Troubleshooting Concrete Cracking

by
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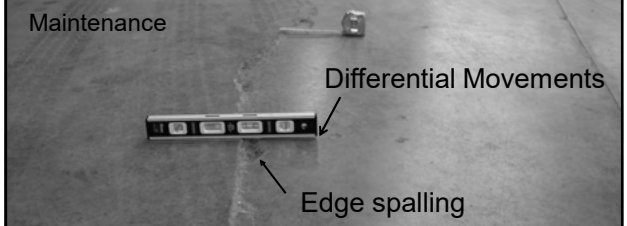
Minnesota Concrete Council
Dedicated to Cast-in-Place Concrete

June 6, 2024

Cracks affect…

Appearance
Performance
Maintenance



Owners do not want these problems

Let's make one thing clear …

Concrete Cracks and That's a Fact!

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Two Basic Causes of Cracking

1. **Tensile stresses due to volume changes**
   - Expansion
   - Shrinkage

   Due to Thermal Cooling & Drying

2. **Tensile stresses due to loading**

Concrete is a *Brittle Material*

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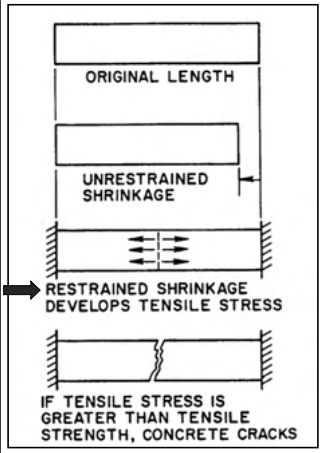

Concrete Drying Shrinkage

+ Restraints = Cracks

What is the tensile capacity of concrete?

About 10% of compressive strength

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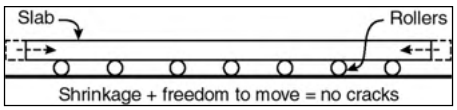
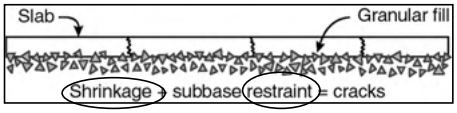
Drying Shrinkage + Restraints = Cracking





Due to thermal and drying shrinkage …
Slabs want to shorten about 1/2 to 3/4 inch per 100 ft

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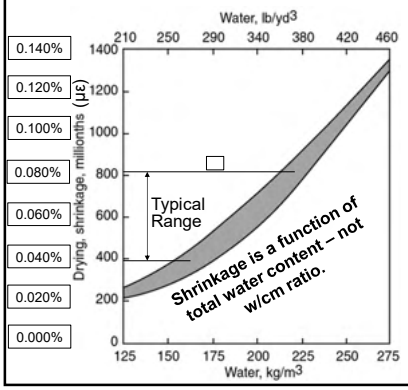
Crack Control Strategies

1. **Reduce Concrete Shrinkage & Restraints**
2. **Jointing**
   - Controls the location of cracks
   - Contraction (control) joints - sawed or tooled
   - Isolation, expansion and construction joints
3. **Reinforcing (Rebar, WWR, and Fibers)**
   - Does not prevent cracking
   - Controls width and frequency of cracks
   - Does not control crack location
4. **Other**
   - Combination of joints & reinforcement
   - Shrink compensating concrete (EXP cements)
   - Post tensioning

Shrinkage & Water Content



Normal Concrete

400 to 800 millionths

(0.000400 inch per inch)

In general …

With effort, shrinkage less than about 0.040% (28-day) obtainable in most parts of country

Difficult to achieve shrinkage less than 0.030% (28-day) without using SRA

About 0.020% (28-day) is lowest obtainable shrinkage

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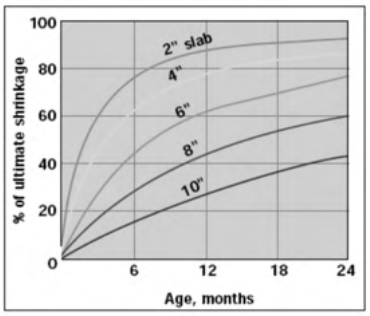
Concrete Shrinkage vs. Time



Time required for slabs on grade of different thicknesses to reach various percentages of ultimate drying shrinkage. Specimens were dried in laboratory air at 50% relative humidity.

