Concrete Slab on Ground Design and Details

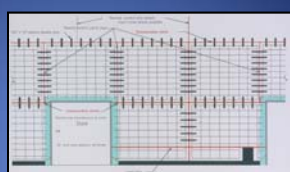
Scott M. Tarr, P.E. FACI
North S.Tarr Concrete Consulting, P.C.
Guidance to Concrete Solutions
STarr@NorthSTarrConcrete.com

Minnesota Concrete Council
Dedicated to Cast-in-Place Concrete

October 13, 2020

1

Slab Design



and Detailing

2

The slab every owner expects to see …

"Lab-Crete"

3


The slab they all too often see …
"Real-Crete"

4


Which often leads to making new friends along the way …
"Legal-Crete"

5


Making it all so much fun …
Balance Sheet
Bankruptcy
"Dis-Crete"

6

American Concrete Institute (ACI 360) Definition

Slab Design - The decision-making process of planning, sizing, detailing, and developing specifications preceding construction of slabs on ground.

7

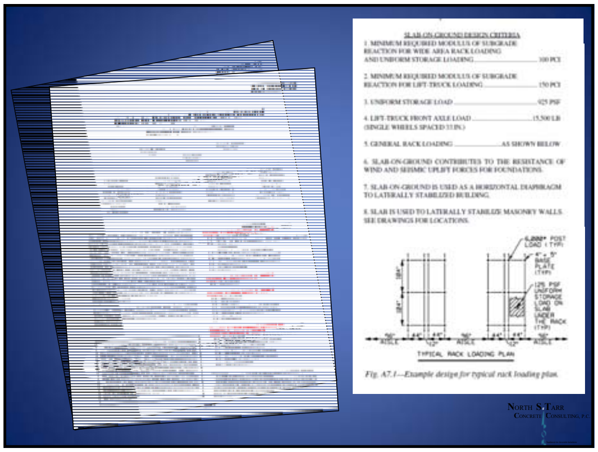
Designer Responsibility: Develop Clear Project Specs…

8

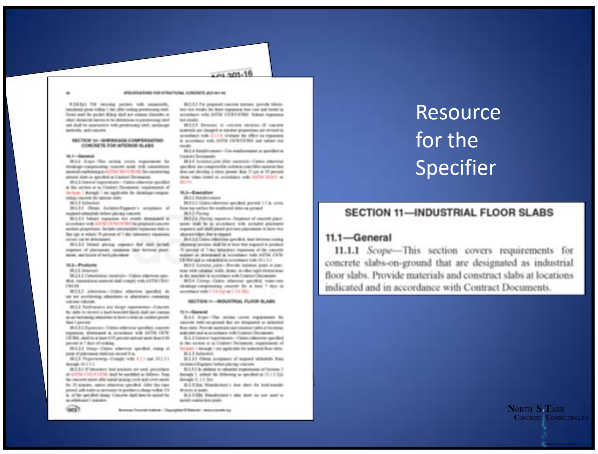
Contractor Responsibility: Follow Project Specifications…

9

Scott M. Tarr, PE FACI
STarr@NorthSTarrConcrete.com


SLAB-ON-GROUND DESIGN CRITERIA
1. MINIMUM REQUIRED MODULUS OF SUBGRADE REACTION FOR WIDE AREA RACK LOADING AND UNIFORM STORAGE LOADING .... 100 PCI
2. MINIMUM REQUIRED MODULUS OF SUBGRADE REACTION FOR LIFT-TRUCK LOADING .... 150 PCI
3. UNIFORM STORAGE LOAD .... 925 PSF
4. LIFT-TRUCK FRONT AXLE LOAD .... 15,500 LB (SINGLE WHEELS SPACED 33 IN.)
5. GENERAL RACK LOADING .... AS SHOWN BELOW
6. SLAB-ON-GROUND CONTRIBUTES TO THE RESISTANCE OF WIND AND SEISMIC UPLIFT FORCES FOR FOUNDATIONS.
7. SLAB-ON-GROUND IS USED AS A HORIZONTAL DIAPHRAGM TO LATERALLY STABILIZED BUILDING.
8. SLAB IS USED TO LATERALLY STABILIZE MASONRY WALLS. SEE DRAWINGS FOR LOCATIONS.
TYPICAL RACK LOADING PLAN
Fig. A7.1—Example design for typical rack loading plan.
NORTH STARR CONCRETE CONSULTING, P.C.

10


Resource
for the
Specifier
SECTION 11—INDUSTRIAL FLOOR SLABS
11.1—General
11.1.1 Scope—This section covers requirements for concrete slabs-on-ground that are designated as industrial floor slabs. Provide materials and construct slabs at locations indicated and in accordance with Contract Documents.
NORTH STARR CONCRETE CONSULTING, P.C.

11


Bending
Slab Design
DO NOT
BEND

12

Load-Carrying Capacity

- Determining Factors
  - ✓ Slab Thickness
  - ✓ Concrete Strength
  - ✓ Subgrade Modulus (k)

Always remember that increasing slab thickness is the most effective way to increase floor load-carrying capacity.

Assuming Load-Transfer is Achieved at Joints

13

Concrete Slab Thickness

PCA Design Method

Typical Loading Conditions:

- Axle Loads – Lift Trucks
- Post Loads – Rack Storage
- Distributed Loads – Pallets, Boxes, Rolls

14

Axle Load Design

In general, 80 to 85% of total loaded vehicle weight on front axle.
Critical Design Axle Load

15

Information Needed for Axle-Load Design

- From materials, site, and designer
  - Concrete compressive strength
  - Subgrade modulus
  - Safety Factor (SF)
  - Joint conditions – Joint Factor (JF)
- From lift truck specifications
  - Lift truck capacity
  - Vehicle weight (total axle load)
  - Wheel configuration and spacing
  - Tire pressure
  - Wheel contact area

16

Design for Maximum Capacity

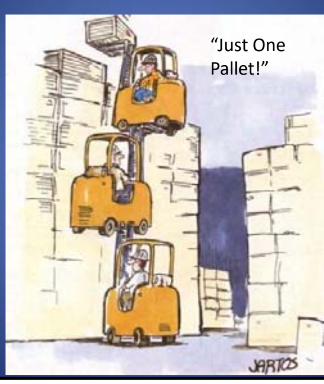
Why?

“I will only
transport one pallet
at a time.

I promise...”

17

Design for Maximum Capacity



18

Scott M. Tarr, PE FACI
STarr@NorthSTarrConcrete.com

19

Maximum Allowable Bending ~~Concrete Working~~ Stress

$$WS = \frac{MR}{SF \times JF}$$

where,

- WS = Working stress
- MR = Modulus of rupture (flexural strength)
- SF = Safety factor
- JF = Joint factor

20

Concrete Working Stress

Concrete Flexural Fatigue Equations

$$\log N = 11.737 - 12.077 SR \quad \text{for SR} \geq 0.55 \quad \text{.....Eq. 1}$$

$$N = \left(\frac{4.2577}{SR - 0.4325} \right)^{3.268} \quad \text{for } 0.45 < \text{SR} < 0.55 \quad \text{.....Eq. 2}$$

$$N = unlimited \quad \text{for SR} \leq 0.45 \quad \text{.....Eq. 3}$$

Where: SR = Stress ratio (flexural stress divided by the flexural strength)
N = Projected number of allowable 16-kip single axle bus load applications to flexural fatigue failure.

