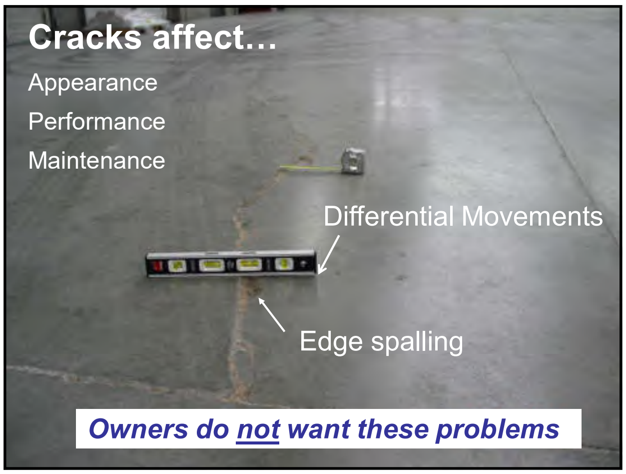


Let's make one thing clear …

Concrete Cracks and That's a Fact!

4/48

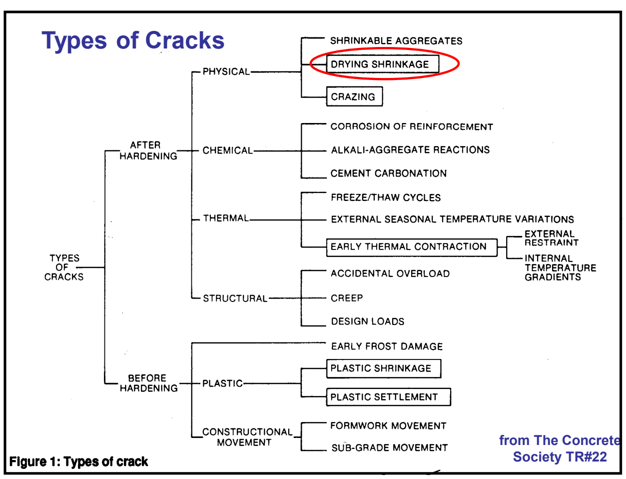


Figure 1: Types of crack

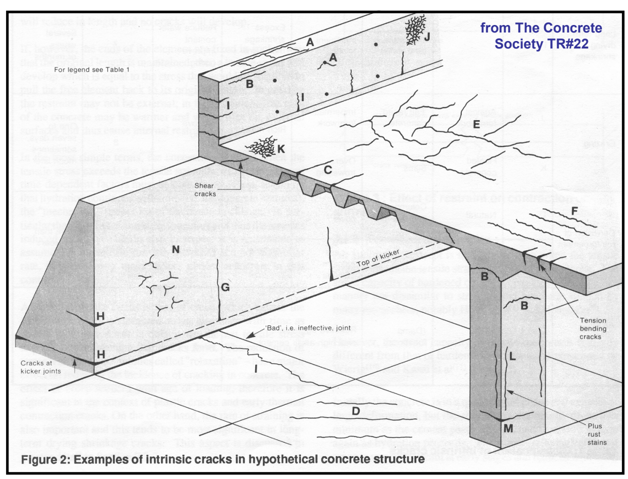


Figure 2: Examples of intrinsic cracks in hypothetical concrete structure

Kim Basham PhD, PE, FACI
KB Engineering, LLC
kbasham@KBEngLLC.com

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 Poor curing	Improve curing and finishing	8	One to seven days, sometimes much later
	K	Floated concrete	Slabs	Over-trowelling				
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

7/154
7/48

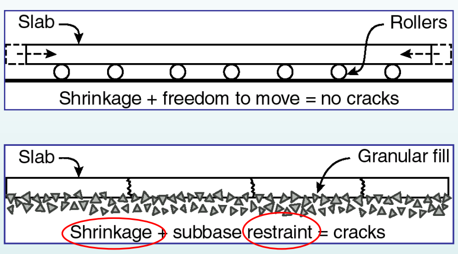
Two Basic Causes of Cracking

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*

8/48

Shrinkage + Restraints = Cracking



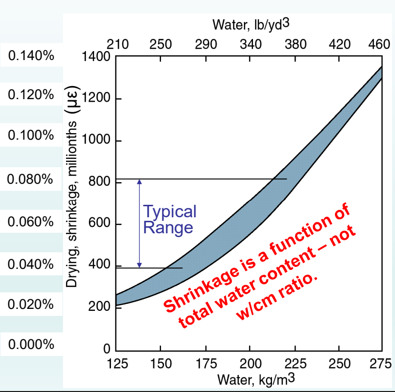
Due to thermal and drying shrinkage …
Slabs want to shorten about 1/2 to 3/4 inch per 100 ft

