# Foundation Performance Association
## Houston

# Causes and Cures of Cracking in Concrete


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# Introduction

Concrete is a durable material.

However, it has characteristics and properties that may result in distress manifestations. These manifestations may be caused in the fresh, unhardened state or in the hardened state.

# If you ask someone a question about concrete…..

- They will probably tell you that all concrete cracks
- And somewhere in the conversation they will probably call concrete “cement”.

# Cause of Concrete Cracks

- Concrete is very strong in compression
  - 28-day compressive strength ranges from about 3000 psi to over 10,000 psi
- But it is weak in tension
  - Tensile capacity is about 10% of its compressive strength

# Source of Tension in Concrete

- External or "Structural" Sources
  - Gravity loads: dead and live loads
  - Lateral loads: wind and seismic
  - Loads from subgrade settlement or swelling
- "Internal" Mechanisms
  - Volume change restraint due to temperature changes or drying shrinkage
  - Expansion due to corrosion of reinforcing steel or deleterious chemical reactions

# CAUSES OF CRACKING IN PLASTIC CONCRETE

# Plastic Shrinkage

- Very Rapid Loss of Moisture

  Factors are:

  – Concrete and air temperature

  – Relative humidity

  – Wind velocity

- Results in differential volume change in top layer

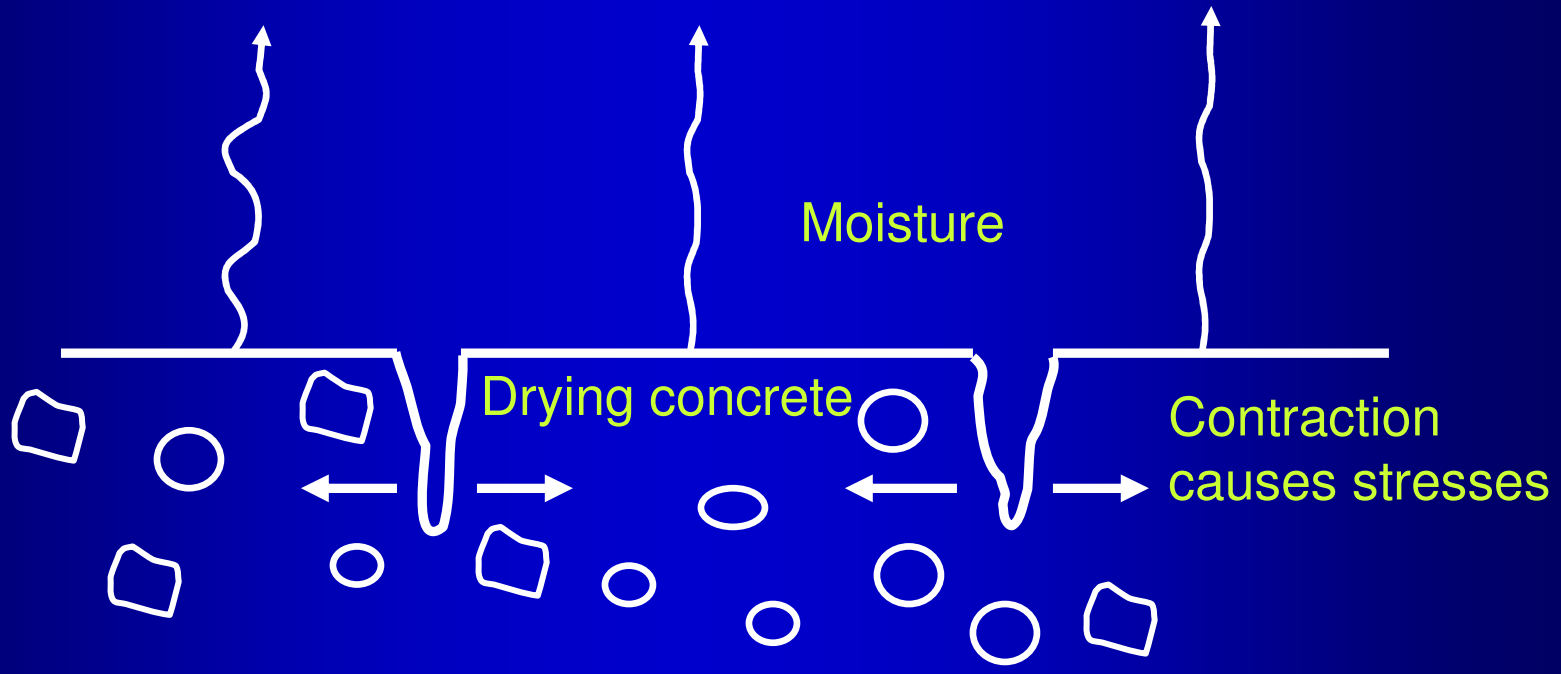
## Plastic Shrinkage

- Moisture migrates to surface.
- “Bleeding” results in moisture on the surface of concrete caused by settling of the heavier components of mixture.

- If moisture evaporates faster than water is being supplied to surface by bleeding, there is tendency for reduction in volume near surface.

- Tensile stresses result.

# Contraction Caused by Evaporation



# Similar to “Shrunk” Soil

# Plastic Shrinkage Crack

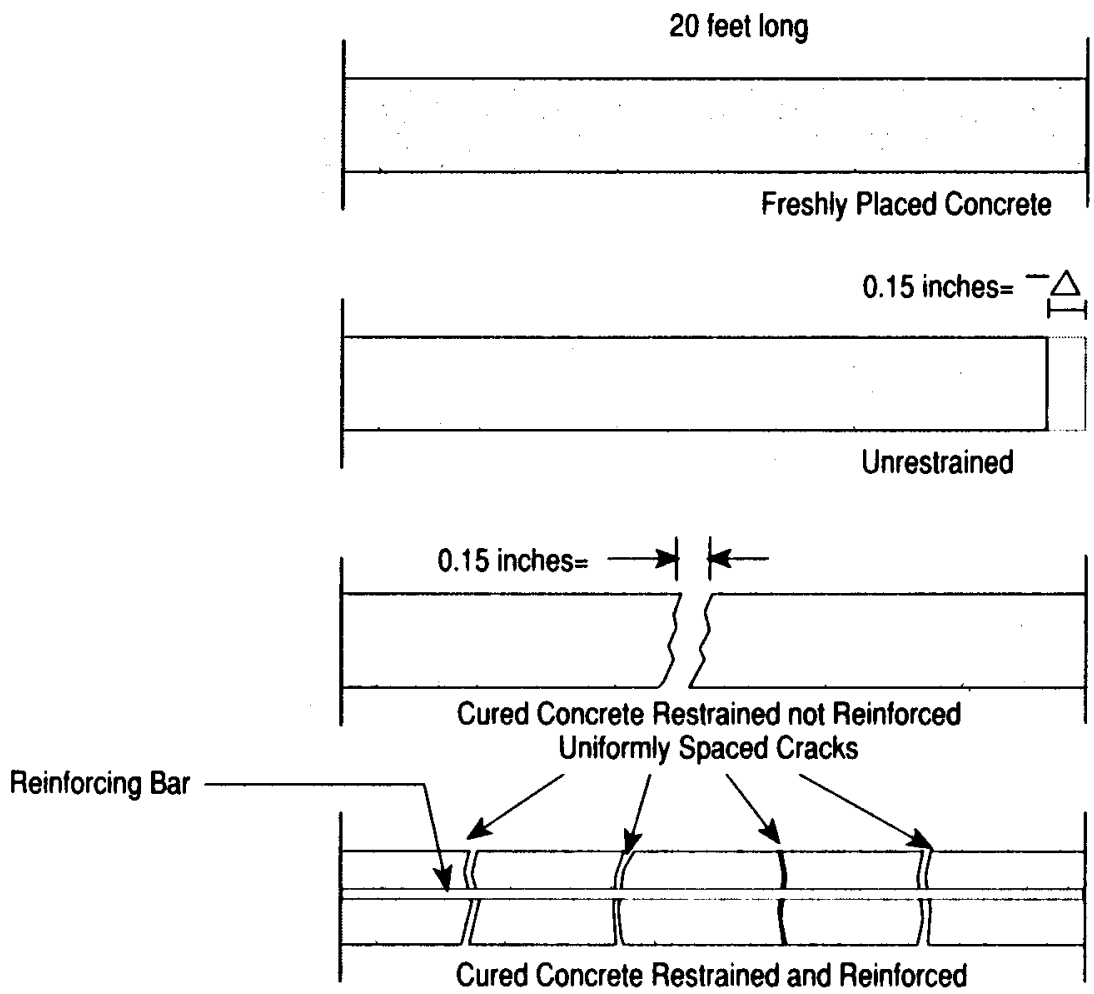
# Plastic Shrinkage Cracking

# CRACKING IN HARDENED CONCRETE

# Drying Shrinkage

- Long-term change in volume of concrete caused by loss of moisture.
- Shrinkage without restraint results in no stresses.

- Restraint can result from:
  - –Another part of the structure
  - –Foundation
  - –Concrete on the interior of a slab, beam or other component which shrinks less than concrete on the exterior.
- Combination of shrinkage and restraint can result in cracking.
- Reinforcing steel can uniformly distribute the cracking.




# Example of Drying Shrinkage

Slab length =
20 feet (6m)

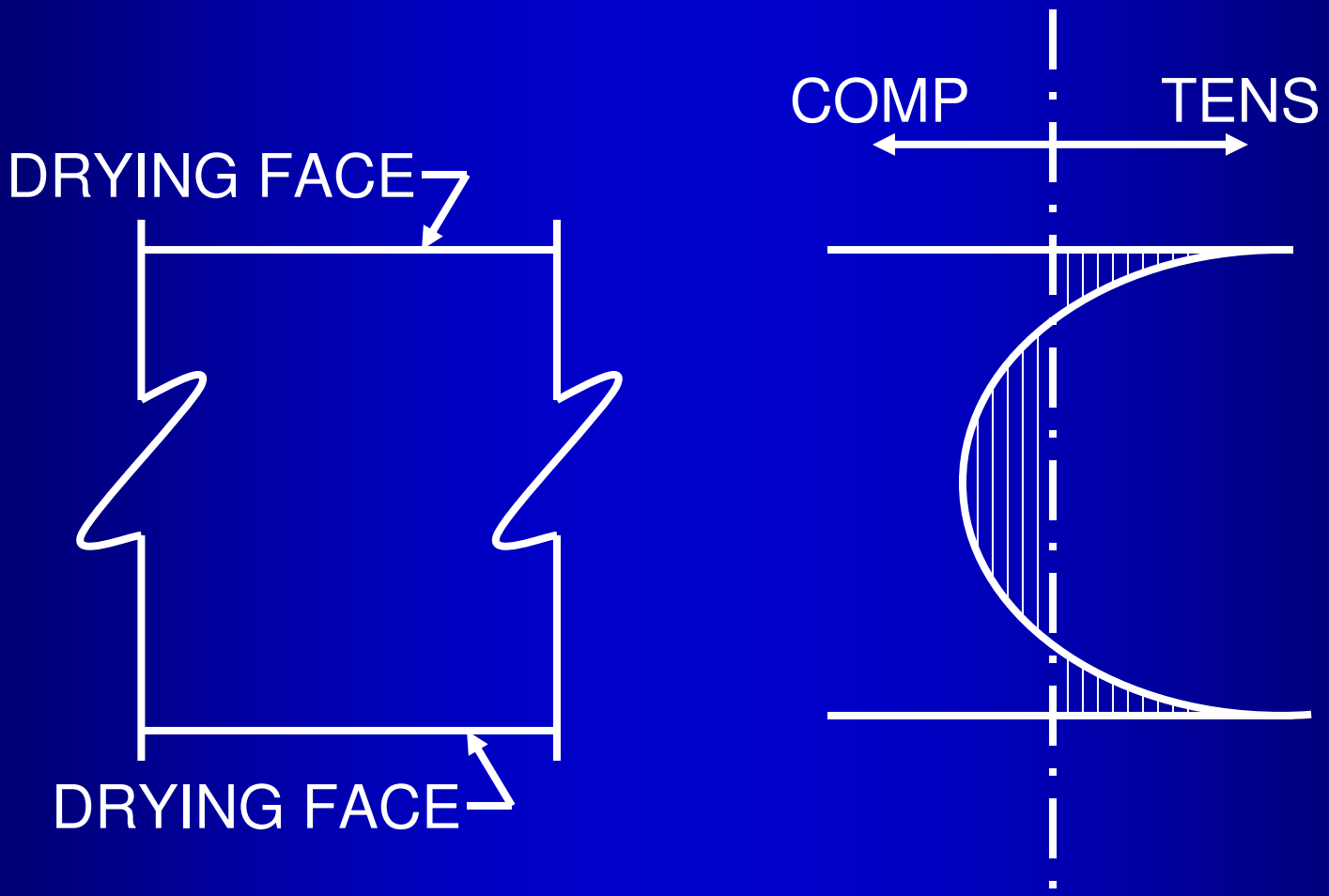
Drying shrinkage =
600 microstrains

Shrinkage of slab =
0.15 inches (4mm)

