Modern Slabs on Grade and Reinforcing Technologies

65th Annual Institute for Building Officials
January 6–21, 2021

January 12, 2021

John D. Lee, P.E., LEED AP®

minnesota concrete council
Dedicated to Cast-in-Place Concrete

1

Agenda

- Concrete slab on grade construction is constantly evolving. Whether it is an interior industrial slab or exterior paving, engineers, contractors and materials suppliers are utilizing many new technologies and systems that result in better forming concrete slabs. This presentation will discuss concrete thicknesses design, cracking, and proper jointing and reinforcing techniques. It will also cover some new technologies in concrete fibers and composite reinforcing bars.

2

Agenda

- Basic considerations when looking at designing slabs on ground
- The use of temperature and shrinkage reinforcement
- Types of temperature and shrinkage reinforcement
- The concept of reducing joints in slabs

3

Design

What Concerns Does the Owner Have?

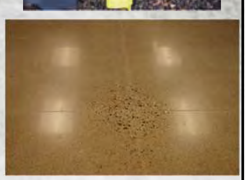
- What kind of traffic will the slab see?
  - Vehicles
    - Standard Cars and Trucks
    - Construction Equipment
      - Tracked Vehicles
  - Forklift
    - What Size?
- What kind of loadings?
  - Uniform loads
    - Stacked goods – How much and how are they stacked?
    - Racking loads – Post size, spacing, loads

4

Design

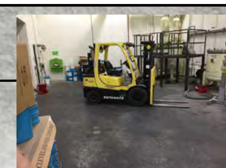
How will the slab be used?

- What appearance is the owner looking for?
- Is flatness and levelness a concern?
- Is moisture a concern?
  - Use of a vapor retarder
    - Placement
- Has the owner had previous issues with a slab?
  - Joint deterioration
  - Curling
  - Cracking – Can they live with some cracking?
- What sort of maintenance is the owner expecting?



5

Design



Slab Design – Engineers Perspective

- Loads
- Soil conditions – k-value
  - Subgrade Type
- Vapor retarder
- Environmental conditions (Temperature and Humidity)
- Reinforcing options available
- Placement techniques
  - How will this be installed?
  - Means and methods concerns?
- Penetrations within the slab
  - Detailing
- Curing
- Maintenance concerns

6

Design

Slab Design – Contractor Perspective
- Soil conditions
  - Subgrade Type
- Vapor retarder
- Environmental conditions (Temperature and Humidity)
- Reinforcing options available
- Load transfer devices
- Placement techniques
- Penetrations within the slab
  - Detailing
- Curing
- Joint type, locations
- Floor flatness requirements


7

Design/Install

Pre-Install Conference
- Attendees
  - Owner, Engineer, GC, Contractor, Ready-Mix, Testing, etc.
- Agenda
  - Review the specifications
  - Discuss
    - Placement techniques
    - Mix design
    - Joints
    - Reinforcing
    - Curing
    - Etc.

8

Why Do We Joint Slabs?

Three Guarantees of Concrete:
- Concrete will "Get Hard"
- Turn White/Grey/Color
- It's Going to Crack

Multiple Types of Cracking:
- Plastic shrinkage
- Plastic settlement
- Drying shrinkage/temperature
  - Worse with restraint

9

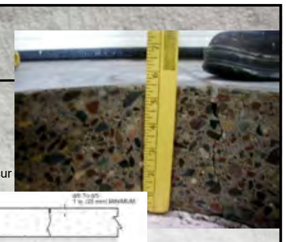
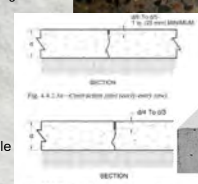
Why Do We Joint Slabs?

Why joint concrete?
- Concrete Shrinks
  - Leads to cracking
- Weakens the concrete plane
  - Generally determines where the cracking will occur

How often should I cut the concrete?
- ~~24 to 36 times the slab thickness~~
  - ~~8' to 12' – 4" slab~~
  - 10' to 15' – 5" slab

How deep should the joint be?
- ¼ of the slab thickness

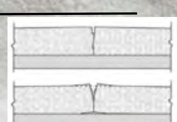
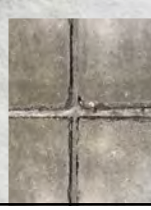
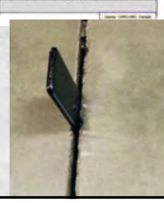
What shape should the panels be?
- Panels should be as square as possible


10

Why Do We Joint Slabs?