21

Joint Factor

- Original PCA Charts developed for interior loading by pneumatic tired wheels
- Stresses due to edge loading are higher - up to 60% higher
- Edge loading occurs at joints that do not have complete load transfer
  - Smooth dowel bars or dowel plates
  - Aggregate interlock decreases when joint opens

22

Joint Factor

Concrete Shrinkage

*Table 5-2. Joint Factors Based on Ultimate Concrete Shrinkage**

Ultimate concrete shrinkage, %	Joint factor
<0.052%	1.0
0.052 to 0.057	1.1
0.057 to 0.062	1.2
0.062 to 0.067	1.3
0.067 to 0.072	1.4
0.072 to 0.078	1.5
>0.078	1.6

23

Engineering Judgement

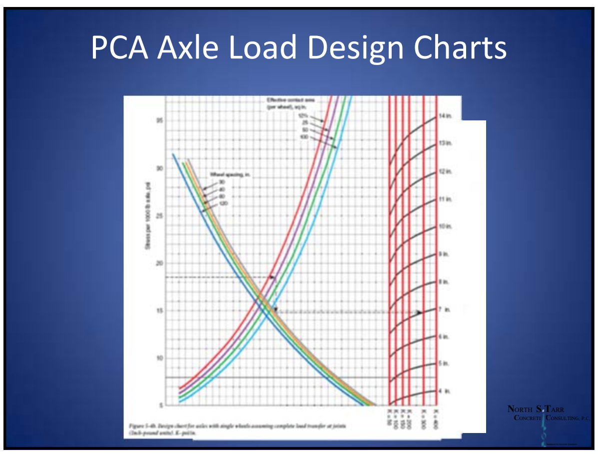
- Joint Factor (JF)
- Safety Factor (SF)
- Applied Load Considerations
  - Effective Contact Area
  - Back-to-Back Post Legs
  - Aisle Width v. Load Width

Complete Set of Design Assumptions
Must Be Considered!

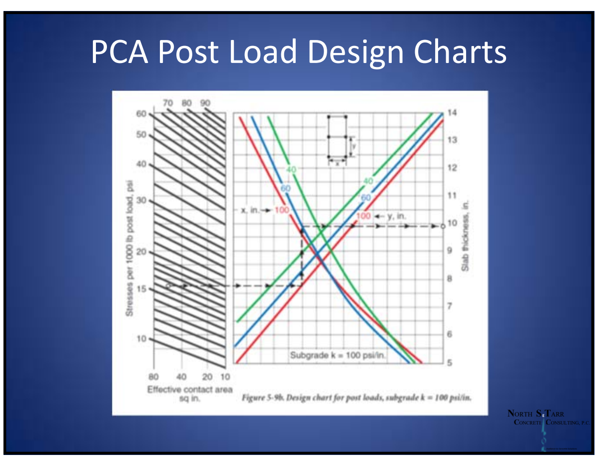
24


Too Safe?

25


PCA Axle Load Design Charts

26


PCA Post Load Design Charts
Stresses per 1000-lb post load, psi
Effective contact area sq in.
Subgrade k = 100 psi/in.
Slab thickness, in.
Figure 5-9b. Design chart for post loads, subgrade k = 100 psi/in.

27

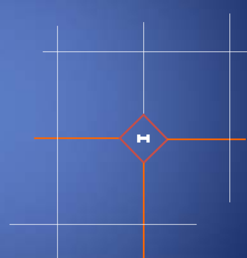
Responsibility
of the
Contractor

Perform Construction
Per Specifications
And Per
Industry Standards

28

Jointing

- Joint Types
  - Construction
  - Isolation
  - Contraction/Control



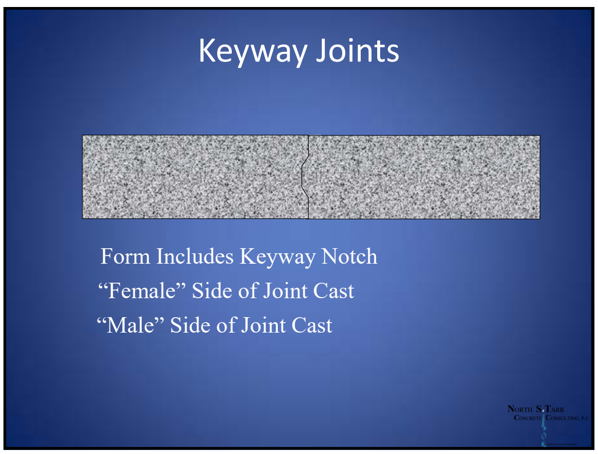
29

Construction Joints

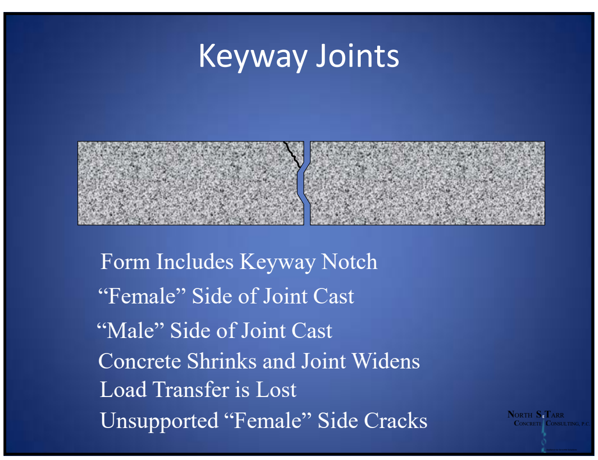
- Designate Pour Limits
  - Single Days Placement
- Butt-Type (Formed)
  - Keyways Not Recommended
- Must be Doweled
  - Load Transfer
  - Prevent Differential Movement

30

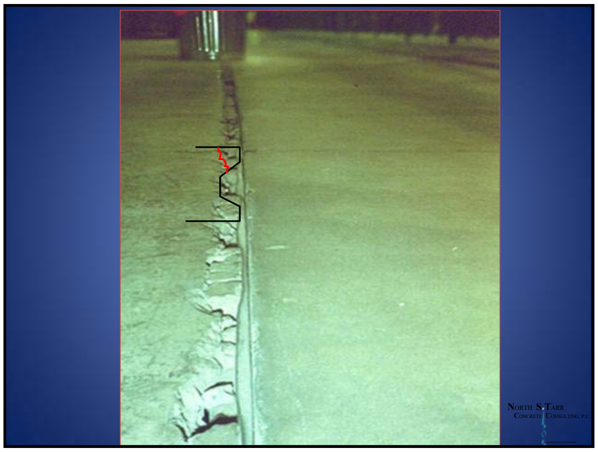
31


Keyway Joints
Form Includes Keyway Notch
“Female” Side of Joint Cast
“Male” Side of Joint Cast

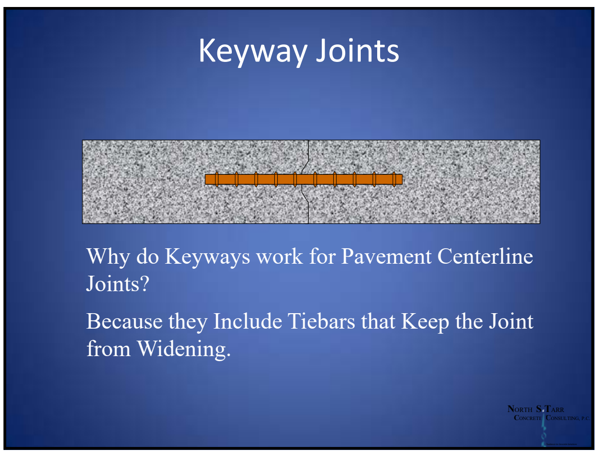
32


Keyway Joints
Form Includes Keyway Notch
“Female” Side of Joint Cast
“Male” Side of Joint Cast
Concrete Shrinks and Joint Widens
Load Transfer is Lost
Unsupported “Female” Side Cracks

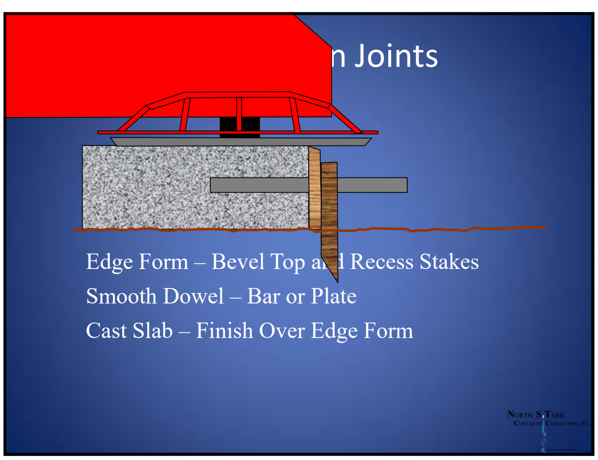
33



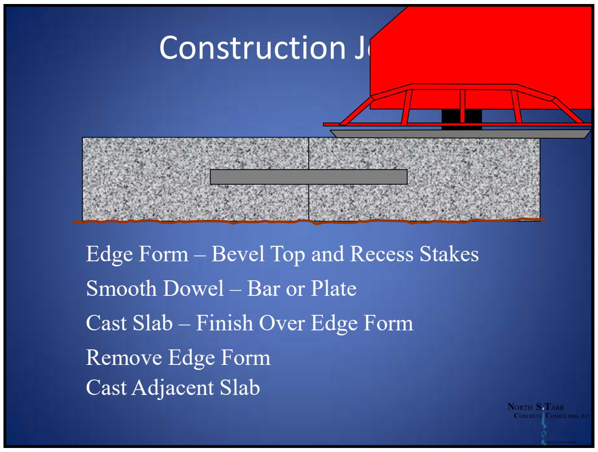
34


Keyway Joints
Why do Keyways work for Pavement Centerline Joints?
Because they Include Tiebars that Keep the Joint from Widening.

