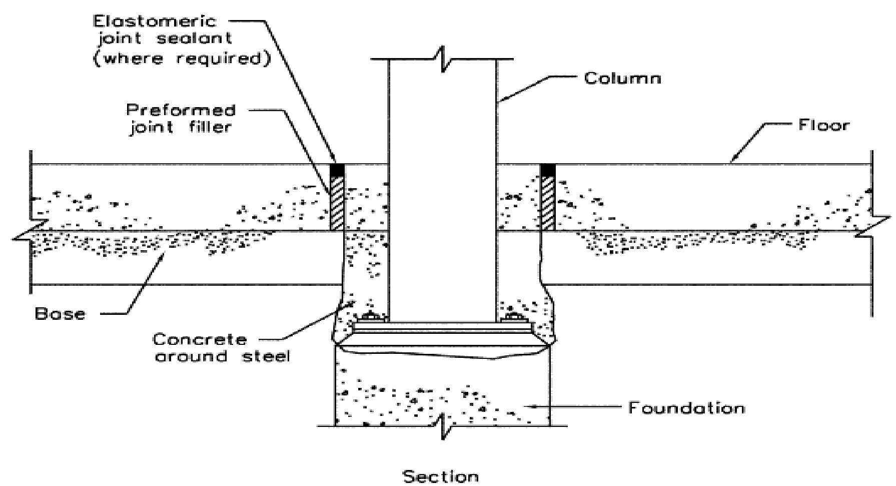
Isolation / Expansion Joint











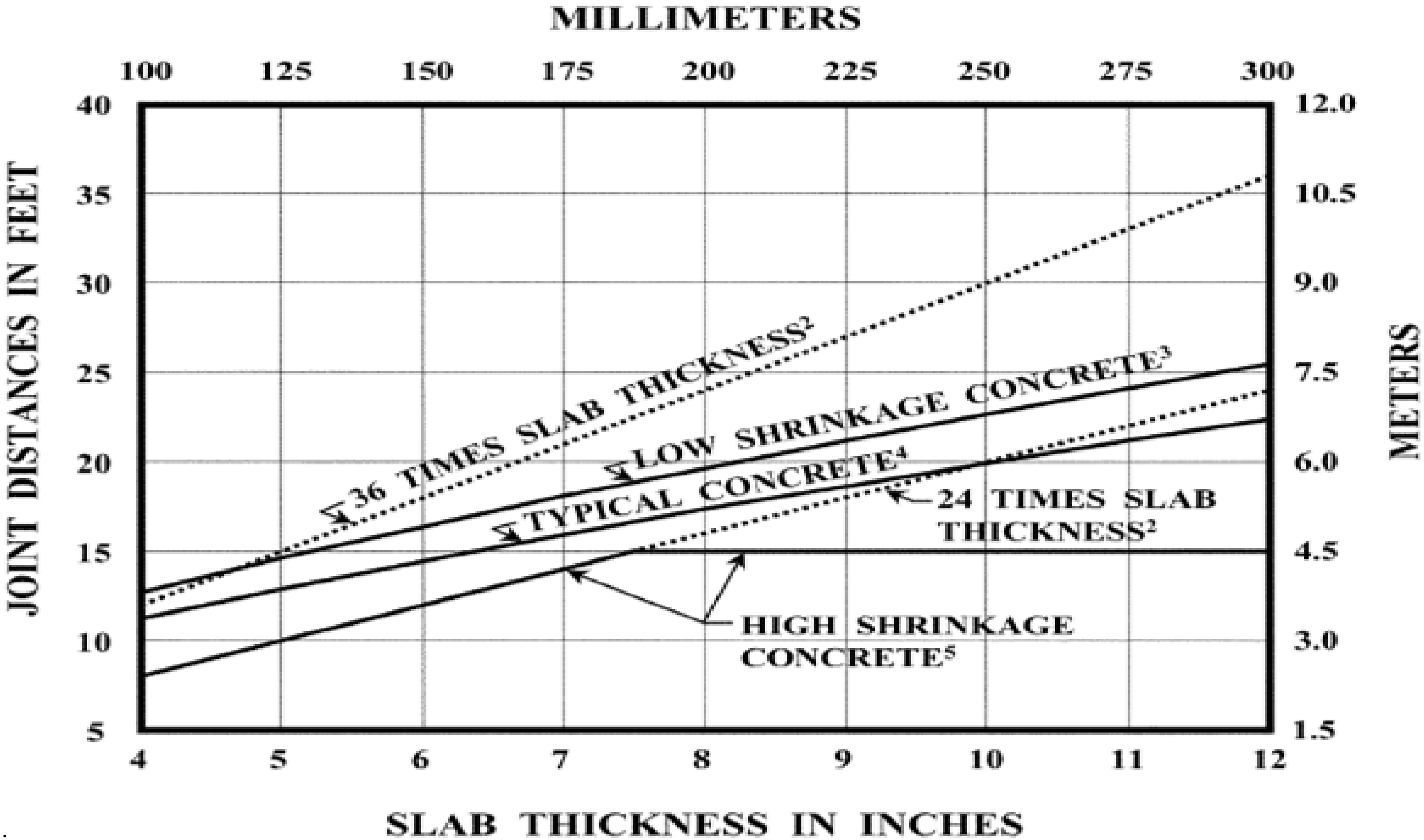
Concrete Slab on Ground

Joint Spacing

Joint Spacing

- Spacing typically per ACI 360R-10 Fig. 6-6
  - For unreinforced, reinforced for crack-width control or shrinkage-compensating concrete
  - Smaller aggregate size, higher water contents, and local experience may dictate use of closer joints
- Eliminate saw cut contraction joints with reinforcement
  - Use minimum steel ratio of 0.5% (PCA 2001)
  - Use continuous amount of reinforcement in the direction where the contraction joints are eliminated
- Aspect ratio
  - Maximum of 1.5 to1; 1 to 1 is preferred
  - L- and T-shaped panels should be avoided

Joint Spacing



<u>Notes</u>:

1. Joint spacing recommendations based on reducing the curling stresses to minimize mid-panel cracking (Walker-Holland 2001). See discussion in Section 5.2 for joint spacing for aggregate interlock.
2. Joint spacing criteria of 36 and 24 times the slab thickness which has been utilized in the past is shown for reference.