Why do we need to mitigate/control the cracking?
- Concrete shrinks
  - Drying process
  - Concrete is dryer at the top than the bottom
    - Vapor retarder
    - Air exposure
    - Evaporation
- Shrinkage leads to stress
- Shrinkage leads to joint openings
- Stress leads to cracking
  - Concrete is not good in tension

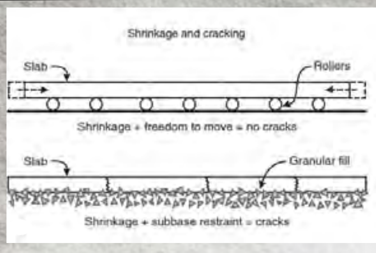
11

Why Do We Joint Slabs?

Cracking

12

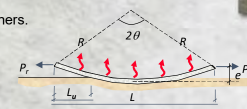
Why Do We Joint Slabs?



13

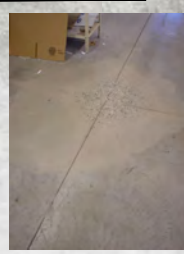
Why Do We Joint Slabs?

- Slabs dry from the top and are moist at the bottom.
- Differential shrinkage causes slab edges to lift (curl) and joints to open.
- The mass of unsupported concrete causes the slab center to sink into the soil.
- As joints open:
  - Shear transfer at joints is reduced.
  - Loads applied along the joint can cause cracking in the unsupported length.
- Curling is more pronounced at corners.



14

Why Do We Joint Slabs?

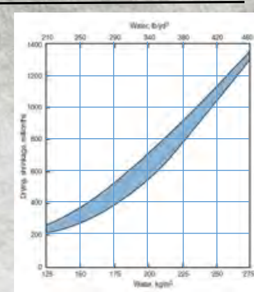


15

Reducing Drying Shrinkage

- Lower Total Water (& Paste) Content
- Increase Coarse Aggregate Content & Topsize
- Shrinkage Compensation
- Shrinkage-Reducing Admixtures

A low water-cementitious materials ratio (w/cm) does not imply a low total water content!



16

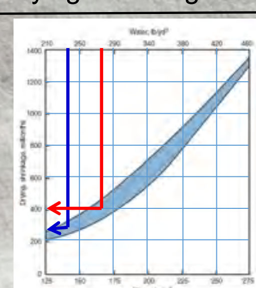
Reducing Drying Shrinkage

	Mix #1	Mix #2
Cement, lb/yd³	517	611
Water, lb/yd³	233	**275**

w/cm = 0.45

17

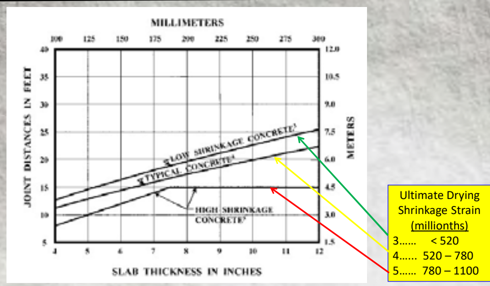
Reducing Drying Shrinkage



18

Why Do We Joint Slabs?

ACI 360 Fig. 6.6



19

Shrinkage Reinforcement - Slabs

Why do we need reinforcement?
- Load transfer via aggregate interlock
- Maintain tight cracks and joints

- Does it make the concrete stronger?
  - Only after cracking
- Do we need it for every slab?
  - Can be omitted provided
    - Shrinkage/restraint is dealt with
      - Design – Thickness, Joints, etc.
      - Subgrade
      - Mixture
      - Curing

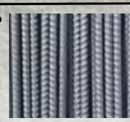

20

Shrinkage Reinforcement – Traditional

How do we mitigate/control the cracking?
- Traditional secondary reinforcement
  - Welded wire mesh
  - Light gauge rebar

Why use secondary reinforcement?
- Maintain tight joints/cracks
- It does not increase the concrete strength
  - More steel I not always better

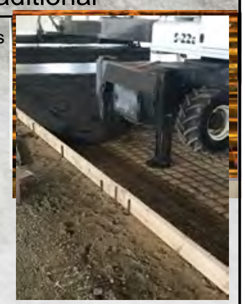
Benefits
- When designed and placed properly, it works
- Material costs are generally cost effective
- Engineers are familiar with the design
- Can be field verified by inspection agency



21

Shrinkage Reinforcement – Traditional

Traditional Secondary Reinforcement - Drawbacks
- Needs to be properly designed
  - Designer needs to understand the anticipated and future loads
- Placement is everything
  - Needs to be properly placed within the slab cross-section
    - Generally in the top ½ of the slab
      - Properly engage the cracked/jointed concrete
  - Needs to be uniformly placed
    - Wavy WWF is ineffective
    - Sheets are expensive



