
Concrete Cracking
by
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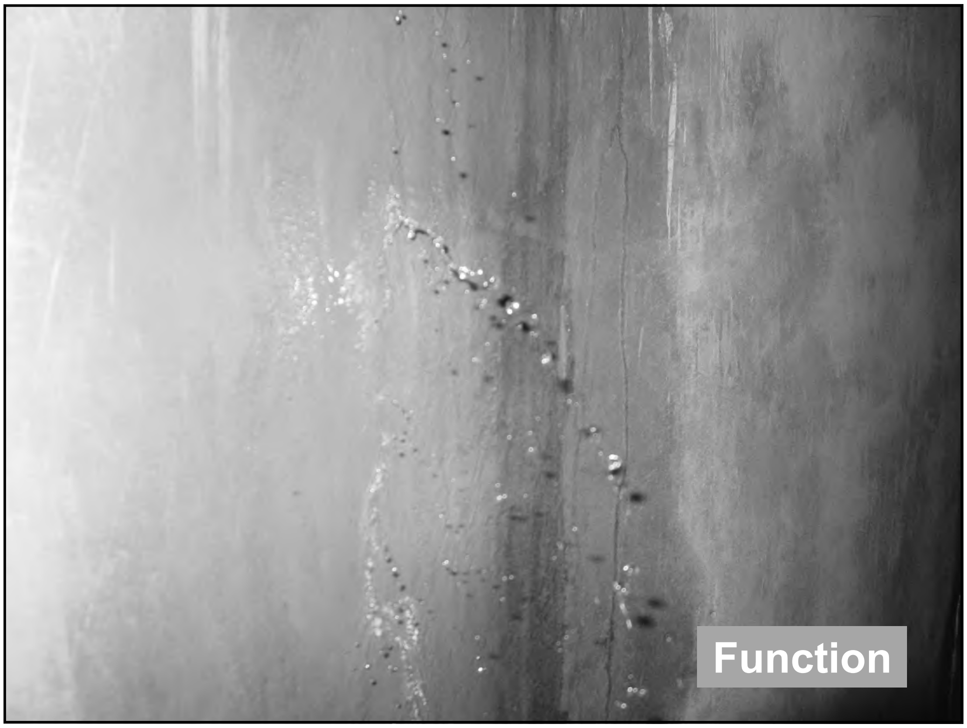
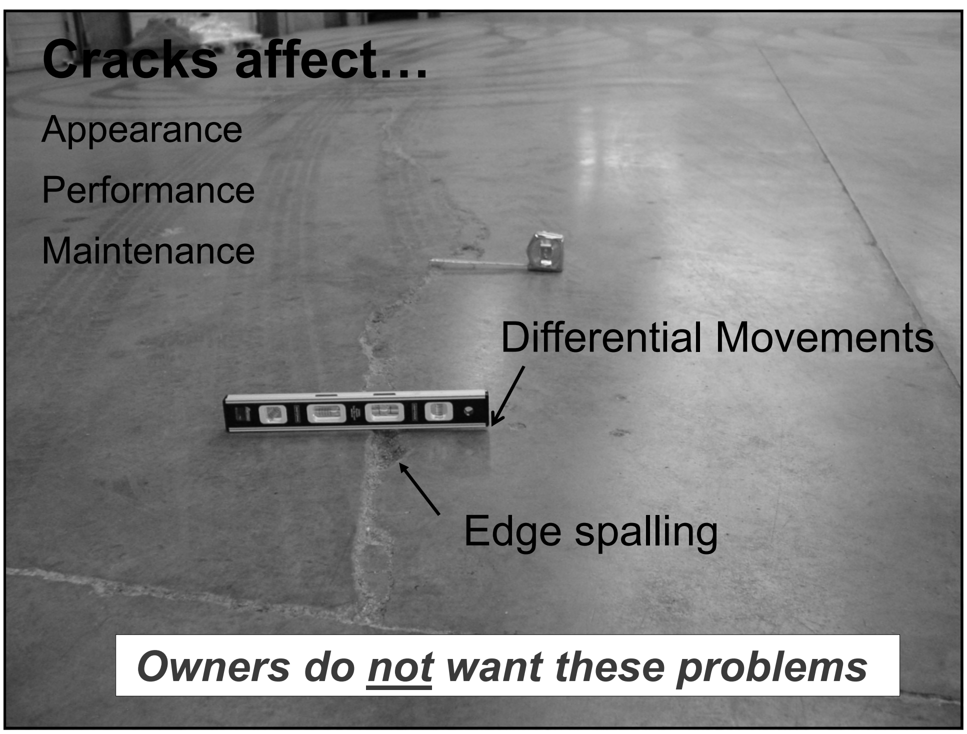
Aesthetics





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Let's make one thing clear …

Concrete Cracks
and
That's a Fact!

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Types of Cracks

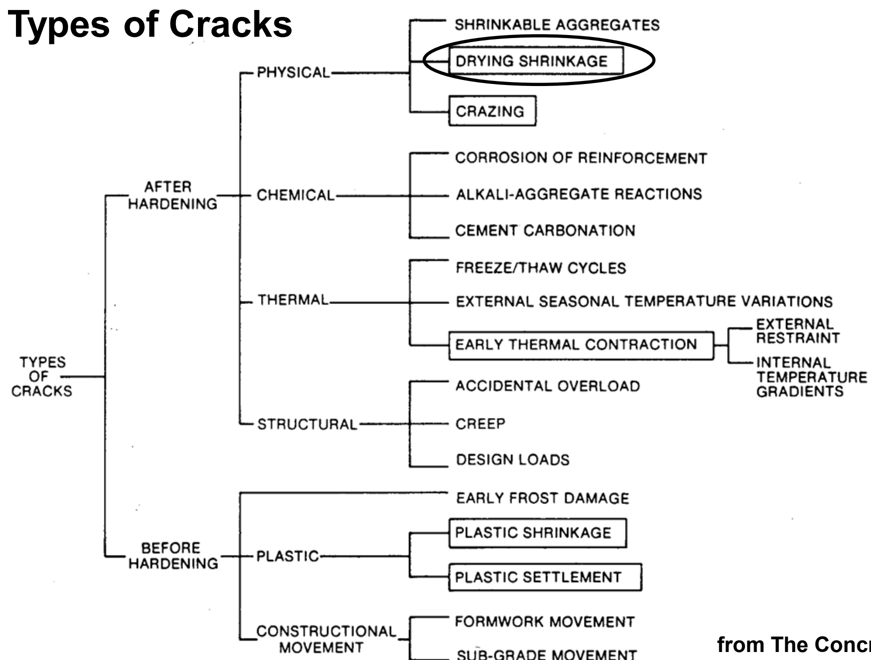

Figure 1: Types of crack

from The Concrete Society TR#22

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from The Concrete Society TR#22