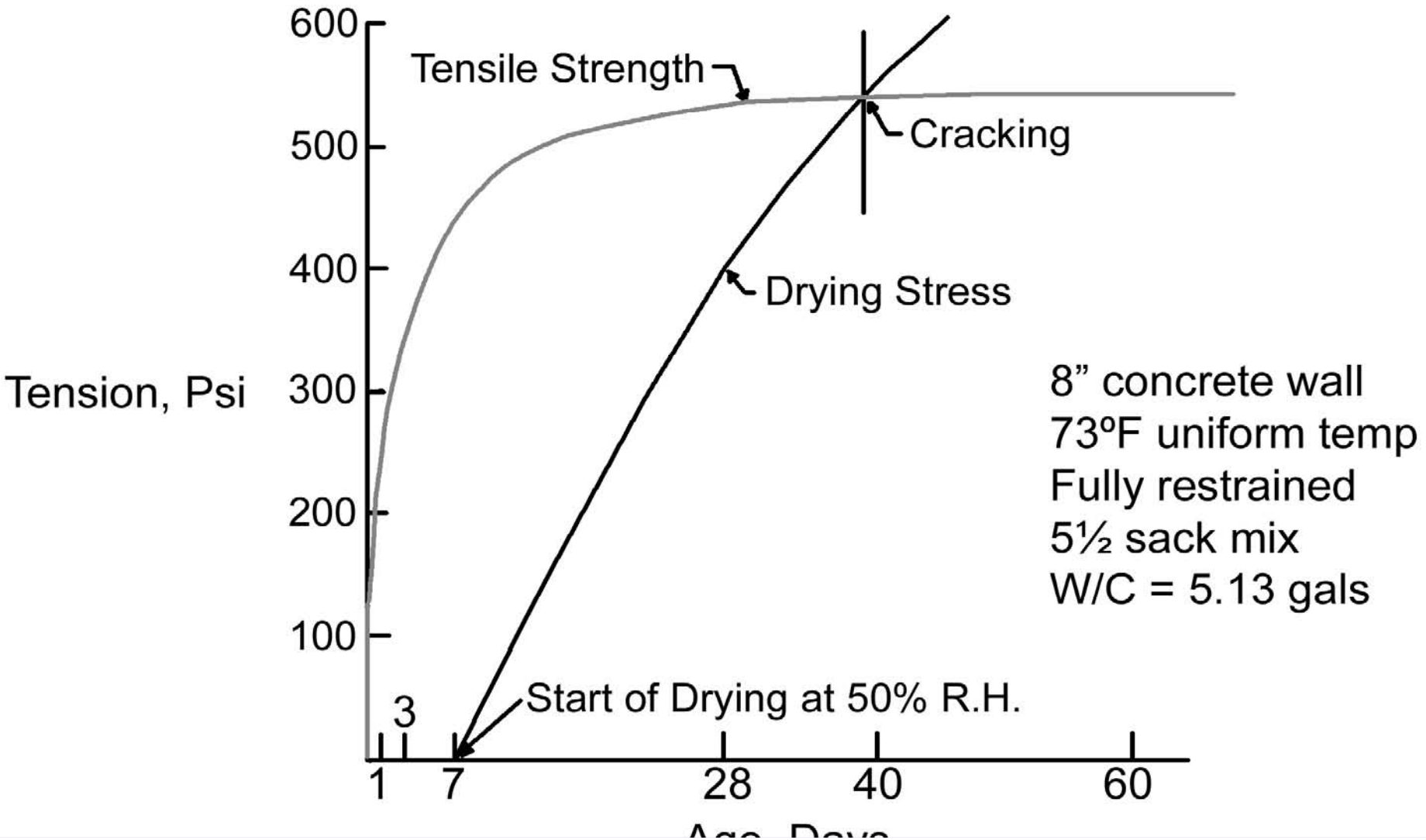
# Important!

- Reinforcing steel does not prevent cracking
- Rather, it minimizes crack widths by distributing the cracks
- Rather than one wide crack, there will be many narrow cracks

# Theoretical Shrinkage Stresses

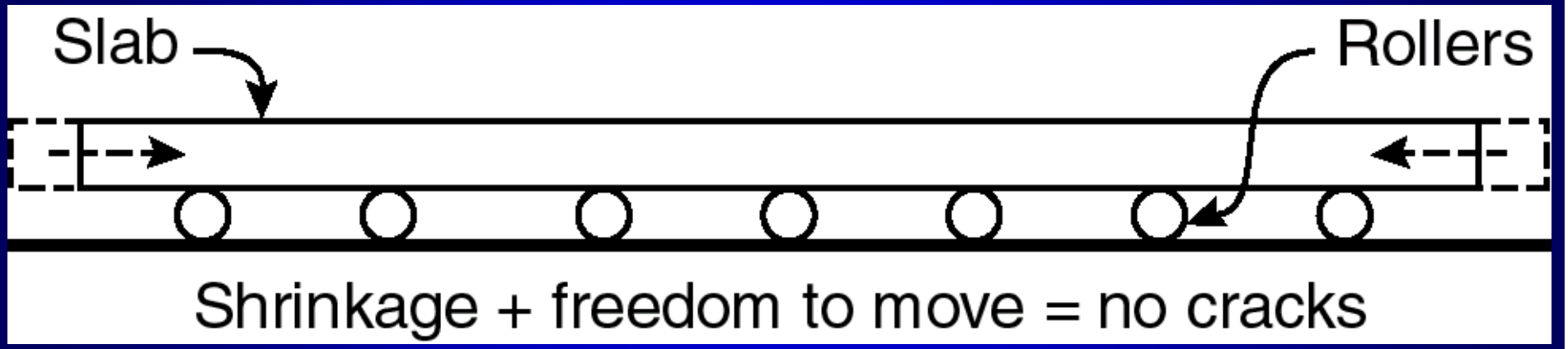


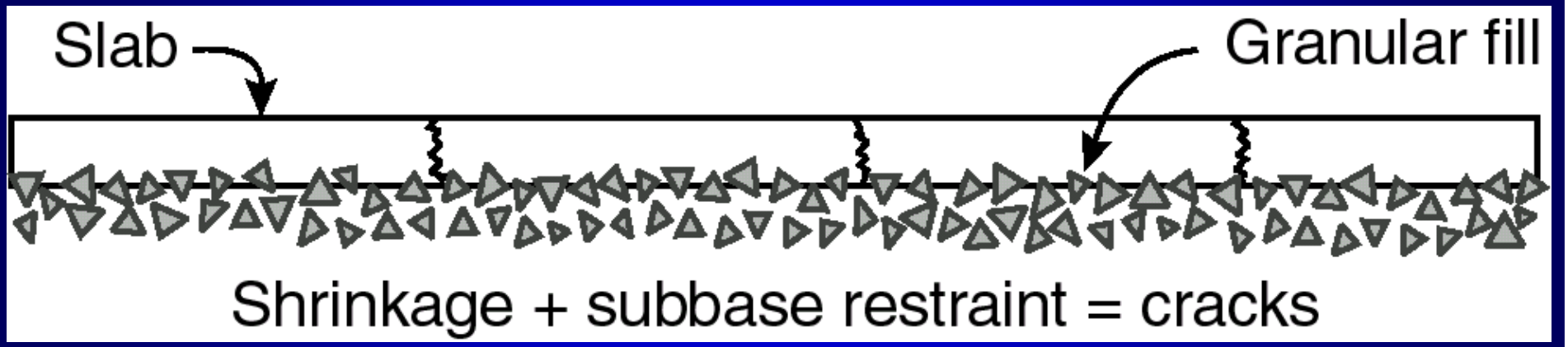
# The "Horse Race"



# Drying Shrinkage

# Shrinkage and Cracking




Properly Designed Joints

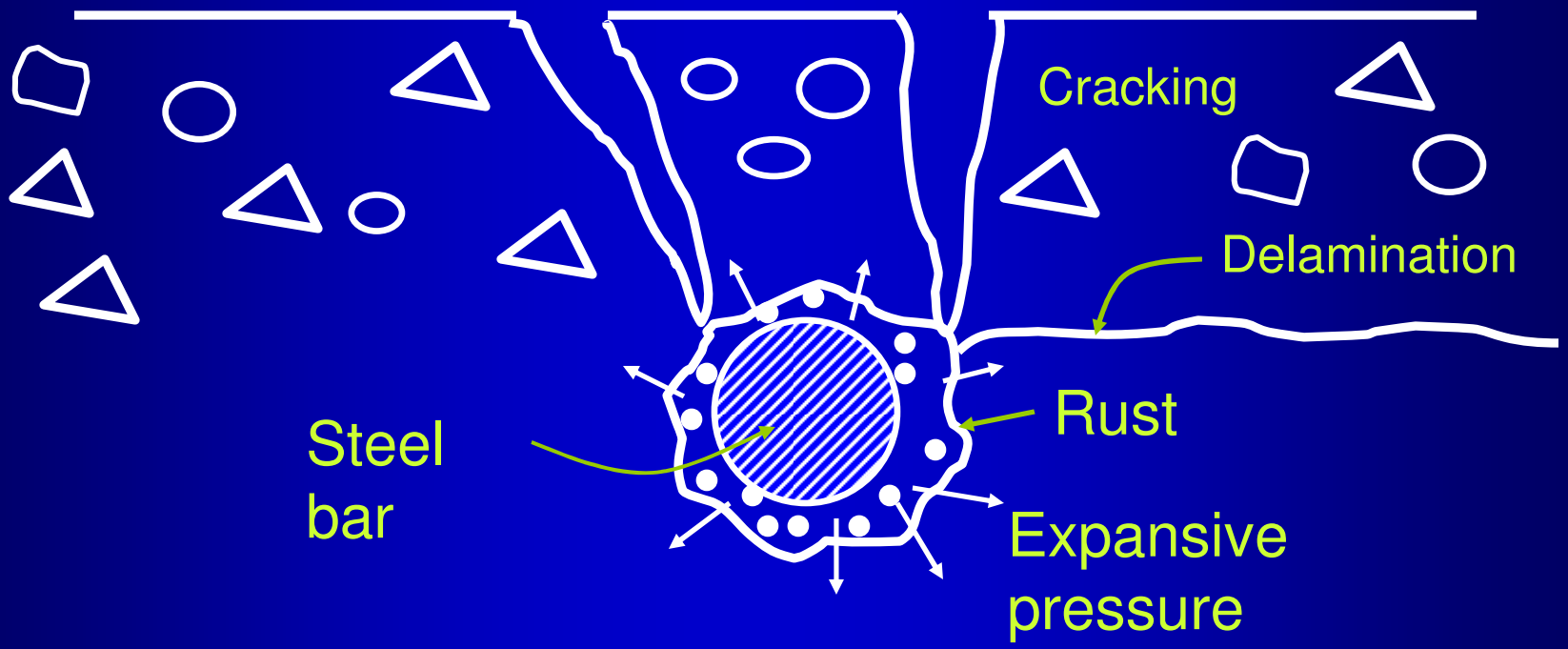
# Crack at Sawed Control Joint

# Sawing Joint to Relieve Drying Shrinkage

Too Late! Crack forms ahead of saw cutting

# Corrosion of Reinforcement

# Corrosion of Reinforcement



| Symptom | Cause |
| --- | --- |
| Spalling of concrete over rebar | Corrosion of rebar initiated by chlorides (from roadway above) |

# Chemical Reactions

- Between cement paste and aggregate
- Between sulfates in water or soil and cement paste

