Ira A. FULTON school of engineering

Plastic Shrinkage Cracking in Concrete

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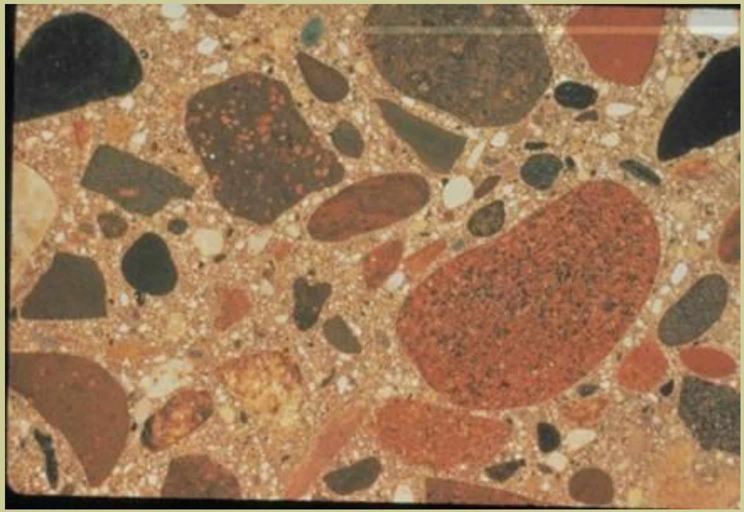
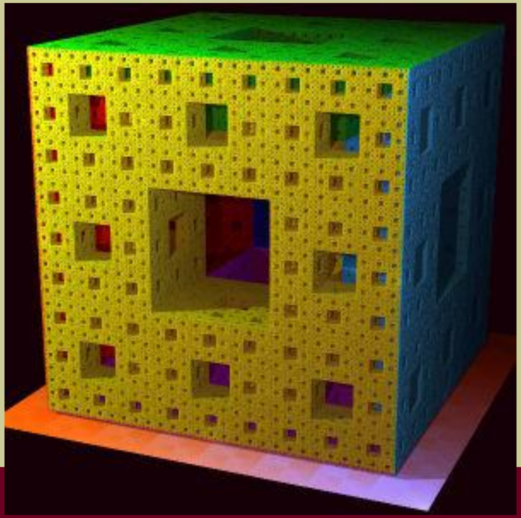
ASU/ADOT Pavement Materials Conference, 2011

Hydration Products

- Calcium silicate hydrate, CSH,
  - 50 -60% volume of HCP (hydrated cement paste)
- Calcium Hydroxide, CH
  - 20-25% of HCP
- Calcium sulfoaluminates
- Water
- Pores
  - Capillary pores
  - gel pores



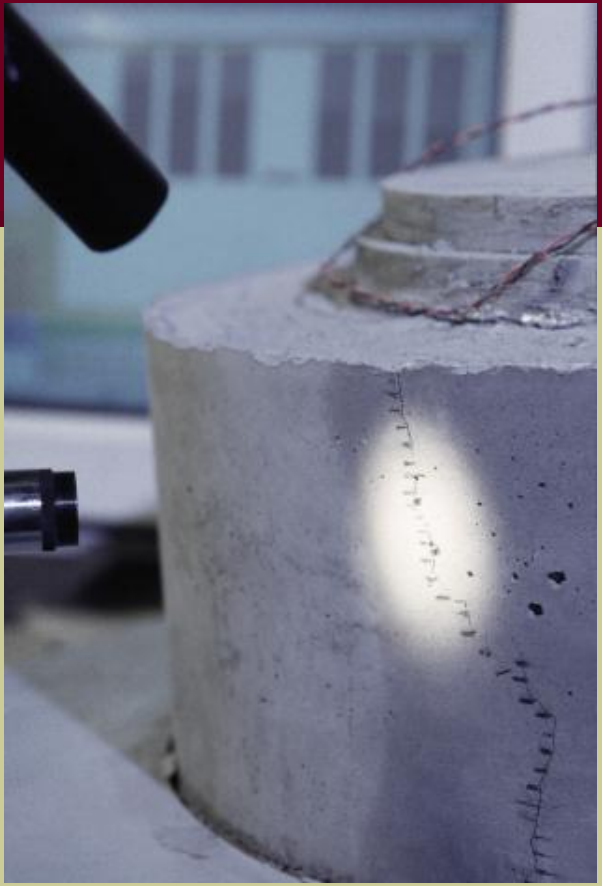


Shrinkage

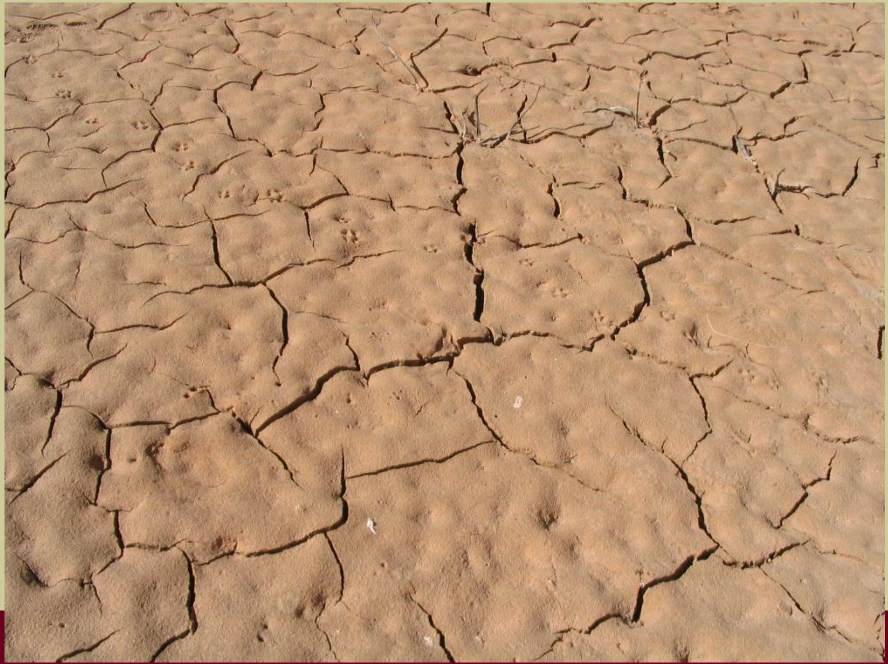
Decrease in Concrete Volume under constant Temperature (Independent of Loading)

Parameters Affecting Shrinkage:

1. Time
2. Water Content or W/C
3. Aggregate Type
4. Ambient Condition (Humidity,Temp.,Wind)
5. Curing Condition
6. Shape Effect (Volume/surface area Ratio)