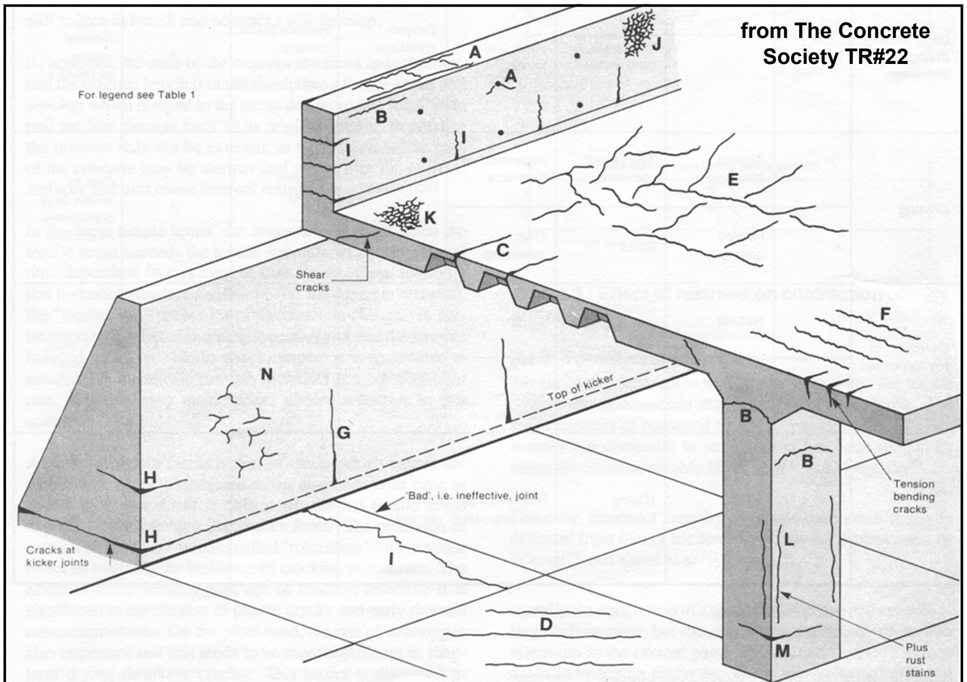

Figure 2: Examples of intrinsic cracks in hypothetical concrete structure

Type of cracking	Letter (see Figure 2)	Subdivision	Most common location	Primary cause (excluding restraint)	Secondary causes/ factors	Remedy (assuming basic redesign is impossible) In all cases reduce restraint	Further details see section ...	Time of appearance
Plastic settlement	A	Over reinforcement	Deep sections	Excess bleeding	Rapid early drying conditions	Reduce bleeding (air entrainment) or revibrate	5.2	Ten minutes to three hours
	B	Arching	Top of columns					
	C	Change of depth	Trough and waffle slabs					
Plastic shrinkage	D	Diagonal	Roads and slabs	Rapid early drying	Low rate of bleeding	Improve early curing	5.3	Thirty minutes to six hours
	E	Random	Reinforced concrete slabs					
	F	Over reinforcement	Reinforced concrete slabs	Ditto plus steel near surface				
Early thermal contraction	G	External restraint	Thick walls	Excess heat generation	Rapid cooling	Reduce heat and/or insulate	6	One day to two or three weeks
	H	Internal restraint	Thick slabs	Excess temperature gradients				
Long-term drying shrinkage	I		Thin slabs (and walls)	Inefficient joints	Excess shrinkage Inefficient curing	Reduce water content Improve curing	7	Several weeks or months
Crazing	J	Against formwork	'Fair faced' concrete	Impermeable formwork	Rich mixes	Improve curing and finishing	8	One to seven days, sometimes much later
	K	Floated concrete	Slabs	Over-trowelling	Poor curing			
Corrosion of reinforcement	L	Natural	Columns and beams	Lack of cover	Poor quality concrete	Eliminate causes listed	9.1	More than two years
	M	Calcium chloride	Precast concrete	Excess calcium chloride				
Alkali-silica reaction	N		(Damp locations)	Reactive aggregrate plus high-alkali cement		Eliminate causes listed	9.2	More than five years

from The Concrete Society TR#22

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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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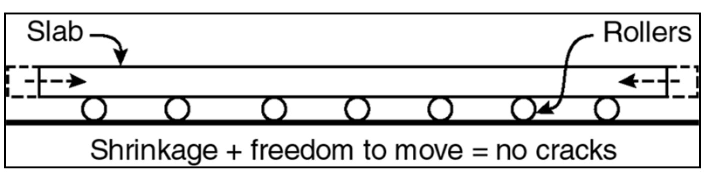
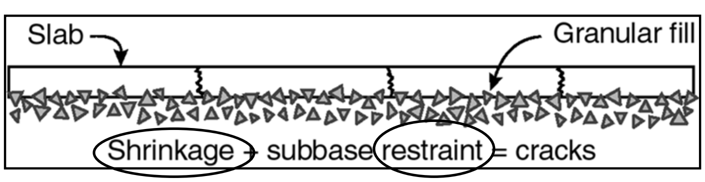
Drying Shrinkage + Restraints = Cracking





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

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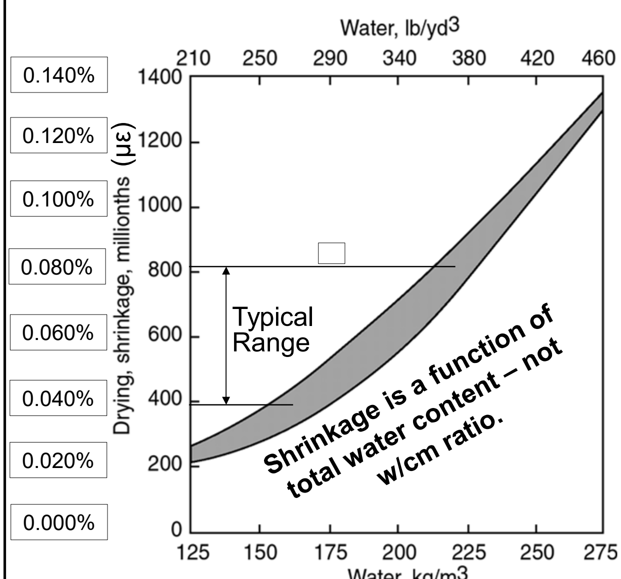
Crack Control Strategies

1. **Reduce Concrete Shrinkage & Restraints**
2. **Jointing**
   - Controls location of cracks
   - Contraction (control) joints - sawed or tooled
   - Isolation, expansion and construction joints
3. **Reinforcing (rebar 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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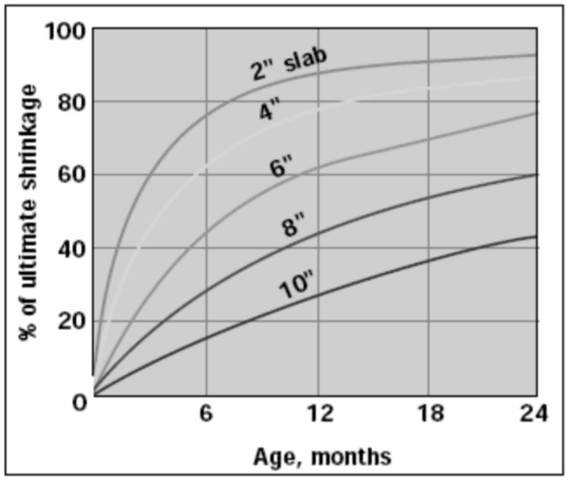
Concrete Shrinkage vs. Time



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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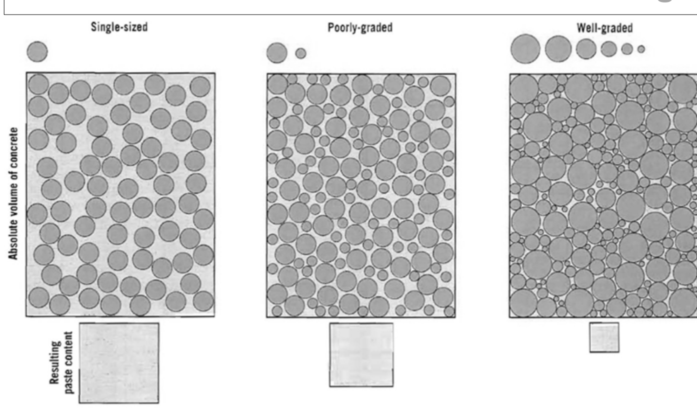
To Reduce Concrete Dry Shrinkage …

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

Combined Gradation

Less Voids = Less Paste = Less Shrinkage



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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)

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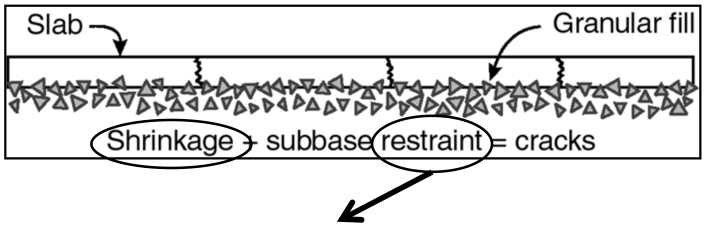
Drying Shrinkage + Restraints = Cracking