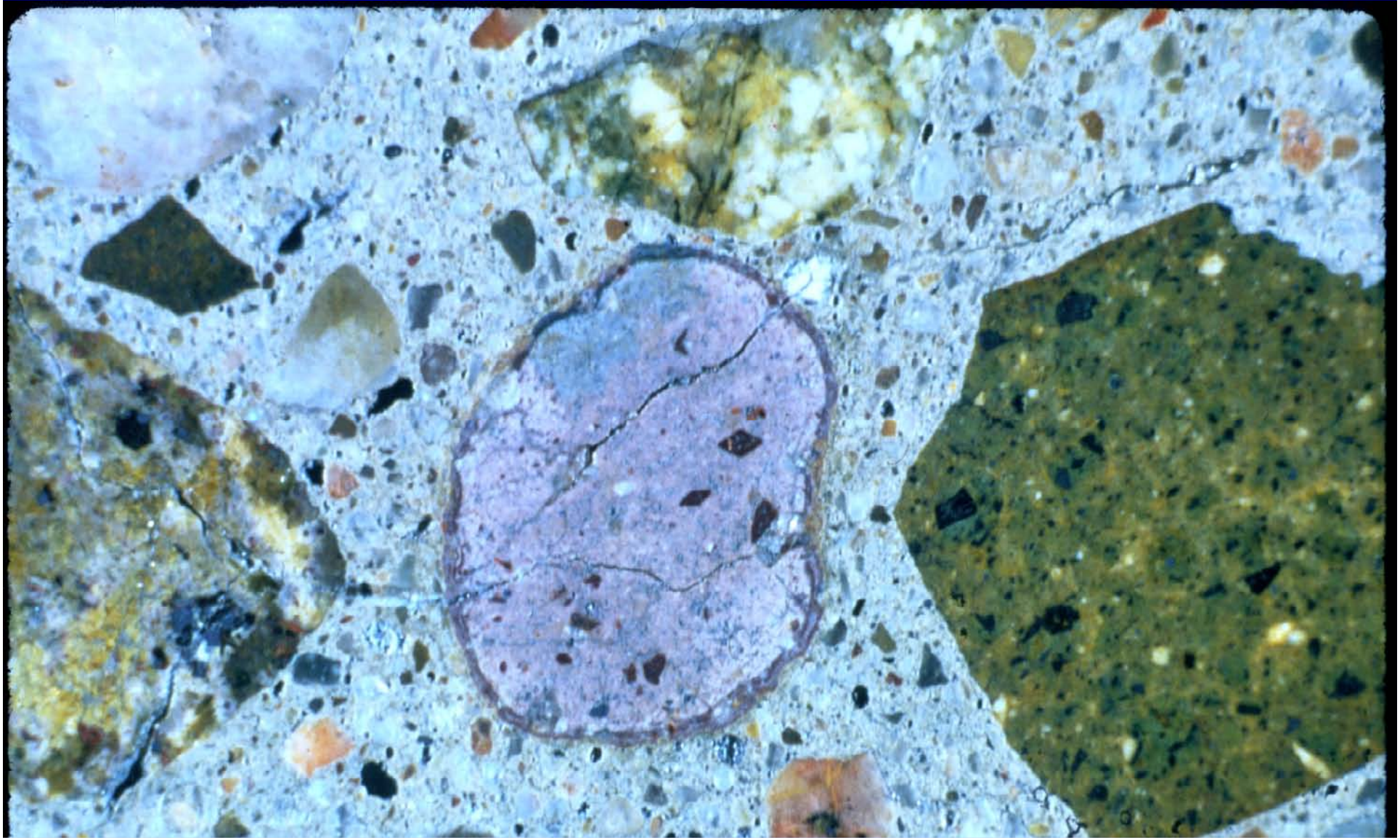
# Alkali-Silica Reaction

- Caused by reaction of alkalies in cement with silica aggregates


ASR Cracking

# ASR Cracking

# ASR: Note Gel Around Stone

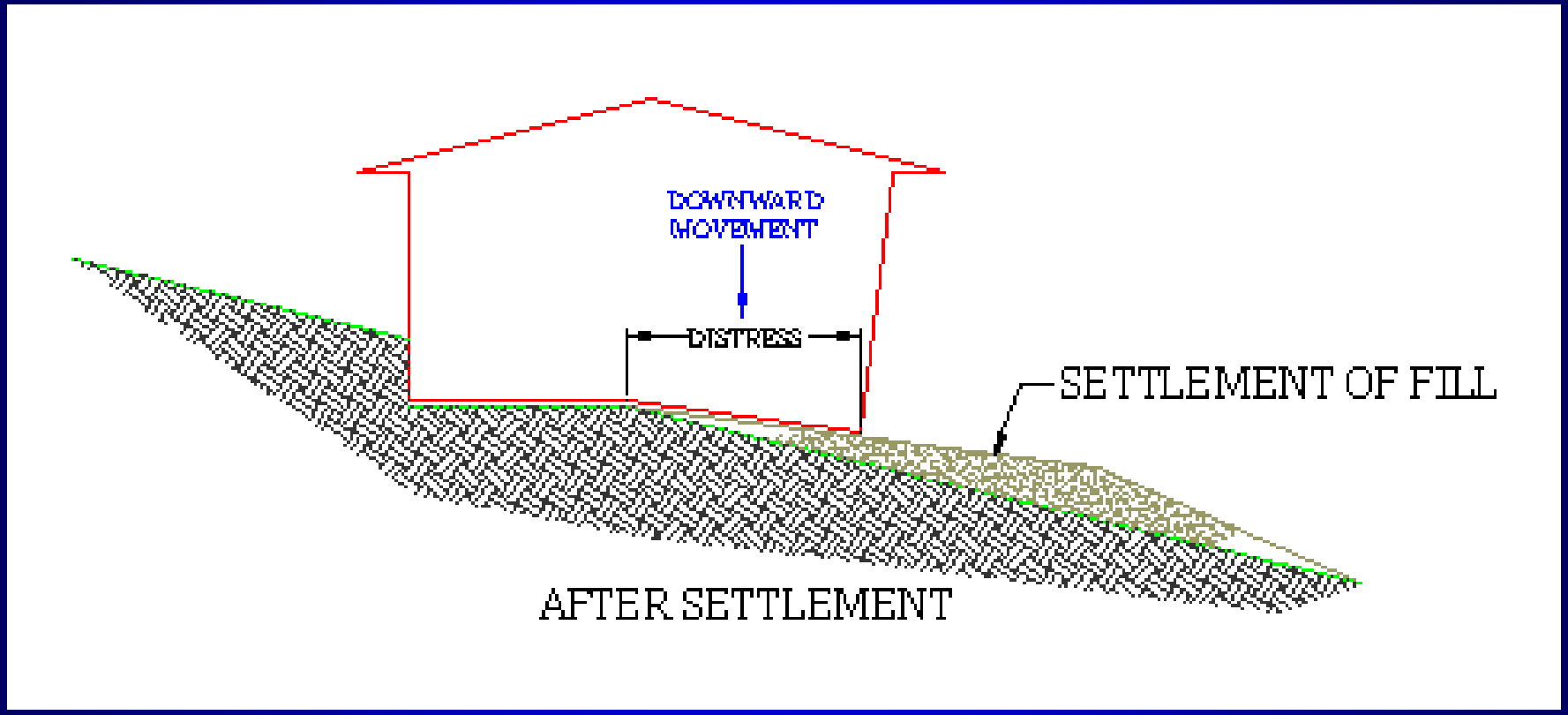


# Swelling/Shrinkage of Soil Beneath Slab

# Causes

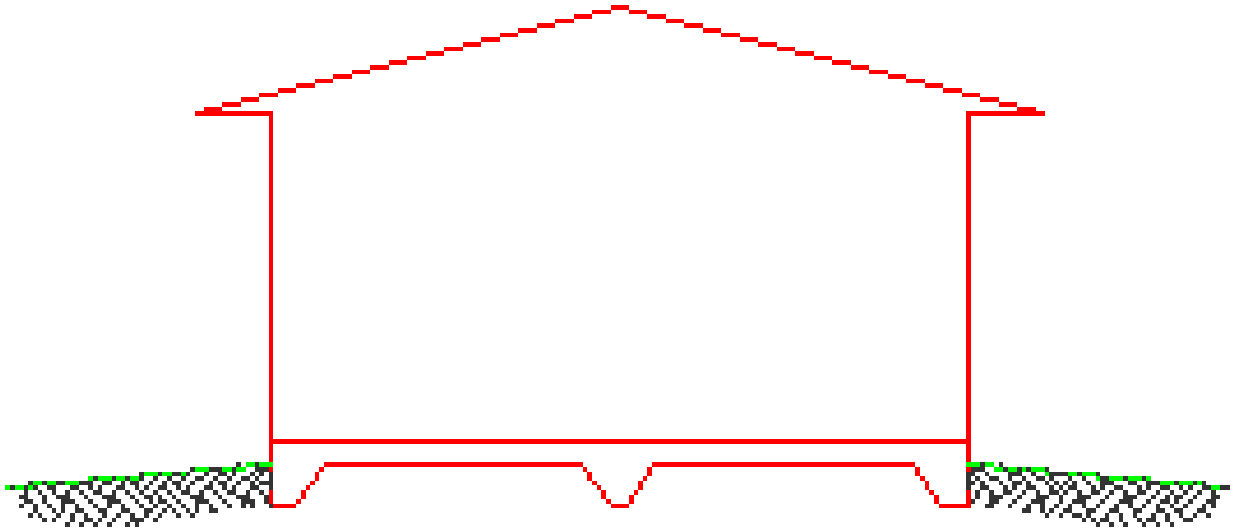
- Settlement of fill
- Differential movement of foundation
  - During wet season,  clay soil beneath edge of slab gets wet, swells and lifts outside edge of slab
  - During drought, soil shrinks around edge of slab and allows edge of slab to drop
  - Walls are put under stress and often crack

# Settlement of Foundation on Fill



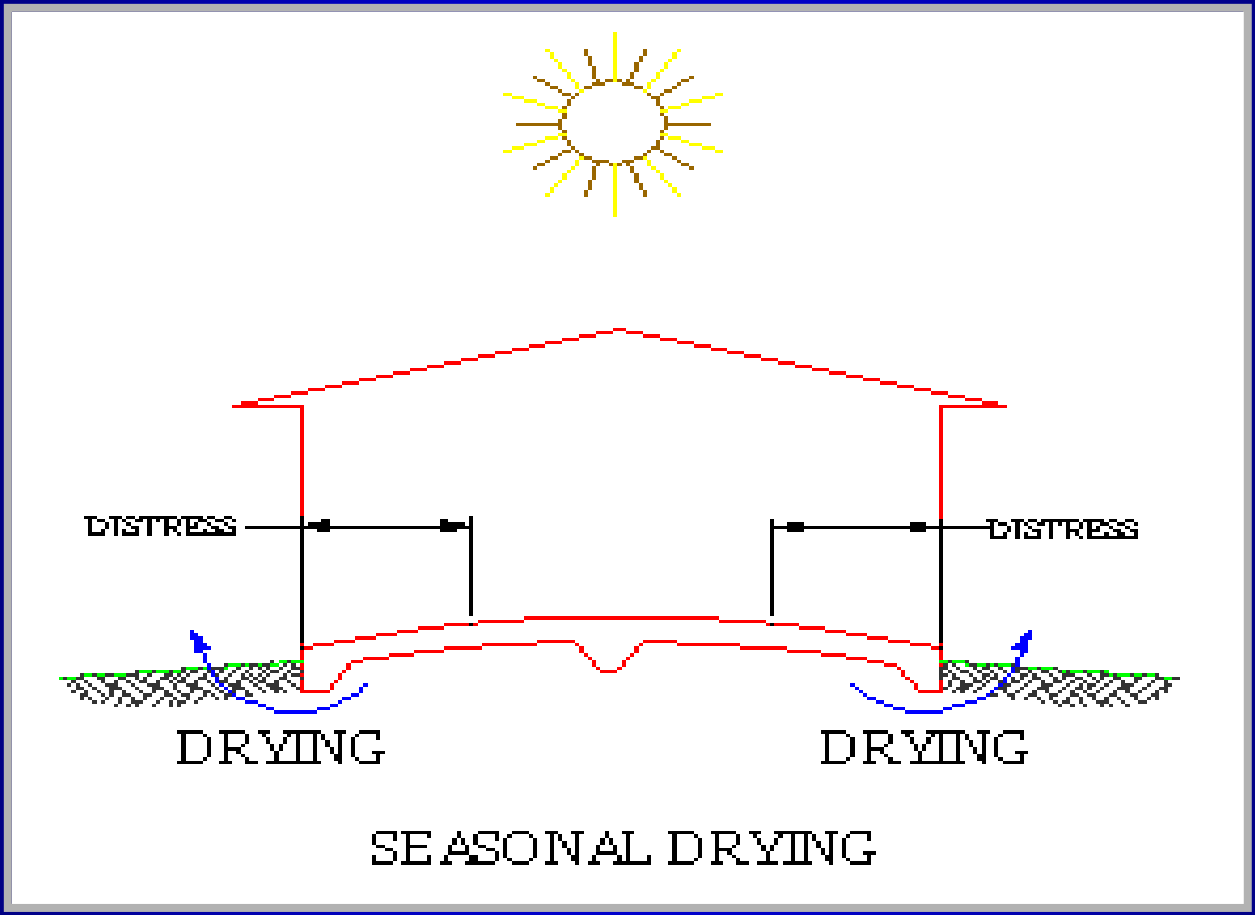

1) Settlement of the underlying soils (typically due to inadequately compacted fill material used to raise site grade during construction)

# Typical Foundation on Grade



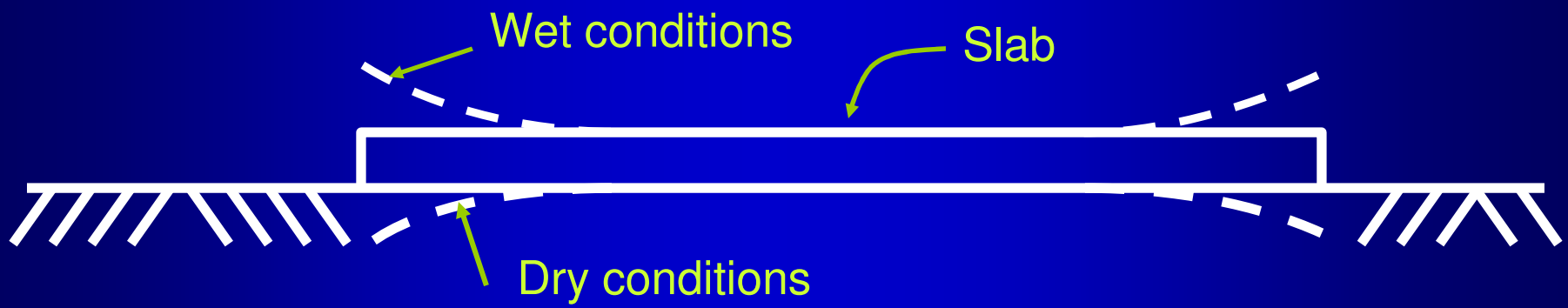
AS CONSTRUCTED
(ASSUMED)