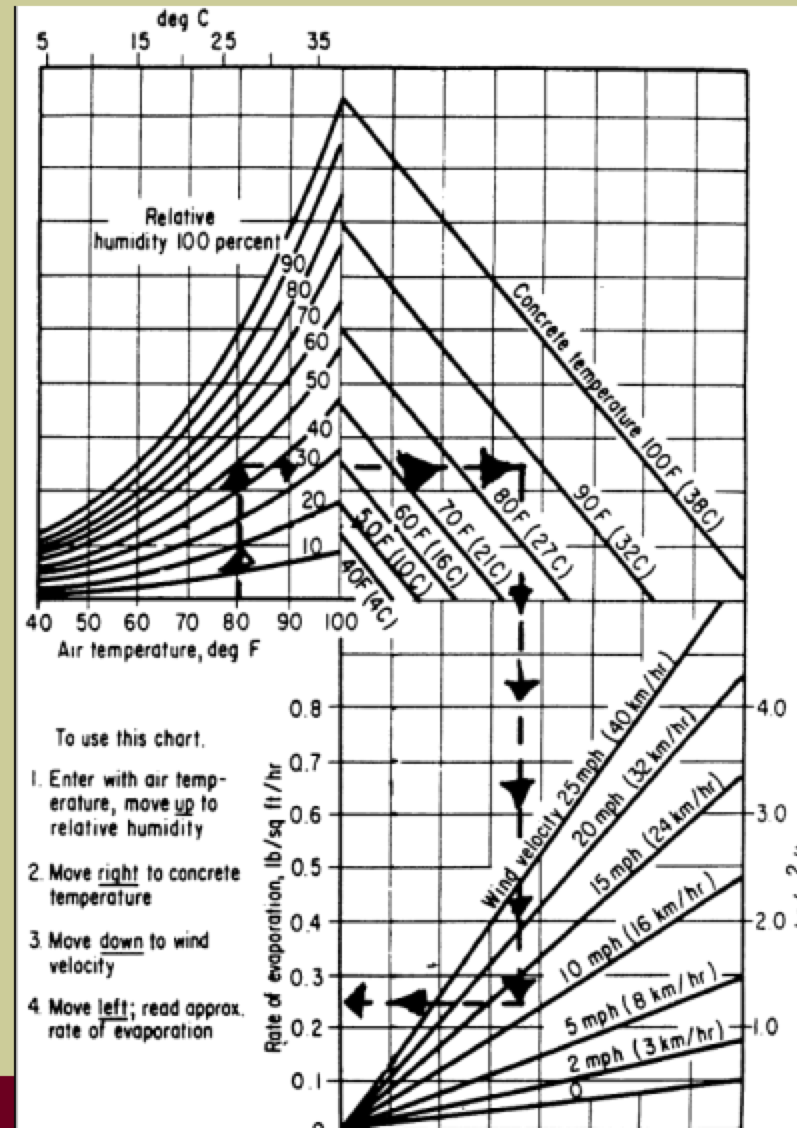


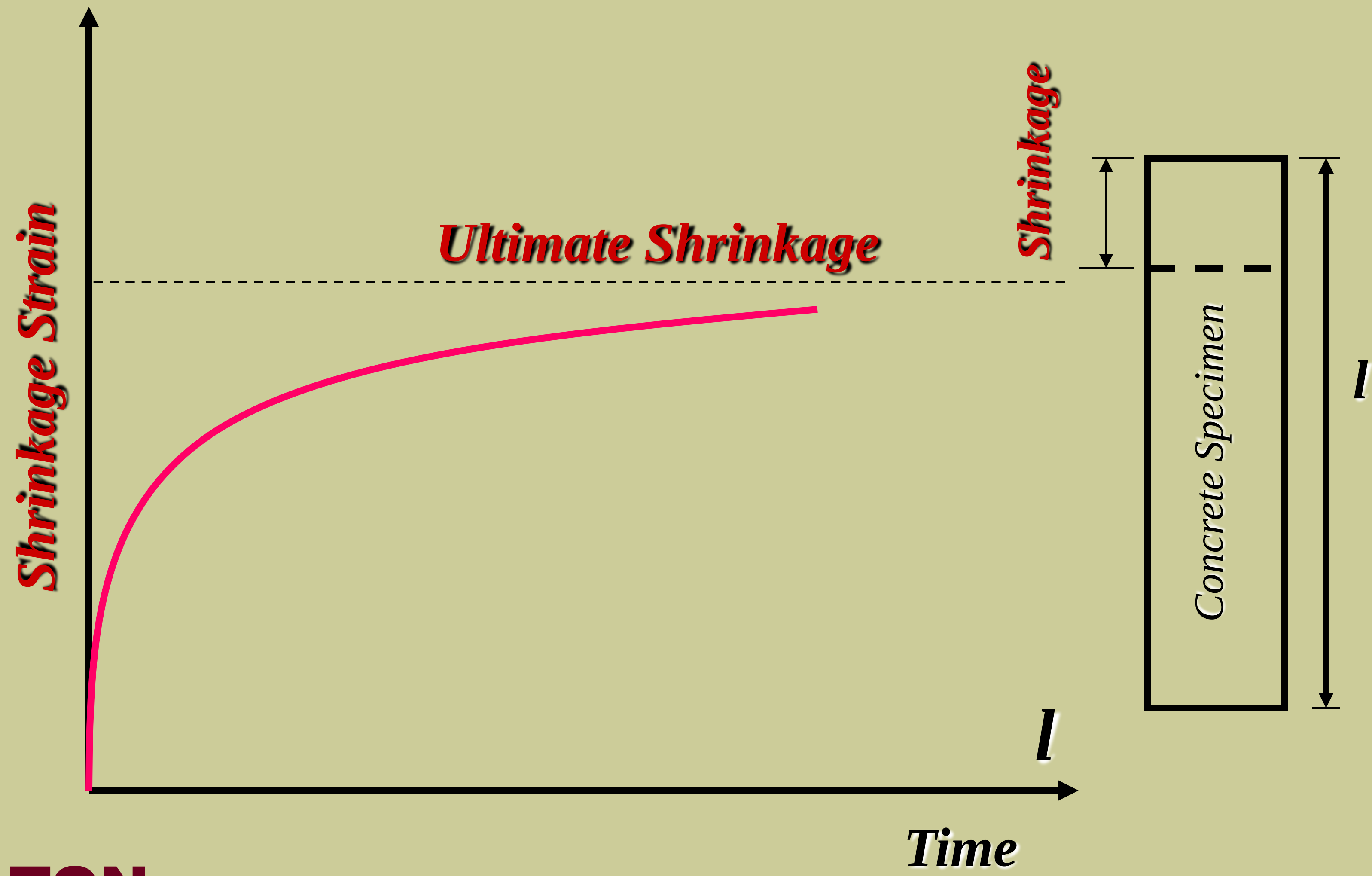
Hot Weather Concrete Standard of Practice

- Origin of ACI nomograph for estimating rate of evaporation of concrete is **MENZEL'S FORMULA**

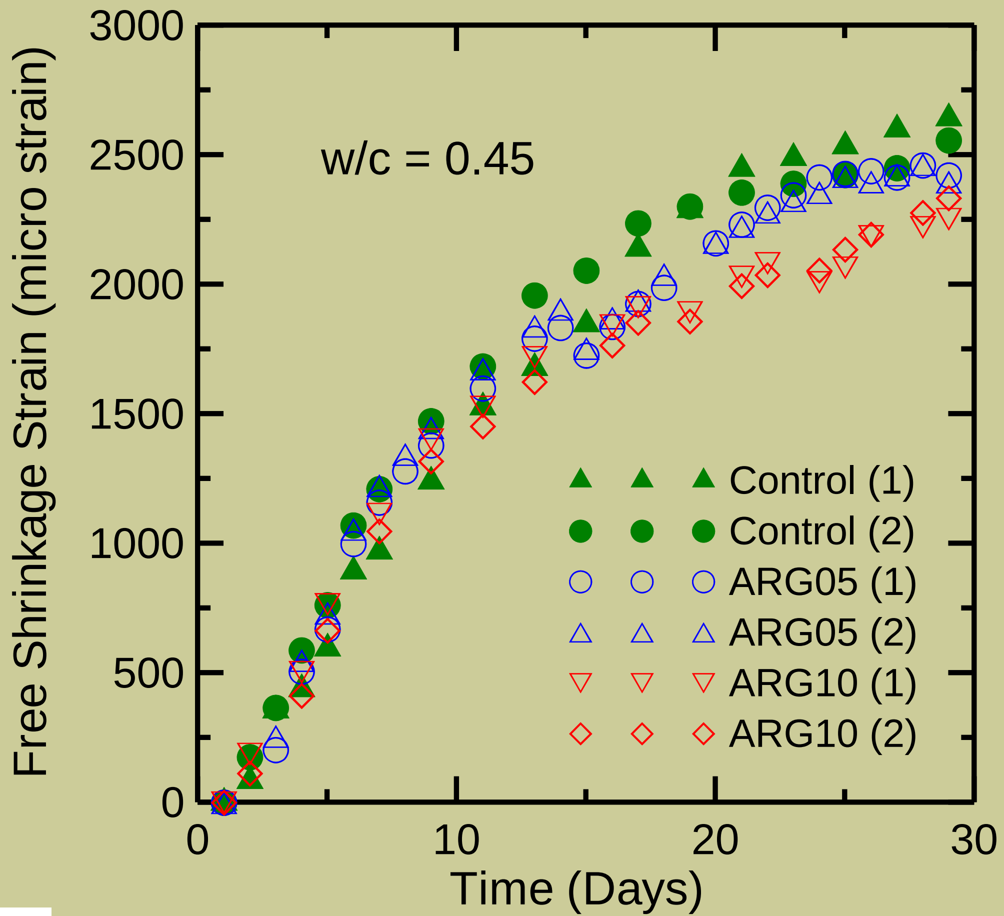
- **Based on lake Hefner near Oklahoma city (1950-2)**



Free Shrinkage

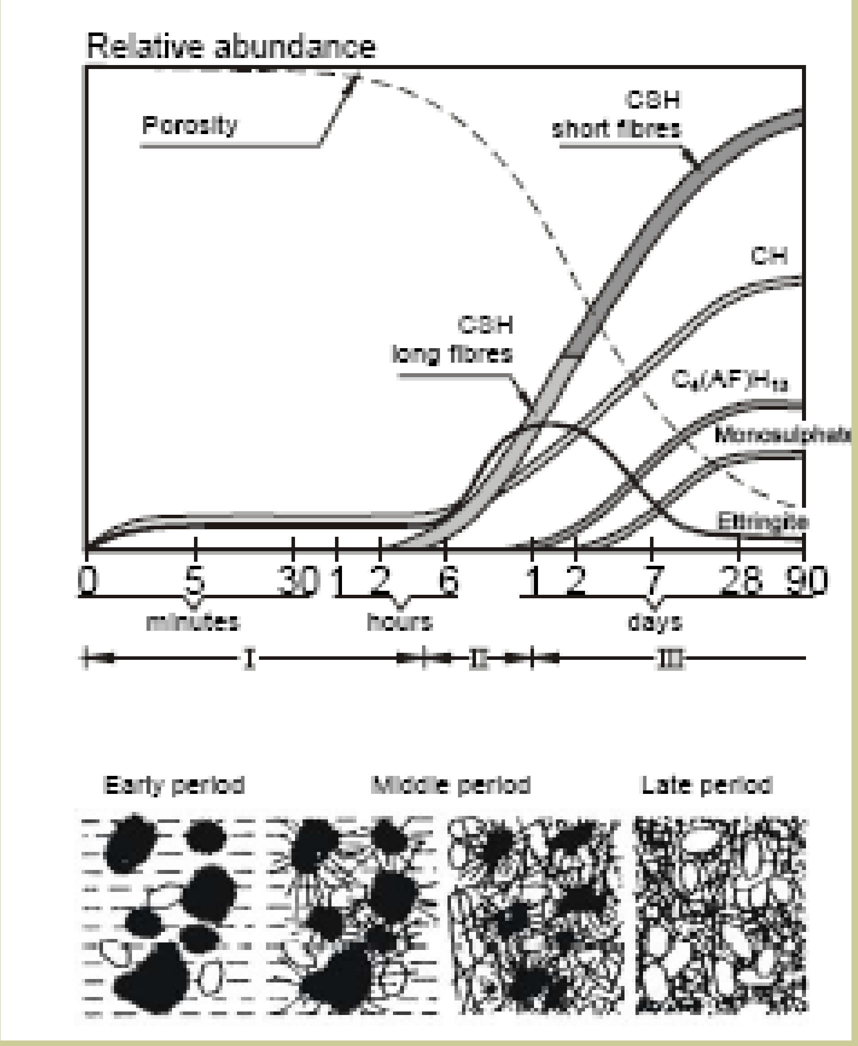


Free shrinkage test



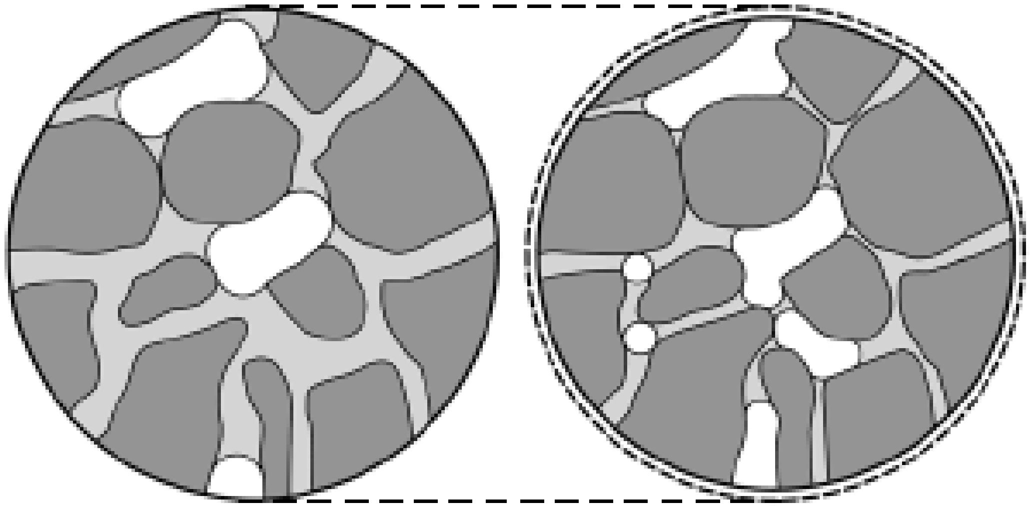
Free shrinkage parameters do not differentiate the contribution of fibers, or cracking

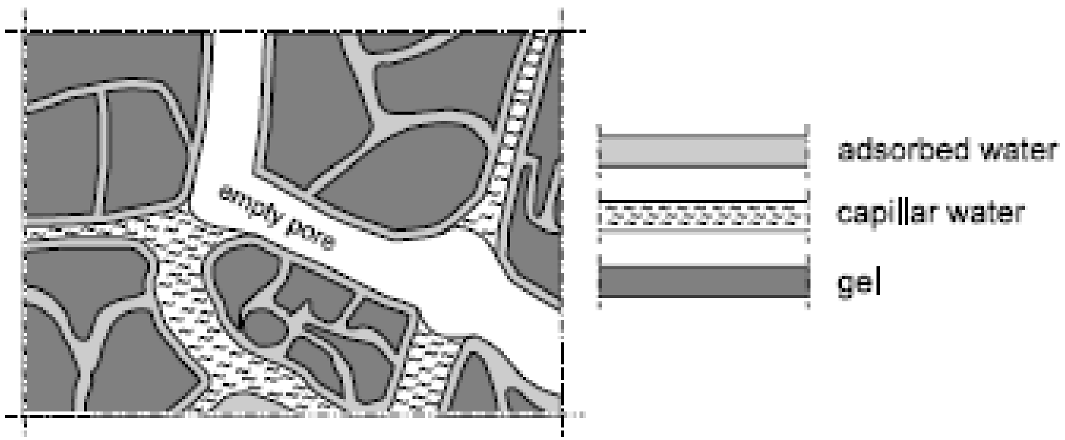
Capillary nad Gel pore System after Hydration of Portland Cement