3. Concrete with an ultimate dry shrinkage strain of less than 520 millionths placed on a dry base material.
4. Concrete with an ultimate dry shrinkage strain of 520 to 780 millionths placed on a dry base material.
5. Concrete with an ultimate dry shrinkage strain of 780 to 1100 millionths placed on a dry base material.

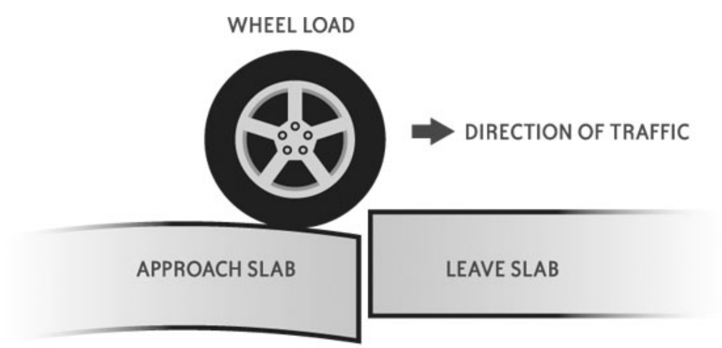
360-10 Figure 6.6 Recommended Joint Spacing for Unreinforced Slabs

Concrete Slab on Ground

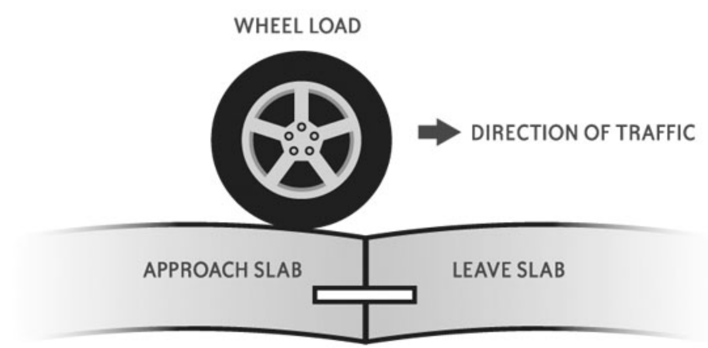
Load Transfer at Joints

Load Transfer at Joints

- Use load transfer devices (typically dowels) at construction and contraction joints where positive load transfer is needed,
  - Unless sufficient post-tensioning force is provided to transfer shear
  - Dowels should be smooth, aligned and supported to remain parallel in the horizontal and vertical planes to allow the joints to open freely as concrete shrinks.
  - Depends on usage need and slab thickness as well