# Damage Due to Seasonal Drying

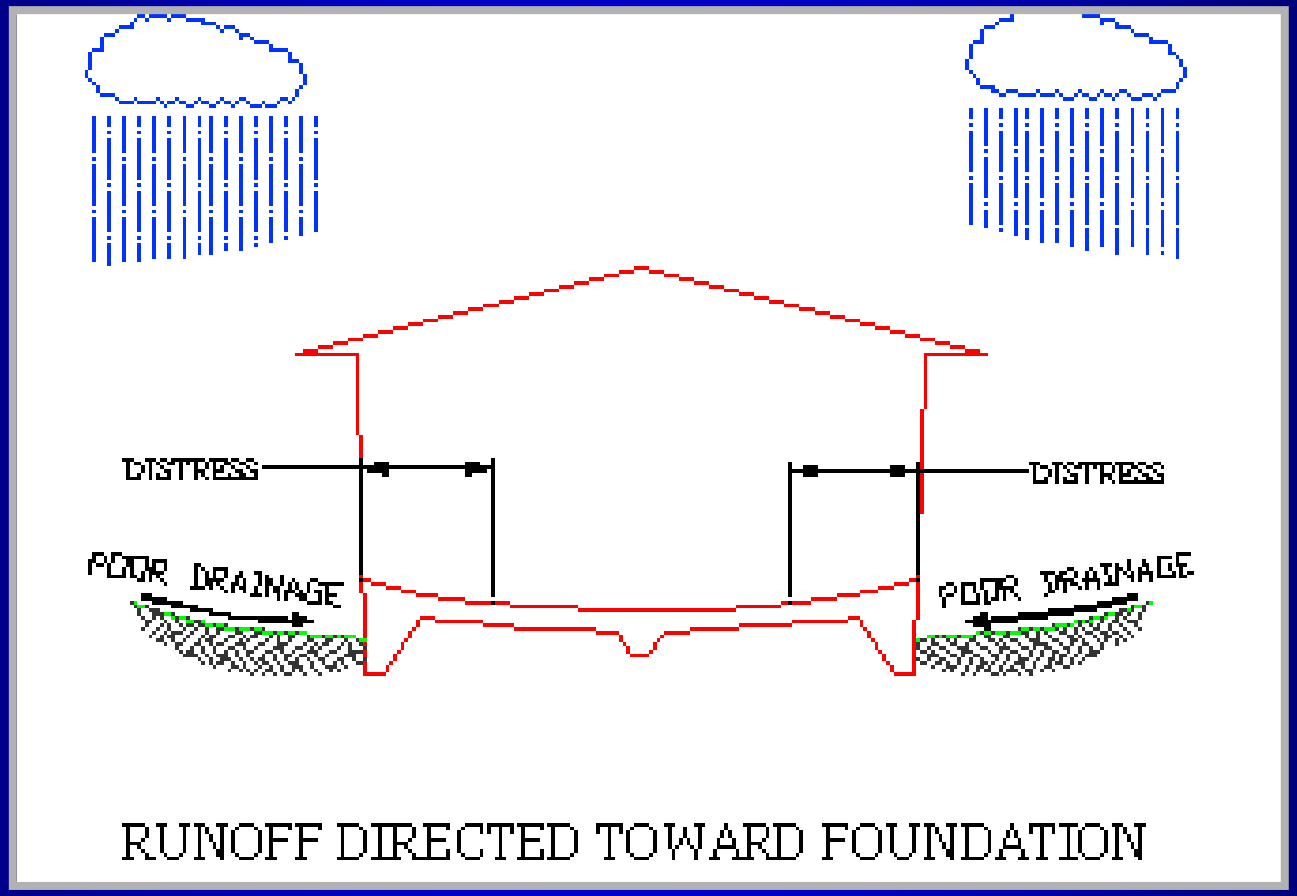



2) Shrinkage or swelling of the underlying soils resulting from moisture changes

# Differential Settlement

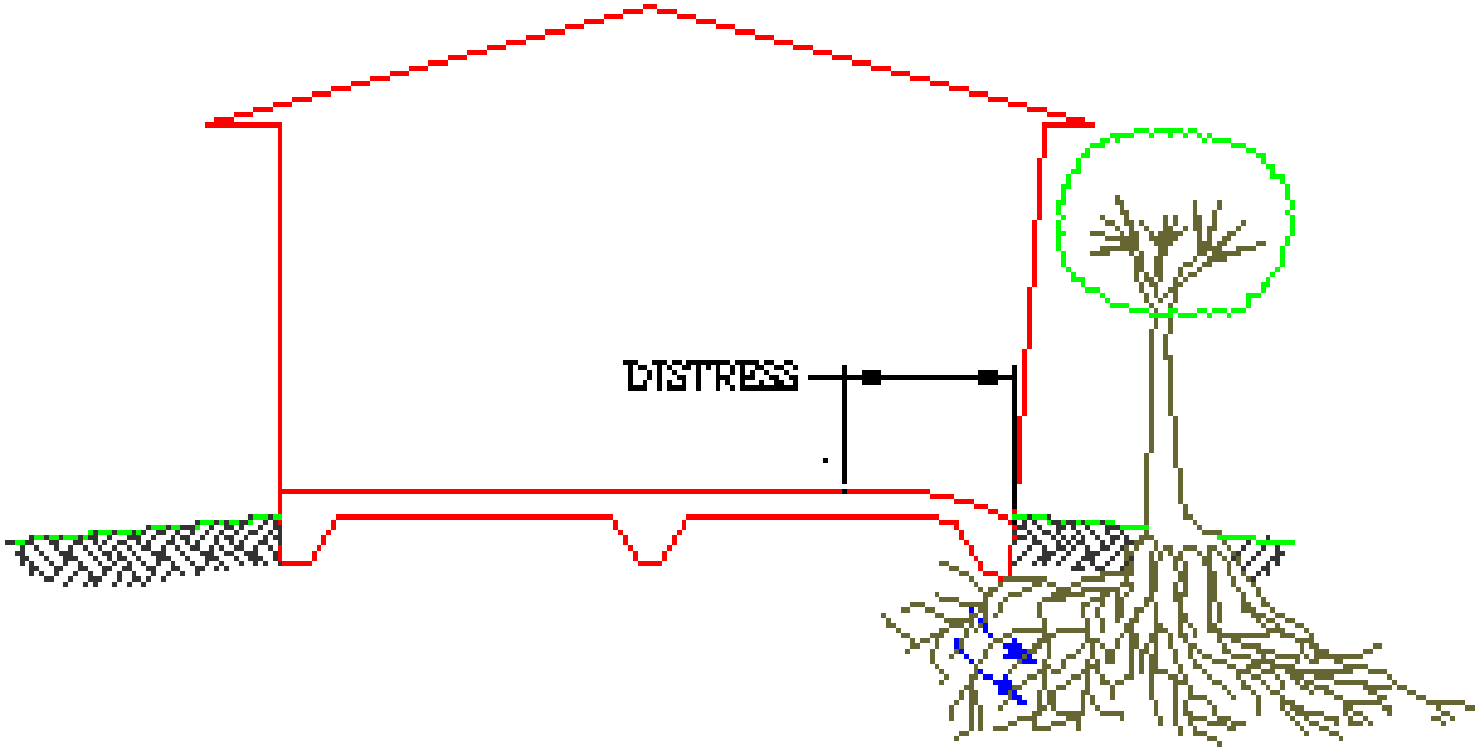


# Damage Due to Site Drainage




2) Shrinkage or swelling of the underlying soils resulting from moisture changes

# Damage Due to Trees




TREES NEAR FOUNDATION

# Poor Construction Practice

- Adding excess water to mixture
- Inadequate consolidation
- Improper placement of steel
- Inadequate cover
- Omitted rebars
- Improper consolidation of fill beneath slad

# Inadequate Design

- Inadequate thickness
- Inadequate reinforcing
- Incorrect geometry
- Incorrect use of materials
- Incorrect detailing

# Case Study

- Cracking in swimming pool

- Note separation at outside curve
- Only location of cracking in brick at inside of headers

- Note location of beginning of crack at point of tangency

# Top of concrete wall moved out about ¾ inch—no steel in top of wall

# What was the cause?

- Soil movement?
- ASR?
- Thermal expansion?
- Moisture expansion?
- Other?

# Most Likely Cause….

- Moisture and thermal expansion of brick
- As brick expanded the radius got larger
- Nothing to prevent outward movement except wall and top of wall was missing vertical steel

- Outward force was large enough to shear concrete
- Inside corners were restrained from moving outward by sidewalk

# Scientific Method of Determining Cause of Cracking

- State problem
- Make observations
- Form hypotheses (possible causes)
- Test the hypotheses by performing tests, making calculations, making more extensive observations, etc.
- Analyze the results and iterate if necessary
- Form conclusions

# Example Evaluation of Cracking

**Possible Causes**

| **Tests** | Plastic shrinkage | Drying Shrinkage | Alkali-Silica Reaction | Overload | Diff. Settlement |
|---|---|---|---|---|---|
| High Evap. Rate | X | | | | |
| Restraint | | X | | | |
| Petrographic exam | | | X | | |
| Cracking pattern | X | O | X | O | O |
| Structural analysis | | | | O | X |