Shrinkage is due to movement of water from various pore systems

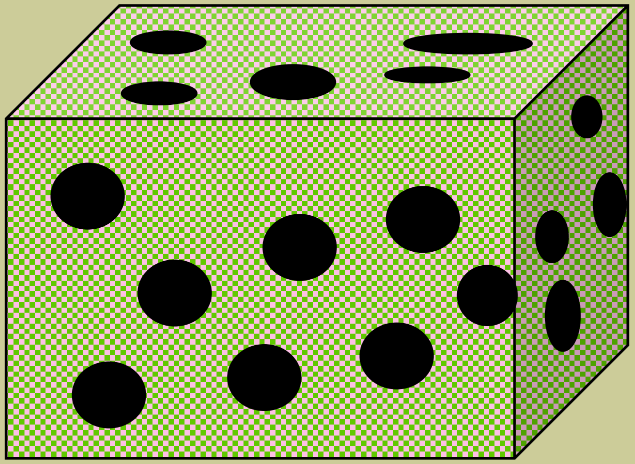
Schematics of Water removal and Internal Shrinkage



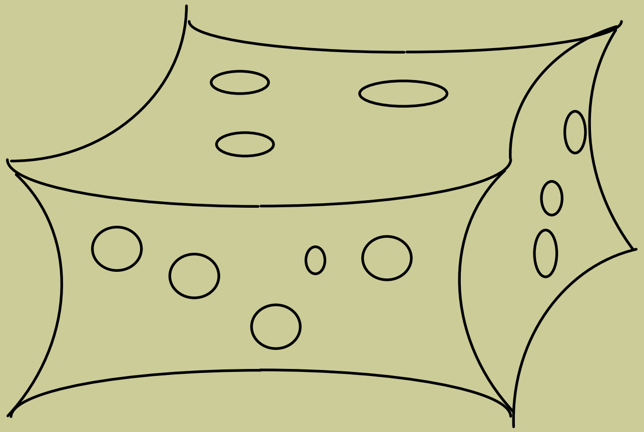


Large pores empty first, followed by smaller pores

Free Shrinkage

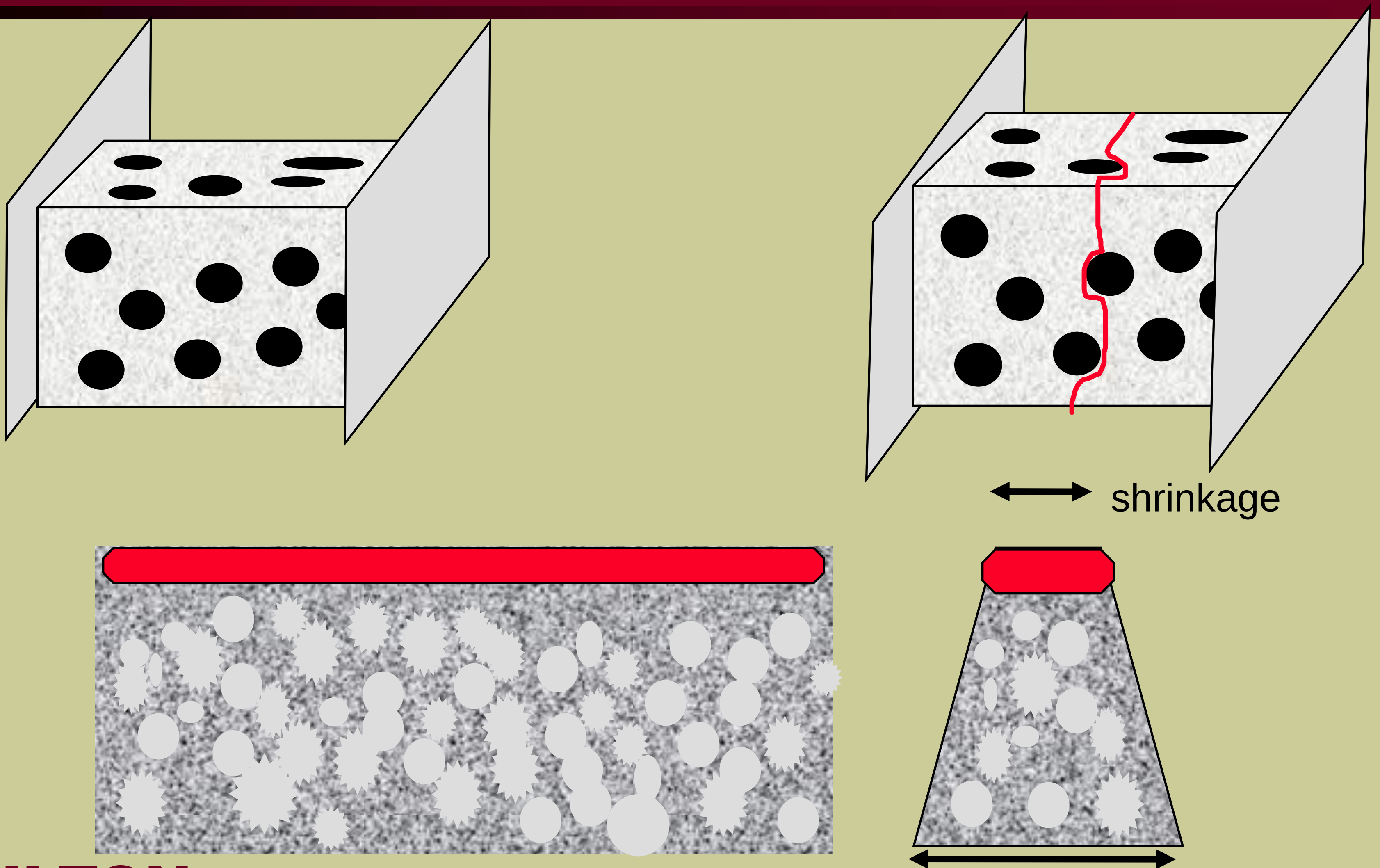


before shrinkage



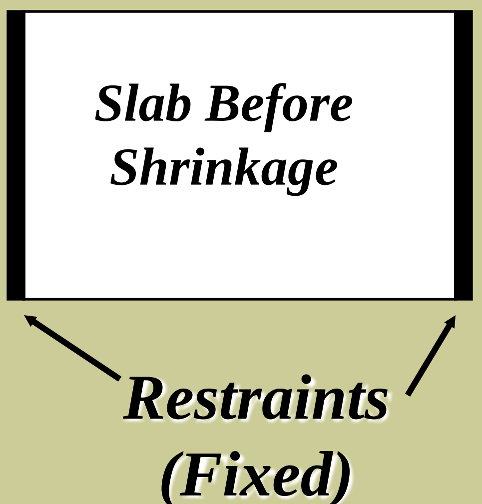
After Shrinkage

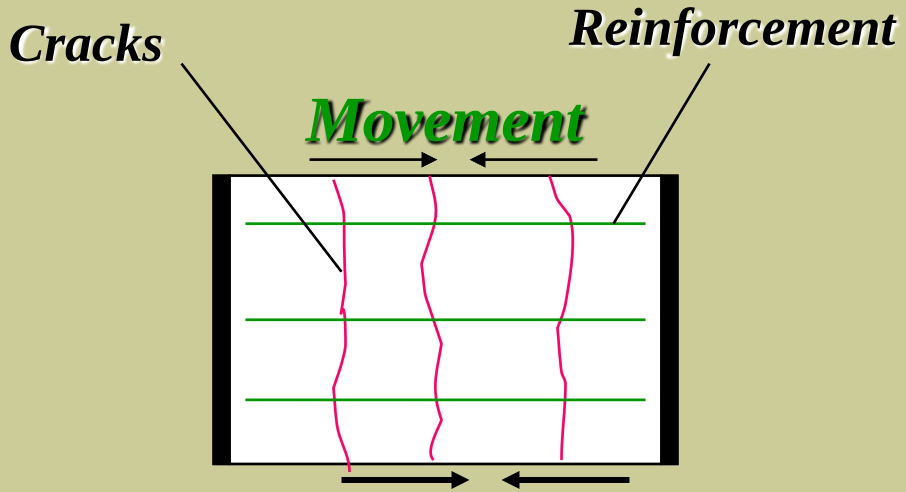
Restrained Shrinkage



Practical Significance of Shrinkage

- When Movement due to shrinkage can not take place freely, tensile Strain (and Stress) will occur and cause CRACKING of Concrete
- Cracking of Roof Slabs, Ground Slabs, Walls, etc





Shrinkage Cracks

Provide Min. Reinf.