Ref: Perenchio, W.F., The Drying Shrinkage Dilemma, *Concrete Construction*, 1997

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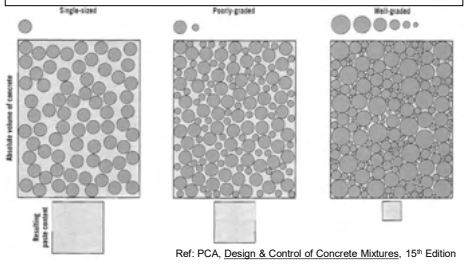
To Reduce Concrete Dry Shrinkage …

1. Reduce total water content of mixture
2. Use uniform aggregate gradations & large top size

Combined Gradation

Less Voids = Less Paste = Less Shrinkage



Ref: PCA, Design & Control of Concrete Mixtures, 15th Edition

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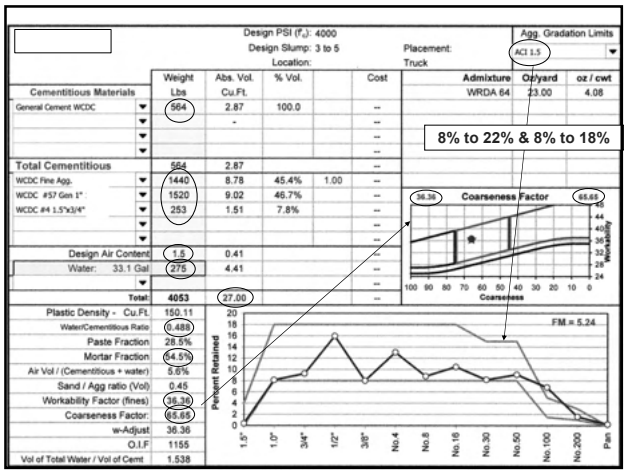

ASTM C157

- Cast & Wet Cure 23½ hr
- Demold & measure length after 24 ± ½ hr (Initial CRD)
- Wet cure for 7 days
- Air dry (73F & 50% RH)
- Measure length after 7, 14, 21 & 28 days from casting

$$Lx = \frac{CRD - Initial\ CRD}{Gage\ Length}$$

Low: ≤ 0.052%
Typical: 0.052 to 0.078%
High: ≥ 0.078%
(**Ultimate Drying Shrinkage** per ACI 360 R & 209R)

CRD = difference between the comparator reading of the specimen and the reference bar at any age

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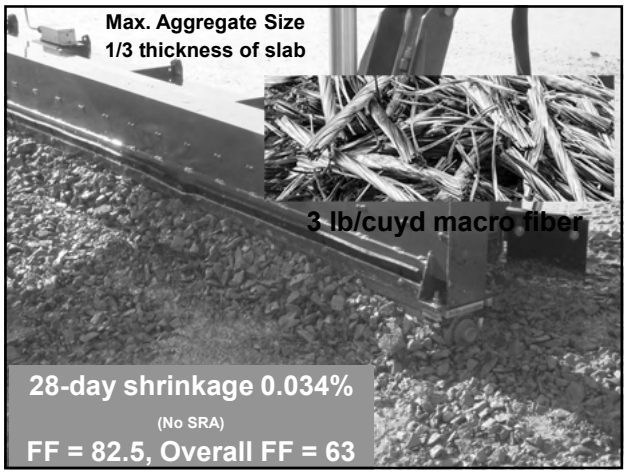
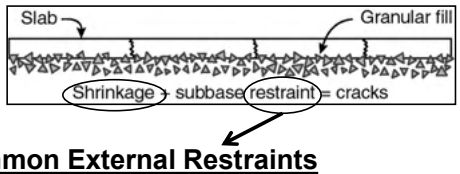


Drying Shrinkage + Restraints = Cracking



Common External Restraints

- Rough, uneven or rutted base materials
- Thickened slab edges or sections, grade beams, etc.
- Column bases, walls, etc. without isolation joints
- Bollards, drains, pipes, conduits, etc.
- Anything that prevents slab from slipping along base

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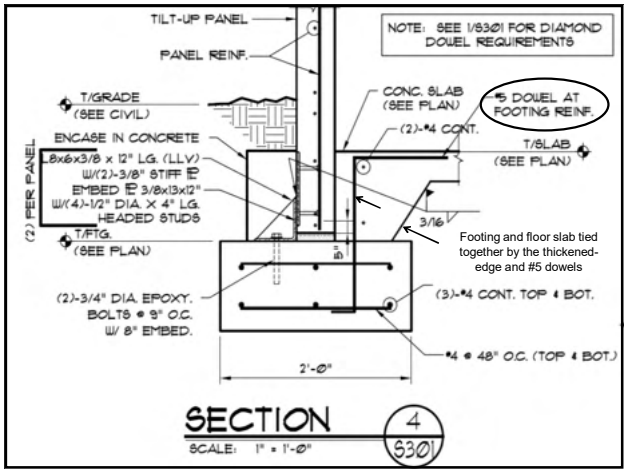