**O** Supports hypothesis

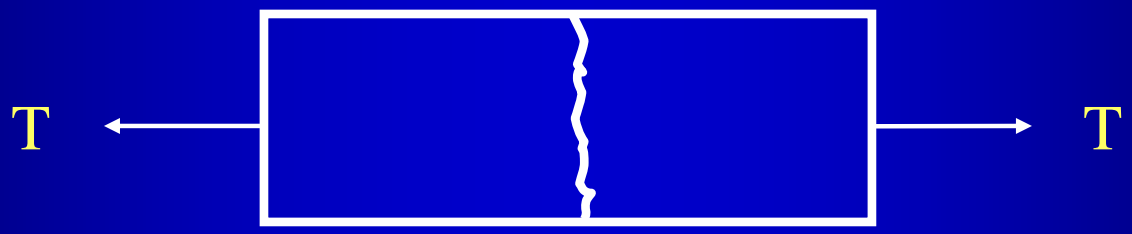
**X** Does not support

# Crack Measurement

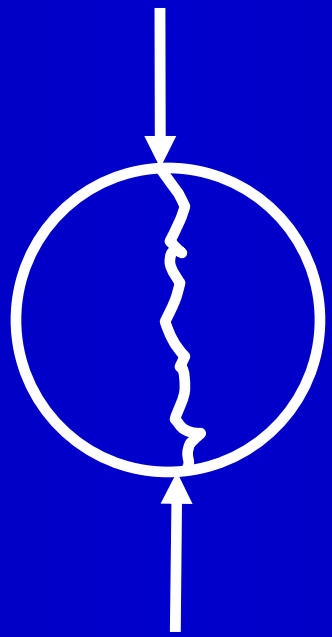
# Reading Cracks

- Orientation
- Location
- Length
- Width
- Depth
- Shape
- Frequency
- Age

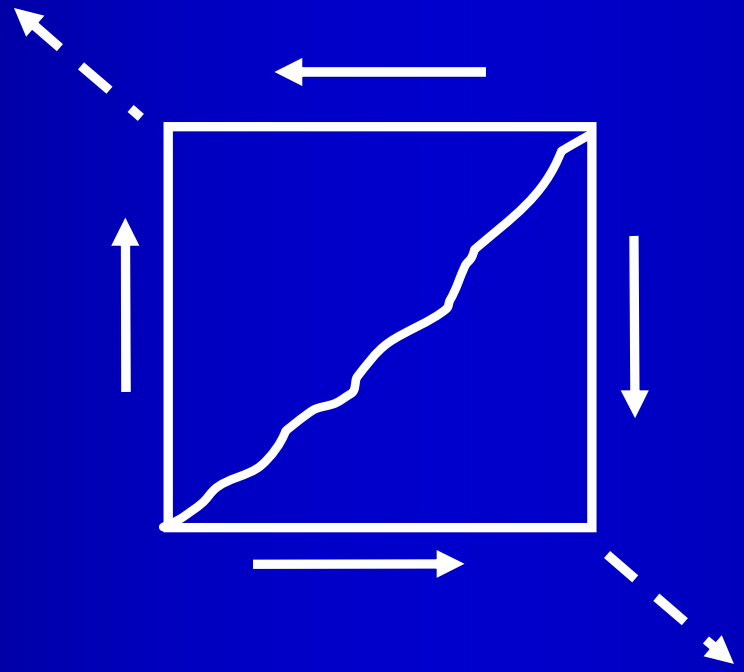
# Pure Tension



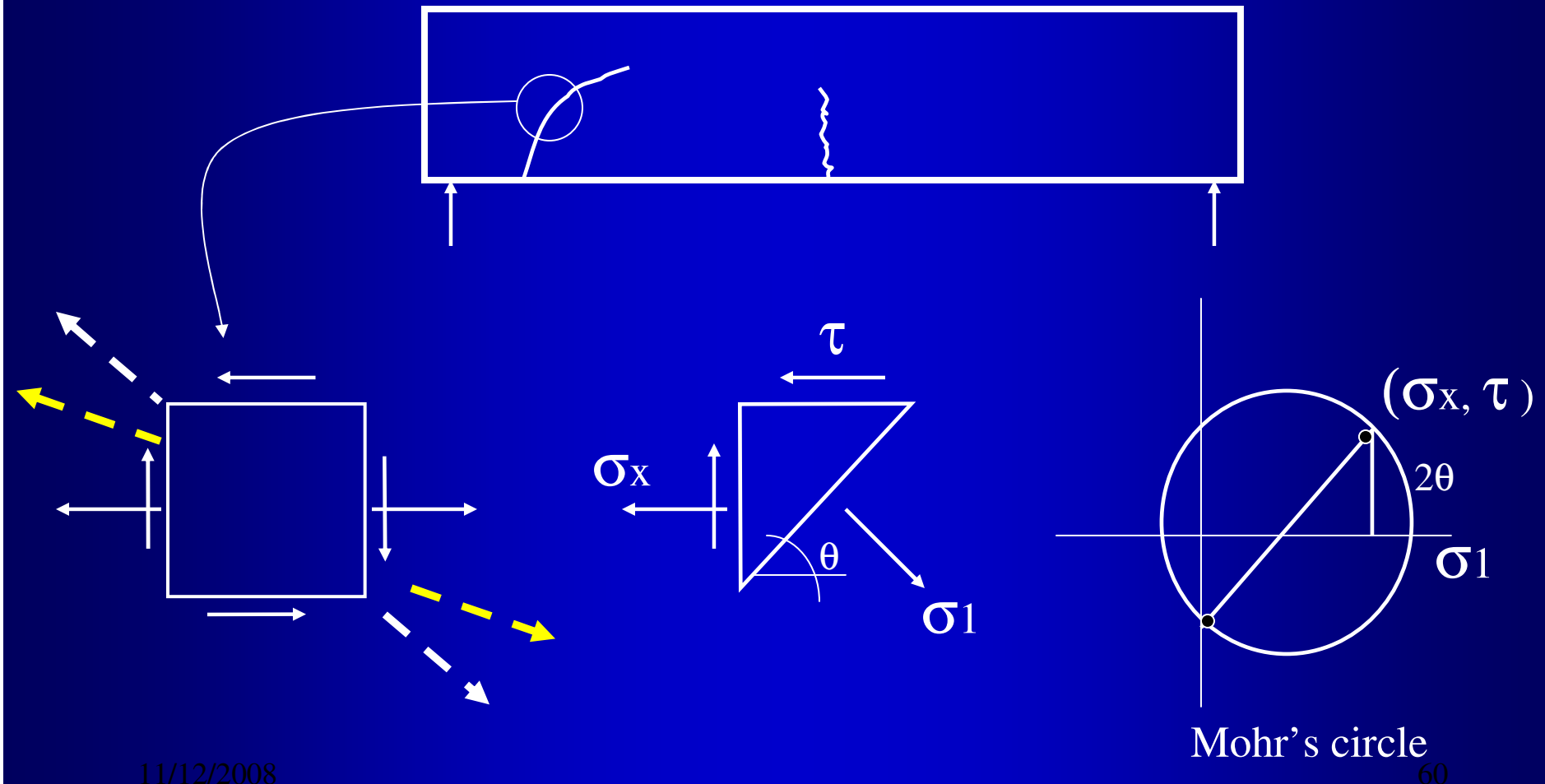
# Indirect Tension



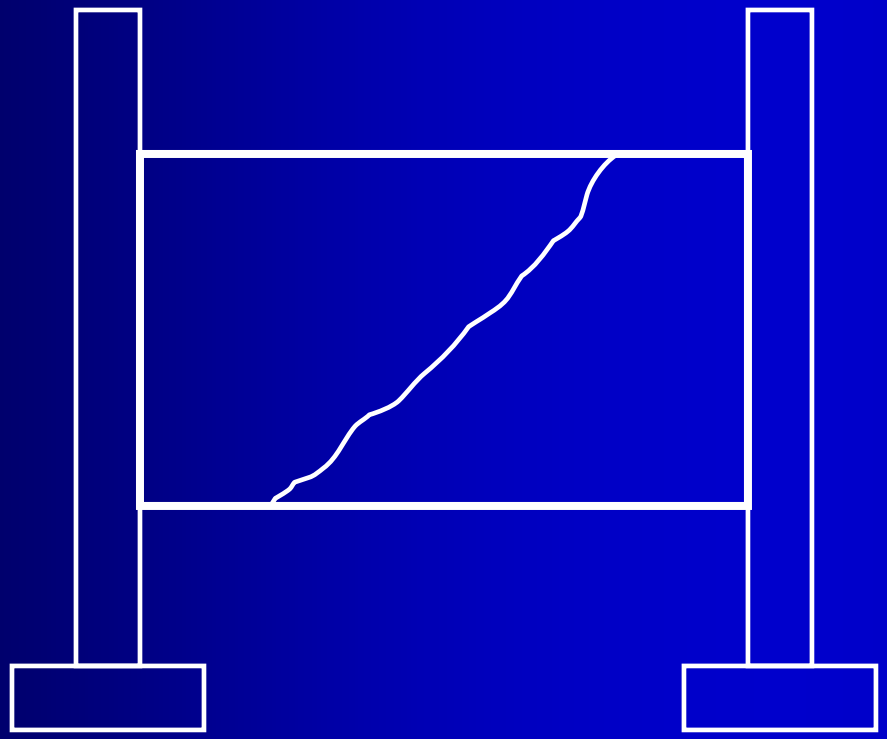
# Pure Shear

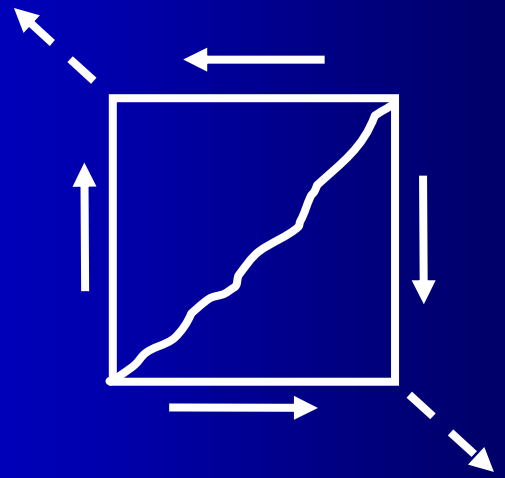


# Combined Shear and Axial Stress



# Example: shear wall





# Two Most Likely Causes

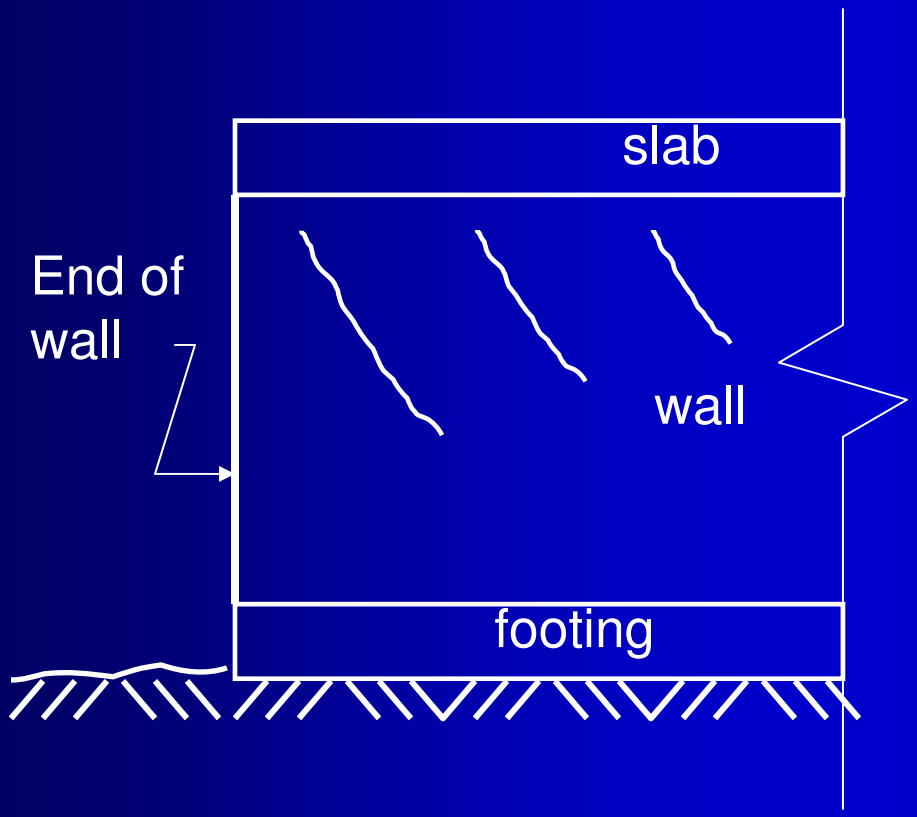
- Differential settlement: check levels
- Lateral force due to wind/earthquake: check history and perform structural analysis

# Matrix Evaluation

**Possible Causes**

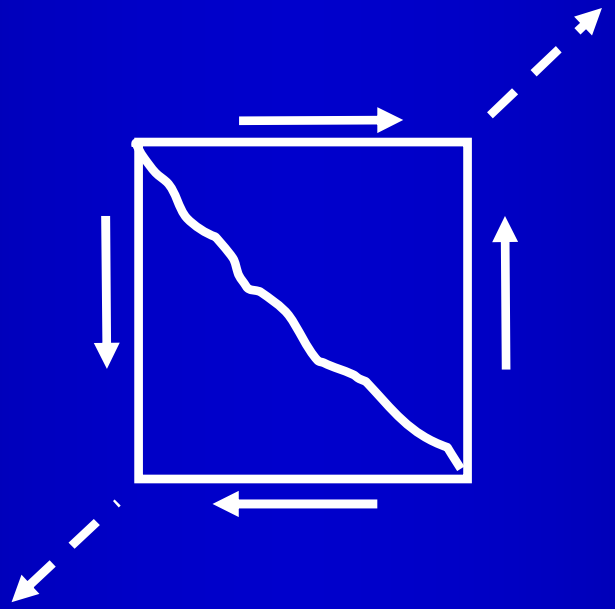
| Observations/Tests | Plastic shrinkage | Settlement | Lateral Load |
|---|---|---|---|
| Evaporation rate | X | | |
| Floor levels | | O | |
| Crack orientation | X | O | O |
| Structural analysis | | | X |

# Example: wall supporting slab




- Footing and wall cast
- Several weeks later, slab placed and tied to wall
- Few weeks later cracks appeared

# Likely cause: shrinkage in slab



# Repair of Cracks

# Should a Crack be Repaired?

- Considerations:
  - Structural vs. non-structural
  - Crack width and length
  - Crack location within a member
  - Environmental exposure condition
  - Type of member
  - Appearance

**At what point should the width of a crack be a concern?**

Criteria found in some homeowner warranties:

# 1/8 in. to 1/4 in.

Width of crack before Homebuilder has an obligation to repair a crack, depending on location of crack

If the only criteria is load transfer across the crack:

0.025 in.

**Research has shown that load transfer due to aggregate interlock is almost fully effective across cracks of 0.025 in. or less. Load transfer across cracks of 0.035 in. is good, but not fully effective.**

Source: PCA Research Bulletin DX124, *Aggregate Interlock at Joints in Concrete Pavements*, Colley and Humphry, 1967

**However, the durability of the concrete member is usually as important as the load transfer characteristics. Durability is enhanced by preventing moisture from reaching embedded reinforcing steel.**

# Tolerable Crack Widths for Conventionally Reinforced Concrete Members[1]

| Exposure Condition | Tolerable Crack Width |
|---|---|
| Dry air or protective membreane | 0.016 in. |
| Humidity, moist air, or soil | 0.012 in. |
| Deicing chemicals | 0.007 in. |
| Seawater; wetting and drying | 0.006 in. |
| Water retaining structures | 0.004 in. |

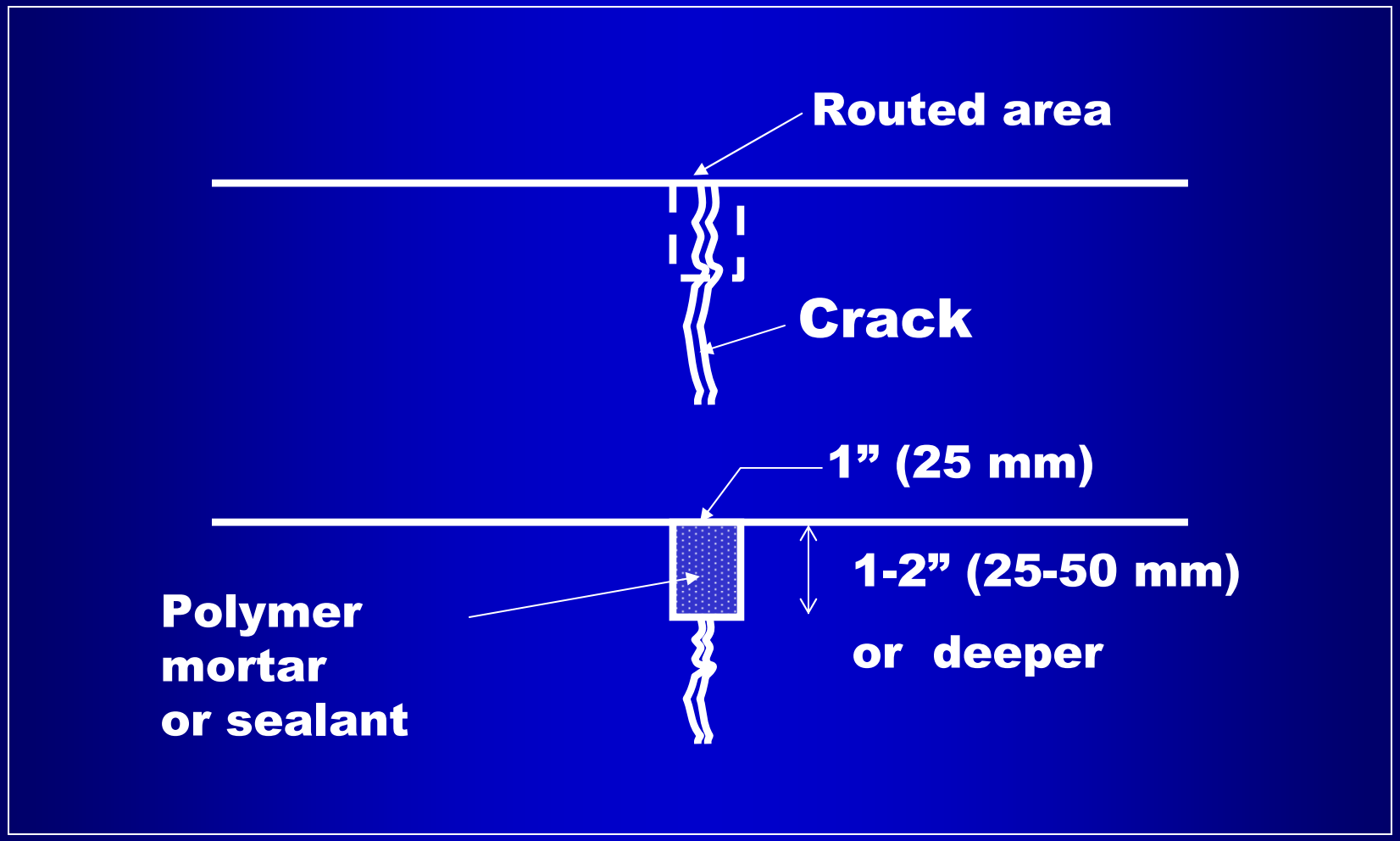
[1] ACI 224R-90, Table 4.1

# ROUTING AND SEALING

# Routing and Filling

- Scabbler (crack chaser) routs crack 1 in. (25 mm) wide and 1-2 in. deep
- Fill with dry sand
- Saturate with monomer/resin
- Good for dirty cracks
- Labor intensive