0% Load Transfer



100% Load Transfer

Load Transfer at Joints

- Enhanced aggregate interlock using reinforcement
  - Depends on a combination of a small amount of the reinforcement continued through the joint and the irregular face of the cracked concrete at the joint
  - 0.1% reinforcement continuous through joints (per ACI 360-10 Fig.6.6.) and placed above mid-depth but below saw cut depth
  - Still need a construction or smooth doweled joints at 125 ft. max. spacing
  - Use an early entry saw to cut all sawcut contraction joints
  - Slab must be uniform thickness
  - Larger percentages of reinforcing restrain joint and can cause random cracking

Concrete Slab on Ground

Reinforcement

Reinforcing Slabs on Grade Purpose

- Shrinkage Control **- Crack Width Control**
  - Presence of steel could exacerbate cracking
- Temperature Control **- Crack Width Control**
  - Steel and concrete have essentially the same coefficient of thermal expansion
- Moment Capacity **– Structural Capacity**
  - Thickness is usually a function of loading, subgrade modulus, modulus of rupture of the concrete, and slab stiffness (see Slab Design Methods)
- Enhanced Aggregate Interlock **- Load Transfer Across Joints**
  - Reference dowels and ACI 360

Reinforcing Slabs on Grade
Typical Reinforcement Types

- **Reinforcing Bars**
  - Tied in place or prefabricated mats
- **Welded Wire Fabric**
  - Mesh – Rolls or Sheets
- **Fibers**
  - Steel or Polypropylene
  - ACI 360 suggests that fibers be treated as an enhancement
- **Post Tensioning**

Reinforcing Slabs on Grade
Design & Detailing Notes

- Smaller bar sizes are better choices than large diameters
- Reinforcing “should be positioned one-fourth the slab thickness below the top surface up to 2.0 in maximum.” ACI 302.1R
- Minimum cover of the steel is per ACI 318 7.7
  - Top cover ¾” inch clear cover for slabs protected from the weather, 1.1/2” for #5 or smaller bars and 2” for larger bars exposed to weather
  - 3” clear between bars and the ground

Concrete Slab on Ground

NRCS Slab Design Guidance

NEM Part 536
536.22 Structural Engineering

- **Design Criteria for Concrete Slabs-on-Ground (SOG)**
  - **Design per ACI 330R Guide for the Design and Construction of Concrete Parking Lots**
    - SOG subject to distributed stationary loads, light vehicular traffic, or infrequent use by heavy truck or heavy agricultural equipment.
  - **Design per ACI 360R Design of Slabs-on-Ground**
    - SOG subject to regular or frequent heavy truck or heavy agricultural equipment traffic.
  - **Design per ACI 350, App. H Environmental Engineering Concrete Structures Appendix H Slabs-on-Soil**
    - Liquid tight SOG, with minimal leakage under normal service conditions.

Concrete Slab on Ground

ACI 360 Design of Slabs on Ground

Design of Unreinforced Concrete Slabs

- **Two objectives of unreinforced slab on ground design**
  - Avoid the formation of random, out-of-joint cracks
  - Maintain adequate joint stability
- **Live loading governs thickness and cross joint shear transfer needed**
  - Thickness determined using allowable concrete flexural tensile stress (MOR modulus of rupture)
  - Slabs normally designed to remain uncracked due to applied loads with a factor of safety of 1.4 to 2.0 relative to the MOR
  - Although effects of any reinforcement are not considered, joints may be reinforced for load transfer across the joint
- **Shrinkage considerations dictate joint spacing**
  - Keep cracks under or at joint locations
  - Joint Spacing typically per ACI 360R-10 Fig. 6-6

Thickness Design Procedures
Unreinforced Concrete Slabs

- **ACI 360R-10 7.2.1 to 7.2.3**
  - Portland Cement Association (**PCA**)
  - Wire Reinforcing Institute (**WRI**)
  - Corps of Engineers (**USACE** or **COE**)

- Avoid live load-induced cracks by providing adequate slab cross section by using adequate factor of safety against rupture
- All 3 methods are generally accepted thickness design methods for unreinforced slabs-on-ground
- All 3 methods assume the slab remains in contact with the ground and curling stresses are not considered
- PCA and WRI methods only consider live loads on the slab’s interior
- COE method only considers live loads on the slabs edges or at joints