Types of Joints

1. **Isolation** (removes restraints from fixed elements)
2. **Expansion** (can act as isolation)
3. **Contraction or Control - 10 Rules**
4. **Construction**

   Can act as isolation, expansion, contraction or tied construction joint

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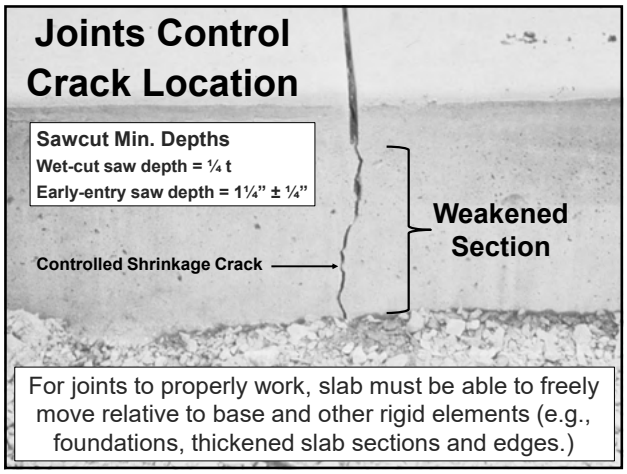
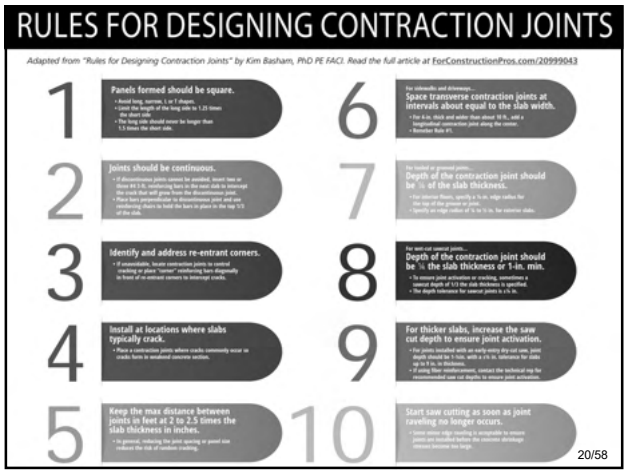
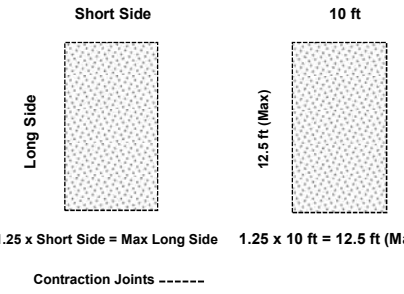
Joints Control Crack Location



For joints to properly work, slab must be able to freely move relative to base and other rigid elements (e.g., foundations, thickened slab sections and edges.)



Rule #1. Panels formed by contraction joints should be as square as possible.



Absolute max **1.5** x short side = long side

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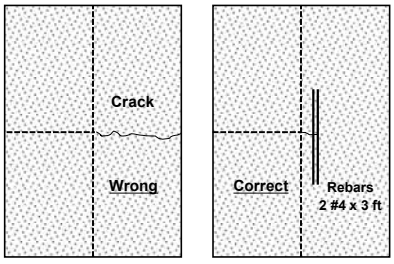
Rule #2. Contraction joints should be continuous, not staggered or offset.



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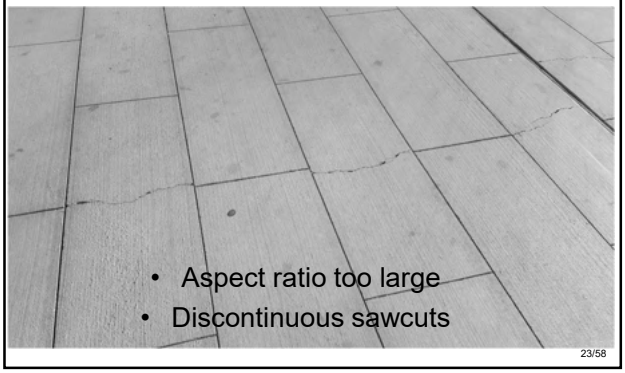
? Rules #1 and #2 ?