9/48

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)**
   - 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)

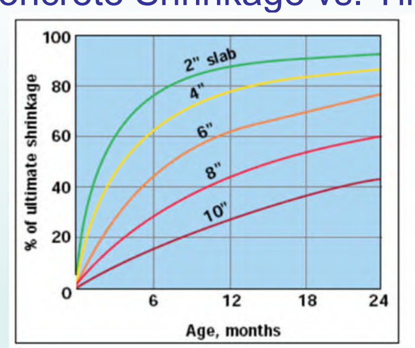
In general …
With effort, shrinkage less than about 0.040% (28-day) obtainable in most parts of country

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

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

11/48

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.

12/48

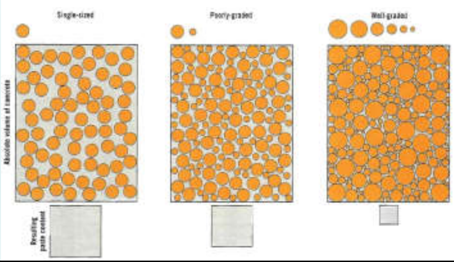
Kim Basham PhD, PE, FACI
KB Engineering, LLC
kbasham@KBEngLLC.com

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



13/48

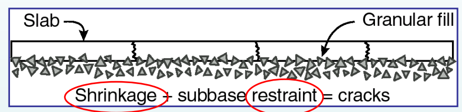
ASTM C157

- 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)

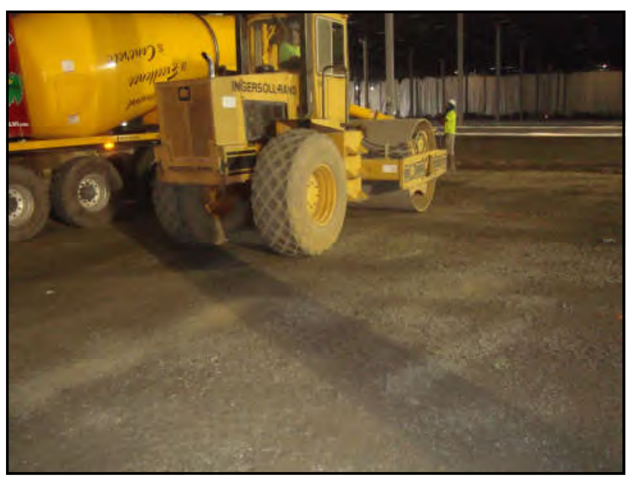
Drying Shrinkage + Restraints = Cracking