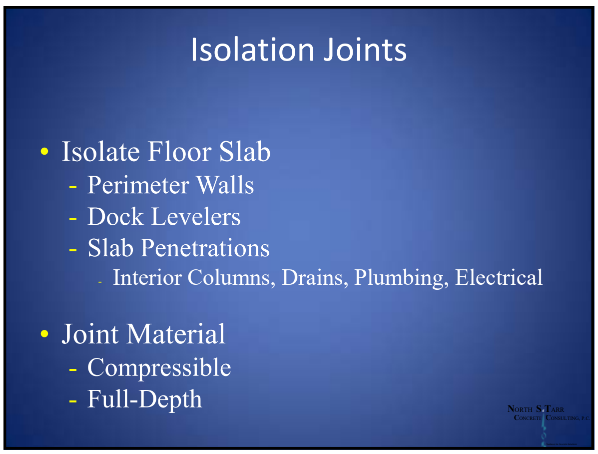
35


n Joints
Edge Form – Bevel Top a d Recess Stakes
Smooth Dowel – Bar or Plate
Cast Slab – Finish Over Edge Form

36


Construction J
Edge Form – Bevel Top and Recess Stakes
Smooth Dowel – Bar or Plate
Cast Slab – Finish Over Edge Form
Remove Edge Form
Cast Adjacent Slab

37


Isolation Joints
• Isolate Floor Slab
- Perimeter Walls
- Dock Levelers
- Slab Penetrations
- Interior Columns, Drains, Plumbing, Electrical
• Joint Material
- Compressible
- Full-Depth

38


Isolation Joint Material Full-Depth
JUL 17 2003

39

40

41

Contraction Joints

- Control Random Cracking Due To Restraint to Concrete Shrinkage
- Installed at Proper:
  - Spacing
  - Depth
  - Timing

42

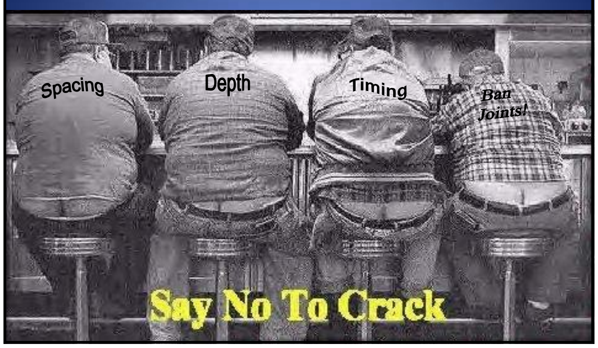
Contraction Joints

Joint - A crack placed where we want it to be.

Crack - A joint placed where the concrete wants it to be.

43

Joints are Generally Preferred



44

Contraction Joint Spacing

- American Concrete Institute (ACI)
  - 36 Times Slab Thickness
    6-in.-thick slab = 18 ft joint spacing
- Portland Cement Association (PCA)
  - Joint Spacing (ft) = 2 to 2.5 Thickness (in.)
    6-in.-thick slab = 12 to 15 ft joint spacing

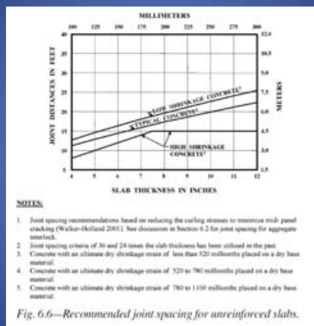
Maximum 30 Times Slab Thickness

15 ft (4.5 m) Maximum - Pavements

45

Contraction Joint Spacing

ACI 360R



Random Crack Control Only!

46

Contraction Joint Depth

- Create a Weakened Plane to determine Crack Location
  - How Deep? Deep Enough to Cause Crack
  - ¼ Slab Thickness
    6-in.-thick slab = 1½-in.-deep joint
- Grooving/Tooling or Sawcutting
  - Beware of Crack Promoting Insert (Vertical?)

47

48

Contraction Joint Timing

- Before Tensile Stress Exceeds Developed Tensile Strength (Crack)
  - Restraint to Volumetric Decrease
    Friction, Penetrations
- Just After Peak Heat of Hydration (Cooling)
  - Drying Shrinkage & Temperature Contraction
  - Generally 8 to 12 Hours After Placement

49

Joint Reinforcement

- Load Transfer

  Transfer load from one panel to the next

  - Aggregate Interlock
  - Mechanical Devices
    Dowel Bars
    Plate Dowels
  - Transferred Steel Reinforcement

50

Aggregate Interlock

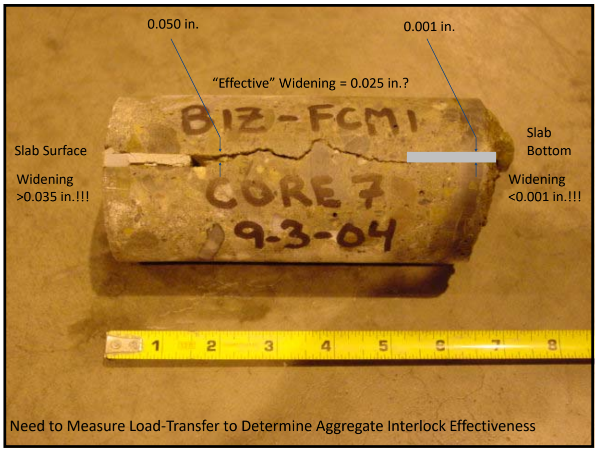
Minimal Opening Required

< 0.035 in.

Minimize Concrete Shrinkage and Joint Spacing

Be Aware of How Cracks Form in Slabs – "v" Shape

51


0.050 in.
0.001 in.
"Effective" Widening = 0.025 in.?
Slab Surface
Widening
>0.035 in.!!!
Slab
Bottom
Widening
<0.001 in.!!!
B12-FCM1
CORE 7
9-3-04
Need to Measure Load-Transfer to Determine Aggregate Interlock Effectiveness

52


Mechanical Load Transfer
Devices Installed in Joint to Transfer Applied Load From
One Slab Panel to the Adjacent Slab Panel.

53


Mechanical Devices
Align Dowels!