- Aspect ratio too large
- Discontinuous sawcuts

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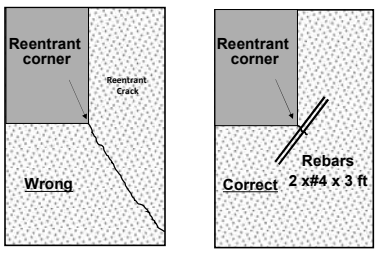
Rule #3. Identify and address reentrant corners.



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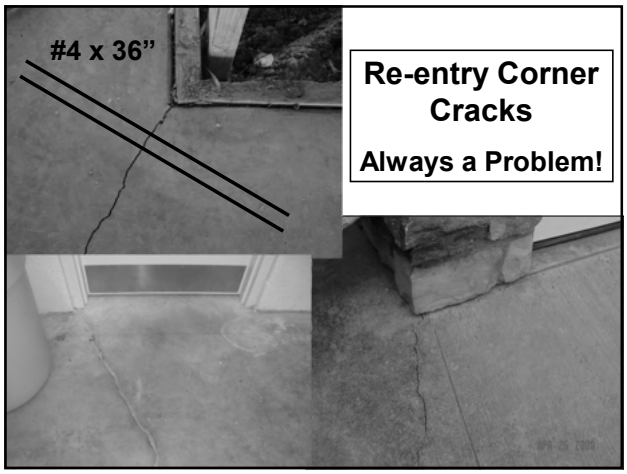
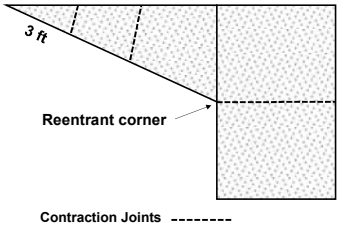


Rule #4. Install contraction joints at locations where slabs typically crack.



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Rule #5. For better crack control keep the maximum distance between joints in feet at 2 to 2.5 times the slab thickness in inches.

Slab Thickness	Slump 4 to 6 inches		Slump less than 4 inches
	Aggregate < ¾ in	Aggregate > ¾ in	
5 in	10 ft	13 ft	15 ft
6 in	12 ft	15 ft	18 ft
7 in	14 ft	18 ft	21 ft
8 in	16 ft	20 ft	24 ft
9 in	18 ft	23 ft	27 ft
10 in	20 ft	25 ft	30 ft
Based on shrinkage potential	2 x t	2½ x t	3 x t

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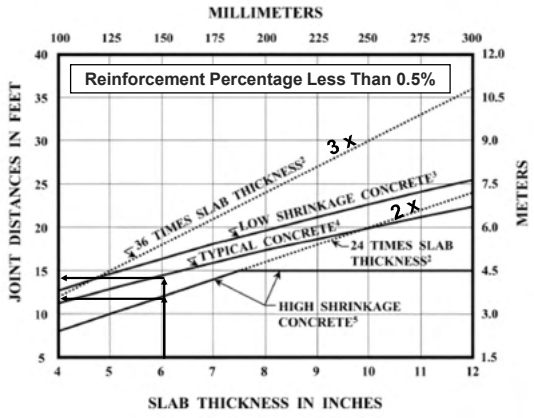

Figure 5.6 from ACI 360-06 Design of Slabs-On-Ground

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Safety Factor
Against Random Cracking

S = ?

2t ***2½t*** ***3t***

Lower Risk of Random Cracking — **Higher Risk of Random Cracking**

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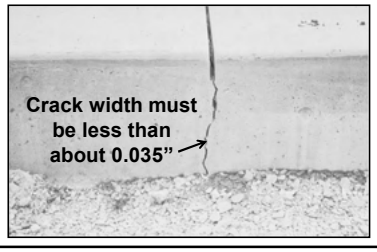
Load Transfer Across Joints

Aggregate Interlock

Load transfer by interlocking aggregate particles

Keep joint spacing under 15 ft



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Load Transfer & Vertical Alignment

If crack or joint opens more than about 0.035", faulting can occur.

Load Transfer Devices at Construction Joints

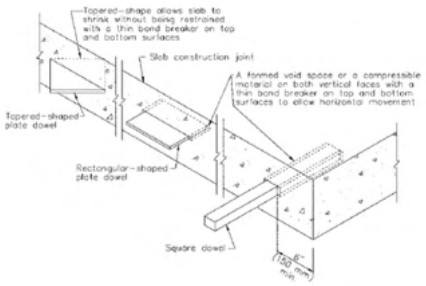

Fig. 6.10—Isometric view indicating provisions for longitudinal movement at doweled construction joints.