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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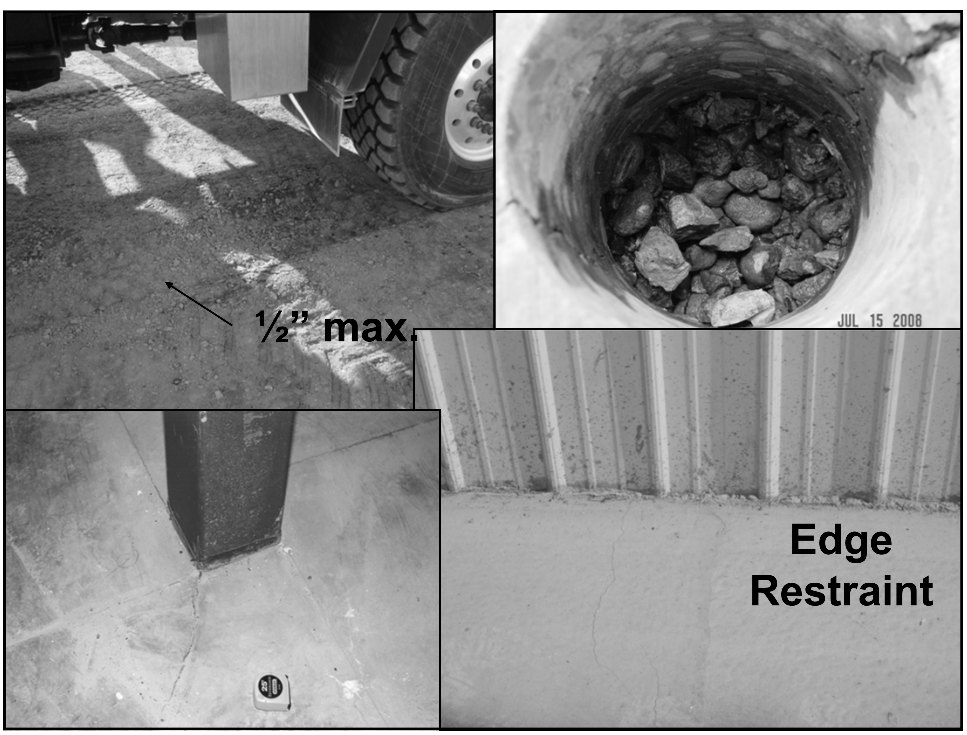

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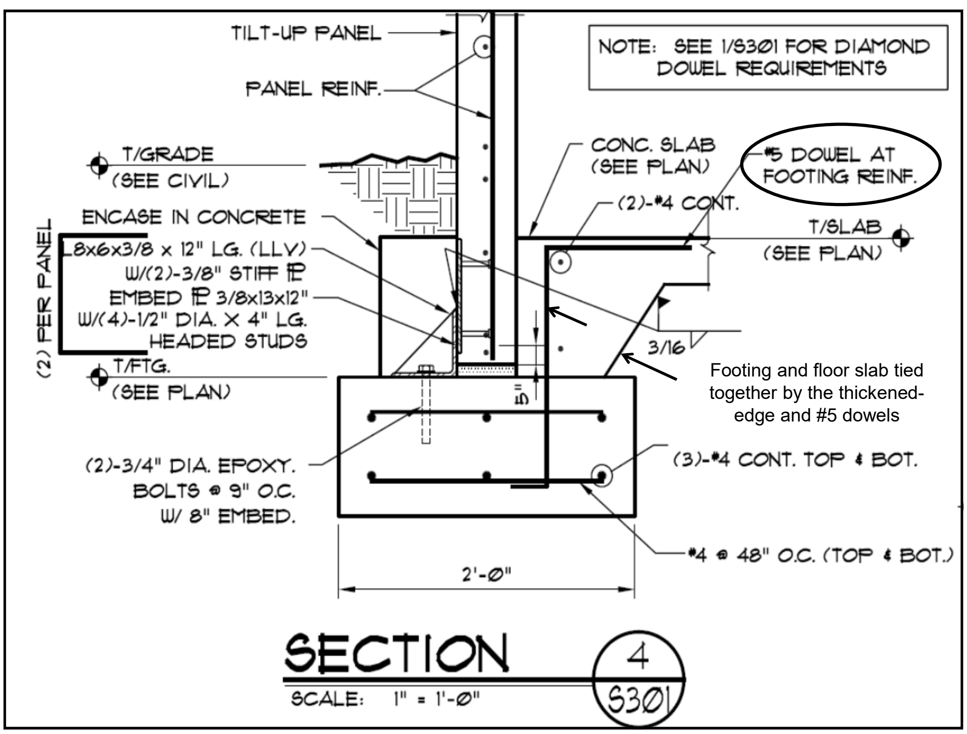

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Types of Joints

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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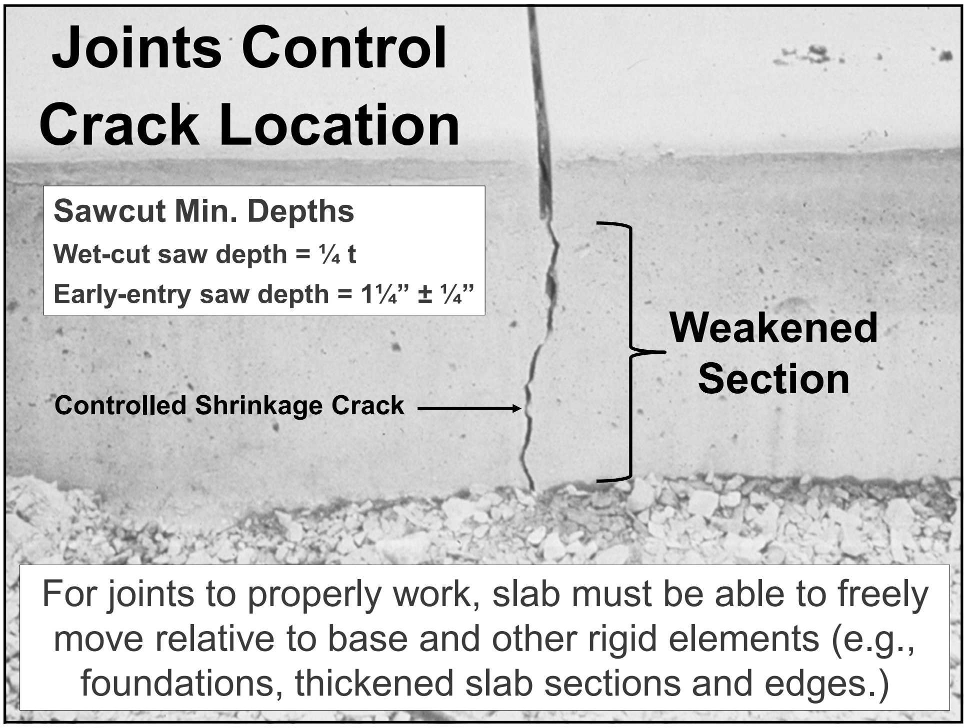
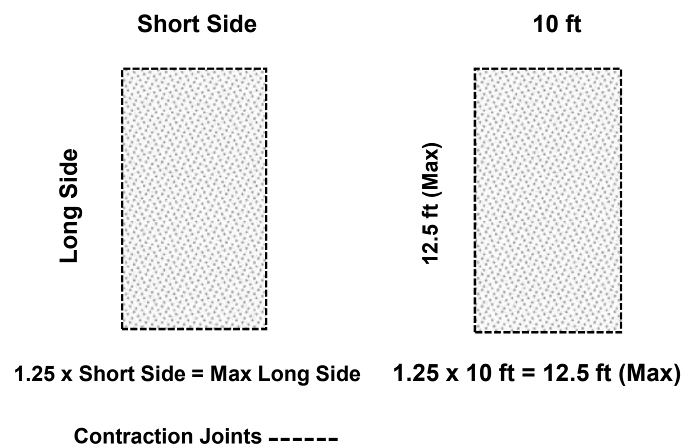
Joints Control Crack Location

Sawcut Min. Depths
Wet-cut saw depth = ¼ t
Early-entry saw depth = 1¼” ± ¼”



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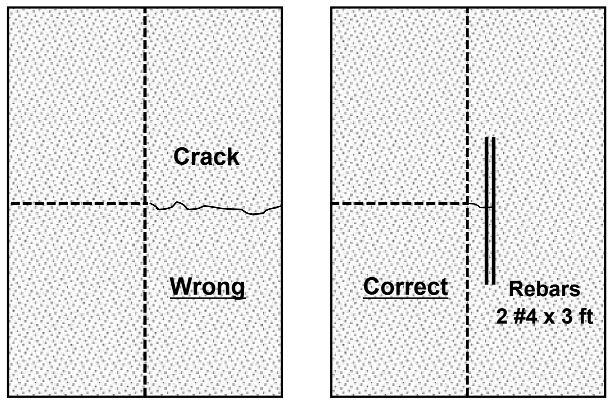
Rule #2. Contraction joints should be continuous, not staggered or offset.