54


Mechanical Devices

55

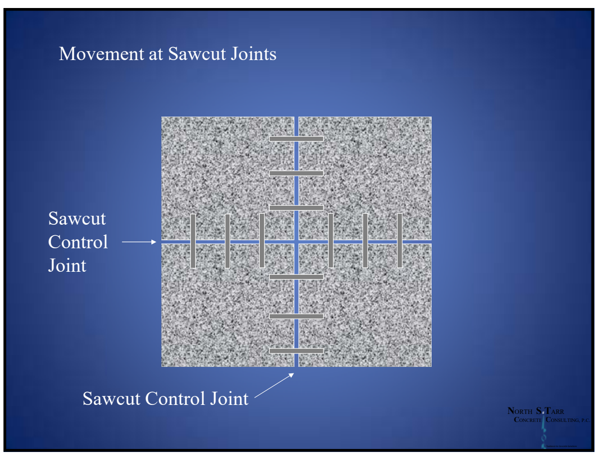

Mechanical Devices

56

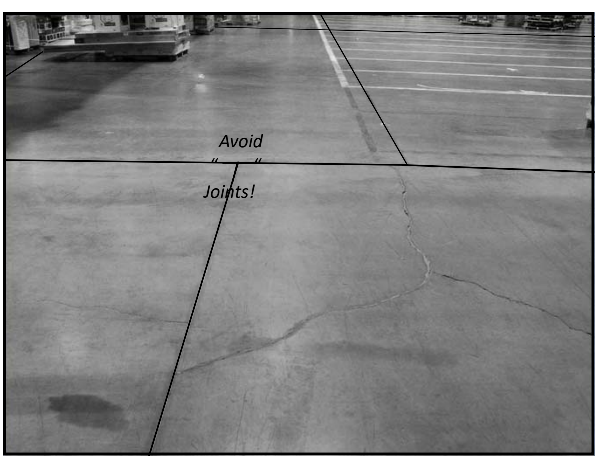

Mechanical Devices

57

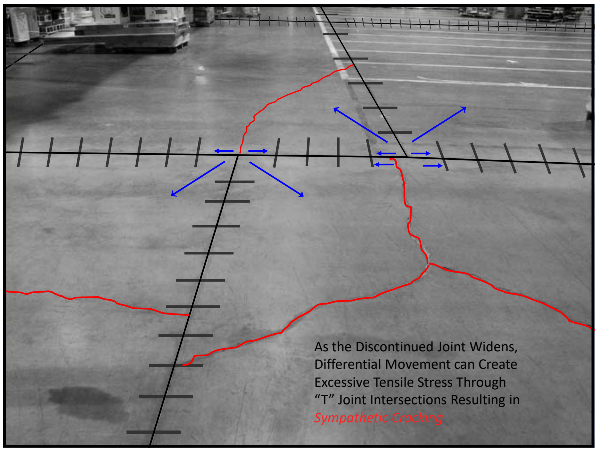
58


Movement at Sawcut Joints
Sawcut Control Joint
Sawcut Control Joint

59


Avoid
Joints!

60



61

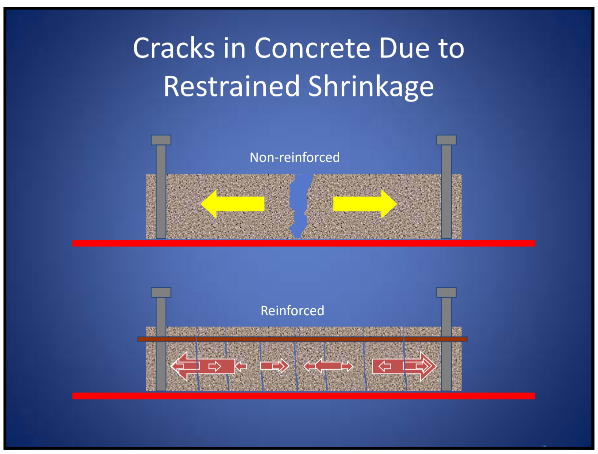
Reinforcement Transferred Through Joints

- Welded Wire Fabric (WWF)
  - Mesh - Rolls or Sheets
- Reinforcing Bars
  - Mats
- Post-Tensioning
- Shrinkage-Compensating

62

63

64


Cracks in Concrete Due to
Restrained Shrinkage
Non-reinforced
Reinforced

65

66

Transfer Steel Through Joints

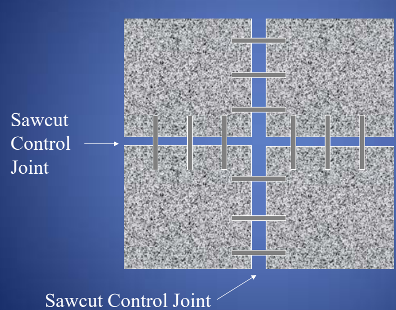
- ACI 360
  - <0.1% Steel per Area of Concrete Cross-Section
    - Enhanced Aggregate-Interlock
    - Cracking occurs beneath sawcuts only
    - Joint Spacing per ACI 360R Figure 6.6
  - >0.5% Steel per Area of Concrete Cross-Section
    - Conventionally Reinforced Slab
    - Visible tight cracks expected at 3-5 ft spacing
    - No sawcut joints necessary – no "control"
  - 0.1-0.5% Steel per Area of Concrete Cross-Section
    - "Legalcrete"
    - Visible random cracks that require filling

67

Transfer Steel Through Joints

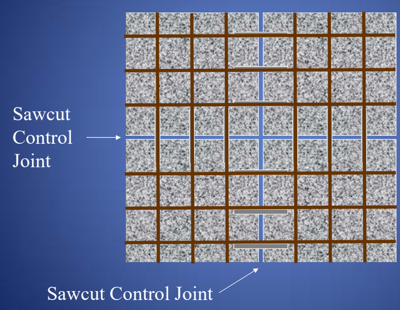
68

Movement at Sawcut Joints



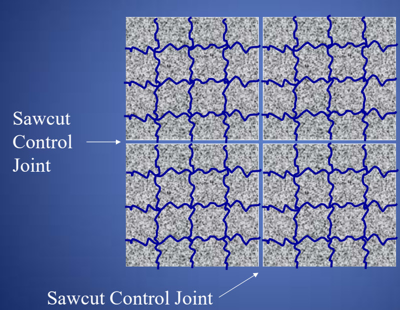
69

Transfer Steel Through Joints



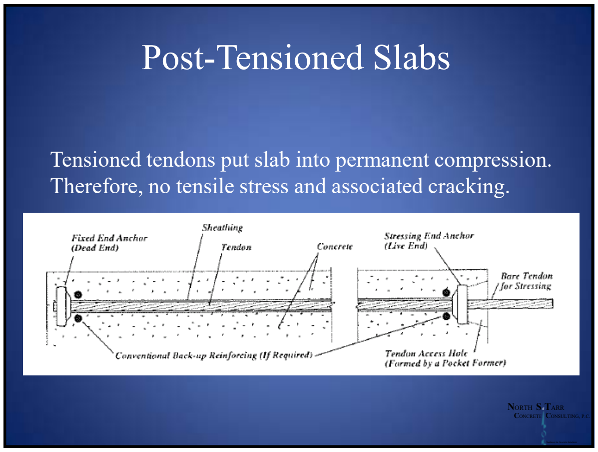
70

Transfer Steel Through Joints

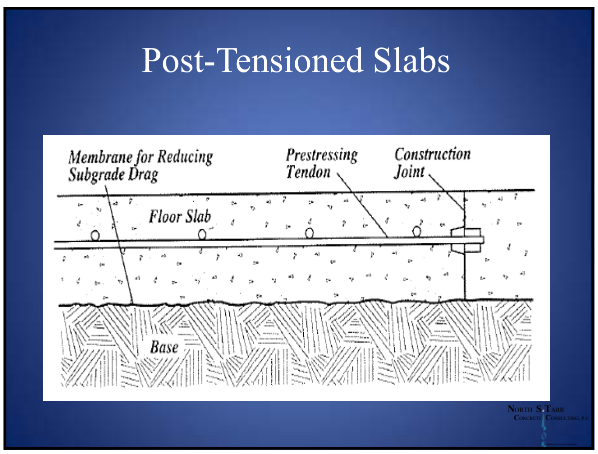


71

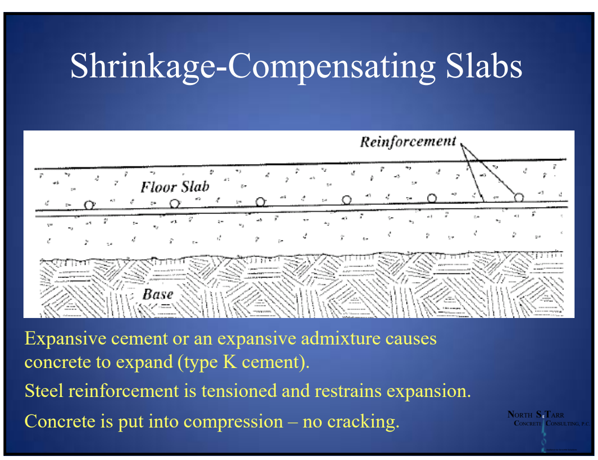
72


Post-Tensioned Slabs
Tensioned tendons put slab into permanent compression.
Therefore, no tensile stress and associated cracking.
Fixed End Anchor (Dead End)
Sheathing
Tendon
Concrete
Stressing End Anchor (Live End)
Bare Tendon for Stressing
Conventional Back-up Reinforcing (If Required)
Tendon Access Hole (Formed by a Pocket Former)

73


Post-Tensioned Slabs
Membrane for Reducing Subgrade Drag
Prestressing Tendon
Construction Joint
Floor Slab
Base

74


Shrinkage-Compensating Slabs
Reinforcement
Floor Slab
Base
Expansive cement or an expansive admixture causes concrete to expand (type K cement).
Steel reinforcement is tensioned and restrains expansion.
Concrete is put into compression – no cracking.