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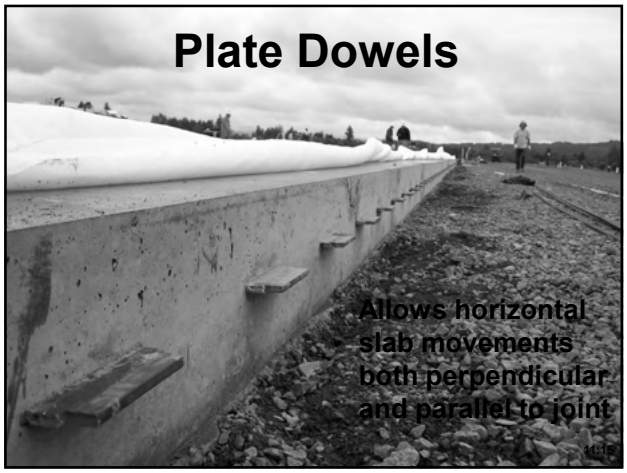
Plate Dowels



Allows horizontal slab movements both perpendicular and parallel to joint

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Load Transfer Devices at Sawcut Contraction Joints

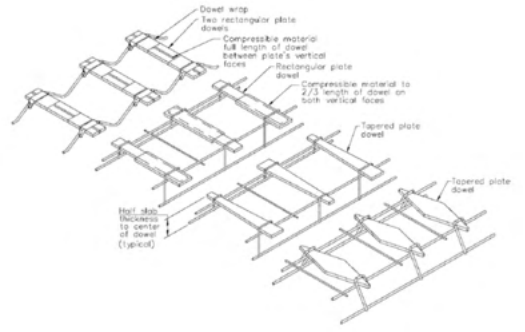

Fig. 6.12—Different plate dowel basket assemblies.

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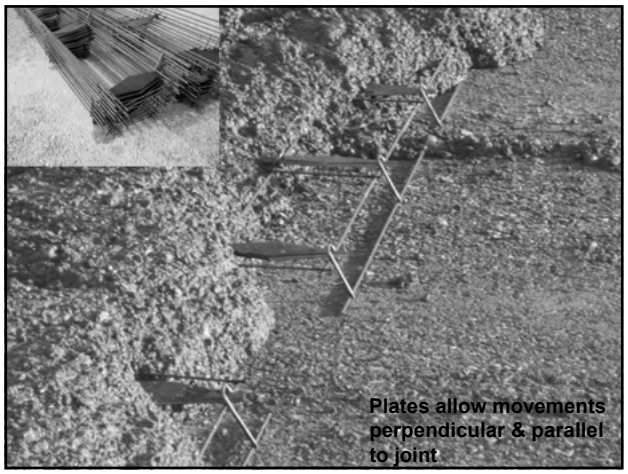

Plates allow movements perpendicular & parallel to joint

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Extended Joint Spacing Based on ASTM C157 28-day Shrinkage

In general …

- Greater than about 0.040% — **Typ. Relies on Aggregate Interlock for Load Transfer at Joints**
  15 ft maximum
- Less than about 0.040% — **Requires Load Transfer Devices at Joints**
  Up to about 30 ft (with extra smooth base)
- Less than about 0.020% — **Requires Load Transfer Devices & Armor Joints**
  Up to about 60 ft (placed on slip sheet)

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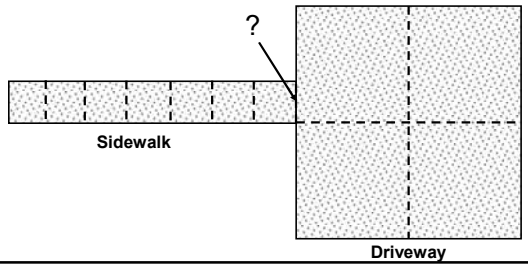
Rule #6. For sidewalks and driveways, space transverse contraction joints at intervals about equal to the slab width.



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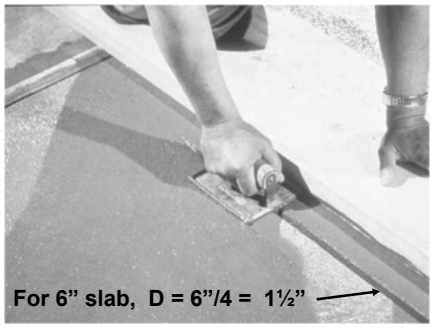
Rule #7. For tooled or grooved joints, depth of the contraction joint should be 1/4 of the slab thickness.



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Rule #8. For wet-cut sawcut joints, depth of the contraction joint should be 1/4 the slab thickness or a minimum of 1 inch.