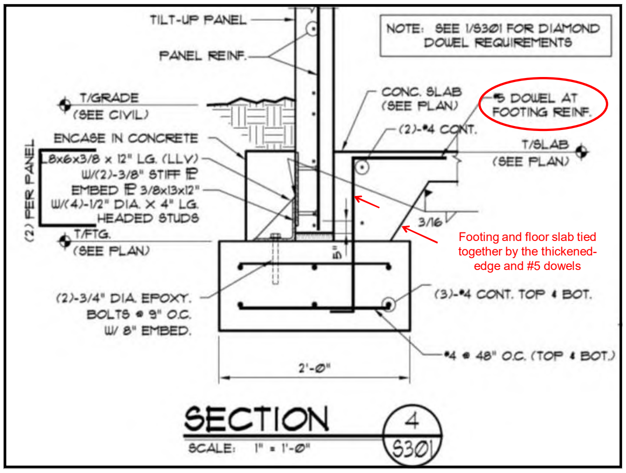
Common External Restraints

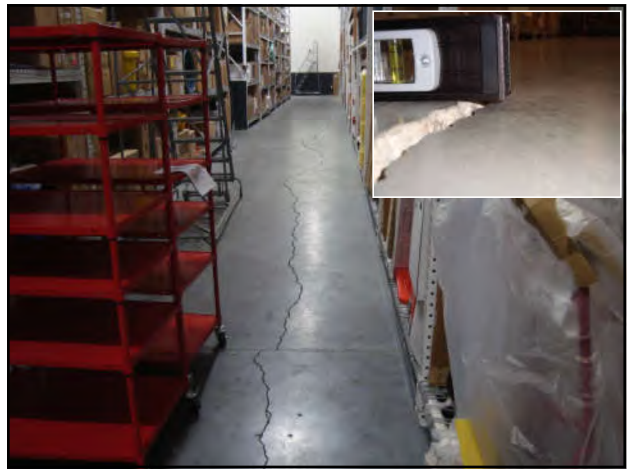
- Rough, uneven or rutted base materials
- Thickened slab edges or sections, grade beams, etc.
- Column bases, walls, etc. without isolation joints
- Bollards, drains, pipes, conduits, etc.
- Anything that prevents slab from slipping along base

16/48



Kim Basham PhD, PE, FACI
KB Engineering, LLC
kbasham@KBEngLLC.com



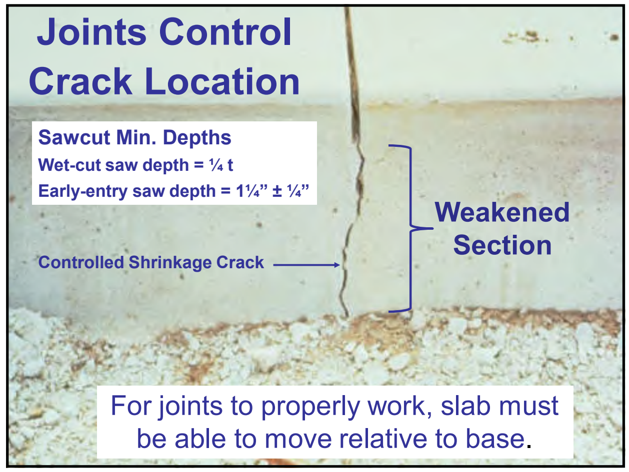


Types of Joints

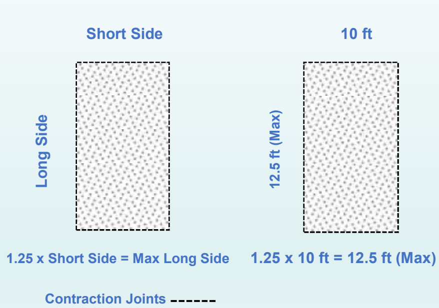
1. **Isolation** (removes restraints from fixed elements)
2. **Expansion** (can act as isolation)
3. **Contraction or Control - 10 Rules**
4. **Construction**

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

21/48



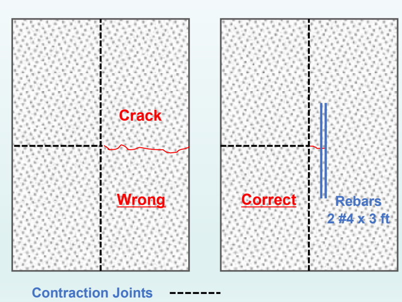
Rule #1. Panels formed by contraction joints should be as square as possible.



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

23/48

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

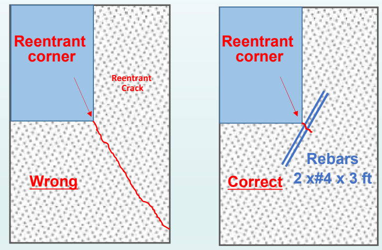


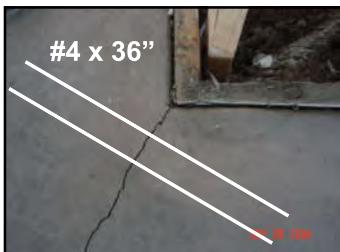
24/48

? Rules #1 and #2 ?

- Aspect ratio too large
- Discontinuous sawcuts

Rule #3. Identify and address reentrant corners.

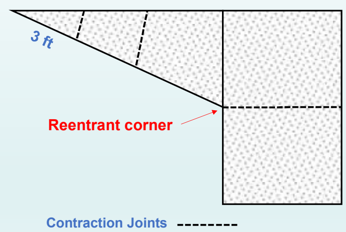




Re-entry Corner Cracks

Always a Problem!