75

Extended-Joint Slab Systems

- Design Extends Joint Spacing Beyond that Recommended by ACI 360.
  - Presumably Assumes No/Minimal Out-of-Joint Random Cracking or Achieves Serviceable Cracking.
    - Owner Should be Informed of Expectation
  - Must Accomplish One or More of the Following:
    - Reduce Concrete Shrinkage Potential to Negligible
    - Reduce Restraint
    - Keep Random Cracks Tight and Closely-Spaced
  - Design for Joint Widening (1/4 the Joints Results in 4 Times the Widening Per Joint)
  - Slab Systems That Require Sawcut Contraction Joints Shrink and Curl.

76

Fiber Reinforcement

- Microsynthetic (0.1% or Less)
  - Monofilament
  - Fibrillated
- Macrosynthetic
  - 0.25 to 1%
- Steel (0.25 to 0.5%)
  - Smooth
  - Deformed

77

78

79


Time for a break …….

80


Biggest Problems With Slabs
"Joints & Cracks"
Biggest Problems With Joints & Cracks
"Maintenance"
Biggest Factor Causing Problems
Shrinkage

81

Concrete Mix Design and Placement Conditions

- ~~High Compressive Strength~~
- ~~Low Water/Cement Ratio~~
- ~~Low Slump~~

Not for Slabs!

- Low Shrinkage Potential
  - ASTM C 157 and ACI 209R
- Good Workability/Finishability
- Required Strength and Durability

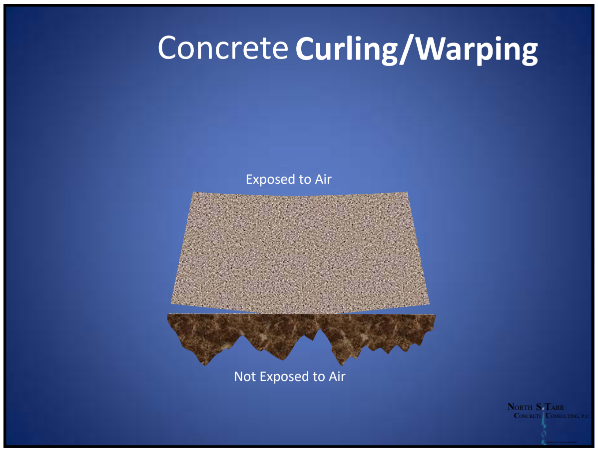
82

83

Concrete Shrinkage/Contraction

- Temperature Contraction
  - 3.2 to 7.5 millionths/ º F
    - 1/2 to 1 in. over 100 ft for 100ºF change
- Moisture Loss – Volumetric Shrinkage
  - 0.020% to 0. 200%
    - 1/4 to 2-1/2 in. in 100 ft

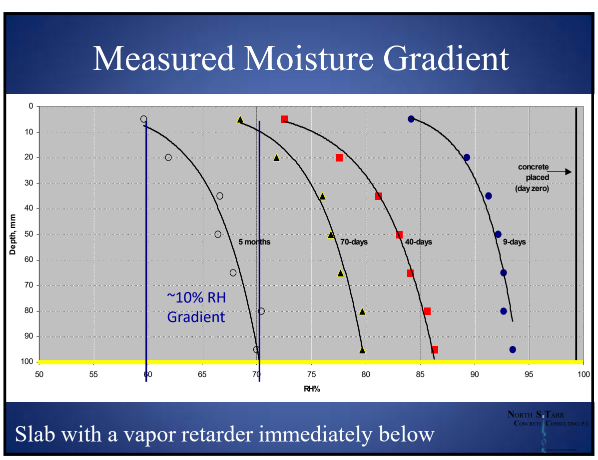
84


Concrete Curling/Warping
Exposed to Air
Not Exposed to Air

85

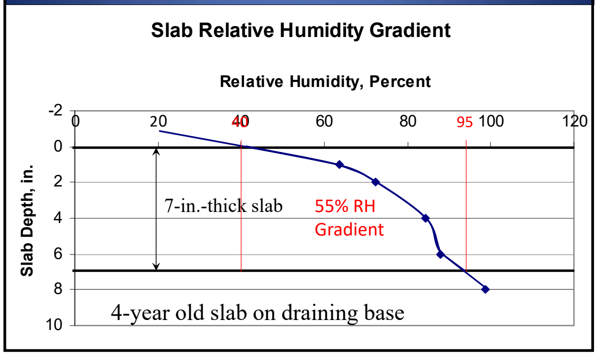

Differential Shrinkage
Temperature Curling
Or
Moisture Warping

86


Measured Moisture Gradient
concrete placed (day zero)
5 months
70-days
40-days
9-days
~10% RH Gradient
Depth, mm
RH%
Slab with a vapor retarder immediately below