22

Shrinkage Reinforcement – Traditional

Traditional Secondary Reinforcement - Drawbacks
- Keeping the reinforcement in place costly
  - Chairs
  - Slows placement working around and on reinforcement
- Difficult to verify after concrete placement
- Depend upon the amount of reinforcement, labor to install is expensive
- Delivery can be expensive
- Safety concern, i.e. trip hazard
- Limits placement techniques
  - Need a pump or conveyor
  - Buggies and laser creeds are ineffective


23

Shrinkage Reinforcement – Composite

Composite Reinforcement
- Manufactured rods
  - Fibers embedded in a polymeric resin
    - Fiberglass
    - Basalt fiber
    - Carbon fiber
- Manufactured in a number of sizes up to #13 bars
- Uses
  - High corrosive environment
    - Bridge Decks
    - Dowels
  - Electrical isolation
  - Slabs on ground
- Benefits
  - Lightweight
    - Safety
  - Non ferrous


24

Shrinkage Reinforcement – Composite

Composite Reinforcement

- Design guidance - ACI 440.1 R-15
- Testing – ASTM D7205
- Material properties

Table 4.2.1—Typical tensile properties of reinforcing bars*

	Steel	GFRP	CFRP
Nominal yield stress, ksi (MPa)	40 to 75 (276 to 517)	NA	NA
Tensile strength, ksi (MPa)	70 to 100 (483 to 690)	70 to 230 (483 to 1600)	87 to 535 (600 to 3690)
Elastic modulus, ×10³ ksi (GPa)	29.0 (200.0)	5.1 to 7.4 (35.0 to 51.0)	15.9 to 84.0 (120.0 to 580.0)
Yield strain, percent	0.14 to 0.25	NA	NA
Rupture strain, percent	6.0 to 12.0	1.2 to 3.1	0.5 to 1.7

*Typical values for fiber volume fractions ranging from 0.5 to 0.7.

- They do not yield – No ductility
- More info can be found in the ACI document

25

Shrinkage Reinforcement – Composite

Composite Reinforcement

- Slab on Grade Usage
  - Temperature and Shrinkage Usage
    - Positioned in the upper 1/3
    - Needs to be chaired
  - ACI 440.1 R-15 – Appendix A
    - Based on:
      - Joint Spacing
      - Subgrade Friction
      - Allowable Stress in Steel
      - Dead Weight of Slab
      - MOE of Composite Bar
    - Generate an Area of Composite Reinforcement
    - Generally, need 2.5 – 3.0 times higher than traditional reinforcing steel
- Other Uses, i.e. walls – Refer to ACI 440.1 R-15

APPENDIX A—SLABS-ON-GROUND

Two of the most common types of construction for slabs-on-ground are discussed in this appendix: plain concrete slabs and slabs reinforced with temperature and shrinkage reinforcement.

A.1—Design of plain concrete slabs

Plain concrete slabs-on-ground transmit loads to the subgrade with minimal distress and are designed to remain uncracked under service loads. To reduce shrinkage crack effects, the spacing of construction joints, contraction joints, or both, is usually limited. For details of design methods of plain concrete slabs-on-ground, refer to ACI 360R.

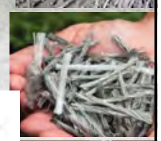
$$A_{f,sh} = \frac{\mu L w}{2(0.0012 E_f)} \qquad (A.2b)$$

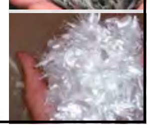
26

Shrinkage Reinforcement - Fibers

Fibers

- Governed by ASTM C1116
- Synthetic Fibers – ASTM D7508
  - Designed to hold joints/cracks together
    - Microfibers
    - Macro Fibers
- Steel Fibers – ASTM A820
  - Designed to reinforce the concrete
    - Numerous types/sizes
    - The type/size matters in terms of dosage.
- Design – ACI 544.4R-18



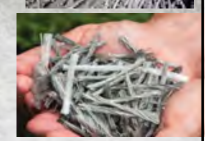


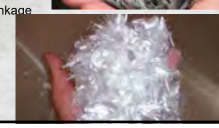
28

Shrinkage Reinforcement - Fibers

Synthetic Fibers

- Governed by ASTM C1116
- Synthetic Fibers – ASTM D7508
  - Different classifications based on performance
    - Level 1 – Plastic Shrinkage
      - Microfibers
    - Level 2 – 6 x 6 - 1.4 x 1.4 WWM
      - Microfibers
      - Macro Fibers
    - Level 3 – WWM and rebar for Temperature and Shrinkage
      - Macro Fibers
    - Level 4 – Primary steel replacement
      - Macro Fibers
  - Designed to hold joints/cracks together