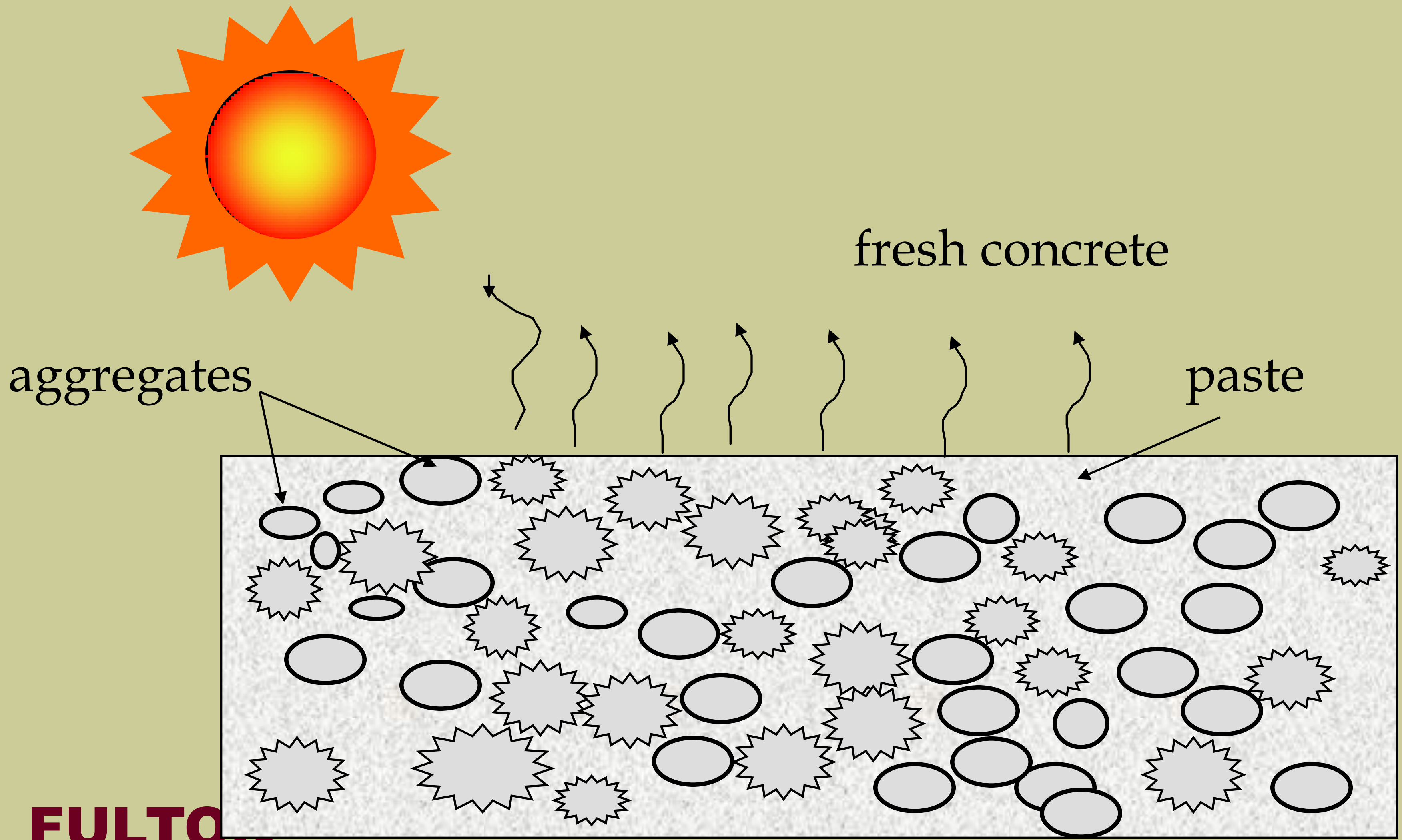
High Performance Concrete

- Can high performance concrete address the problems?
- Shrinkage is a major issue due to the use of Silica fume and high paste content, with low water content.

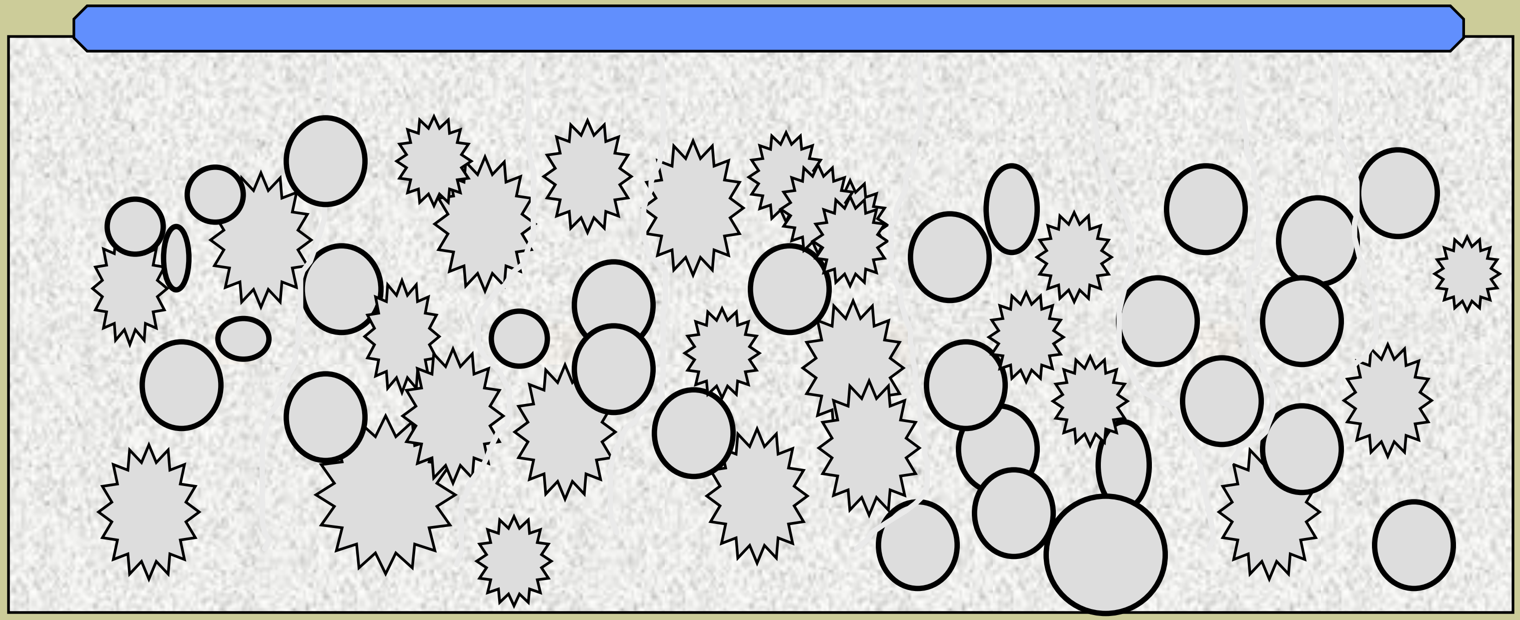
Bleeding and its control

- problems
  - poor pumpability
  - delays in finishing
  - high w/c at the top
  - poor bond between two layers
- causes
  - lack of fines
  - too much water content
- Remedies
  - more fines
  - adjust grading
  - entrained air
  - reduce water content