Contraction Joints -------

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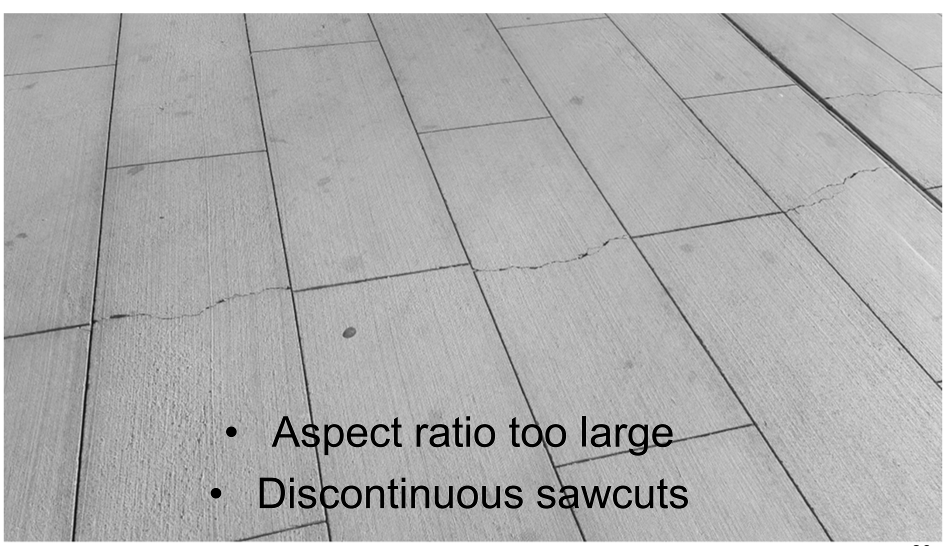
? Rules #1 and #2 ?



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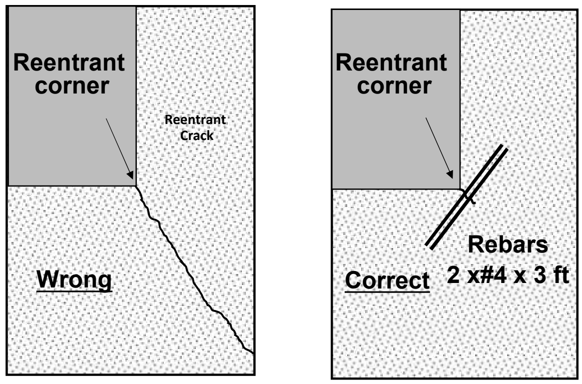
Rule #3. Identify and address reentrant corners.



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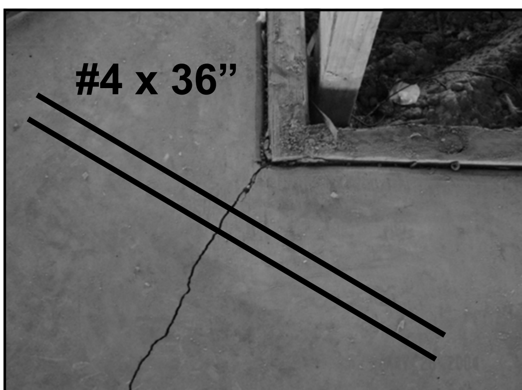
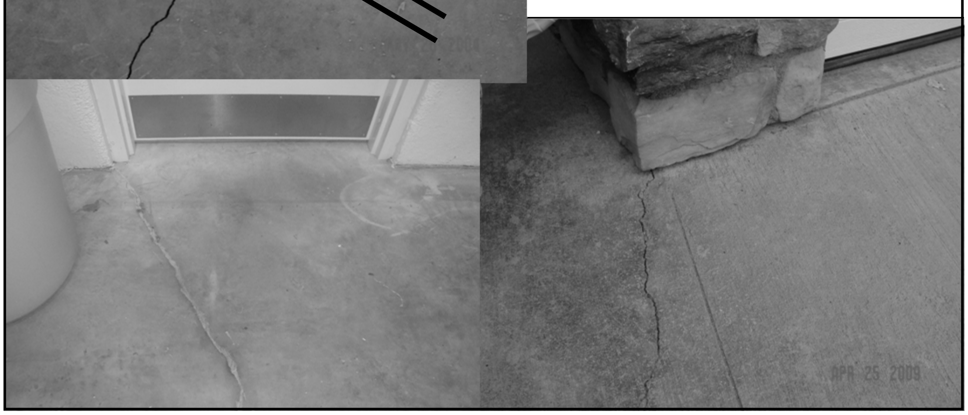


Re-entry Corner Cracks

Always a Problem!



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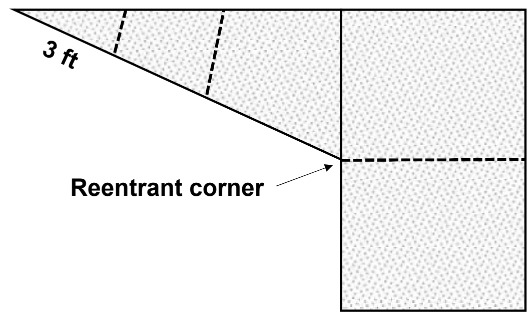
Rule #4. Install contraction joints at locations where slabs typically crack.



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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
	2 x t	2½ x t	3 x t

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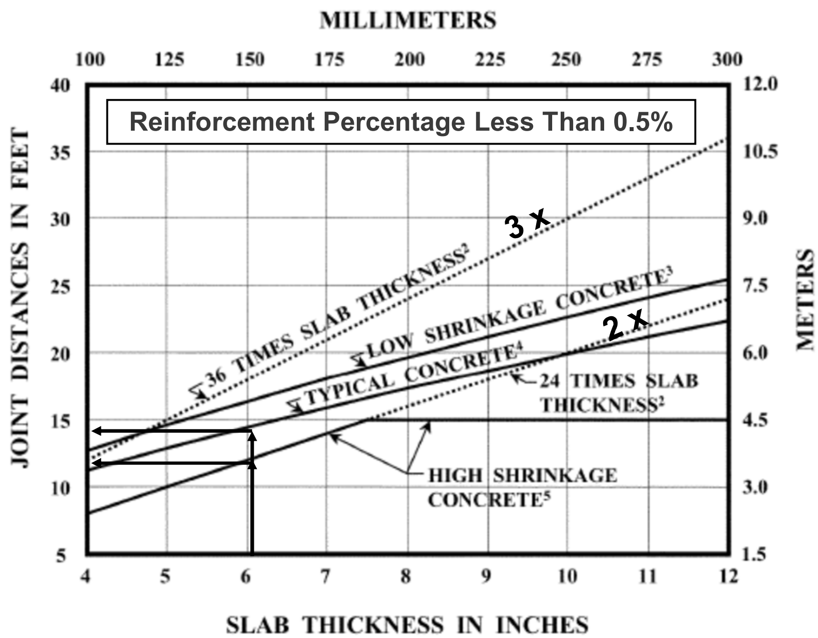

Figure 5.6 from ACI 360-06 Design of Slabs-On-Ground

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Safety Factor

Against Random Cracking

S = ?

2*t*	2½*t*	3*t*

Lower Risk of Random Cracking	Higher Risk of Random Cracking

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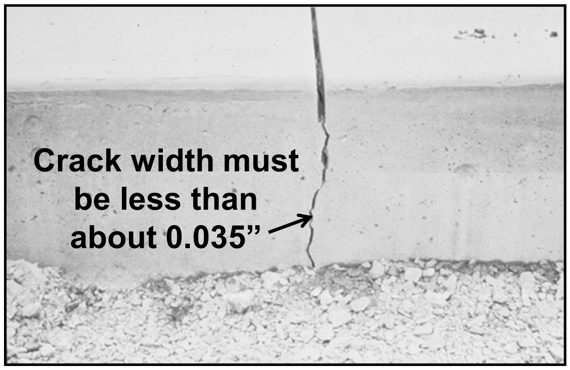
Load Transfer Across Joints