# Routing and Sealing

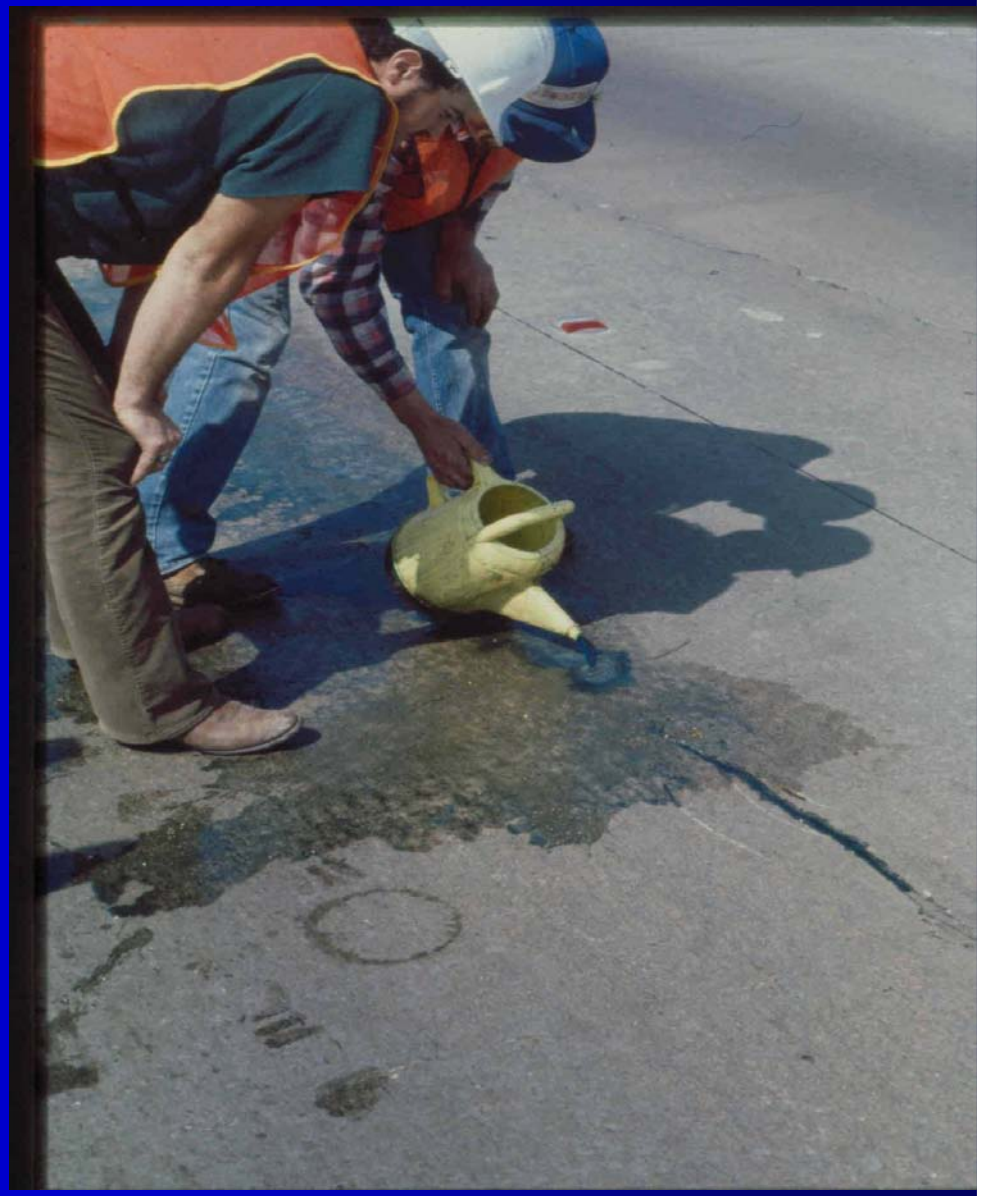


# Routing Cracks with Crack Chaser

# Cart to Apply Sand to Crack

# Applying Monomer

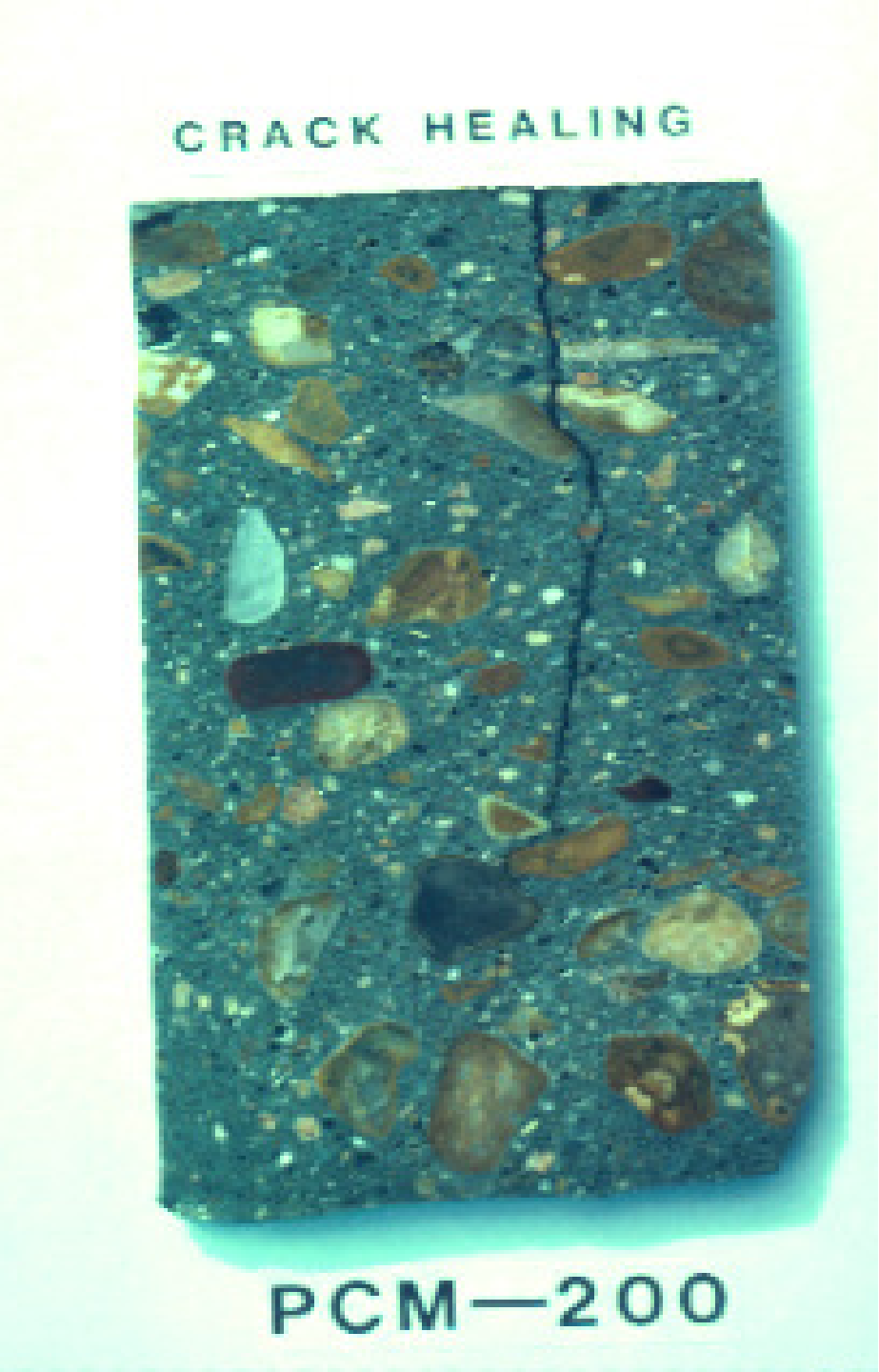
- Clean crack is filled with dry, clean sand
- High molecular weight methacrylate is poured over the sand with this high tech applicator
- Cures in about 20 min.



# Repaired Crack

# Gravity Filled

Filled Crack ~ 0.2 mm at Top



# Recracked Slab—
# Broke Outside of Repair

# Applying HMWM to Cracked I-20 Bridge

# Applying HMWM with Spray Bar

# Applying Sand

# Comparison of Application Methods

# Case Study: Cracking in Tank Farm Walls

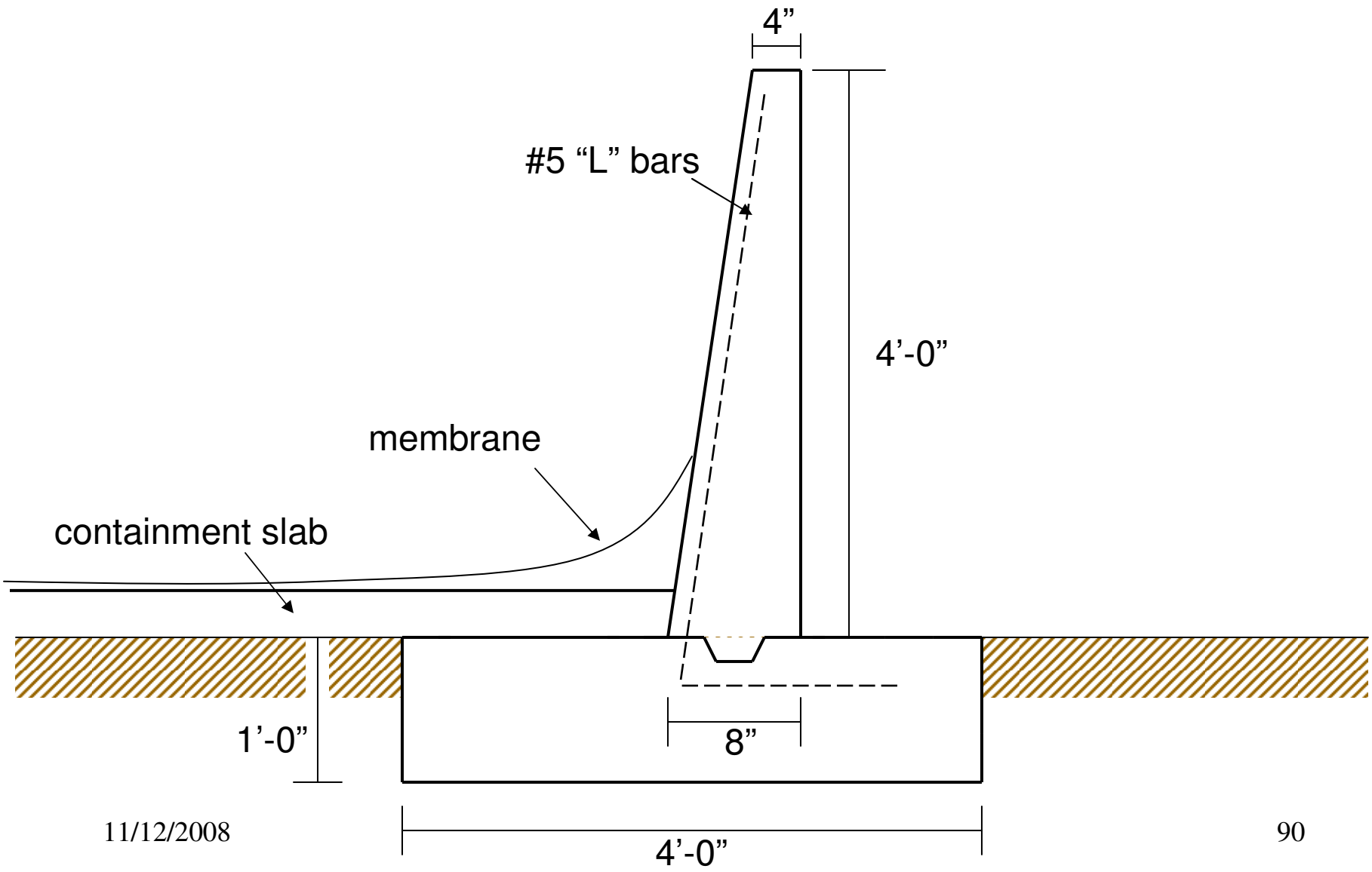
# Case Study: Tank Farm Walls

- Containment walls (200 ft. x 200 ft.) for diesel fuel tanks showed considerable cracking.
- The owner was concerned that:
  - The cracking would permit fuel oil spills to leak through the walls
  - The cracks might seriously reduce the strength
  - The cracking might continue

# Investigation

- Walls were shown be cast monolithically cast with strip footing.
- However, it was stated that walls were cast one or two months after footings were placed.
- A shear key and “L-shaped” rebars were used.

# Wall Section

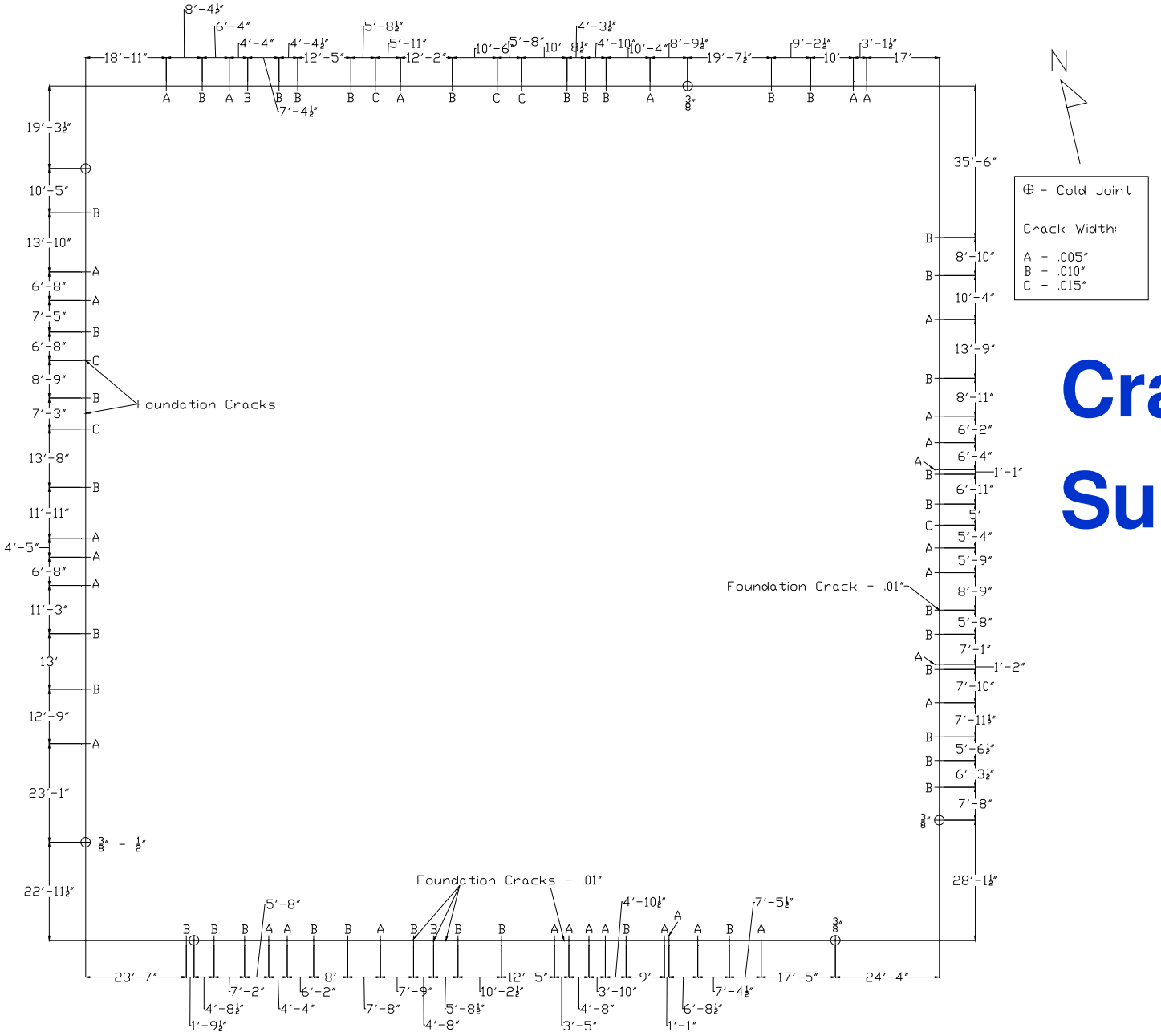


# Overall View of Tank Farm

# Cracks in Walls

# Investigation

- Site visit was made.
- The cracks were mapped.
- Locations along wall and crack widths were measured.
- Construction history was documented.