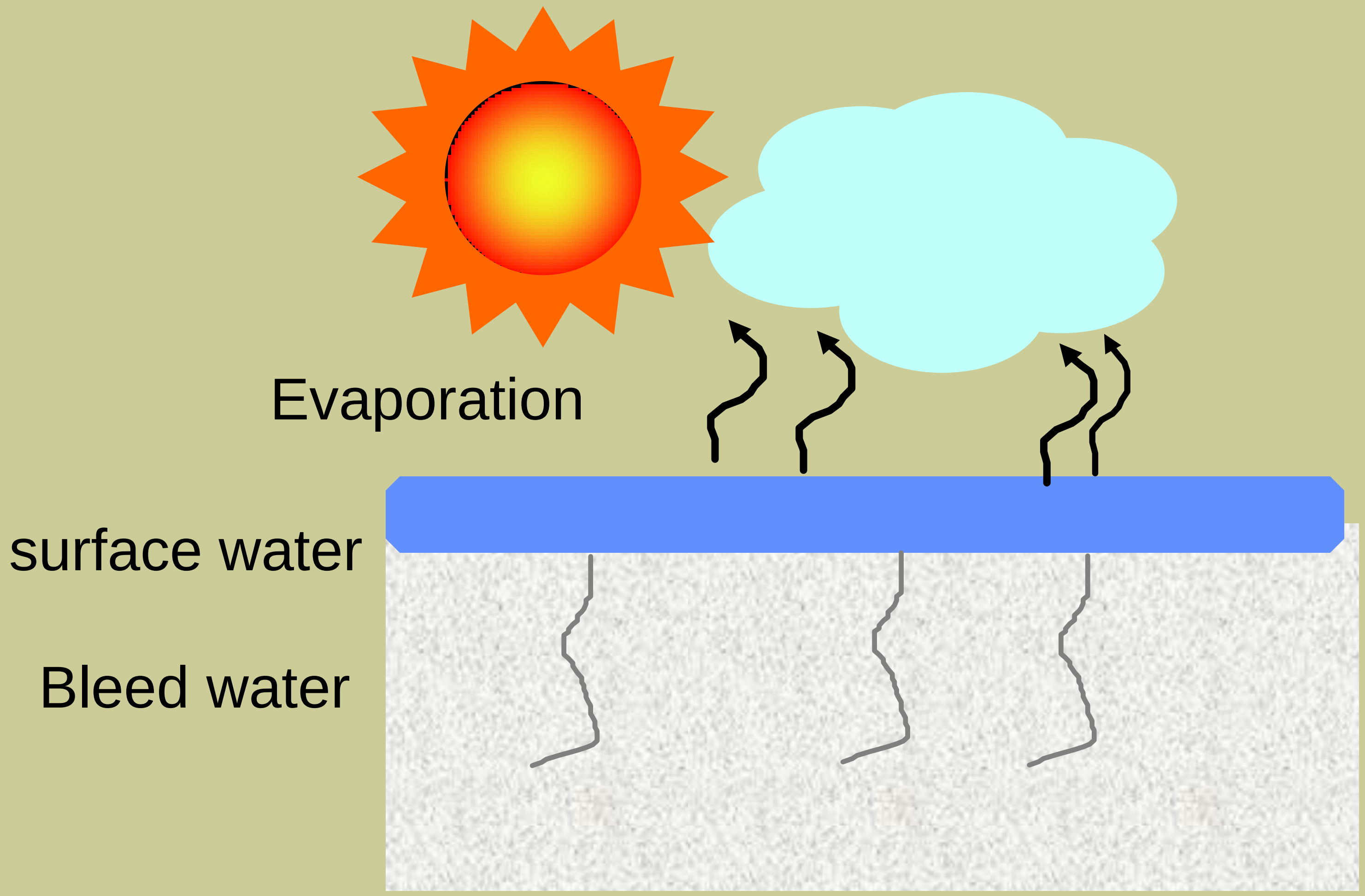
Temperature, Humidity, Wind Control



Bleeding

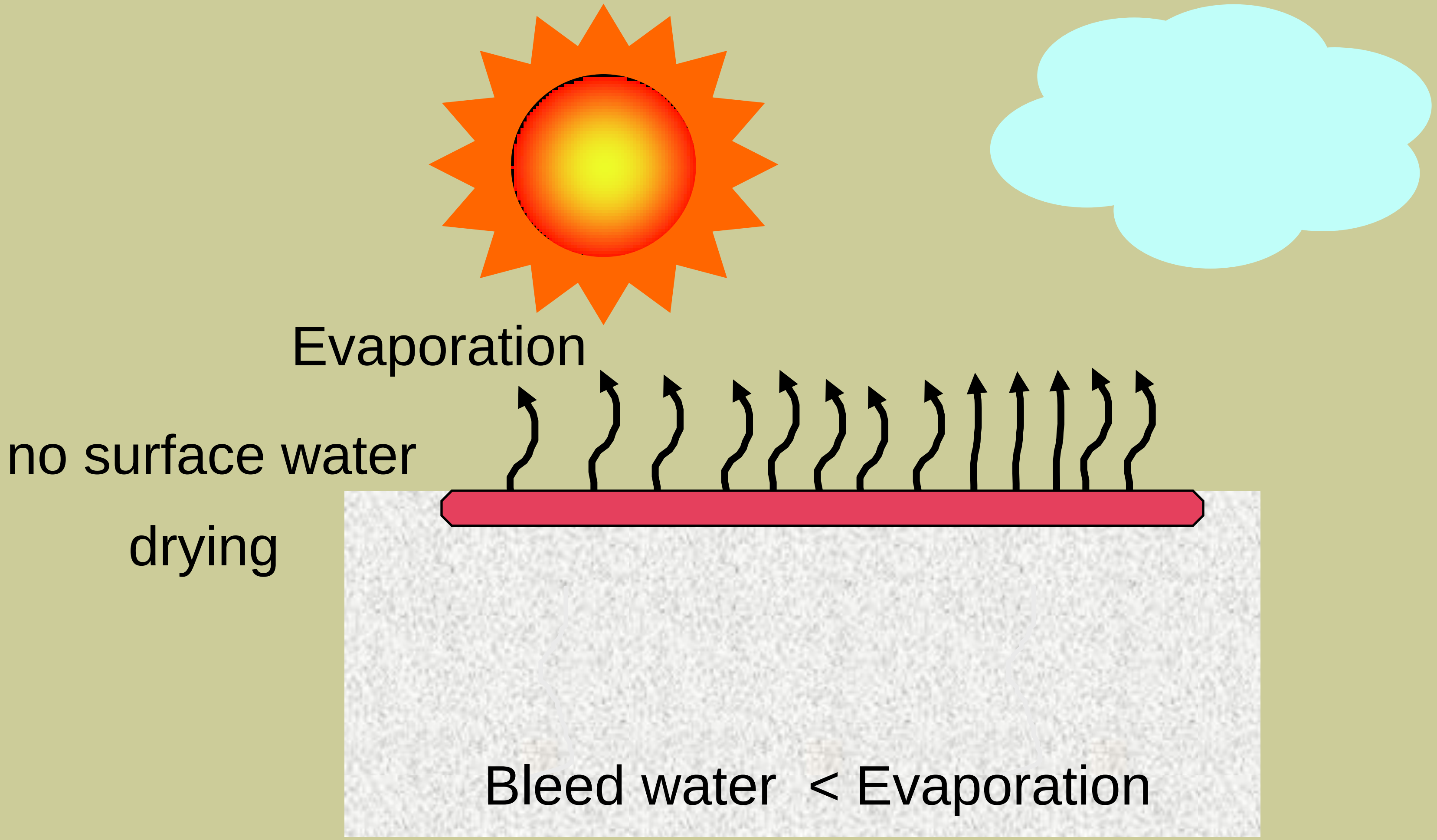


Interaction between bleeding and evaporation



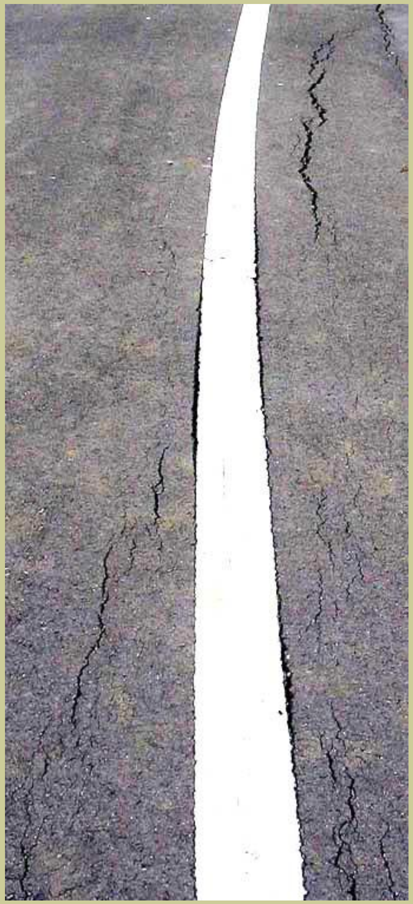
Bleed water = evaporation

Too much evaporation

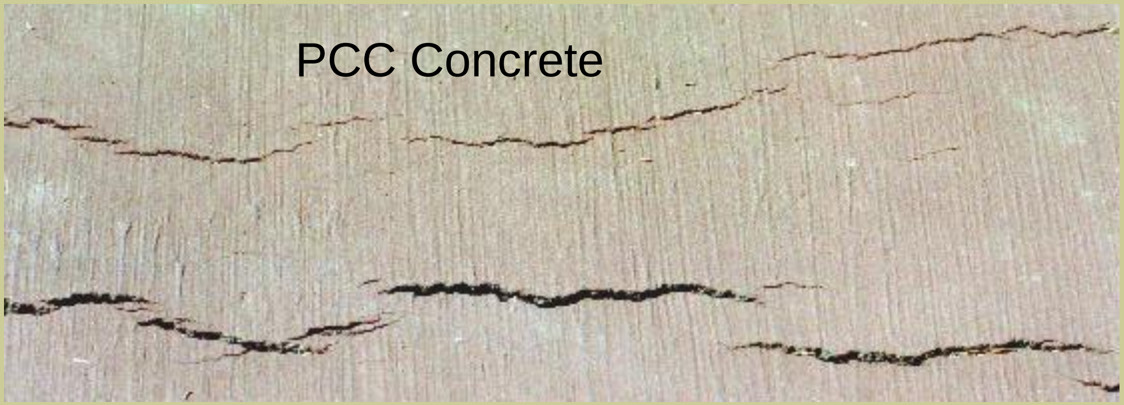


Cracks are Dominant form of failure in many engineering, art, natural events

Cracks

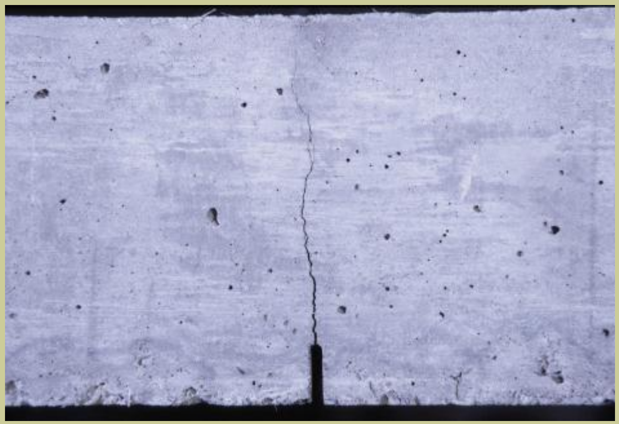


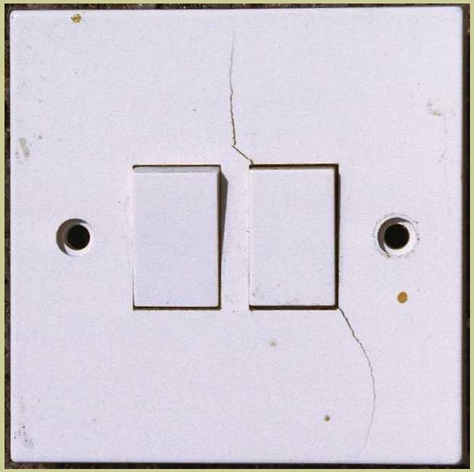
Asphalt Concrete



Rocks

Cracks initiate from points where stresses change rapidly





Plastic shrinkage cracks

- Commonly occur in the surfaces of floors and slabs when job conditions are so dry that moisture is removed from the concrete surface faster than it is replaced by bleed water.
- Occur before the start of curing, before or after final finishing. As the moisture is removed, the surface concrete contracts, resulting in tensile stresses in the weak material.

Control of shrinkage cracking

- *Reduction of cracking tendency*
  - Lower paste Content
  - less water
  - largest practical maximum-size aggregate
  - well-graded aggregate
  - stiffer consistency
  - lower initial temperature of the concrete
  - Curing
- *Construction*
  - *Reinforcement*
  - Construction Joints

Shrinkage

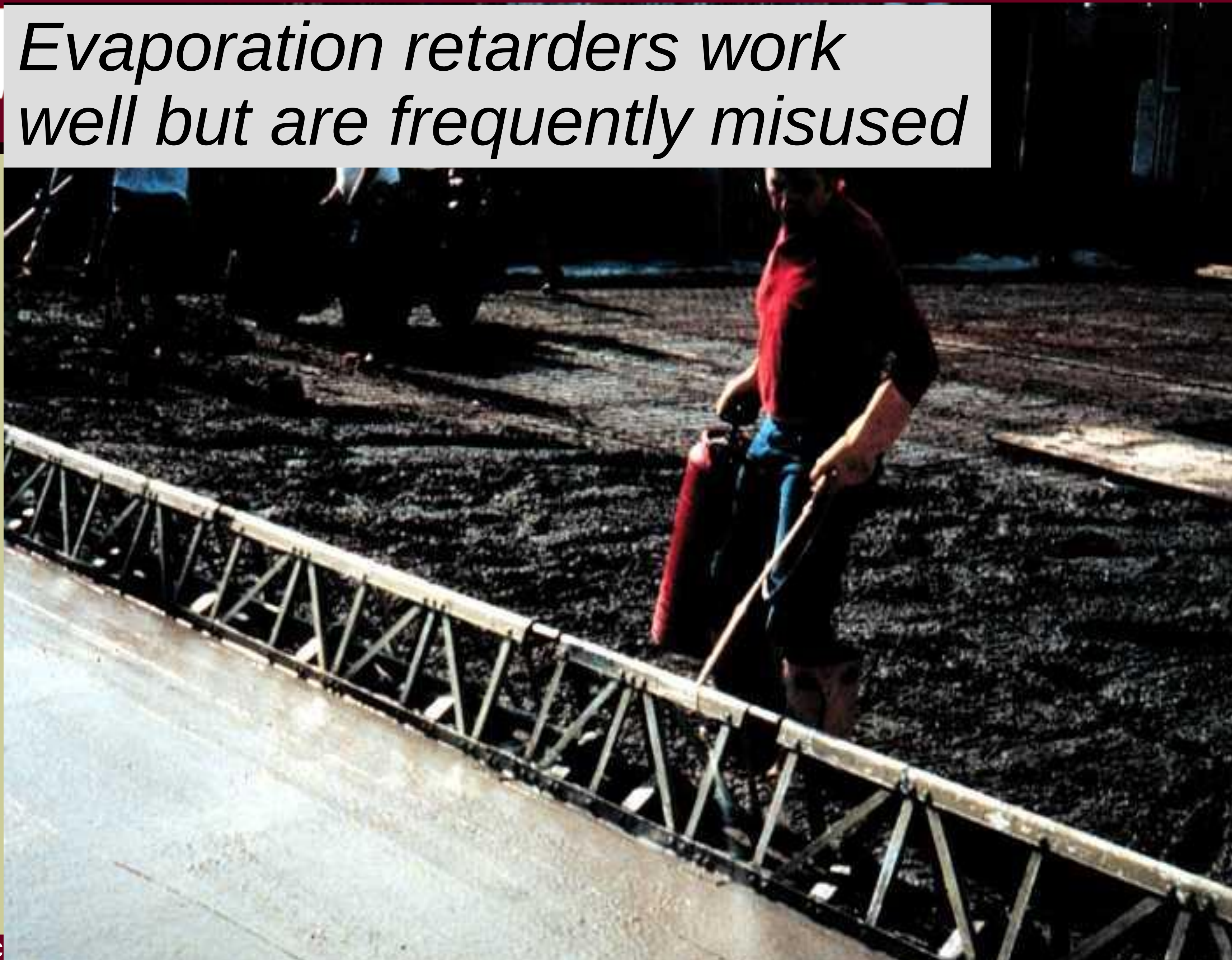
- *Mix design*
  - avoiding oversanded mixtures, using the largest maximum aggregate size practical, and using aggregate with the most favorable shape and grading conducive to workability.
- *Effect of water content*
  - Surface drying will occur except when the surface is submerged or below grade. Drying shrinkage strains of up to 600×10^{-6} or more are likely.
  - Keep the concrete wet as long as possible so that the concrete will have time to develop more strength to resist cracking forces.