Thickness Design Procedures
Unreinforced Concrete Slabs

- **Portland Cement Association (PCA) (ACI 360R-10 7.2.1)**
  - Based on Pickett's analysis
  - Utilizes a series of charts for various loading conditions (wheels, racks, posts, etc)
  - Used for <u>interior loadings only</u> (not adjacent to edges)
- **Wire Reinforcing Institute (WRI) (ACI 360R-10 7.2.2)**
  - Based on discrete element computer model
  - Uses slab stiffness factor, E, trial slab thickness, diameter of equivalent loaded area, distance between wheels, flexural strength, working stress, and subgrade modulus.
  - Used for <u>interior loadings only</u> (not adjacent to edges)
- **Corp. of Engineers (USACE or COE)(ACI 360R-10 7.2.3)**
  - Based on Westergaard's formula for edge stresses
  - Intended for wheel and axle <u>loadings at edges or joints only</u>
  - Concentrated, uniform, construction, line, and strip loads are not considered.

Design of Concrete Slabs

Reinforced for Crack-Width Control

- **Reinforcing will not prevent cracking**
  - Actually increases crack frequency
  - But reduces crack widths so serviceability not affected
- **Benefits of reinforcing**
  - Limiting shrinkage crack widths
  - Use of longer joint spacing than unreinforced slabs
  - Providing flexural strength and stability at cracked sections
- **Thickness based on assumption of uncracked and unreinforced slab**
  - Thickness determined using design procedures (PCA, WRI, COE) for unreinforced concrete slab to prevent cracking due to external loads

Design of Concrete Slabs
Reinforced for Crack-Width Control

- **Reinforcement required is function of joint spacing and thickness**
- **Joint Spacing typically per ACI 360R-10 Fig. 6-6**
  - For unreinforced, reinforced for crack-width control or shrinkage-compensating concrete
  - Smaller aggregate size, higher water contents, and local experience may dictate use of closer joints
- **Eliminate saw cut contraction joints with reinforcement**
  - Use minimum steel ratio of 0.5% (PCA 2001)
  - Use continuous amount of reinforcement in the direction where the contraction joints are eliminated

PCA Method - Example

- Enter from slab (stress per 1000 lb of axle load)
  13.4 psi
- Move right to wheel contact area line
  114 in^2
- Move vertically to wheel spacing line
  40 in
- Move right to k line
  100 pci
- Obtain slab thickness
  8 in.