Aggregate Interlock

Load transfer by interlocking aggregate particles

Keep joint spacing under 15 ft



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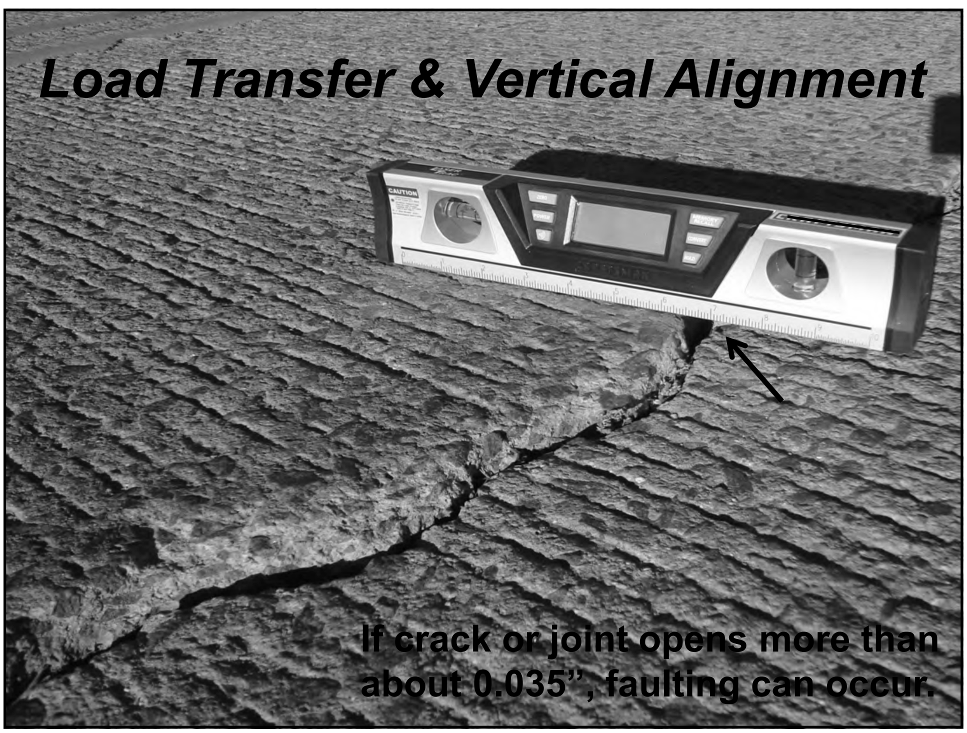
Load Transfer & Vertical Alignment



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<u>Extended</u> Joint Spacing Based on ASTM C57 28-day Shrinkage

In general …

- Greater than about 0.040%

  15 ft maximum

- Less than about 0.040%

  Up to about 30 ft (with extra <u>smooth</u> base)

- Less than about 0.020%

  Up to about 60 ft (placed on slip sheet)

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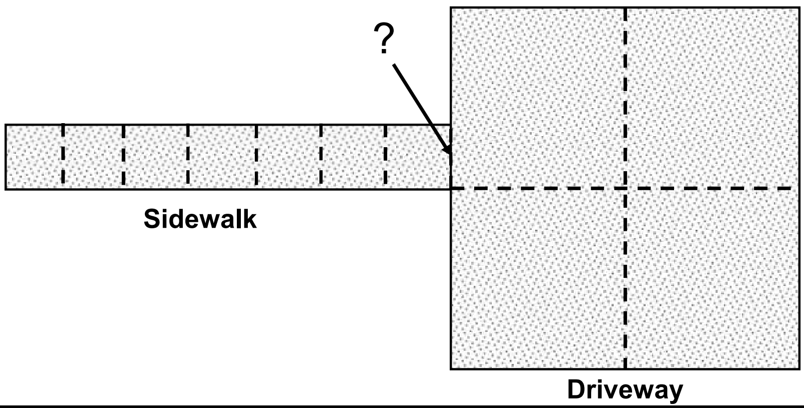
Rule #6. For sidewalks and driveways, space transverse contraction joints at intervals about equal to the slab width.



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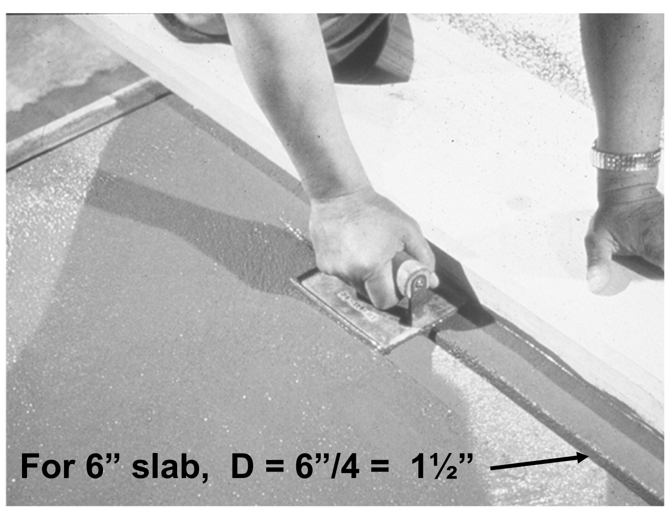
Rule #7. For tooled or grooved joints, depth of the contraction joint should be 1/4 of the slab thickness.



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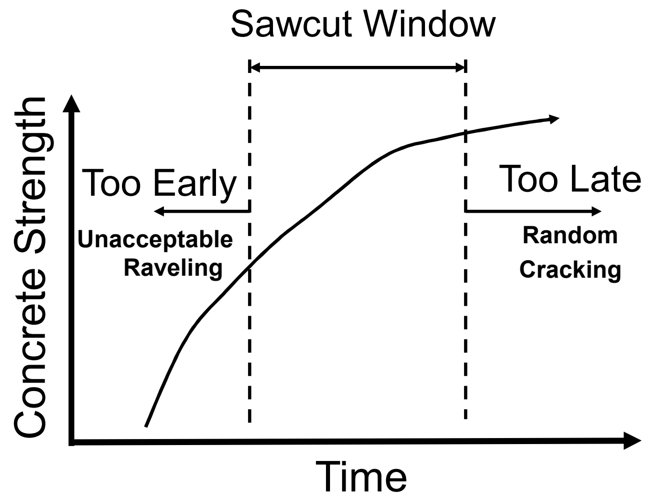
Rule #10. Start saw cutting as soon as joint raveling (loss of aggregate particles) no longer occurs.



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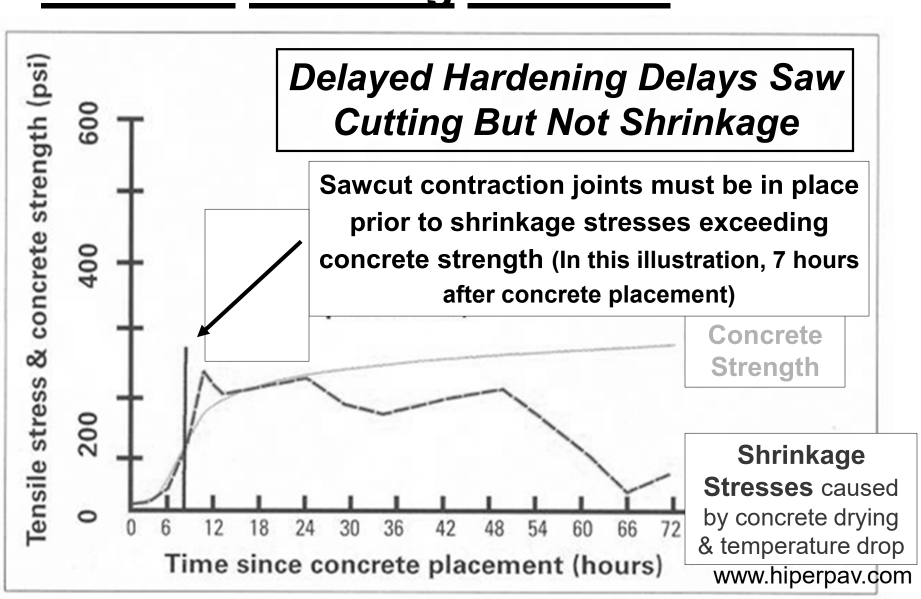
Delayed Concrete Hardening Can <u>Increase</u> <u>Cracking</u> <u>Potential</u> for Slabs