29

Shrinkage Reinforcement - Fibers

Why Use Synthetic Fibers

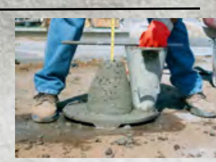
- Reduce plastic shrinkage/settlement cracking
- Provide multi-directional post crack reinforcement
  - Maintain Aggregate interlock
  - Increase post crack strength
  - Improve shear resistance
- Increase ductility and impact resistance
- Increase moment capacity
  - Can result in slab thickness reduction
- Ease of concrete placement – Truck placed
- Greatly reduce labor when compared to conventional reinforcement
  - Improved site safety – No trip hazards
  - Reinforcing positioned correctly within the slab when using fibers

30

Shrinkage Reinforcement - Fibers

Synthetic Fibers - Drawbacks

- Engineer familiarity
  - Design
- Can reduce the slump of the concrete
  - Depends on dosage and fiber type
- Hard to verify in the field
  - Test development is under consideration
- Can result in a "hairy" surface
- Ready mix driver dosing
  - Opening bags vs tossing bags in
- Contractor familiarity with finishing



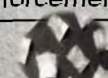
31

Shrinkage Reinforcement - Fibers

Synthetic Fibers - Microfibers
- Code Perspective
  - ICC AC32 - 1993
    - Primarily used for evaluating microfibers
    - Tests performed
      - Compressive , Flexural and Bond Strength
      - Freeze/thaw Resistance
      - Plastic Shrinkage Reduction
      - Post Crack Performance
      - Alkali Resistance

32

Shrinkage Reinforcement - Fibers



Synthetic Fibers
- Micro
  - Monofilament
    - Plastic shrinkage
    - Plastic settlement cracking
    - Not a substitute for WWM or light gauge rebar
    - Typical dosage 0.5 lbs/yd^3
  - Fibrillated
    - Plastic shrinkage
    - Plastic settlement cracking
    - Substitute for 6 x 6 W1.4 x 1.4 WWM
    - Typical dosage – 1.5 lbs/yd^3

33

Shrinkage Reinforcement - Fibers

Synthetic Fibers – Macro Fibers
- Code Perspective
  - ICC AC383 - 2016
    - Used for evaluating macrofibers
    - Tests performed
      - Compressive, Post Peak Flexural and Bond Strength
      - Freeze/thaw Resistance
      - Fire Resistance
      - Plastic Shrinkage Reduction
      - Restrained Shrinkage
      - Alkali Resistance
      - SOMD per SDI

34

Shrinkage Reinforcement - Fibers

Macro Fibers
- Selection is everything
- Finishing matters

"Hairy" Appearance & Rough Texture

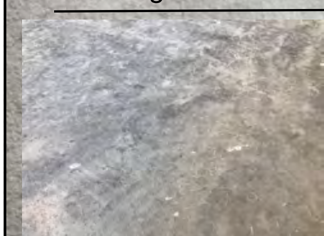
"Whirly Birds"

Fiber Clumping

Fibers Not Laying Flat

35

Shrinkage Reinforcement - Fibers



36

Shrinkage Reinforcement - Fibers

Stick (embossed)

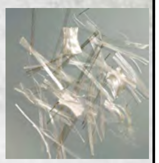
Tape (serrated)

Rope

37

Shrinkage Reinforcement - Fibers

Synthetic Fibers – Macro Fibers
- Used to replace
  - Welded wire mesh
  - Light gauge rebar
- Needs to be designed, i.e. dosage matters
- Typical dosage 3.0 – 7.5 lbs/yd^3
- Used in creating reduced or joint free slabs
- Can be used for slab over metal deck
  - SDI/ANSI
- Generally, not used for plastic shrinkage/settlement control
- A lot of varieties
  - Finishing issues

38

Shrinkage Reinforcement - Fibers

Synthetic Fibers – Macro Fibers
- Hybrid Fibers
  - Blend of Macro and Micro
  - Designed for hard trowel finish
  - Non hairy appearance
  - Uniform distribution
  - Smooth surface texture
  - Can be polished at high dosages


39

Shrinkage Reinforcement - Fibers

Plain Concrete WWF Reinforced Fiber reinforced 2 Sledgehammer blows

40

Shrinkage Reinforcement - Fibers

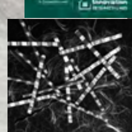
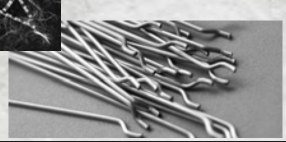
9 Sledgehammer blows 18 Sledgehammer blows

41

Shrinkage Reinforcement - Fibers

Steel Fibers
- Used for:
  - Drying and temperature replacement
  - Can replace primary steel
  - Impact resistance
- Applications
  - Industrial floors
  - Tipping floors
  - Cast in place walls
  - Foundations
- Code Perspective
  - ICC AC208
    - Compressive, Post Peak Flexural and Bond Strength
    - Freeze/thaw Resistance
    - Fire Resistance