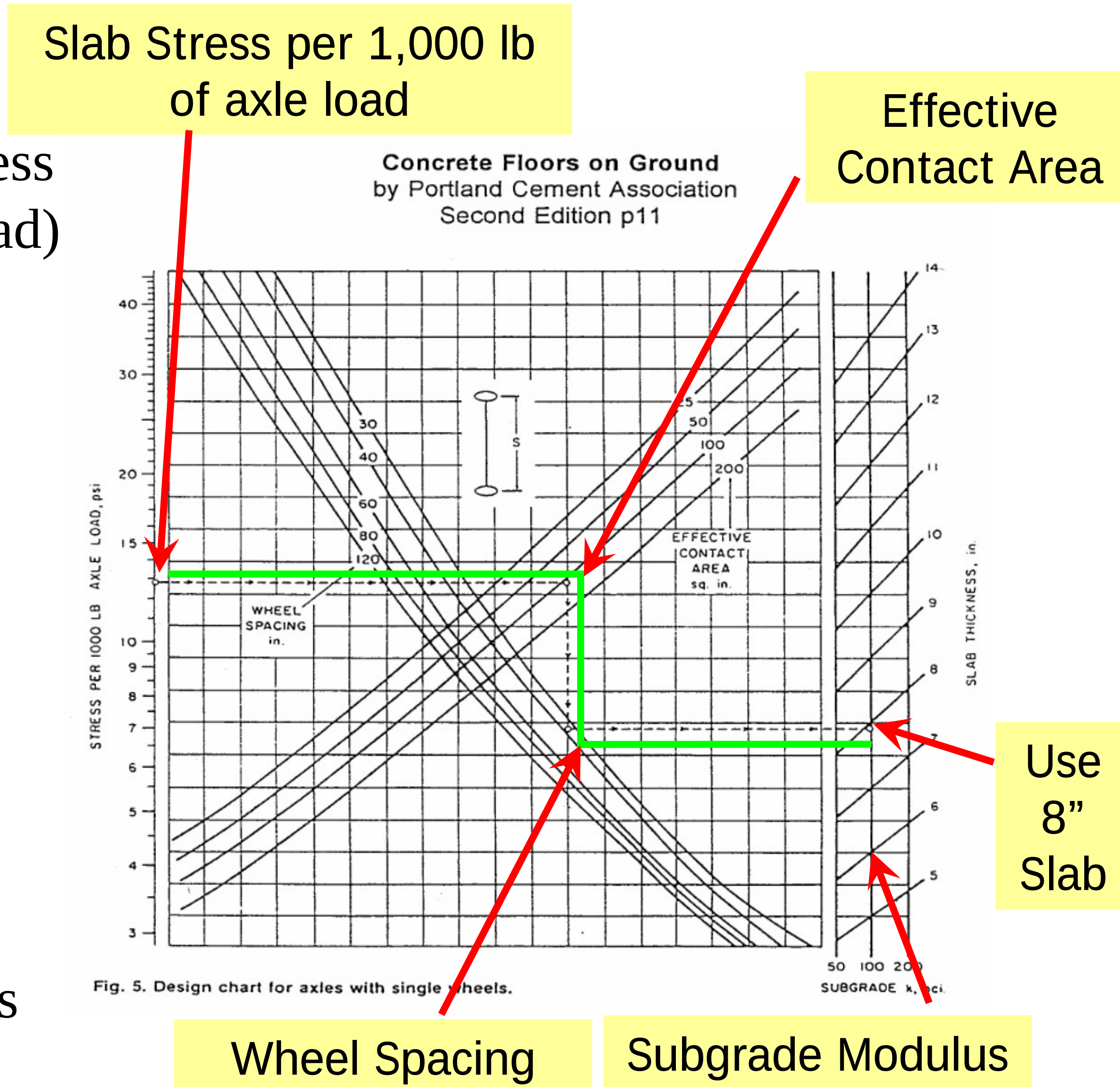


Fig. 5. Design chart for axles with single wheels.

PCA Method - Example

- **Slab Thickness Design Summary**
  - Slab Thickness = 8”
  - Slab reinforcing to eliminate contraction joints
    - Use 0.5% reinforcement with expansion joints at 150 ft.
    - 0.005 * 8” * 12” = 0.48 in^2 Use #5 @ 8”   As = 0.47 in^2
  - Slab reinforcing for enhanced aggregate interlock
    - At joints, continue 0.1% reinforcement through joints
    - 0.001 * 8” * 12” = 0.10 in^2 Use #3 @ 12”   As = 0.11 in^2
    - Slab joint spacing per ACI 360-10 Fig. 6.6
      - For 8” slab use 17.5 ft.

Concrete Slab on Ground

ACI 330R-08
Guide for the Design and Construction of Concrete Parking Lots

ACI 330R-08

Guide for the Design and Construction of Concrete Parking Lots

General Approach

- General Scope of 330R:
  - Traffic, 0 to 700 Trucks/Day
  - Pavement Thickness, 4” to 9”
  - Load Transfer, none to moderate
- Recommendations for MOR based on aggregate used (smooth or coarse).
- Variables include
  - Assumed traffic category, ADT, k, CBR, f’c
  - Simple tables provided to determine traffic categories, k, CBR
- Slab thickness determined using Table 3.4
- Joint spacing recommendations are provided in Table 3.5
- Tables allow for easy comparison of concrete strength versus thickness Reinforcing steel can be added if larger joint spacing is required
  - Method provided (similar to older subgrade drag formula)
  - Recommends smaller panels rather than reinforcing
- Notes that experience has shown that dowels or other load-transfer devices are not needed for most parking lot conditions.

ACI 330R-08
Guide for the Design and Construction of Concrete Parking Lots

Table 3.3—Traffic categories*

1. Car parking areas and access lanes—Category A
2. Shopping center entrance and service lanes—Category B
3. Bus parking areas, city and school buses Parking area and interior lanes—Category B Entrance and exterior lanes—Category C
4. Truck parking areas—Category B, C, or D

Truck type	Parking areas and interior lanes	Entrance and exterior lanes
Single units (bobtailed trucks)	Category B	Category C
Multiple units (tractor trailer units with one or more trailers)	Category C	Category D

*Select A, B, C, or D for use with Table 3.4.