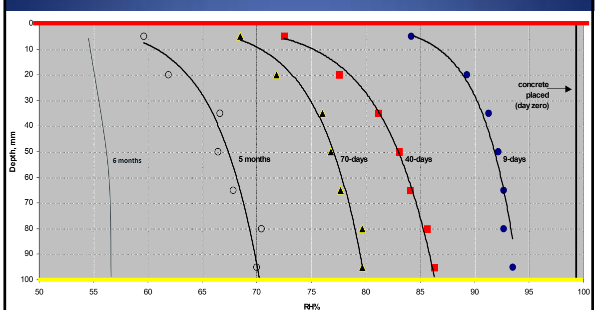
87

Measured Moisture Gradient



88

Measured Moisture Gradient

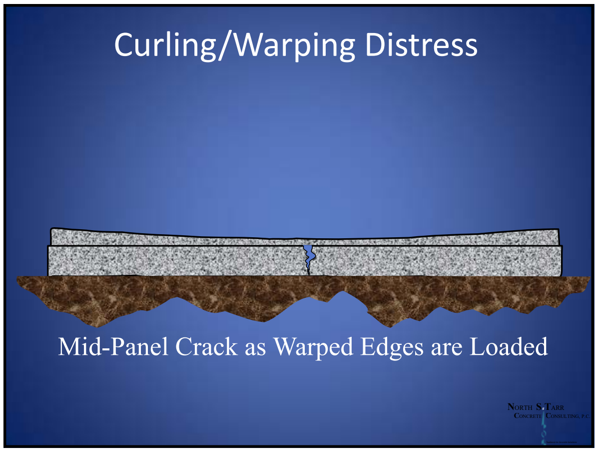


Slab with a vapor retarder immediately below

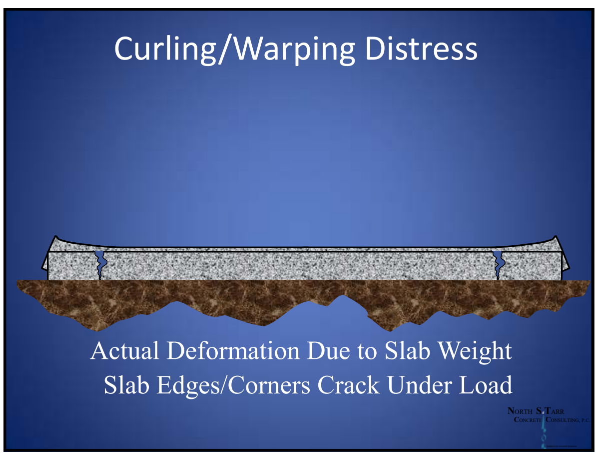
89

Floor Covering Failure Due to Warping

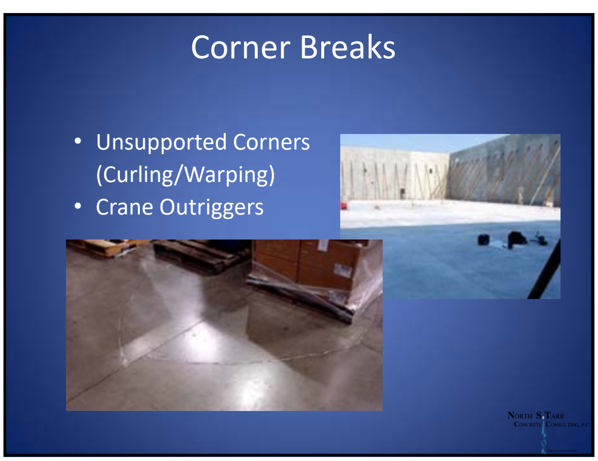
90


Curling/Warping Distress
Mid-Panel Crack as Warped Edges are Loaded

91


Curling/Warping Distress
Actual Deformation Due to Slab Weight
Slab Edges/Corners Crack Under Load

92


Corner Breaks
• Unsupported Corners (Curling/Warping)
• Crane Outriggers

93

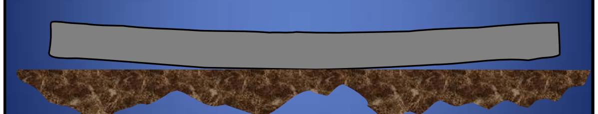
94

Problems with Slab Warping

- Decreased Load-Carrying Capacity Resulting in Long-Term Slab Cracking
  - Mid-Panel Cracks
  - Corner Breaks
- Slab Rocking – Joint Stability

95

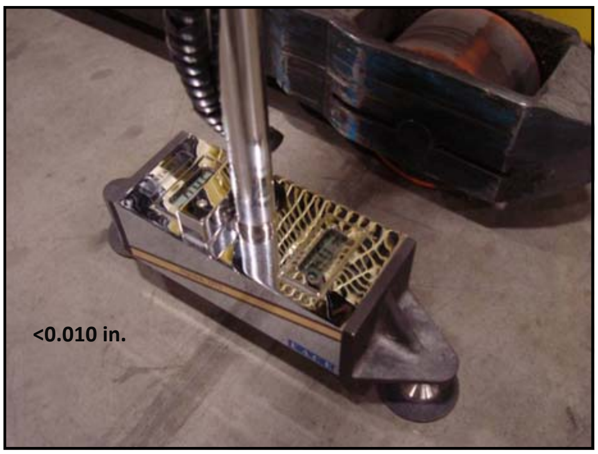
Joint Stability



Rocking as Warped Slab Panels are Trafficked

96

97

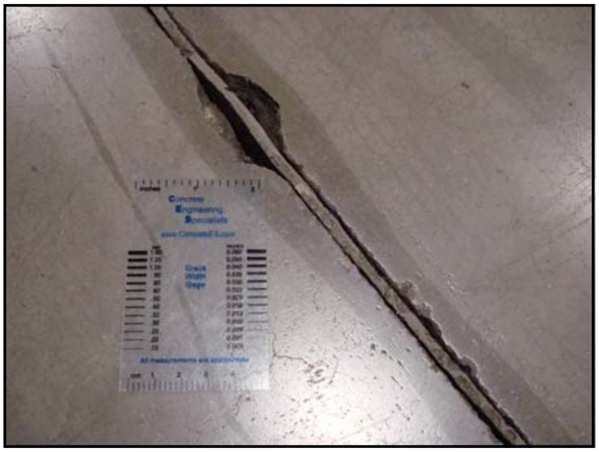


98

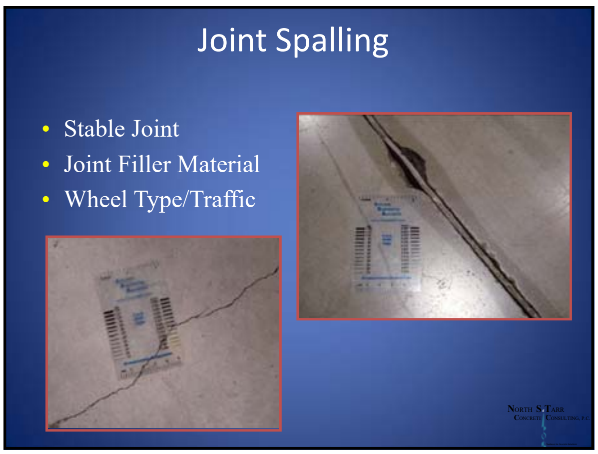
Problems with Slab Warping

- Decreased Load-Carrying Capacity Resulting in Long-Term Slab Cracking
  - Mid-Panel Cracks
  - Corner Breaks
- Slab Rocking – Joint Stability
- Joint Spalling (Joint Filler Breakdown)

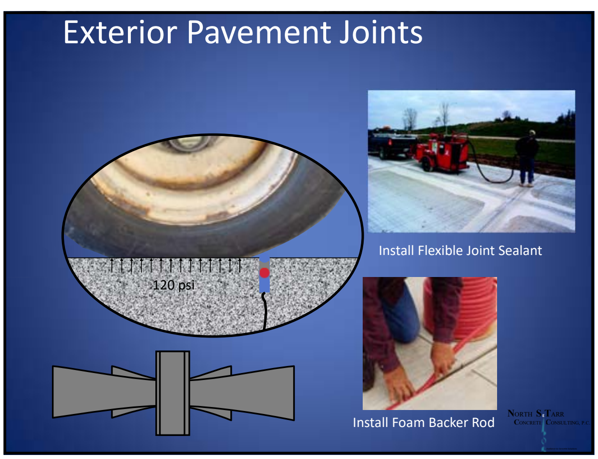
99



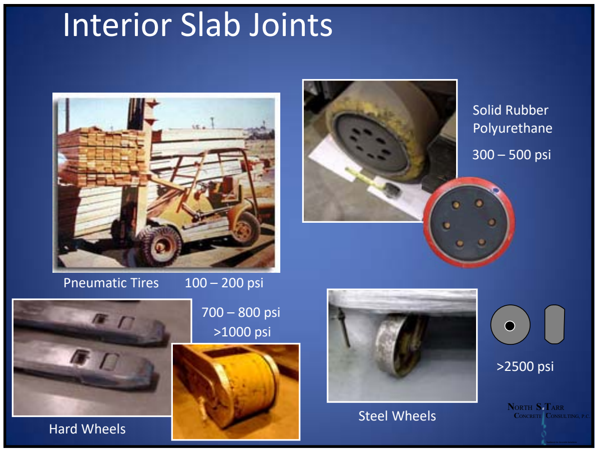
100


Joint Spalling
Stable Joint
Joint Filler Material
Wheel Type/Traffic

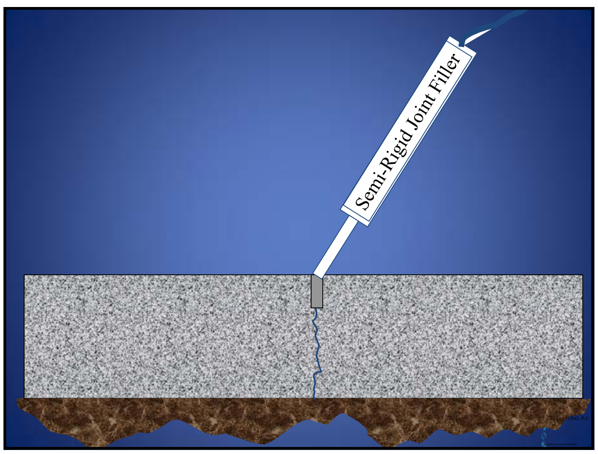
101


Exterior Pavement Joints
120 psi
Install Flexible Joint Sealant
Install Foam Backer Rod