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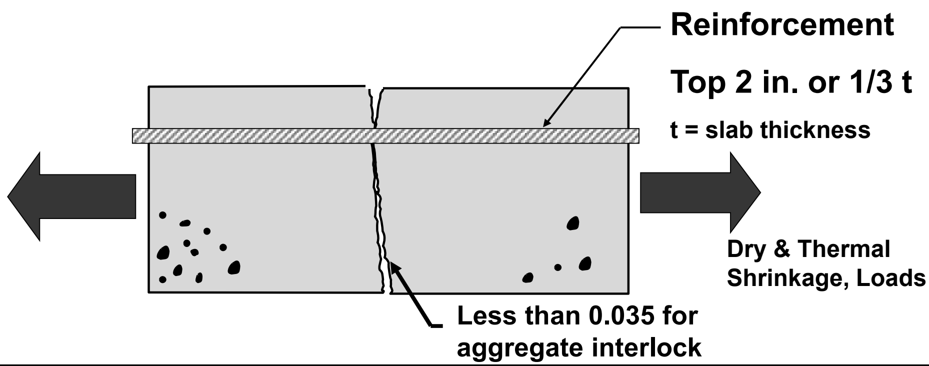
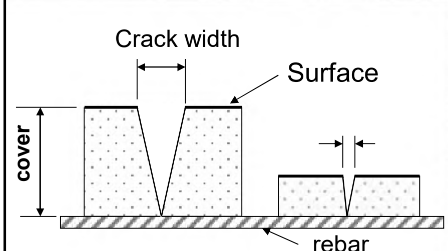
Reinforcement Controls Crack Widths

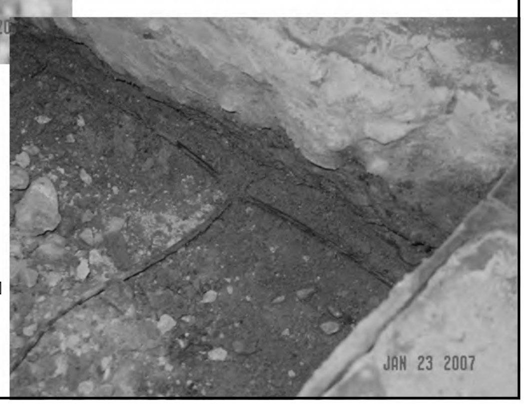
- Rebar amount & spacing is important
- Increasing amount of reinforcement decreases steel reinforcing stresses
- Decreasing reinforcing stresses reduces crack widths



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



Increasing concrete cover increases crack width at surface



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Reinforcement in 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
- When reinforcement crossing contraction joints equals or exceeds **0.50%**, **joints totally ineffective**

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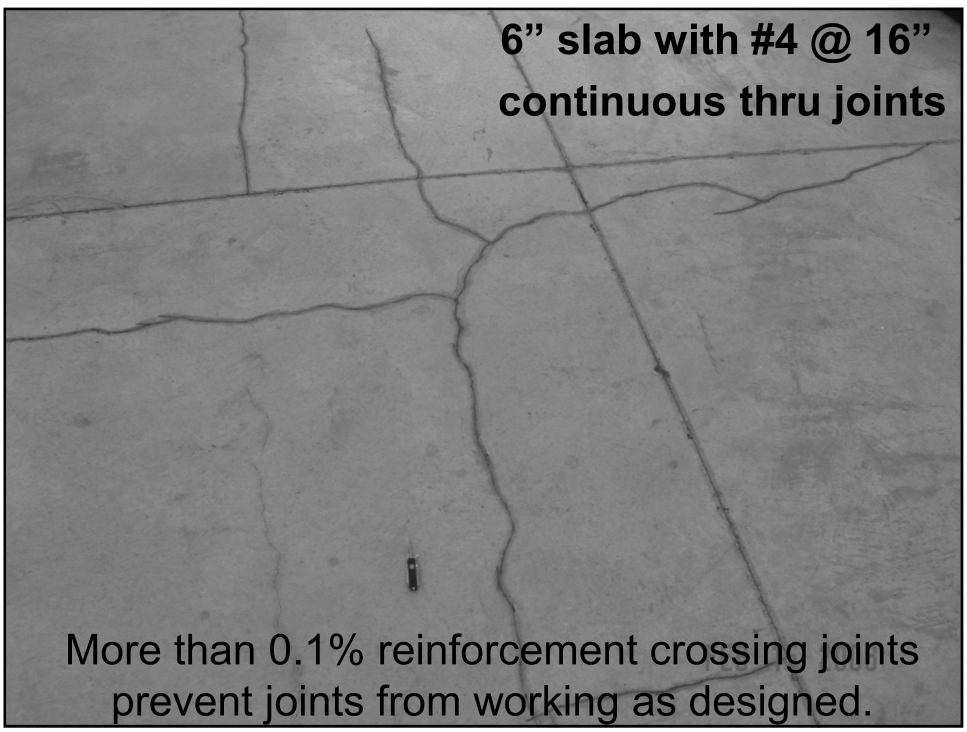

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#3 or #4 @ 18" spacing, 6" slab
Must every other bar be cut?

#3@18" = 0.07 sqin/ft

$\frac{0.07}{6" \times 12"} \times 100 = 0.097\%$ — **less than 0.1%**
OK, no cutting required

#4@18" = 0.13 sqin/ft

$\frac{0.13}{6" \times 12"} \times 100 = 0.181\%$ — **greater than 0.1%**
must cut every other bar
(.181%/2 = 0.091%)

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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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For ***walls***, how do we control cracking?

- **Joints** – weakened section to control location of shrinkage cracks (just like slabs)
- **Reinforcing** – controls crack widths and frequency of cracks
  - ACI 318 – Building Code for Structural Concrete
    Min. Temperature and Shrinkage Reinforcement
    0.18% (ratio of reinforcement area to gross concrete area)
  - What about water retaining structures (minimize leaks)?
    ACI 350 - Code Requirements for Environmental Engineering Concrete Structures

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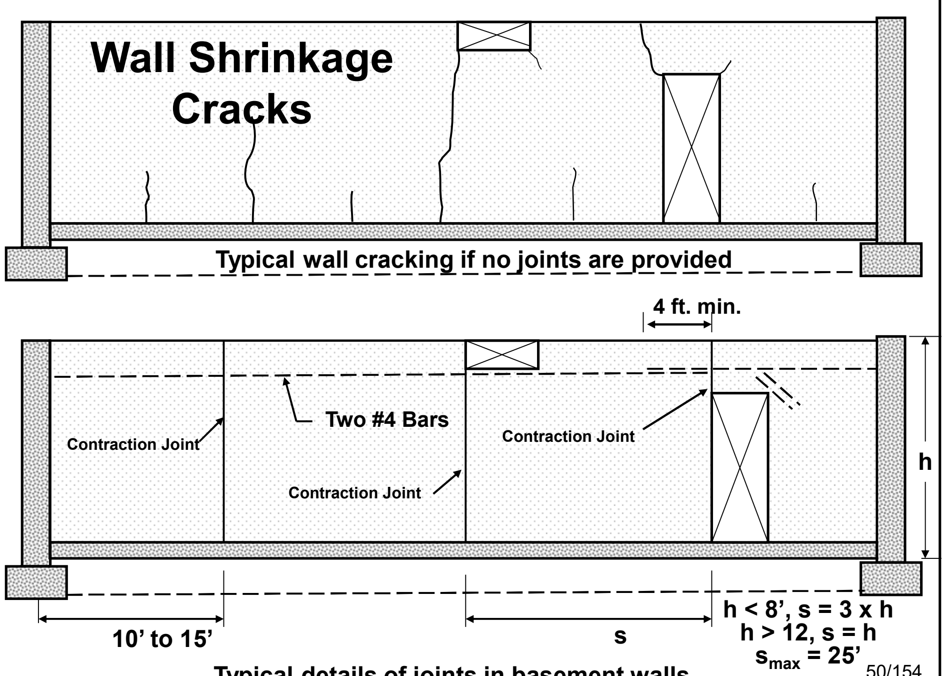

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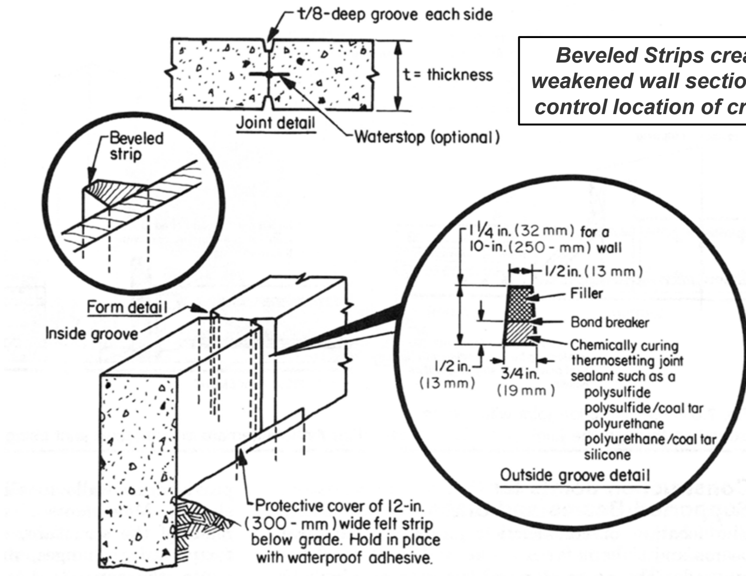
Contraction Joints for Walls