ACI 330R-08

Guide for the Design and Construction of Concrete Parking Lots

Sample Design Input:

Given:

Traffic B

ADTT = 300

CBR = 10 or

k = 200

MOR = Mr =550

Use:

6” thick slab

Traffic category	k = 500, CBR = 50, M_R				k = 400, CBR = 38, M_R				k = 300, CBR = 26, M_R			
	650	600	550	500	650	600	550	500	650	600	550	500
A (ADTT= 0)*	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	4.0
A-1 (ADTT =1)*	3.5	3.5	4.0	4.0	3.5	4.0	4.0	4.0	4.0	4.0	4.0	4.5
A-1 (ADTT = 10)	4.0	4.5	4.5	5.0	4.5	4.5	5.0	5.0	4.5	4.5	5.0	5.5
B (ADTT = 25)	4.0	4.5	4.5	5.0	4.5	4.5	5.0	5.5	4.5	4.5	5.0	5.5
B (ADTT = 300)	5.0	5.0	5.0	5.5	5.0	5.0	5.5	6.0	5.0	5.5	5.5	6.0
C (ADTT = 100)	4.5	5.0	5.5	6.0	5.0	5.0	5.5	6.0	5.0	5.5	5.5	6.0
C (ADTT = 300)	5.0	5.5	5.5	6.0	5.0	5.5	6.0	6.0	5.5	5.5	6.0	6.5
C (ADTT = 700)	5.5	5.5	6.0	6.0	5.5	5.5	6.0	6.5	5.5	6.0	6.0	6.5
D (ADTT = 700)	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5

Traffic category	k = 200, CBR = 10, M_R				k = 100, CBR = 3, M_R				k = 50, CBR = 2, M_R			
	650	600	550	500	650	600	550	500	650	600	550	500
A (ADTT= 0)	3.5	3.5	[illegible]	4.0	3.5	3.5	3.5	4.0	4.0	4.0	4.0	4.0
A-1 (ADTT =1)	4.0	4.0	[illegible]	4.5	4.0	4.5	4.5	5.0	4.5	5.0	5.0	5.5
A-1 (ADTT = 10)	4.5	5.0	[illegible]	5.5	5.0	5.5	6.0	6.0	5.5	6.0	6.5	7.0
B (ADTT = 25)	4.5	5.0	[illegible]	6.0	5.0	5.5	6.0	6.5	5.5	6.0	6.5	7.0
B (ADTT = 300)	[illegible]	[illegible]	6.0	6.5	5.5	6.0	6.5	7.0	6.5	6.5	7.0	7.5
C (ADTT = 100)	5.5	5.5	6.0	6.5	6.0	6.0	6.5	7.0	6.5	7.0	7.5	8.0
C (ADTT = 300)	5.5	6.0	6.5	7.0	6.0	6.5	7.0	7.5	6.5	7.0	7.5	8.0
C (ADTT = 700)	6.0	6.0	6.5	7.0	6.5	6.5	7.0	7.5	7.0	7.5	8.0	8.5
D (ADTT = 700)	7.0	7.0	7.0	7.0	8.0	8.0	8.0	8.0	9.0	9.0	9.0	9.0

Thickness Design – ACI 330 Table 3.4

Concrete Slab on Ground

ACI 350 Appendix H

ACI 350 Appendix. H - Slabs on Soil
Prescriptive Approach

- **H.1 Scope – Three types of slabs**
  - Structural slabs
  - **Slabs-on-grade**
  - Membrane slabs
- **H.3 Slab thickness**
  - **4 in. min for slabs with one layer of nonprestressed reinforcement**
  - 5 in. min for slabs with prestressed reinforcement
  - **6 in. min for slabs with top and bottom nonprestressed reinforcement.**
  - Tolerances for finished slab surface: +3/4 and -0 with no greater difference than ±1/4 in. in 10 ft.
- **H.4 Reinforcement**
  - **Slabs-on-grade shall be reinforced in 1 or 2 layers.** Membrane slabs shall be reinforced with 1 layer.
  - **Min reinf. shall not be less than the requirements for T&S for structural slabs per ACI 350**
  - Prestressed reinforcement, if used, shall not be less than the amount required to impart a final compression of 200 psi
  - **Min reinf. Ratio 0.5% in each orthogonal direction for nonprestressed membrane slabs.**
  - Additional reinf. shall be provided at floor edges and other discontinuities as required by the design.
  - WWF or deformed bar reinf. shall be used.
  - Max. WWF spacing shall be 4 in.
  - **Max. bar reinf. Spacing shall be the lesser of 12 in. or two times the slab thickness.**

Contact Information

John Van Leeuwen, PE

- (817) 509-3758
- John.VanLeeuwen@ftw.usda.gov

Phuc H. Vu, PE

- (817) 509-3764
- phuc.vu@ftw.usda.gov

THE END