# Crack Survey



Figure 1: Crack Map

New Diesel Fuel Tanks
Kirby Yard
San Antonio, Texas

# Summary of Wall Crack Survey

| | North Wall | East Wall | South Wall | West Wall |
|---|---|---|---|---|
| Total # of Cracks | 20 | 20 | 22 | 14 |
| Avg. Crack Width | .00925” | .00825” | .0075” | .00821” |
| Avg. Crack Spacing | 9.1’ | 8.2’ | 7.4’ | 10.5’ |

# Footing Cracks

# Summary of Footing Cracks

- All cracks measured 0.01 in.
- West wall: two cracks
- North wall: none
- East wall: one
- South wall: four

# Observations

- Cracking was very uniform in width and in spacing in walls.
- There was essentially no cracking in the footings.
- What could the cause of the cracking be?

# Hypothesis

- Footing was placed first—free to shrink
- Wall was placed one to two months later after most of wall drying shrinkage had taken place
- As wall tried to shrink, it was restrained by rebars that tied wall to footing.
- Remember: no restraint, no cracking.
- Likely cause: drying shrinkage cracking.

# Hypothesis

- The strain on the north wall, for example, is
  20 cracks x 0.00925 in./200 ft. x 12 in.
  = 0.000077 in./in.
- Some strain is taken by the cold joints and if this movement were known the calculated strain in the concrete would be even higher.
- But this strain is well within anticipated values of drying shrinkage

# Recommendations

- The cracking did not reduce the flexural capacity of the walls.
- The biggest concern is the ability of the walls to contain spilled fuel.
- ACI 224 *Control of Cracking* recommends the following maximum crack widths:
  - Humidity, moist air or soil 0.012 in.
  - Protective membrane 0.016 in.
  - Water retaining structure 0.004 in.

# Recommendations

- The maximum measured crack width was 0.015 in.
- With a protective membrane, the cracks are adequate.
- The obvious solution is to extend the membrane to the top of the wall; the concrete alone does not have to act as a retention structure.

# Case Study:
# Cracked Slab Foundation

# Case Study: Cracked Slab on Grade

- One-story wood-framed residence was constructed on concrete slab on grade.
- Construction was during wet weather.
- Cracking was noted in slab within 6 months.

# Complaints by Owner

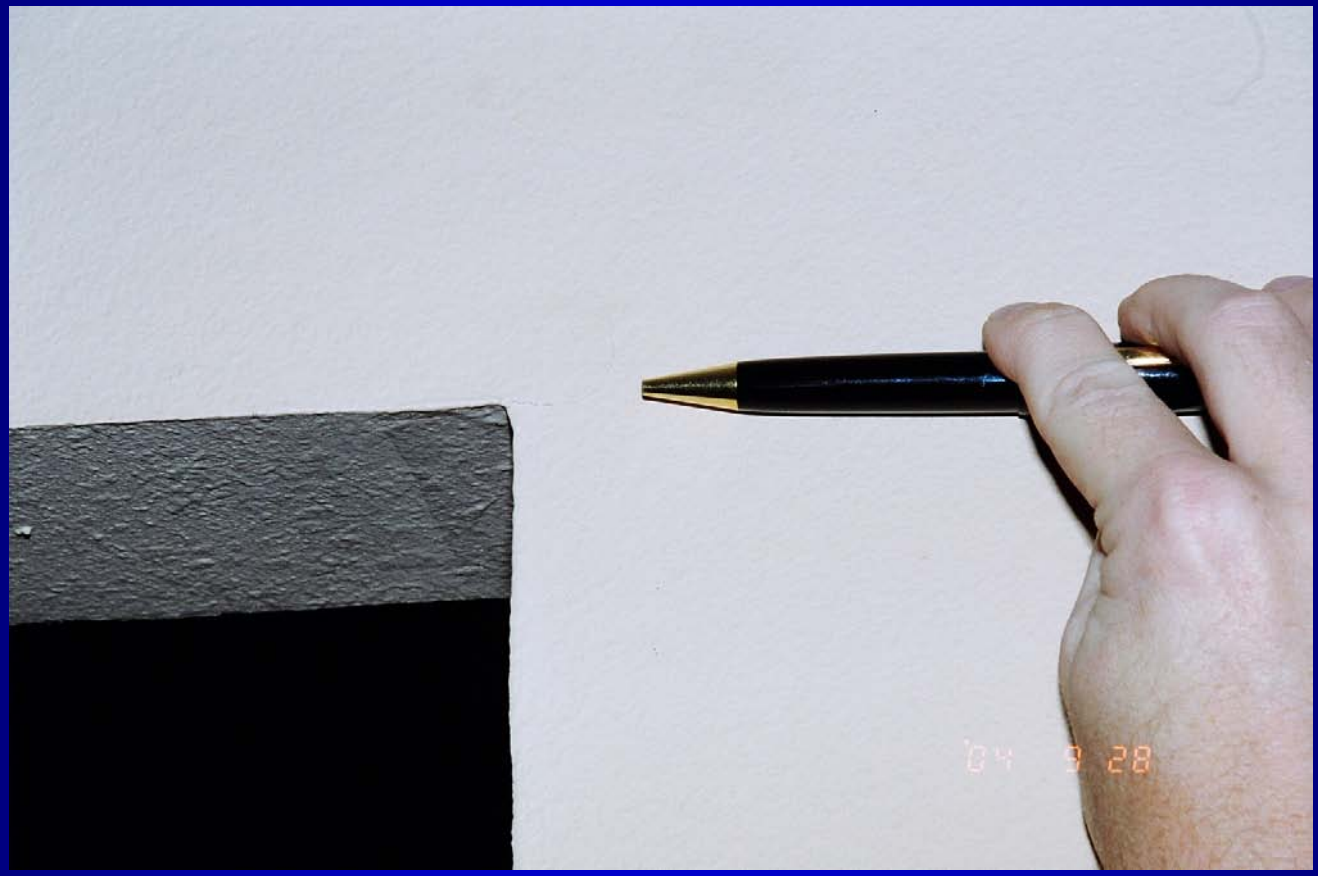
- “Cracks in walls”
- “Numerous, severe cracks in foundation”
- “Doors not opening properly due to foundation failure”
- “Improper operation of windows due to foundation failures”
- (doors and windows no longer an issue when I made my inspection)

# Investigation

- At request of builder, I made an inspection approximately three years after slab was constructed.
- The only remaining complaints involved cracks in walls and cracks in foundation.
- Both of these complaints, if valid, suggested that foundation movement was the cause

# 1. Cracks in Walls

- A careful investigation found only five hairline cracks in the gypsum wallboard.
- These cracks were more indicative of shrinkage of the joint compound or shrinkage or expansion of wood framing due to changes in humidity.


'04 9 28

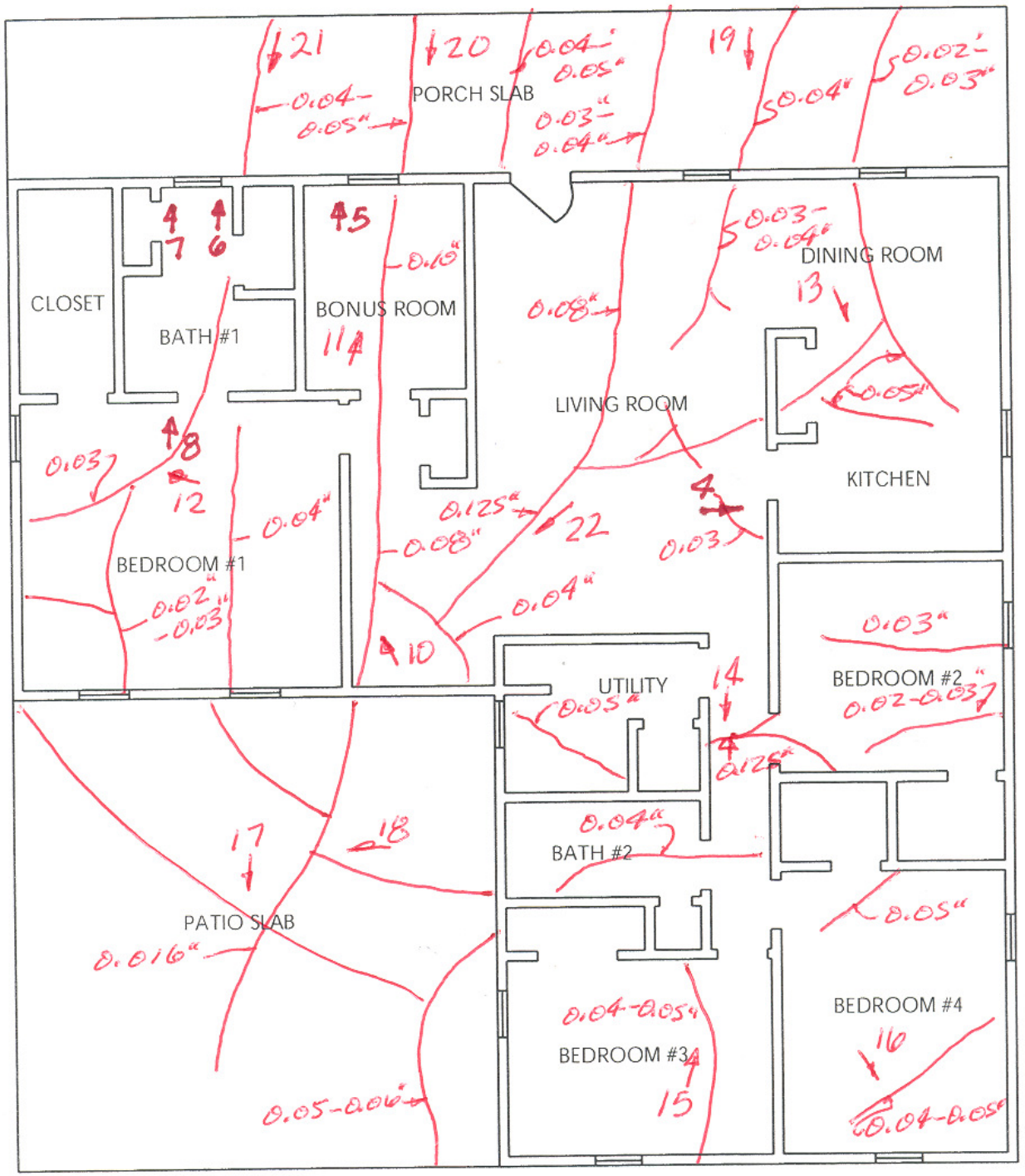
# Finding

- Cracks were insignificant and typical of those found in new homes without significant foundation movement.
- Homeowner warranty indicated that small cracks, nail pops, seam lines….should be expected and were not considered to be  a defect.