Beveled Strips create weakened wall sections to control location of cracks

Ref: <u>The Contractor's Guide to Quality Concrete Construction</u>, ACI/ASCC 1, Aug. 1992

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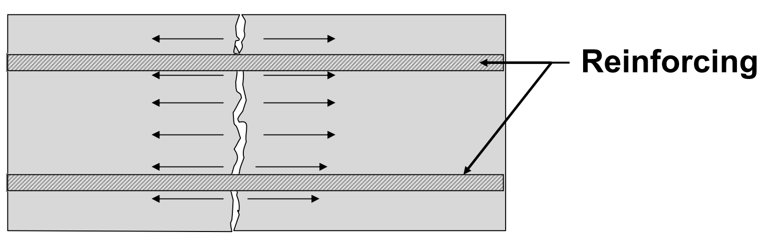
Wall reinforcing <u>controls crack widths</u> by <u>holding concrete together across cracks</u>.



Amount (%) of reinforcement crossing crack determines width of cracks.

Bar <u>size</u> and <u>spacing</u> determines both crack width & frequency of cracks.

In general…

Lots of small bars produces lots of narrow cracks.

A few big bars produces a few wide cracks.

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Computer Modeling for Walls:

Crack Widths vs Reinforcing %

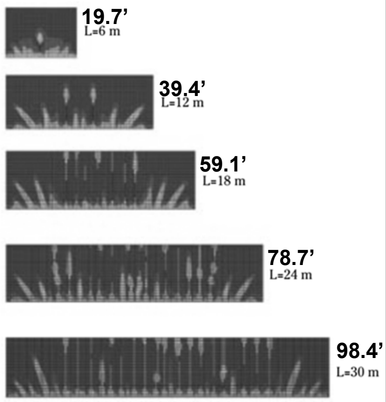

Fig. 4: Cracking patterns in 4 m (13 ft) tall, 300 mm (12 in.) thick walls of various lengths with a temperature and shrinkage strain of 600 με (1 m = 3.28 ft)

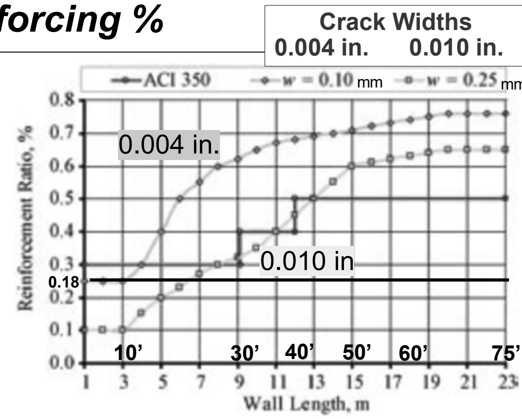

Fig. 5: Comparison of minimum shrinkage and temperature reinforcement ratios for temperature and shrinkage strain of 600 με. Shown ratios are based on the use of Grade 420 (Grade 60) reinforcing steel (1 m = 3.28 ft)

Cracks with widths larger than about 0.004 in. leak!

Ref: Cracking in Liquid-Containing Structures by Kianoush, M.R., Acarcan, M., & Dullerud, E. April 2006, *Concrete International*

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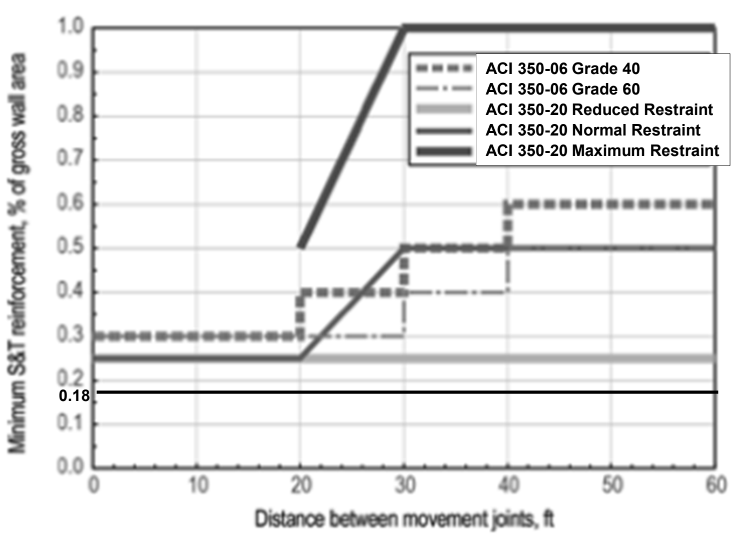

Fig. 2: Minimum S&T reinforcement per ACI 350-06 and ACI 350-20[7] (Note: 1 ft = 0.30 m)

Ref: ACI 350 Shrinkage and Temperature Reinforcement by Roller, J., April 2021, *Concrete International*

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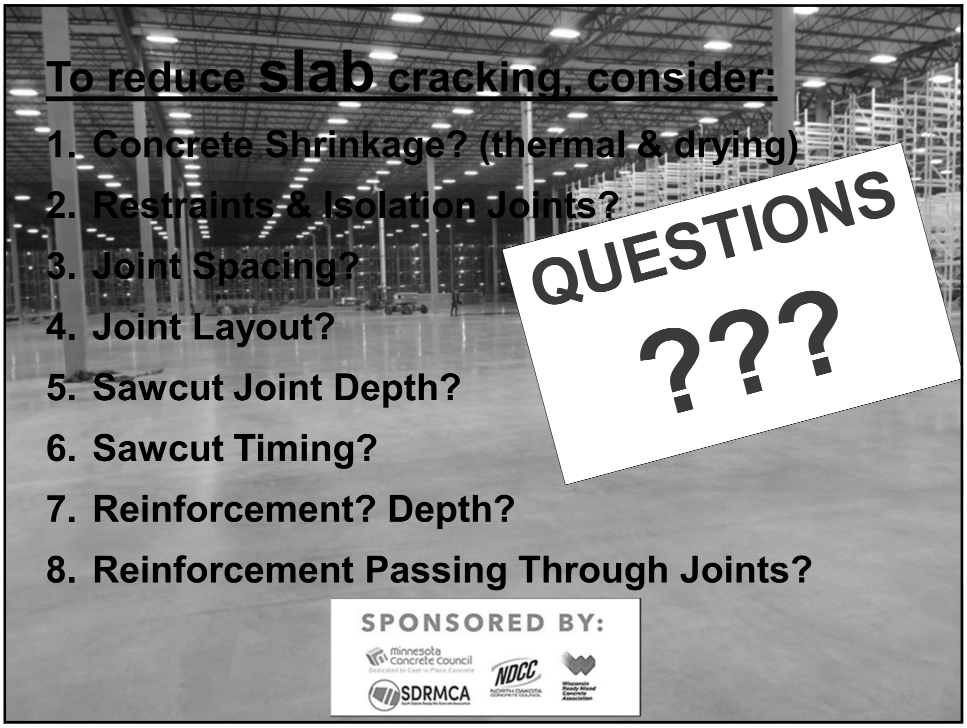