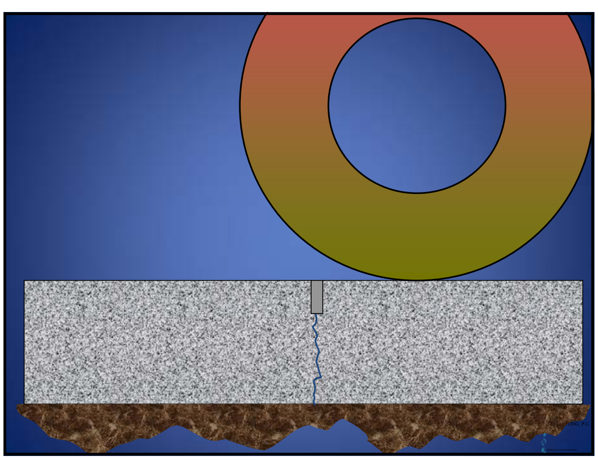
102


Interior Slab Joints
Solid Rubber
Polyurethane
300 – 500 psi
Pneumatic Tires
100 – 200 psi
700 – 800 psi
>1000 psi
>2500 psi
Hard Wheels
Steel Wheels

103


Semi-Rigid Joint Filler

104

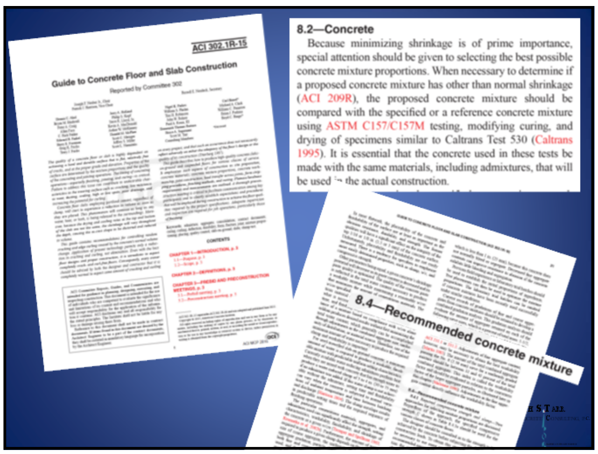


105

"Minimizing" Shrinkage and Slab Warping

- Use Quality Aggregate
- Minimize Paste Quantity
  - Increase Aggregate Size
  - Optimize Aggregate Gradation
  - Minimize Cement Content
- Maximize Paste Quality
  - Reasonable Water/Cement Ratio
  - Just Enough Water for Workable Slump

106



107

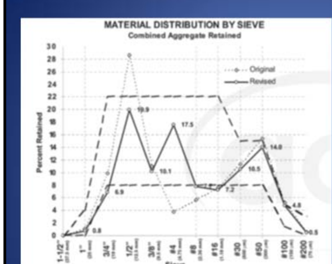


Fig. 8.9.4a—Material sieve analysis showing change in aggregate distribution with blending of 3/8 in. (9.5 mm) aggregate.

Haystack Curve

~~8 – 18 Gradation?~~

In general, 5 – 22 percent retained provides workable mix

Blend aggregates to minimize alternating high and low retainage on successive sieves.

108

Tarantula Curve

Figure 1. Individual Percent Retained Chart - Combined aggregate distribution by sieve size

Cook D, Ghaeezadah A, Ley T. Investigation of Optimized Graded Concrete for Oklahoma- Phase 1. FHWA-OK-13-12. Oklahoma City, OK: Oklahoma Department of Transportation; 2013.

109

Coarseness Factor

Workability Factor

- Percent combined aggregate passing #8 sieve

Coarseness Factor

- Percent plus #8 retained on 3/8 in. sieve

Zone I
- Blistering, Spalling, Scaling

Zone II
- Optimal Mix

Zone III
- Optimal Mix for max. aggregate <1/2 in.

Zone IV
- High Shrinkage

Zone V
- Too coarse – non-plastic

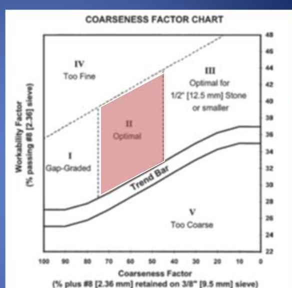


Fig. 8.9.2.2—Coarseness factor chart for evaluating potential performance of mixture.

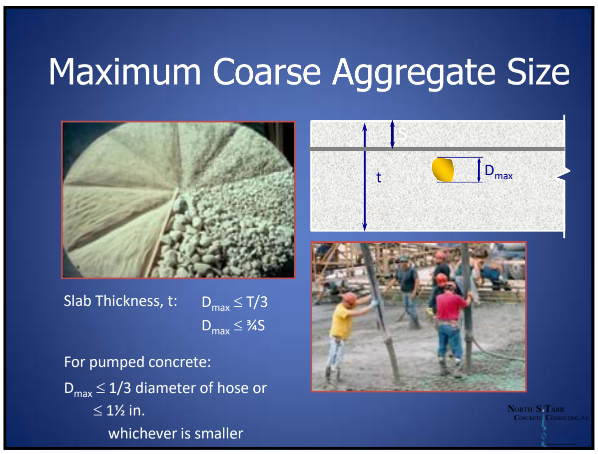
110

Minimizing Water (Paste)

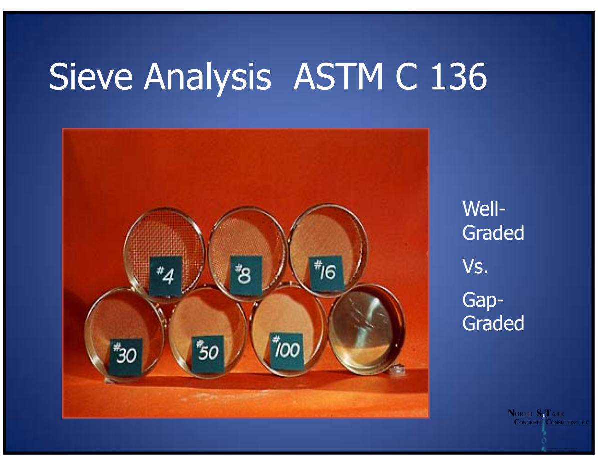
- Use Good Quality Well-Graded Aggregate
- Maximize Coarse Aggregate Topsize to Decrease Total Water in Mix

111

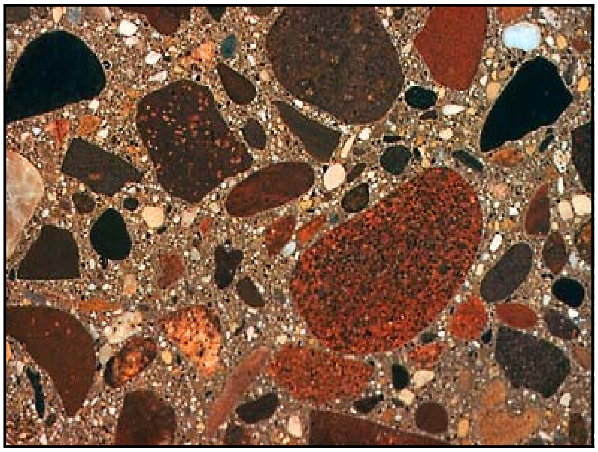
112


Maximum Coarse Aggregate Size
t
D_{max}
Slab Thickness, t: $D_{max} \leq T/3$
$D_{max} \leq ¾S$
For pumped concrete:
$D_{max} \leq 1/3$ diameter of hose or
$\leq 1½$ in.
whichever is smaller