# So, what could it be??

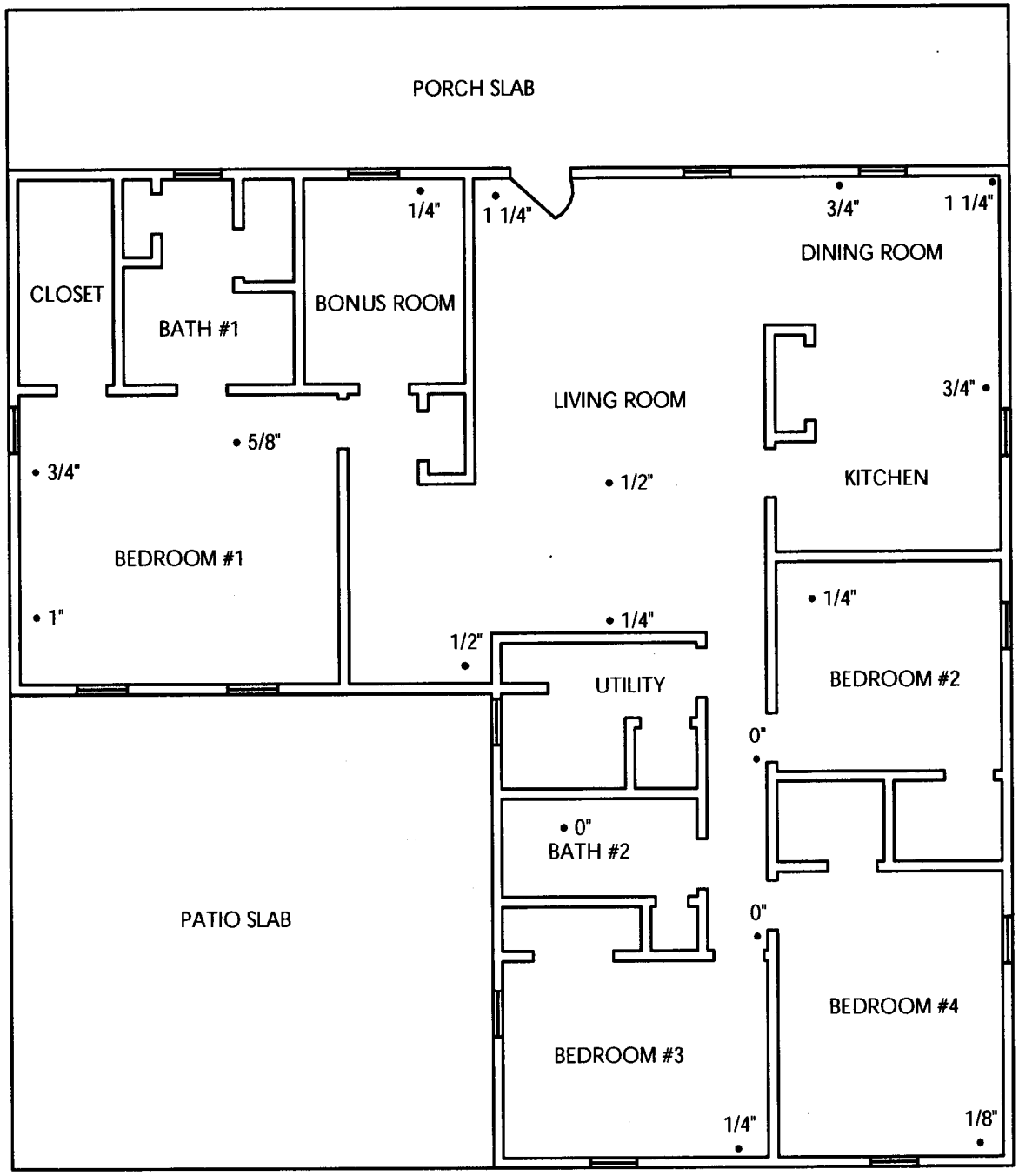
# 2. Numerous Cracks in Slab

- A visual survey of the slab, which had not been covered, revealed numerous cracks.
- Cracks were sketched on a plan.
- Crack widths were noted.


PORCH SLAB
CLOSET
BATH #1
BONUS ROOM
LIVING ROOM
DINING ROOM
KITCHEN
BEDROOM #1
UTILITY
BEDROOM #2
BATH #2
PATIO SLAB
BEDROOM #3
BEDROOM #4

11/12/2008

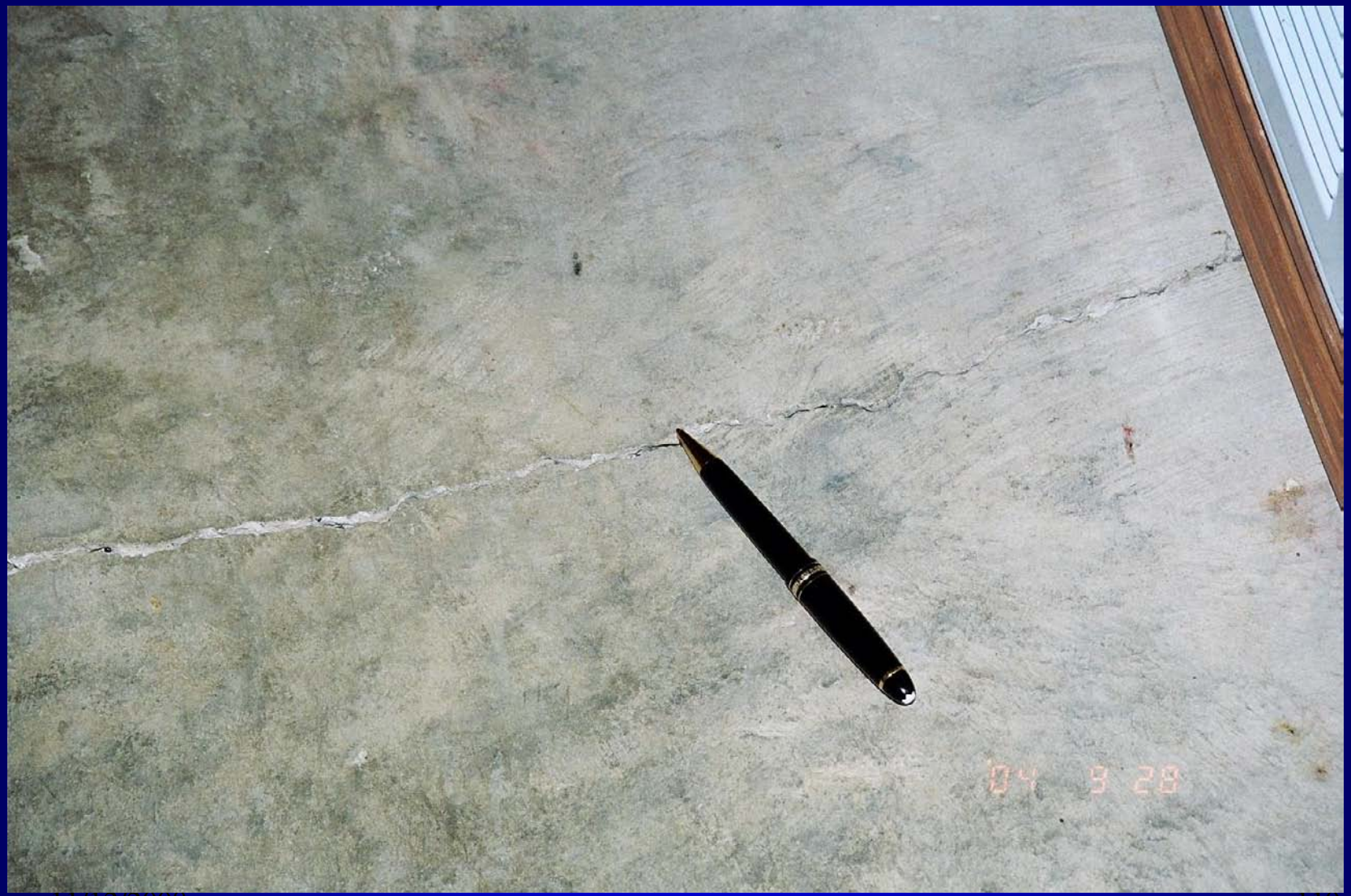
- A limited relative foundation survey was performed to determine the out of level of the slab.


PORCH SLAB
CLOSET
BATH #1
BONUS ROOM
1/4"
1 1/4"
3/4"
1 1/4"
DINING ROOM
LIVING ROOM
3/4"
KITCHEN
5/8"
3/4"
1/2"
BEDROOM #1
1"
1/4"
1/2"
UTILITY
1/4"
BEDROOM #2
0"
0"
BATH #2
PATIO SLAB
0"
BEDROOM #4
BEDROOM #3
1/4"
1/8"

# Finding

- Cracking was uniformly distributed throughout the slab.
- Even in areas where there was little difference in elevations.
- In the bedroom wing where the variation in level was only ¼ inch, there was a wide crack in the hall.
- Most of the slab is within ¾ inch.
- Worst unlevel is 1 ¼ in—no wall cracking in that area.

# 0.125-in. in hall in BR wing



# 0.125-in. crack in Living Room

- Quite likely that slab was not constructed level.
- If flexural stress due to soil movement existed, curvature of the slab would have to occur that would be associated with an unlevel slab.
- The wall cracking was insignificant.
- If the slab cracking had been caused by foundation movement, much more severe cracking in the wall board would be expected.

# Summary of Findings

- The two primary indications of significant foundation movement,
  - SignIficantly unlevel slabs
  - Severe cracks in wallboard

  were absent in this house.

# If not foundation movement, what could cause cracking??

- Plaintiff's expert cited a number of possible causes:
  - Lack of compaction
  - Wet conditions at time of placement
  - Rapid placement of plastic membrane just prior to concrete placement
  - Voids beneath the slab
  - Lack of reinforcement in the beams.

- Cores taken by plaintiff's experts indicated that:
  - Concrete was not 4 in. thick as required by plans
  - Bottom of slab was quite irregular
  - Voids were found beneath the slab
- Plaintiff's experts also found that beams were of adequate depth, that wire mesh was found in the slab, and that reinforcing had been used in the beams

# Findings

- The foundation met the 2000 International Residential Code.
- The slab thickness did not meet the 4-in. thickness specified in the plans.
- The most likely cause of cracking was not foundation movement but drying shrinkage.

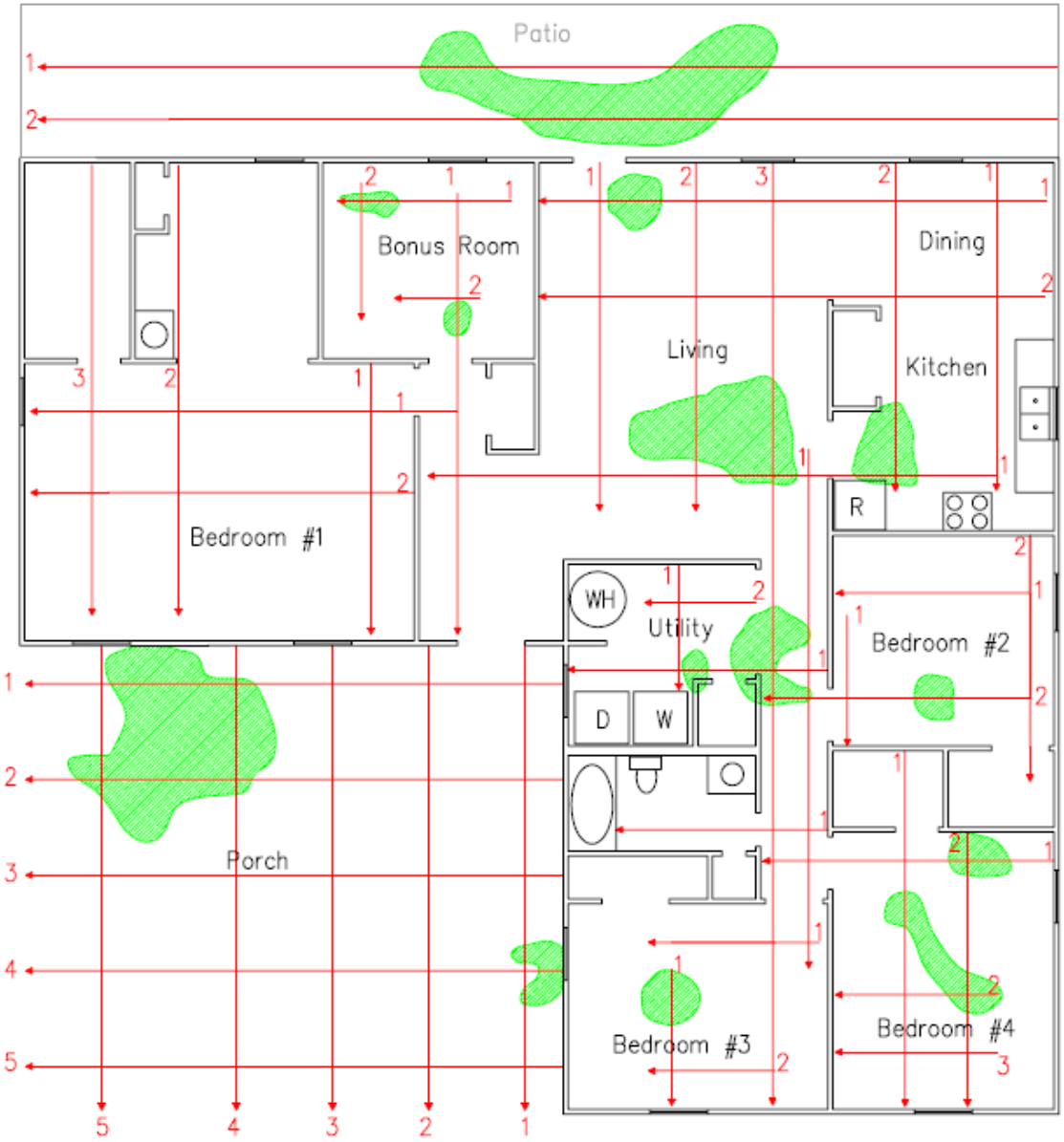
# Recommendations

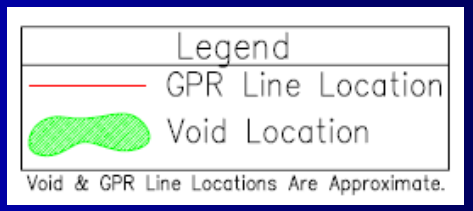
- Plaintiff's expert had recommended placing piers beneath the beams.
- My recommendation was to epoxy inject the cracks that were 0.035 in. or wider.
- I further recommended that the builder have the slab checked for voids beneath the slab using ground penetrating radar.

# Outcome

- The attorneys permitted the experts to meet.
- It was agreed that the recommendations to use epoxy injection be adopted.
- Ground penetrating radar (GPR) was used to locate voids.

# Voids Using GPR



# Outcome

- The cracks were epoxied in early 2005.
- It is not known if they filled voids beneath the slab.
- In early 2008, plaintiff's engineer said that they have had no calls or complaints—apparently the fix has worked.

# Summary

- Concrete cracks
- It can be controlled and in some cases eliminated with proper design
- But cracking provides a life-time annuity for many of you!
- It is very important to determine the cause of cracking before repairs are made