Min. Depth 1/4 (1/3) Slab Thickness

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Rule #9. For joints installed with an early-entry dry-cut saw, joint depth should be 1-1/4 inches with a ± 1/4 inch tolerance for slabs with thicknesses up to 9 inches.

Min. Depth 1"

(1¼" ± ¼")

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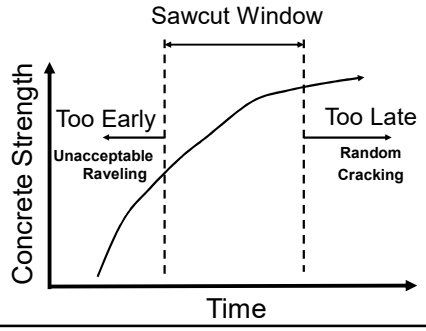
Rule #10. Start saw cutting as soon as joint raveling (loss of aggregate particles) no longer occurs.



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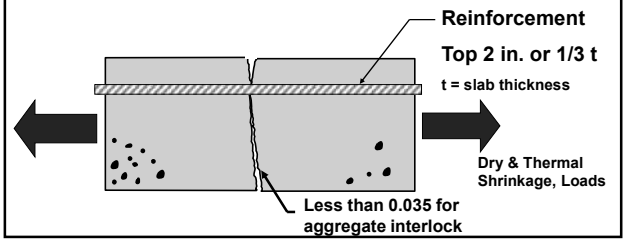
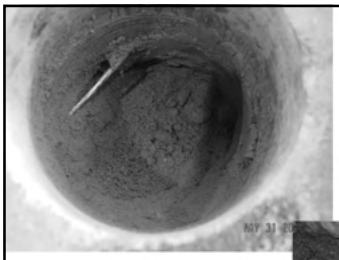
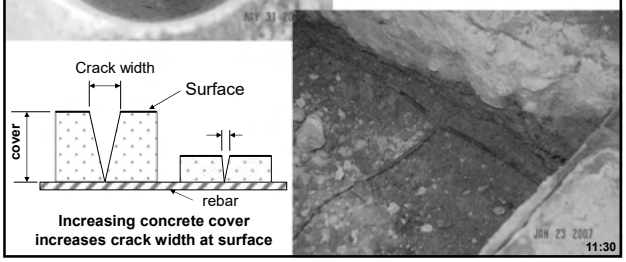
Reinforcement Controls Crack Widths

- Rebar amount & spacing is important
- Increasing amount of reinforcement decreases steel reinforcing stresses
- Decreasing reinforcing stresses reduces crack widths





Many times, temperature/shrinkage reinforcement located beneath or in bottom of slab.



Increasing concrete cover increases crack width at surface

ACI 318-19: BUILDING CODE REQUIREMENTS FOR STRUCTURAL CONCRETE

If slab-on-ground transmits vertical loads or lateral forces from other portions of the structure to the soil... Slab is a structural slab --- USE ACI 318*

24.4.3.2 The ratio of deformed shrinkage and temperature reinforcement area to gross concrete area shall be greater than or equal to 0.0018. → **0.18%**

24.4.3.3 The spacing of deformed shrinkage and temperature reinforcement shall not exceed the lesser of $5h$ and 18 in.

** By 2024 IBC, ACI 318, and ACI 360*

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Reinforced/Cracked Slabs

At contraction joints,

***too much steel* will limit joint activation**

- **0.10% max. reinforcement crossing joints for contraction joints to work as designed**
- Some steel crossing joint will provide load transfer
- Helps maintain aggregate interlock to provide "stable" joints
- **Need 0.50% min. to control crack widths to acceptable level (ACI 224R recommends 0.60% or more)**

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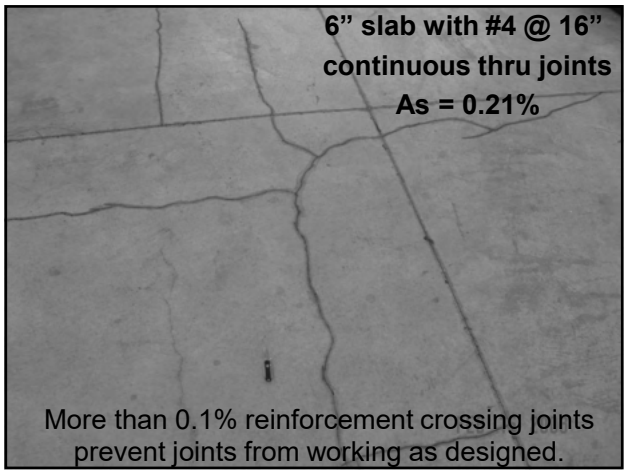