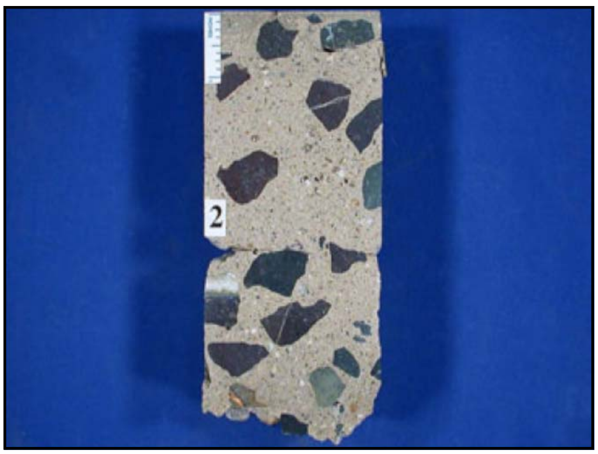
113


Sieve Analysis ASTM C 136
#4
#8
#16
#30
#50
#100
Well-Graded
Vs.
Gap-Graded

114



115



116

Minimizing Paste Quantity

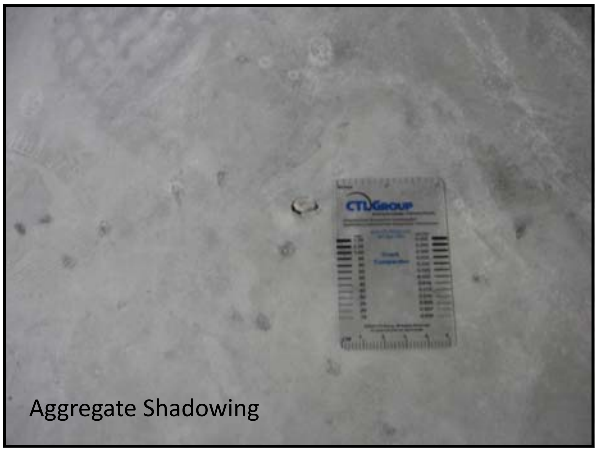
Balance Between:

Low Shrinkage

and

Workability/Finishability

117



Aggregate Shadowing

118

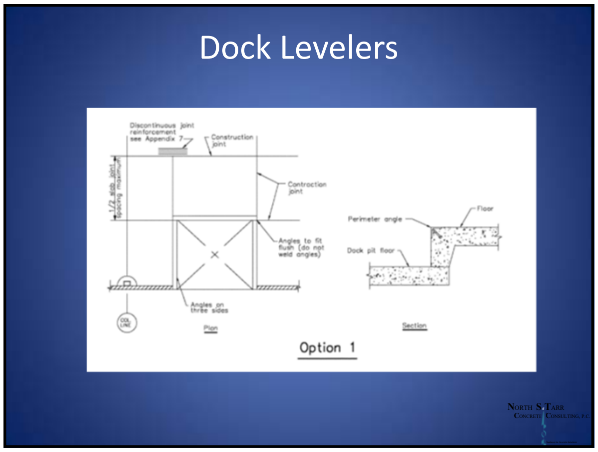
Expected Shrinkage

- ACI 360
  - Low Shrinkage - <0.052%
  - "Typical" Shrinkage – 0.052 to 0.078%
  - High Shrinkage - >0.078%
- PCA 400 to 800 millionths
- CSA

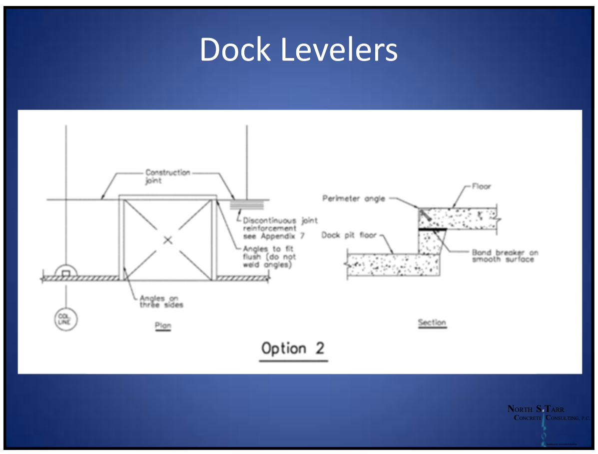
119

Pay Attention to the Details

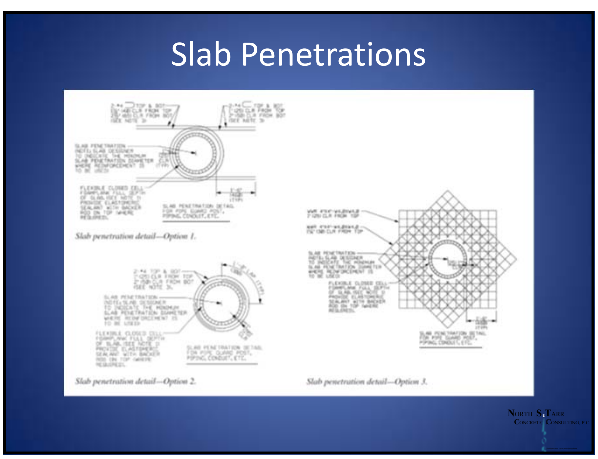
120


Dock Levelers
Discontinuous joint reinforcement see Appendix 7
Construction joint
1/2 slab joint spacing maximum
Contraction joint
Angles to fit flush (do not weld angles)
Angles on three sides
COL LINE
Plan
Perimeter angle
Floor
Dock pit floor
Section
Option 1

121

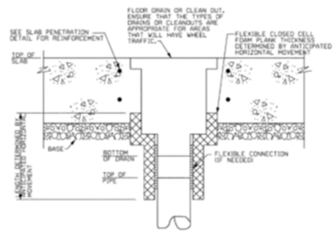

Dock Levelers
Construction joint
Discontinuous joint reinforcement see Appendix 7
Angles to fit flush (do not weld angles)
Angles on three sides
COL LINE
Plan
Perimeter angle
Floor
Dock pit floor
Bond breaker on smooth surface
Section
Option 2

122


Slab Penetrations
Slab penetration detail—Option 1.
Slab penetration detail—Option 2.
Slab penetration detail—Option 3.

123

Floor Drain and Cleanout

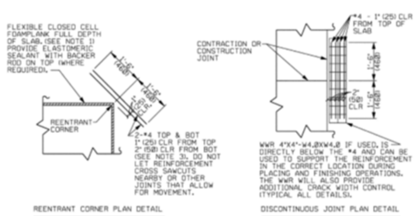


Floor drain and cleanout detail.

124

Re-Entrant Corners and Discontinuous Joints

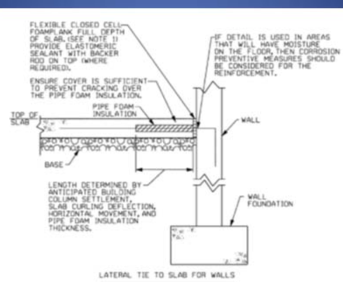
A7.3.3 *Reentrant corners and discontinuous joints*



Reentrant corner and discontinuous joint detail.

125

Lateral Tie to Slab for Walls



Lateral tie to slab for walls.

126

Slab on Ground Design and Details Conclusions

- Design and build for serviceability in accordance with owners expectations
- Anticipate the drying shrinkage potential for local materials when determining joint reinforcement

Aggregate Interlock → Dowels or Light Reinforcement → Heavy Reinforcement → Post-Tensioned or Shrinkage-Compensated

127

Slab on Ground Design and Details Conclusions

- Design and build for serviceability in accordance with owners expectations
- Anticipate the drying shrinkage potential for local materials when determining joint reinforcement
- Predict the impact of each design and construction feature and advise the owner

128

129

130

Slab on Ground Design and Details Conclusions

- Design and build for serviceability in accordance with owners expectations
- Anticipate the drying shrinkage potential for local materials when determining joint reinforcement
- Predict the impact of each design and construction feature and advise the owner
- Always "design" an industrial floor slab. Don't simply "specify" slabs

131

132

Slab on Ground Design and Details Conclusions

- Design and build for serviceability in accordance with owners expectations
- Anticipate the drying shrinkage potential for local materials when determining joint reinforcement
- Predict the impact of each design and construction feature and advise the owner
- Always "design" an industrial floor slab. Don't simply "specify" slabs
- And remember…

133

Remain Calm!

134

135