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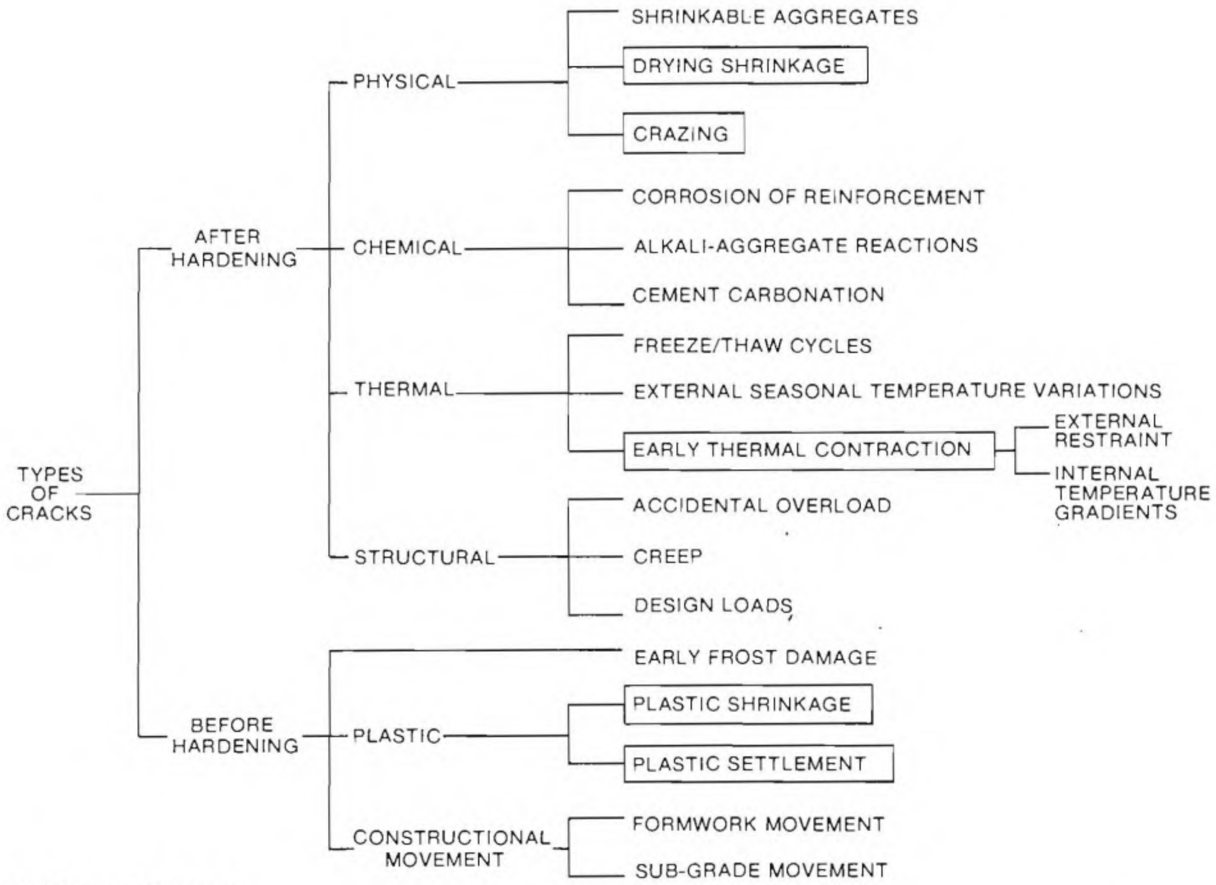

Figure 1: Types of crack

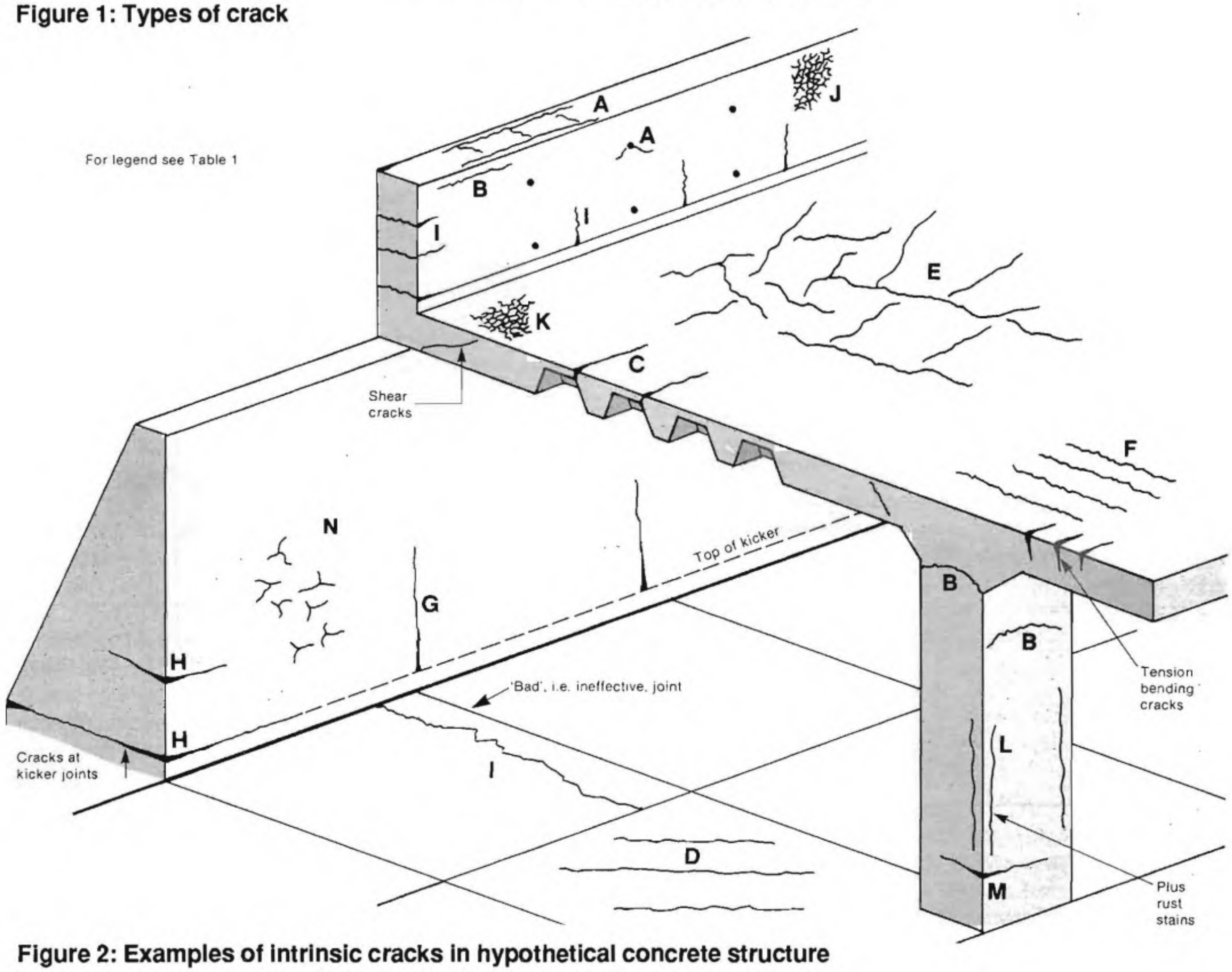

Figure 2: Examples of intrinsic cracks in hypothetical concrete structure

Type of cracking	Letter (see Figure 2)	Subdivision	Most common location	Primary cause (excluding restraint)	Secondary causes/ factors	Remedy (assuming basic redesign is impossible) In all cases reduce restraint	Further details see section ...	Time of appearance
Plastic settlement	A	Over reinforcement	Deep sections	Excess bleeding	Rapid early drying conditions	Reduce bleeding (air entrainment) or revibrate	5.2	Ten minutes to three hours
	B	Arching	Top of columns					
	C	Change of depth	Trough and waffle slabs					
Plastic shrinkage	D	Diagonal	Roads and slabs	Rapid early drying	Low rate of bleeding	Improve early curing	5.3	Thirty minutes to six hours
	E	Random	Reinforced concrete slabs					
	F	Over reinforcement	Reinforced concrete slabs	Ditto plus steel near surface				
Early thermal contraction	G	External restraint	Thick walls	Excess heat generation	Rapid cooling	Reduce heat and/or insulate	6	One day to two or three weeks
	H	Internal restraint	Thick slabs	Excess temperature gradients				
Long-term drying shrinkage	I		Thin slabs (and walls)	Inefficient joints	Excess shrinkage Inefficient curing	Reduce water content Improve curing	7	Several weeks or months
Crazing	J	Against formwork	'Fair faced' concrete	Impermeable formwork	Rich mixes	Improve curing and finishing	8	One to seven days, sometimes much later
	K	Floated concrete	Slabs	Over-trowelling	Poor curing			
Corrosion of reinforcement	L	Natural	Columns and beams	Lack of cover	Poor quality concrete	Eliminate causes listed	9.1	More than two years
	M	Calcium chloride	Precast concrete	Excess calcium chloride				
Alkali-silica reaction	N		(Damp locations)	Reactive aggregrate plus high-alkali cement		Eliminate causes listed	9.2	More than five years

REF: Concrete Society Technical Report #22 Non-structural cracks in concrete
The Concrete Society, 1992, www.concrete.org.uk

Table 1: Classification of intrinsic cracks