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



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	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

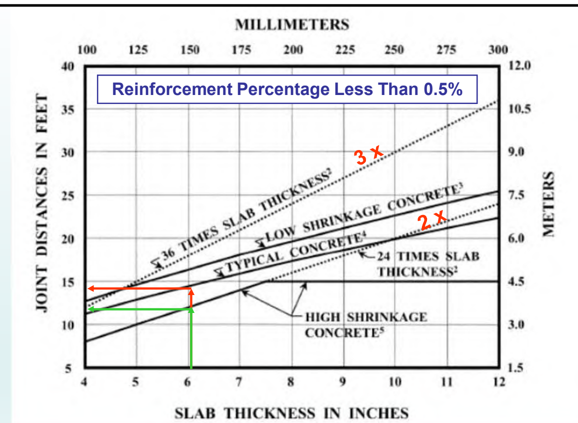


Figure 5.6 from ACI 360-06 Design of Slabs-On-Ground

Kim Basham PhD, PE, FACI
KB Engineering, LLC
kbasham@KBEngLLC.com

Safety Factor
Against Random Cracking

S = ?

2*t* **2½*t*** **3*t***

Lower Risk of Random Cracking

Higher Risk of Random Cracking

31/48

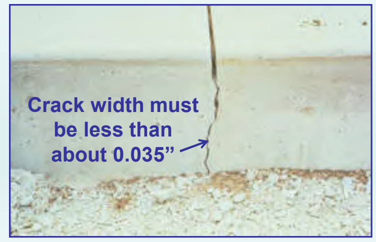
Load Transfer Across Joints

Aggregate Interlock

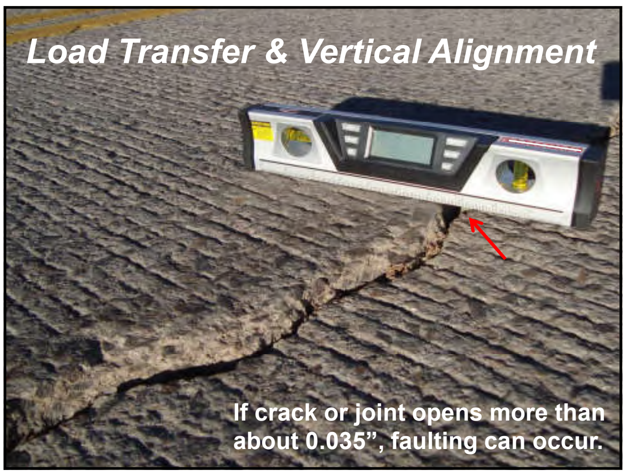
Load transfer by interlocking aggregate particles

Keep joint spacing under 15 ft

based on typical concrete shrinkage



32/48



Extended Joint Spacing Based on Shrinkage

In general …

- Greater than about 0.040% (28-day)

  15 ft maximum

- Less than about 0.040%

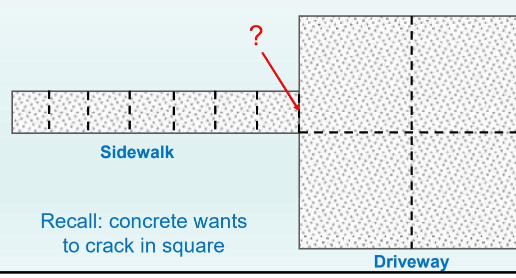
  Up to about 30 ft (with extra smooth base)

- Less than about 0.020%

  Up to about 60 ft (placed on slip sheet)

35/48

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

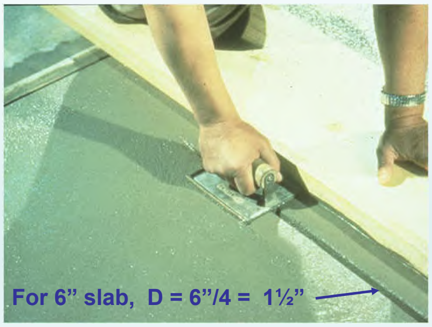


Recall: concrete wants to crack in square

36/48

Kim Basham PhD, PE, FACI
KB Engineering, LLC
kbasham@KBEngLLC.com

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



32/48

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

38/48

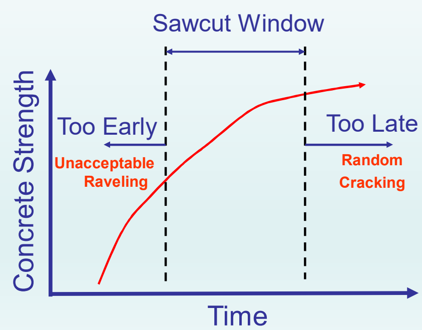
Rule #9. For joints installed with an early-entry dry-cut saw, joint depth should be 1-1/4 inches with a ± 1/4 inch tolerance for slabs with thicknesses up to about 9 inches.