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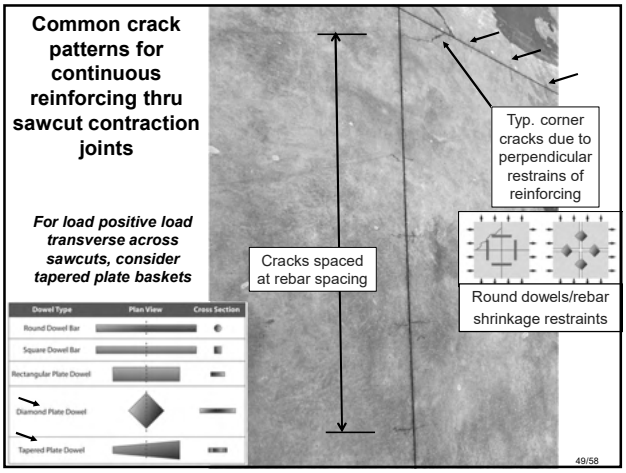
Common crack patterns for continuous reinforcing thru sawcut contraction joints

For load positive load transverse across sawcuts, consider tapered plate baskets



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Cracked/Reinforced Slab
#3 & #4 @ 18" spacing, 6" slab

#3@18" = 0.07 sqin/ft

0.07 *x 100 = 0.097%* — **Less than 0.1%**
6"x12" — ***OK, contraction joints should work as designed***

#4@18" = 0.13 sqin/ft

0.13 *x 100 = 0.181%* — **Greater than 0.1%**
6"x12" — ***Contraction joints will <u>not</u> work as designed***

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Areas of Bars per Foot Width of Slab – sqin per ft

Bar size	Bar spacing (in.)												
	6	7	8	9	10	11	12	13	14	15	16	17	18
#3	0.22	0.19	0.17	0.15	0.13	0.12	0.11	0.10	0.09	0.09	0.08	0.08	0.07
#4	0.40	0.34	0.30	0.27	0.24	0.22	0.20	0.18	0.17	0.16	0.15	0.14	0.13
#5	0.62	0.53	0.46	0.41	0.37	0.34	0.31	0.29	0.27	0.25	0.23	0.22	0.21
#6	0.88	0.75	0.66	0.59	0.53	0.48	0.44	0.41	0.38	0.35	0.33	0.31	0.29
#7	1.20	1.03	0.90	0.80	0.72	0.65	0.60	0.55	0.51	0.48	0.45	0.42	0.40
#8	1.58	1.35	1.18	1.05	0.95	0.86	0.79	0.73	0.68	0.63	0.59	0.56	0.53
#9	2.00	1.71	1.50	1.33	1.20	1.09	1.00	0.92	0.86	0.80	0.75	0.71	0.67
#10	2.54	2.18	1.91	1.69	1.52	1.39	1.27	1.17	1.09	1.02	0.95	0.90	0.85
#11	3.12	2.67	2.34	2.08	1.87	1.70	1.56	1.44	1.34	1.25	1.17	1.10	1.04

To compute % of slab reinforcement:

$$\frac{As}{t \times 12"} \times 100 = \% \text{ Reinforcement}$$

As = sqin of steel per ft of slab
t = slab thickness
% = reinforcement percentage

To compute As:

$$As = (\% \times t \times 12") \div 100$$

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Concrete on Metal Decks

How do we control cracking?

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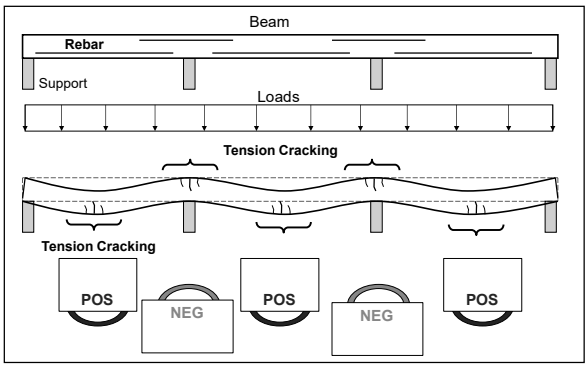
Negative Moment Cracking



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Controlling Cracks in Slabs on Metal Decks

Contraction joints do not work!

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Controlling Crack Widths in Slabs on Metal Decks

Reinforcement for Temperature and Shrinkage Recommendations by SDI:

1. **Welded wire reinforcement or reinforcing bars** with a minimum area of 0.00075 times the area of the concrete above the deck (per foot or meter of width), but **not be less than the area provided by 6 x 6 – W1.4 x W1.4 WWR.**

2. **Steel fibers** meeting the criteria of ASTM A820, Type I , Type II, or Type V, at a dosage rate determined by the fiber manufacturer for the application, but **not less than 25 lb/cu yd**.