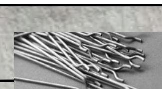
ES ICC EVALUATION SERVICE

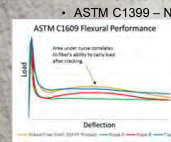




45

Designing with Fibers

Evaluation
- Macro/Steel
  - Need to be designed specifically for the fiber to be used
  - ASTM testing needs to have been done
    - ASTM C1609 w/ASTM C1812 rollers
    - ASTM C1399 – Not applicable – Not recognized by ACI



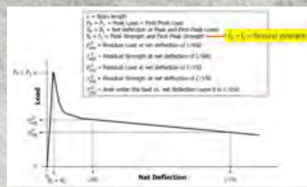



46

Designing with Fibers

ACI 544.4R-18

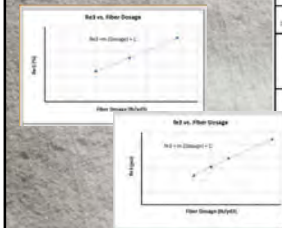
- Design is based on the following:
  - Cracked FRC section
  - Data obtained from ASTM C1609



49

Designing with Fibers

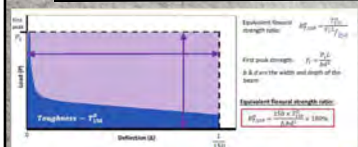
ASTM C1609



Specimen ID		1	2	3	4	5	6	Avg
Dimensions	Width (in.)	6.00	5.90	6.05	5.95	5.90	5.90	**5.95**
	Depth (in.)	6.00	5.90	5.90	5.90	5.90	5.90	**5.90**
Initial Deflections	δ_1 - Deflection at First Crack (in.)	0.0025	0.0024	0.0024	0.0025	0.0024	0.0023	**0.0024**
	δ_P - Deflection at Peak Load (in.)	0.0028	0.0031	0.0027	0.0030	0.0030	0.0028	**0.0029**
Loads	P_1 – First Crack Load (lbf.)	5,932	5,862	5,856	6,086	5,608	5,837	**5,864**
	P_P - Peak Load (lbf.)	6,159	6,472	6,195	6,348	5,958	6,325	**6,243**
	P^{150}_{600} - Load at L/600 (lbf.)	2,213	2,654	2,233	2,129	1,888	2,007	**2,187**
	P^{150}_{150} - Load at L/150 (lbf.)	1,772	1,737	1,336	1,207	1,558	1,455	**1,511**
Stress	f_1 - First Crack Stress (psi)	495	515	500	530	490	510	**505**
	f_P – Peak Stress (psi)	515	565	530	550	520	555	**540**
	f^{150}_{600} - Stress at L/600 (psi)	185	235	190	185	165	175	**190**
	f^{150}_{150} - Stress at L/150 (psi)	150	150	115	105	135	125	**130**
Toughness	T^{150}_{150} - Toughness (in-lbs)	280	310	260	250	250	250	**267**
	$f^{150}_{T,150}$ or Fe_{3} (psi)	194	226	185	181	183	183	**192**
	$R^{150}_{T,150}$ or Re_{3} (%)	39.2	43.9	37.0	34.1	37.3	35.9	**37.9**

50

Designing with Fibers



Equivalent flexural strength (f_{e3}): $f^D_{e,150} = \frac{150 \times T^D_{150}}{bh^2}$

$$R^D_{T,150} = \frac{150 \cdot T^D_{150}}{f_1 \cdot b \cdot d^2} \cdot 100\% = R_{e3}$$

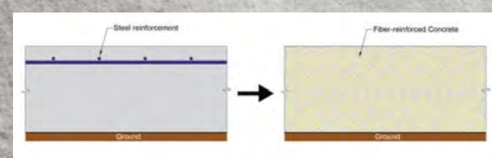
Equivalent Flexural Strength Ratio = $\frac{\text{Equivalent Flexural Strength}}{\text{Flexural Strength}}$ x 100%

$$R_{e3} = \frac{f_{e3}}{f_r} \text{ x } 100\%$$

51

Designing with Fibers

Design Example



52

Designing with Fibers

Design Example

- For the fiber-reinforced concrete with fibers distributed throughout the thickness of the slab, the entire cross-section of the slab is considered to resist tensile stresses. Hence, the tensile stress that must be resisted to achieve equivalent performance with the steel reinforcement is:

$$f_{ts} = \frac{\phi A_s f_y}{bh}$$

- The post-crack tensile strength of a fiber-reinforced concrete, f_{e3}, must be equal to f_{ts} for equivalent performance between the fibers and the steel reinforcement. f_{e3} is obtained from ASTM C 1609 and can be expressed as a percentage (R_{e3}) of the concrete tensile strength (f_r) as:

$$R_{e3} = \frac{f_{e3}}{f_r}$$

53

Designing with Fibers

Design Example

- f_y = Yield strength of the steel = 60,000 psi for steel rebar
- f'_c = The compressive strength of concrete = 4,000 psi
- f_r = Modulus of rupture of concrete; for SOG $f_r = 9\sqrt{f'_c}$
- ρ = Steel reinforcement ratio in % $(100 \times A_s/A_c) = 0.18\%$
- $A_c = bh$ = area of concrete in in^2
- A_s = Area of steel in in^2 placed in the top portion of the slab (only temperature & shrinkage steel)
- h = Slab thickness in inches
- ϕ = Moment capacity factor for steel, 0.9
- SF = Safety factor, 0.667

54

Designing with Fibers

Step 1: Compute the tensile strength requirement provided by steel (f_{ts}):

$$f_{ts} = \frac{\phi A_s f_y}{bh} = 0.9\rho f_y = 0.9 \times 0.0018 \times 60{,}000\ psi = 97.2\ psi$$

Step 2: Compute the working stress provided by the steel reinforcement:

$$f_{ws} = SF \times f_{ts} = 0.667 \times 97.2 = 64.8\ psi$$

55

Designing with Fibers

Step 3: Compute the average equivalent flexural strength f_{e3} (ACI 544.4R-18):

$$f_{e3} = \frac{f_{ws}}{0.37} = \frac{64.8}{0.37} = 175.1\ psi$$

Step 4: Compute $R_{e,3}$ as follows:

$$R_{e3} = \frac{f_{e3}}{f_r} = \frac{f_{e3}}{9\sqrt{f_c'}} = \frac{175.1}{9\sqrt{4{,}000}} = 30.8\%$$

56

Designing with Fibers

$f_c' = 4000$ psi	$f_y = 60$ ksi (typical rebar)	$f_y = 65$ ksi (typical WWR)
Steel Reinforcement Ratio (%)	**Computed R_{e3} (%)**	
0.10	17.1	18.5
0.15	25.7	27.8
0.18	30.8	33.3
0.20	34.2	37.1

Notes:

- Fiber dosage for temperature and shrinkage reinforcement is dependent upon:
  - ASTM C1609 results
  - Compressive strength of concrete
  - Reinforcing steel type (bar or WWM)
  - Reinforcing steel ratio
- Fiber dosage is not dependent on the member size

57

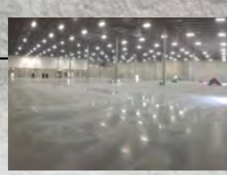
Specifying Fibers

Synthetic Macrofibers:

- **Shall comply with ASTM D7508/D7508M, "Standard Specification for Polyolefin Chopped Strands for Use in Concrete," for use in producing Type III Synthetic Fiber-Reinforced Concrete meeting the requirements of ASTM C1116/C1116M "Standard Specification for Fiber-Reinforced Concrete."**
- **Shall provide a minimum average equivalent strength ratio, R_{e3}, of ____ % when tested in accordance with ASTM C1609/C1609M, using the roller support system described in ASTM C1812/1812M.**
- **Dosage shall be as recommended by the manufacturer.**

58

Extended Joint Spacing Slabs



Performance Slab Solutions

- Generally proprietary systems
  - Shrinkage compensating admixtures
  - Expansive components/cements
  - Higher reinforcing steel content – Cracks will occur
- Complete system
  - Subgrade through curing and protection
- Potential for slab thinning
- Greatly increased joint spacing
- Elimination of reinforcing steel (temperature and sh
  - Steel of Macro synthetic fiber reinforced
- Increased toughness
- Reduced curling
- Exterior and interior applications

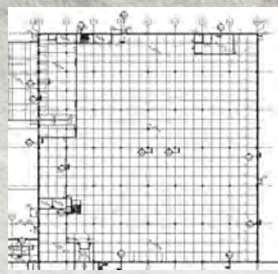
59

Extended Joint Spacing Slabs

60

Extended Joint Spacing Slabs

Potential Joint Removal
- 288' x 300'
  - 36 'x 50' Bays (approx.)
  - 12'x 12' (approx.)
  - 13,500 lf of joints (2.55 miles)
- Potential Joint Spacing
  - 50' x 36'
    - 3,540 lf
  - 50' x 70'
    - 2,340 lf
  - ?? Joints – Proprietary System