Constructions Remedies

- Minimum-Reinforcement
  - Between 0.18 and 0.20%, does not normally control cracks to within generally acceptable design limits.
  - To control cracks to a more acceptable level, min requirement needs to exceed about 0.60%.
- Joints
  - The use of joints is the an effective method of preventing the formation of cracking.
  - Contraction joints in walls are made, for example, by fastening wood or rubber strips to the form, which leave narrow vertical grooves in the concrete on both faces of the wall.

Good fogging

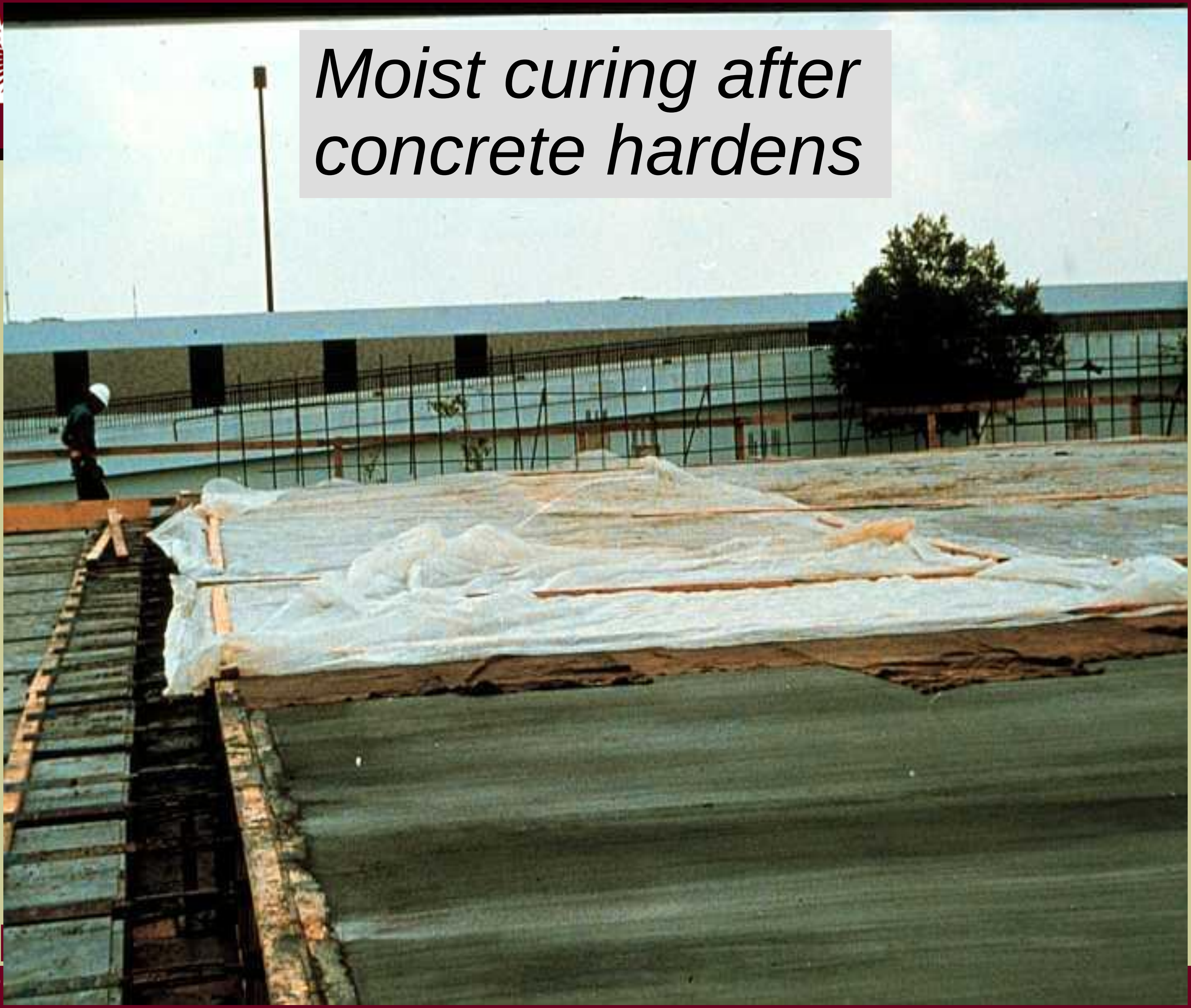
Evaporation retarders work well but are frequently misused



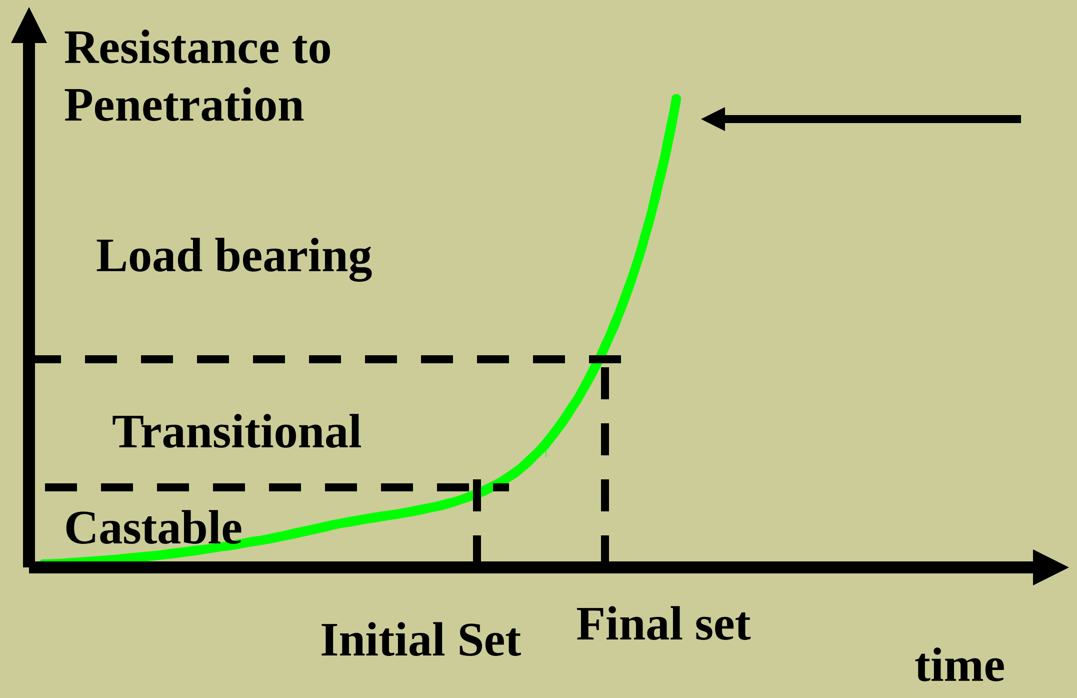
Applying curing compound while concrete is still fresh

"It is recommended that a minimum of 7 days continuous moist curing be specified."

Moist curing after concrete hardens



Sawed Joints for crack control



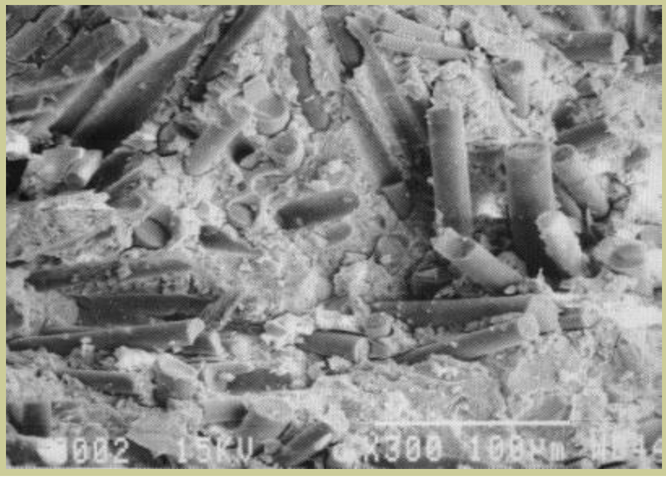
shrinkage-reducing admixtures (SRAs)

- Marketed by numerous chemical admixture companies for reducing drying shrinkage (and its associated cracking) in concrete.
- Most SRAs function by reducing the surface tension of the pore solution in the concrete.
- In addition to reducing or slowing drying shrinkage, this reduction in surface tension can also potentially reduce autogenous shrinkage in low water-binder ratio mortars and concretes and evaporative water loss during early age curing.

Types of Cracks

- During Hardening
  - Construction movement,
    - forms movement
    - Subgrade movement
  - Plastic
    - Plastic shrinkage
    - Plastic settlement
  - Frost Damage
    - Premature freezing
    - Scaling, crazing
- After Hardening
  - Volume instability
    - Drying shrinkage
    - Thermal change
    - creep
- Structural design
  - Design load/overload
  - Design subgrade
  - Fatigue
- Physio-Chemical
  - AAR/ASR/DEF
  - Steel Corrosion
  - Freeze thaw Cycling

Cracks in Concrete Can transfer forces if they are maintained at a very small opening