Min. Depth 1"

(1¼" ± ¼")

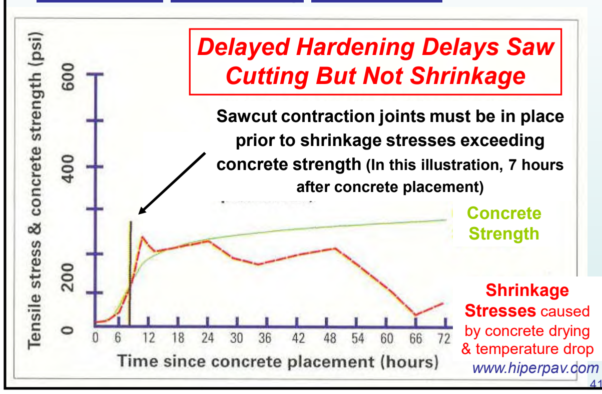
39/48

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



40/48

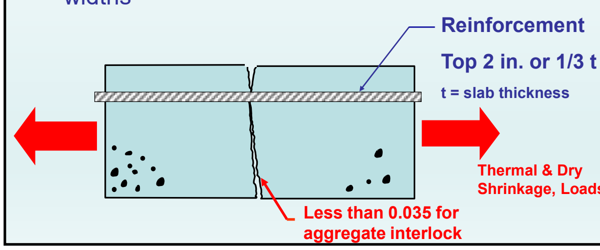
Delayed Concrete Hardening Can Increase Cracking Potential for Slabs



41/48

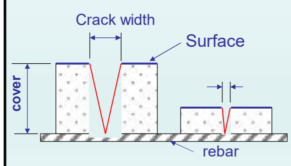
Reinforcement Controls Crack Widths

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



Kim Basham PhD, PE, FACI
KB Engineering, LLC
kbasham@KBEngLLC.com

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



Increasing concrete cover increases crack width at surface

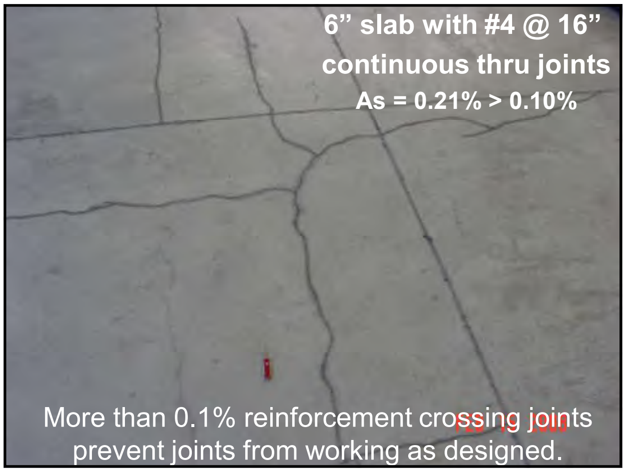
Reinforcement in Slabs

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**

Ref: ACI 360R-10 Guide to Design of Slabs-On-Ground

44/48



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

#3@18" = 0.07 sqin/ft

0.07 x 100 = 0.097% — less than 0.1%
6"x12" — OK, no cutting required

#4@18" = 0.13 sqin/ft

0.13 x 100 = 0.181% — greater than 0.1%
6"x12" — must cut every other bar (.181%/2 = 0.091%)

46/48

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:

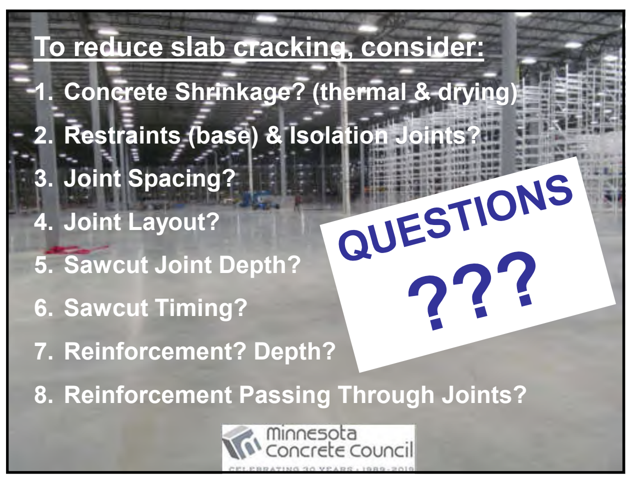
$$\frac{As}{t \times 12''} \times 100 = \%\ Reinforcement$$

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

To compute As:

$$As = (\% \times t \times 12'') \div 100$$

47/48



Kim Basham PhD, PE, FACI
KB Engineering, LLC