61

Extended Joint Spacing Slabs

Systematic Approach
- Limit drying shrinkage of concrete
  - Limit total water content
  - Optimize aggregate gradation
- Use chemical admixtures to further reduce shrinkage
- Use appropriate dosage of synthetic macrofiber
  - Dosage will depend on existing reinforcing steel design
  - Fiber type will depend upon application
- Proper construction practices
  - Properly prepared subgrade – proof rolled
  - Double slip sheet – 6 mil at a minimum
  - Proper curing and protection
    - Ideally water cured

62

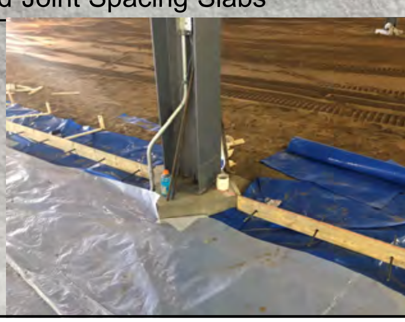
Extended Joint Spacing Slabs

64

Extended Joint Spacing Slabs

65

Extended Joint Spacing Slabs



66

Extended Joint Spacing Slabs

67

Extended Joint Spacing Slabs

Detailing

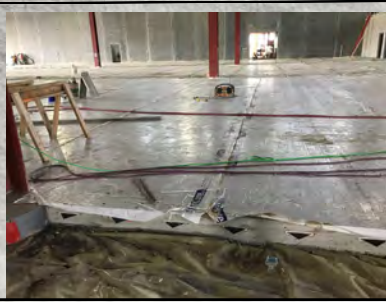


68

Extended Joint Spacing Slabs

78

Extended Joint Spacing Slabs



79

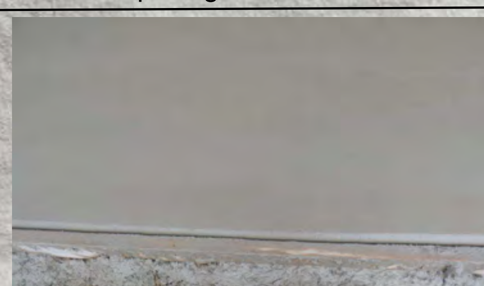
Extended Joint Spacing Slabs

80

Extended Joint Spacing Slabs

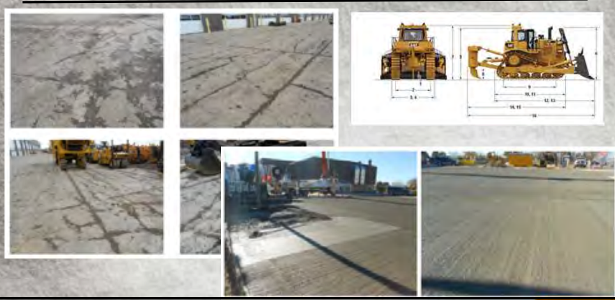
81

Extended Joint Spacing Slabs