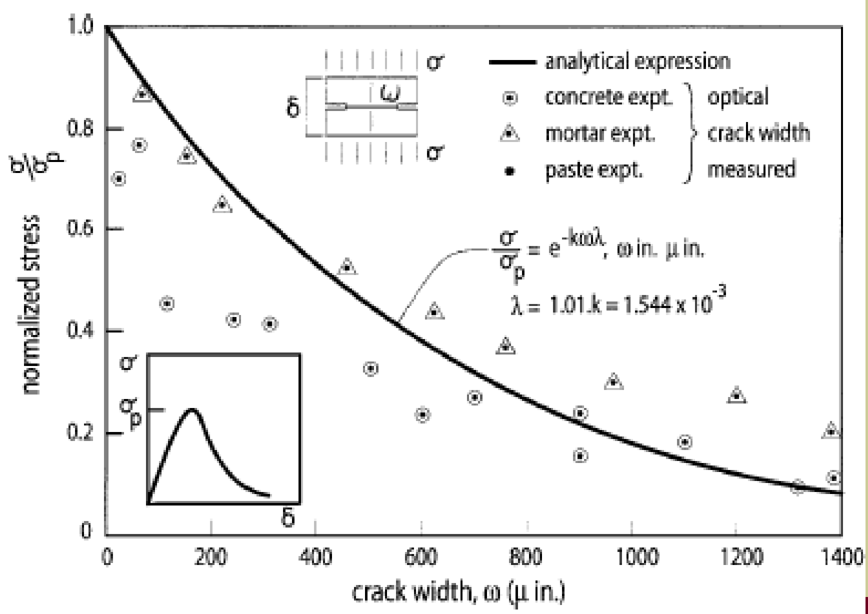
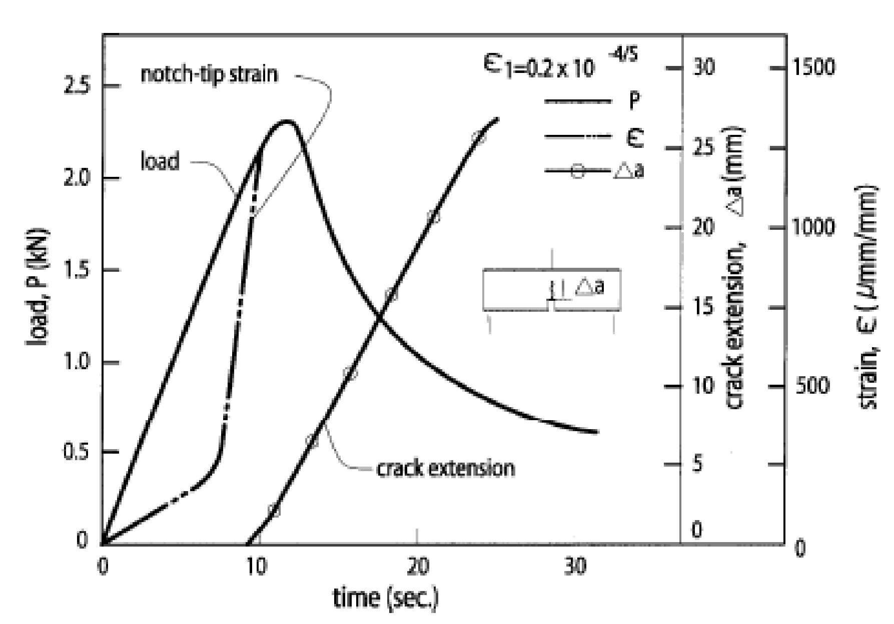


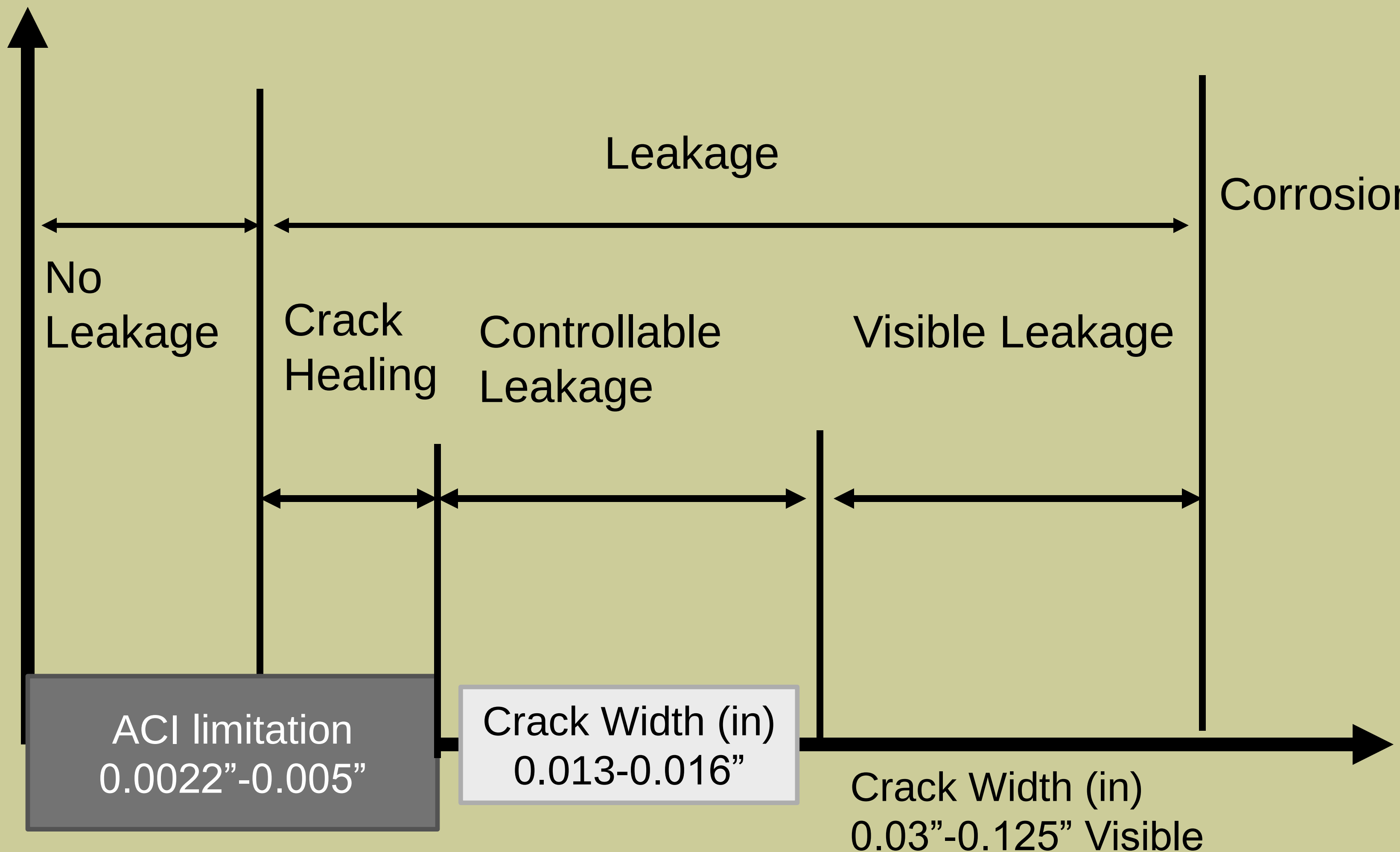
Fig. 2.8—Normalized peak stress versus crack width in unaxial tension (Gopalratnam and Shah 1986).



Reasonable Crack Widths in RC Under Service loads

exposure condition	crack width	
	in	mm
Dry Air or protective membranes	0.016	0.41
Humidity moist air, soil	0.012	0.3
Deicing chemicals	0.007	0.18
Seawater and seawater spray, wetting, drying	0.006	0.15
Water retaining structures	0.004	0.1

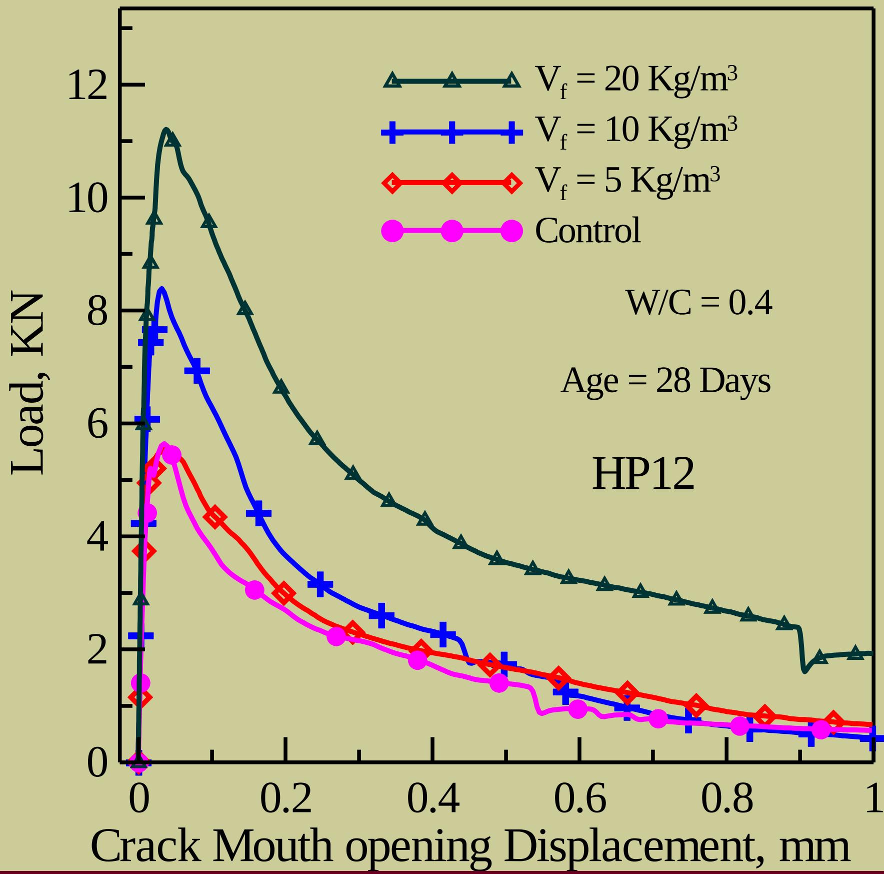
The Importance of Crack Width



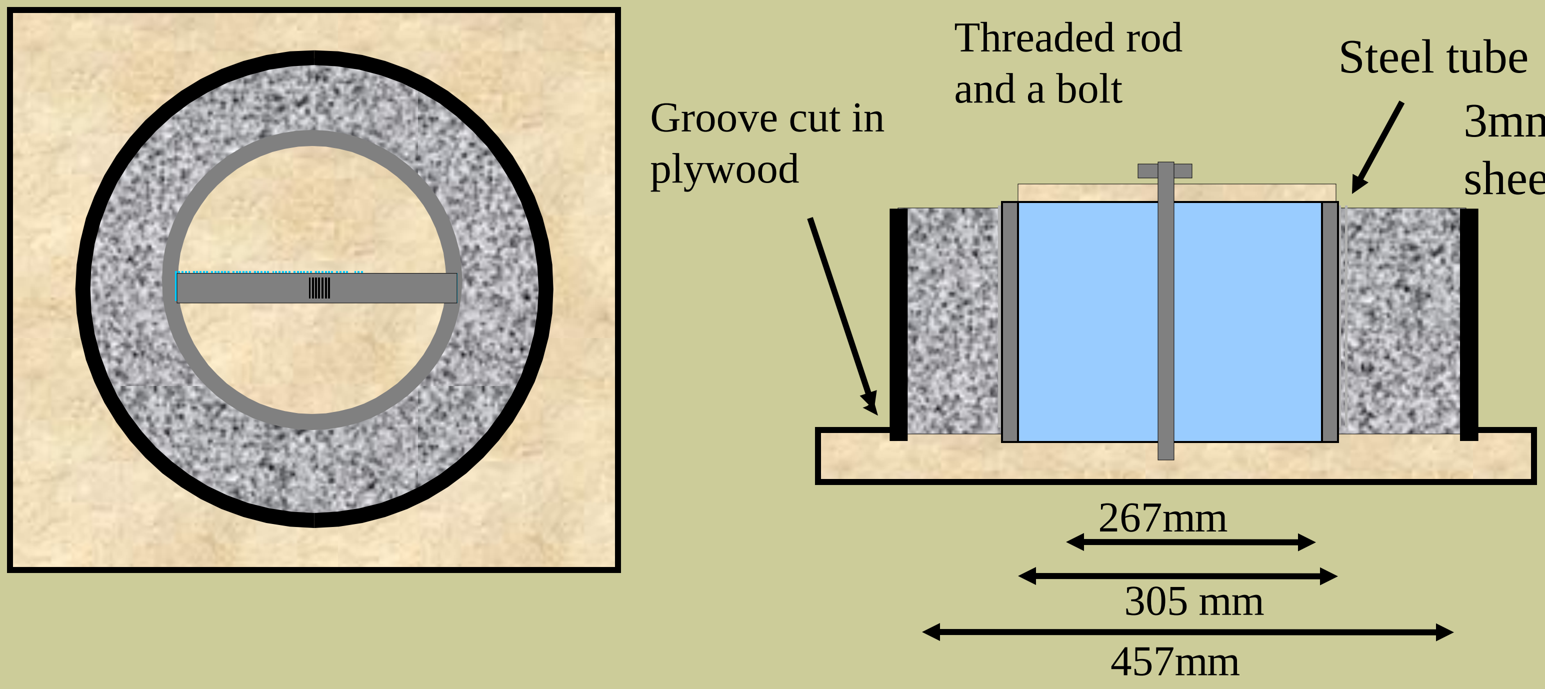
Use of Alkali Resistant Glass Fiber Reinforcement