kbasham@KBEngLLC.com

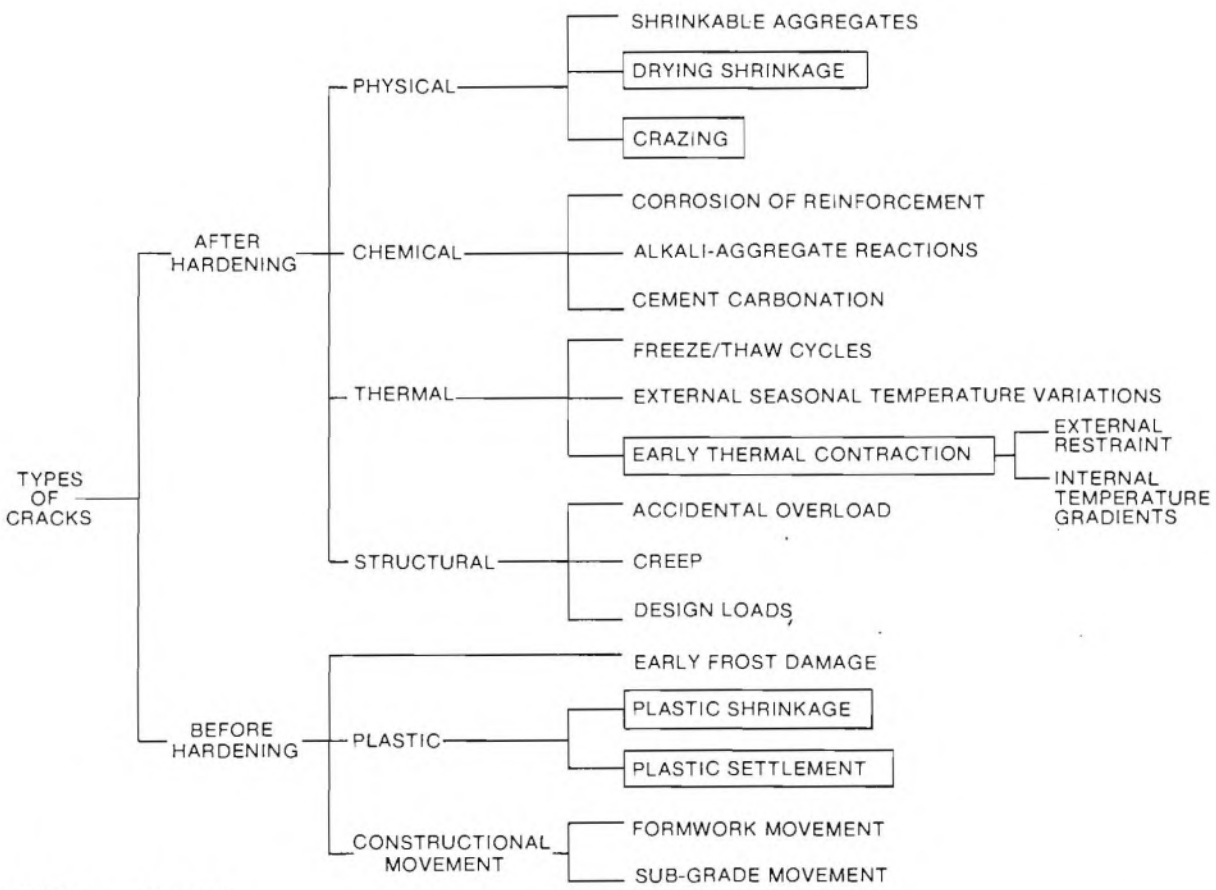


Figure 1: Types of crack

For legend see Table 1

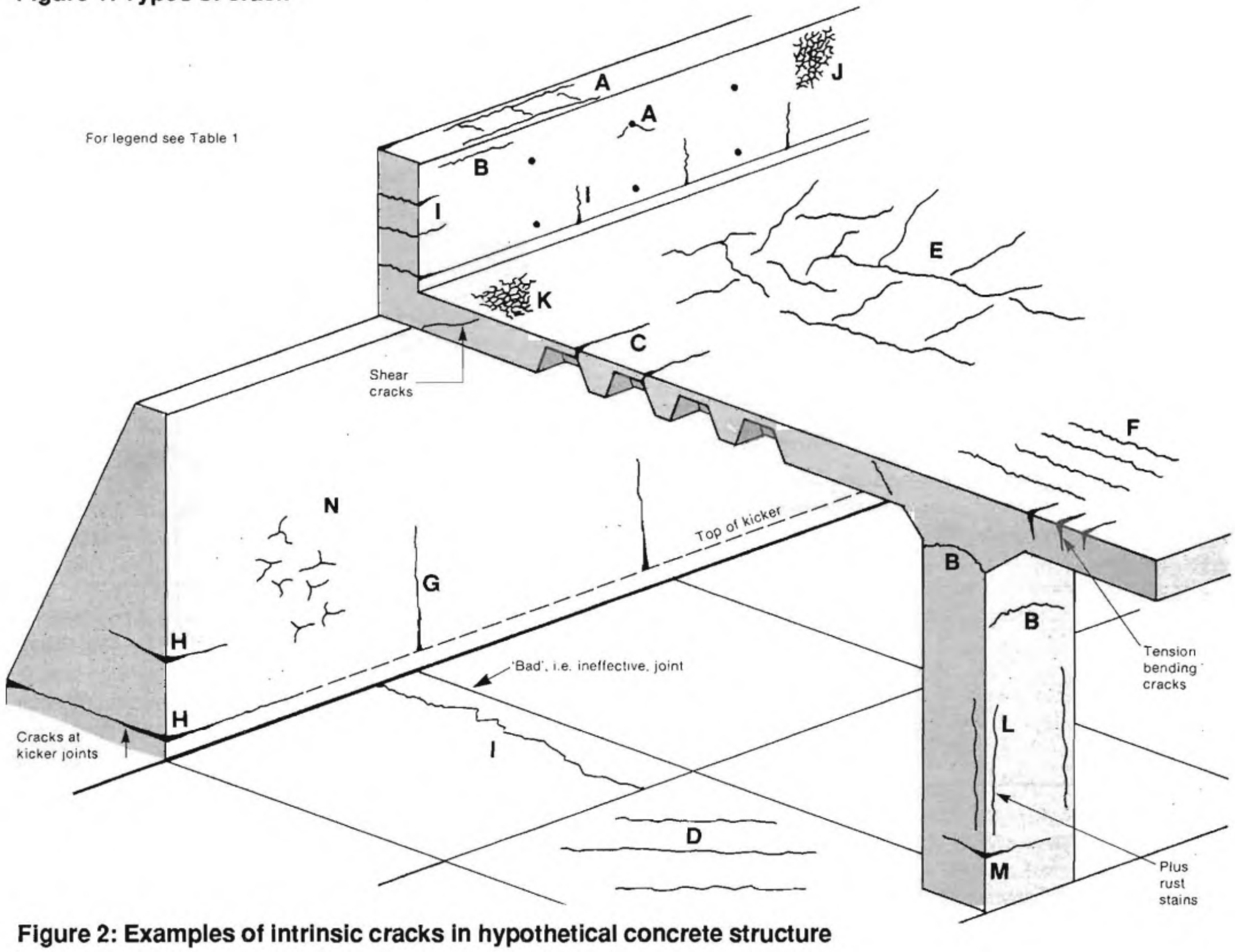


Figure 2: Examples of intrinsic cracks in hypothetical concrete structure

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