3. **Macro synthetic fibers** meeting the criteria of ASTM D7508 at a dosage rate determined by the fiber manufacturer for the application, but **not less than 4 lb./cuyd**.

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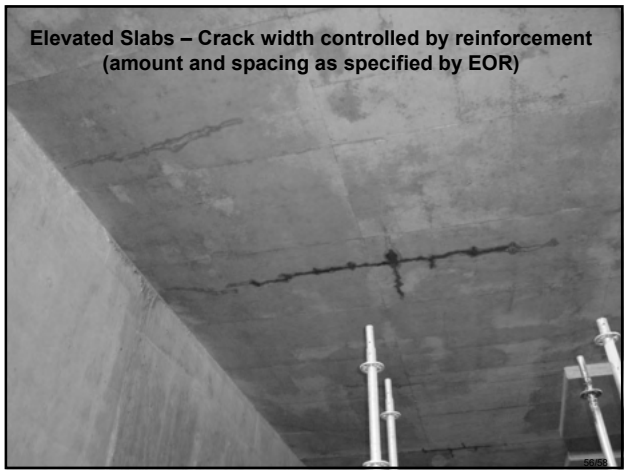

To reduce slab cracking, consider:

1. **Concrete Shrinkage?** *(thermal & drying)*
2. **Slab Restraints?** *Is slab floating within foundation?*
3. **Joint Spacing?** *Designer responsible for specifying*
4. **Joint Layout?** *Designer responsible for layout*
5. **Joint Depth?** *Designer responsible for specifying*
6. **Sawcut Timing?** *Contractor responsible for timing*
7. **Reinforcing? Depth?** *Controls crack widths*
8. **Reinforcing Passing Through Joints**? *≤ 0.1% ??*
9. **Slabs on Metal Decks** *(Use reinforcing to control crack widths – sawcut joints do not work)*
10. **Discuss with owner crack expectations & risks**

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RULES FOR DESIGNING CONTRACTION JOINTS

Adapted from "Rules for Designing Contraction Joints" by Kim Basham, PhD PE FACI. Read the full article at ForConstructionPros.com/20999043

1 Panels formed should be square.

- Avoid long, narrow, L or T shapes.
- Limit the length of the long side to 1.25 times the short side
- The long side should never be longer than 1.5 times the short side.

2 Joints should be continuous.

- If discontinuous joints cannot be avoided, insert two or three #4 3-ft. reinforcing bars in the next slab to intercept the crack that will grow from the discontinuous joint.
- Place bars perpendicular to discontinuous joint and use reinforcing chairs to hold the bars in place in the top 1/3 of the slab.

3 Identify and address re-entrant corners.

- If unavoidable, locate contraction joints to control cracking or place "corner" reinforcing bars diagonally in front of re-entrant corners to intercept cracks.

4 Install at locations where slabs typically crack.

- Place a contraction joints where cracks commonly occur so cracks form in weakend concrete section.

5 Keep the max distance between joints in feet at 2 to 2.5 times the slab thickness in inches.

- In general, reducing the joint spacing or panel size reduces the risk of random cracking.

6 For sidewalks and driveways... Space transverse contraction joints at intervals about equal to the slab width.

- For 4-in. thick and wider than about 10 ft., add a longitudinal contraction joint along the center.
- Remeber Rule #1.

7 For tooled or grooved joints... Depth of the contraction joint should be ¼ of the slab thickness.

- For interior floors, specify a ⅛-in. edge radius for the top of the groove or joint.
- Specify an edge radius of ¼ to ½ in. for exterior slabs.

8 For wet-cut sawcut joints... Depth of the contraction joint should be ¼ the slab thickness or 1-in. min.

- To ensure joint activation or cracking, sometimes a sawcut depth of 1/3 the slab thickness is specified.
- The depth tolerance for sawcut joints is ±¼ in.

9 For thicker slabs, increase the saw cut depth to ensure joint activation.

- For joints installed with an early-entry dry-cut saw, joint depth should be 1-¼in. with a ±¼ in. tolerance for slabs up to 9 in. in thickness.
- If using fiber reinforcement, contact the technical rep for recommended saw cut depths to ensure joint activation.

10 Start saw cutting as soon as joint raveling no longer occurs.

- Some minor edge raveling is acceptable to ensure joints are installed before the concrete shrinkage stresses become too large.