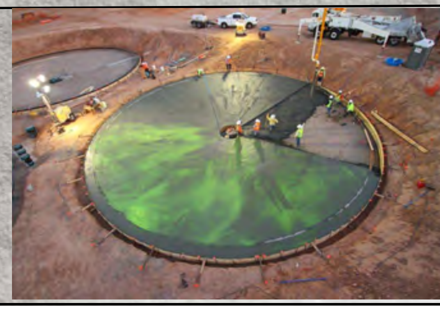
82

Extended Joint Spacing Slabs



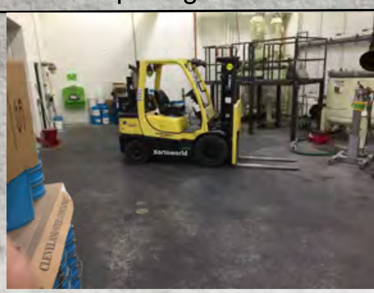
84

Extended Joint Spacing Slabs



85

Extended Joint Spacing Slabs

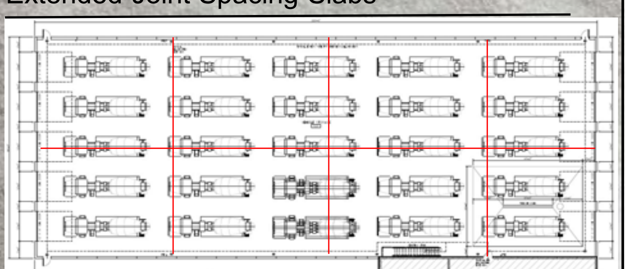


86

Extended Joint Spacing Slabs

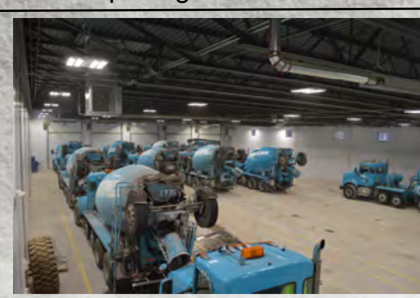
87

Extended Joint Spacing Slabs



88

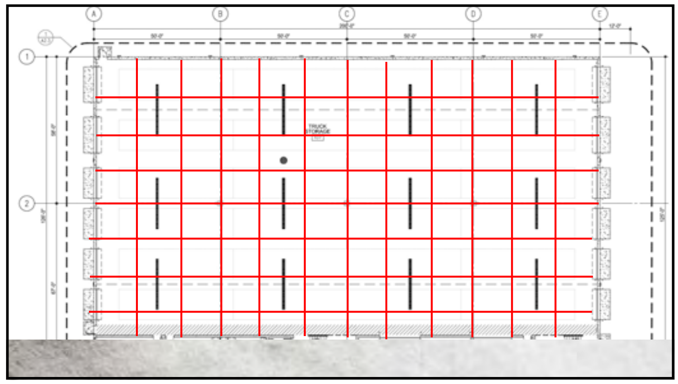
Extended Joint Spacing Slabs



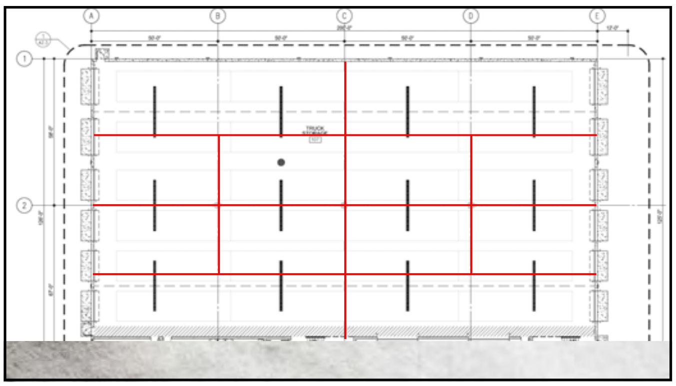
90

Extended Joint Spacing Slabs

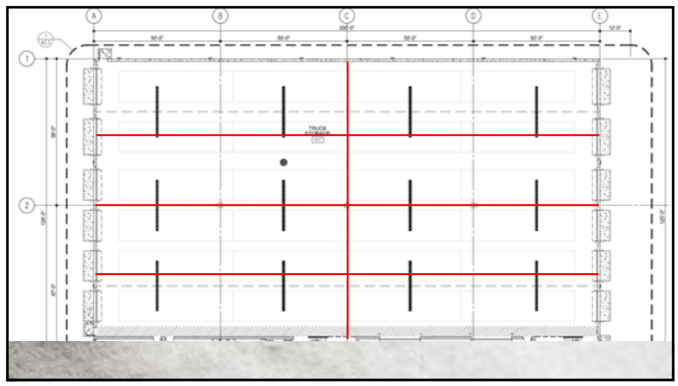
91



92

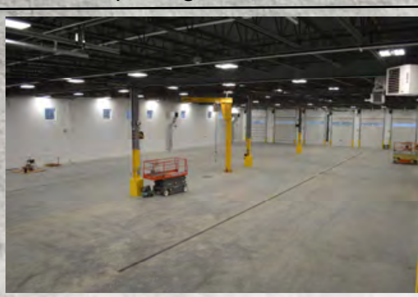


93



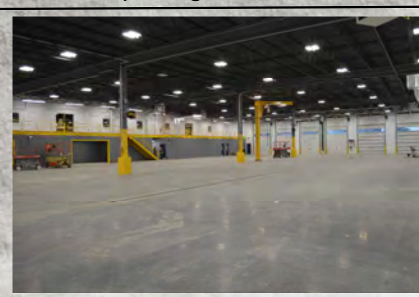
94

Extended Joint Spacing Slabs



96

Extended Joint Spacing Slabs

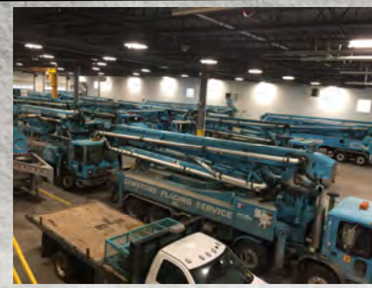


97

Extended Joint Spacing Slabs

98

Extended Joint Spacing Slabs



99

Extended Joint Spacing Slabs

100

Extended Joint Spacing Slabs

101

Extended Joint Spacing Slabs

"The nicest floor they have ever done or finished" - Contractor

102

Extended Joint Spacing Slabs

103

104

105

106

108