St. Gobain Alkali resistant Glass Fibers

Role of Fibers in Toughening



Restrained Shrinkage Testing



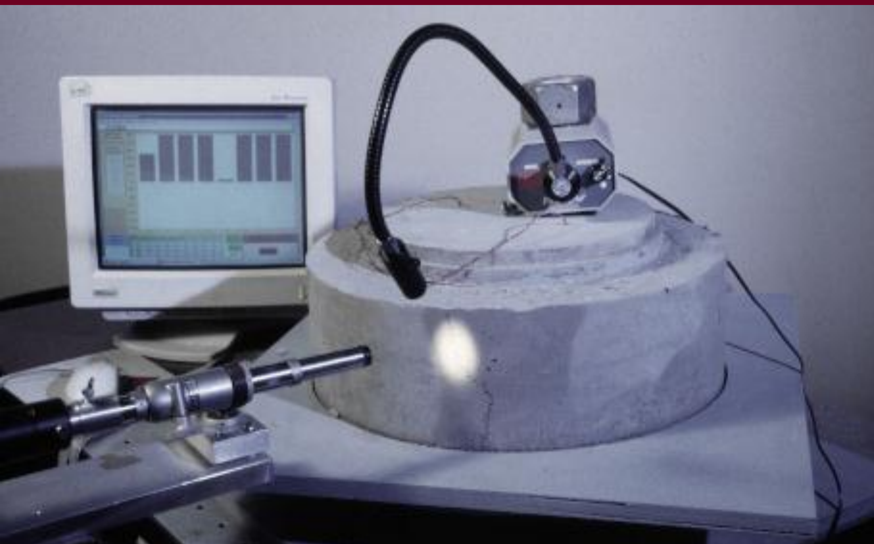
Grzybowski, M.; and Shah, S. P., "A Model to Predict Cracking in Fiber Reinforced Concrete Due to Restrained Shrinkage," ACI MATER J 87 (2):138-148 Mar-Apr 1990.

Experimental Program

restrained shrinkage specimens

Constant humidity chamber subjected to constant flow of air around the specimens.

Crack width Measurements using a microscope with a 10x objective



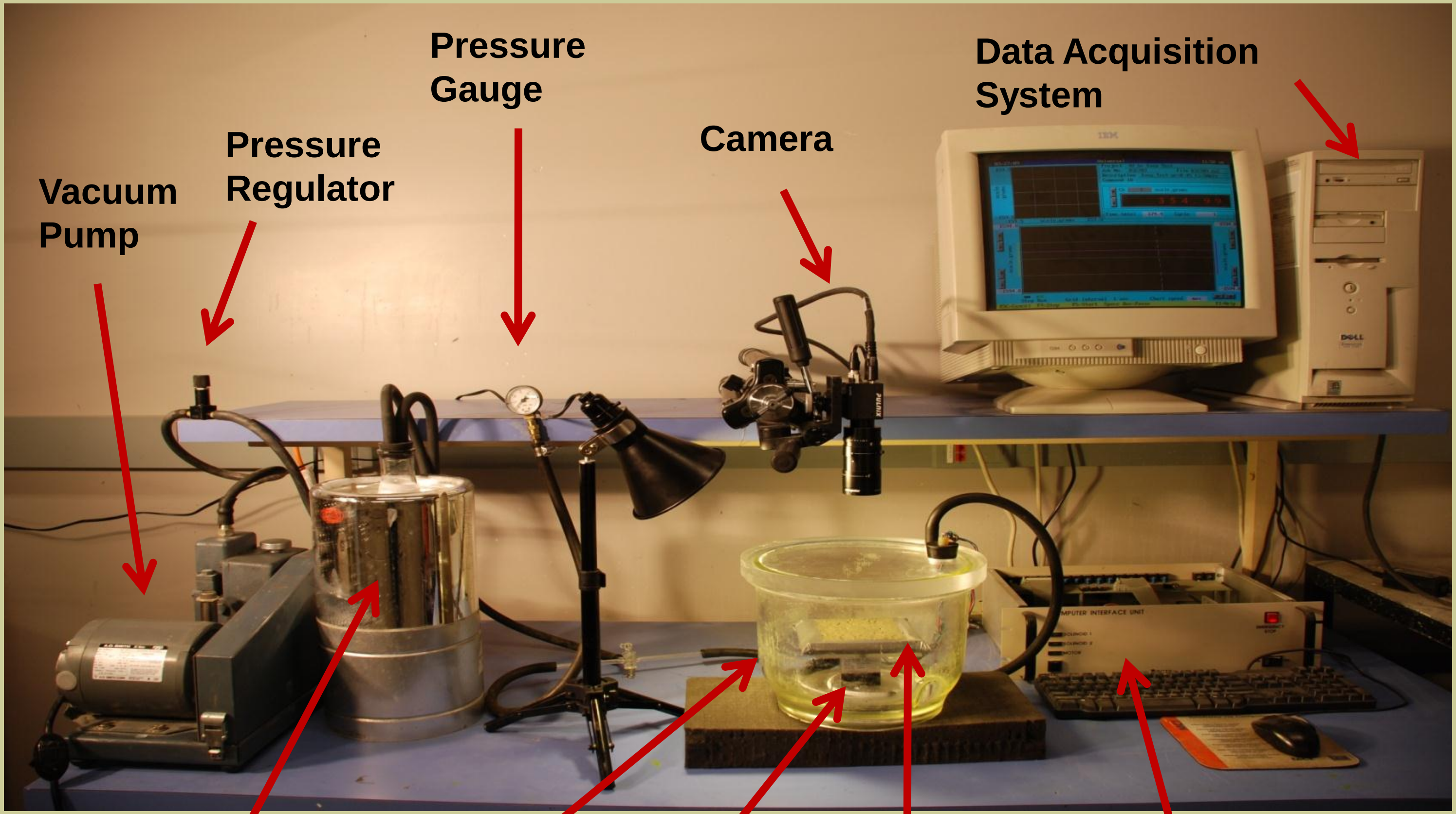
A- HD24

B- HP12

C- Control4

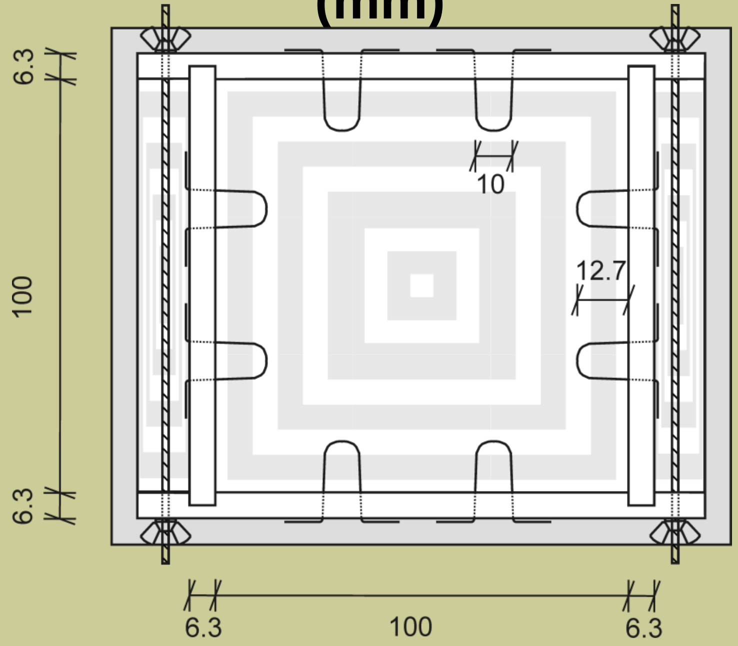
2. Shrinkage Cracking Test Setup

- Evaporation is simulated under low pressure condition.



Scale and Mold

Plan view and of the mold (mm)



- The mold consists of interlocking pieces made of Polycarbonate
- Anchor hooks are used to fully connect the paste with the mold, providing restraints in two directions
- Load cell serves a scale after calibration to weigh the sample continuously.

Effect of Initial Curing Duration

- Cumulative moisture loss:

  Decreased from 65 to 49 and 26 g

  Translates to 24% and 60% reduction

- Evaporation rate:
  - Initial Evaporation rate:

  decreased from 0.42 to 0.39 and 0.34
  - Evaporation rate at 12 h:

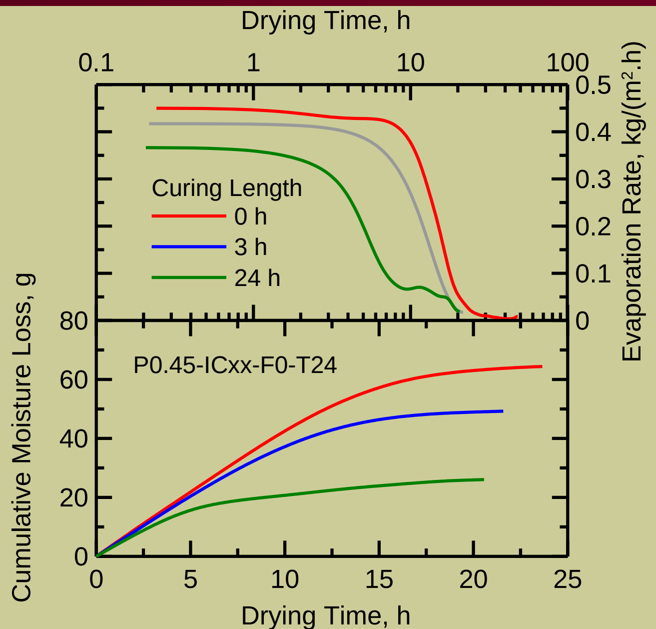
  decreased from 0.3 to 0.2 and 0.07 kg/(m^2h)

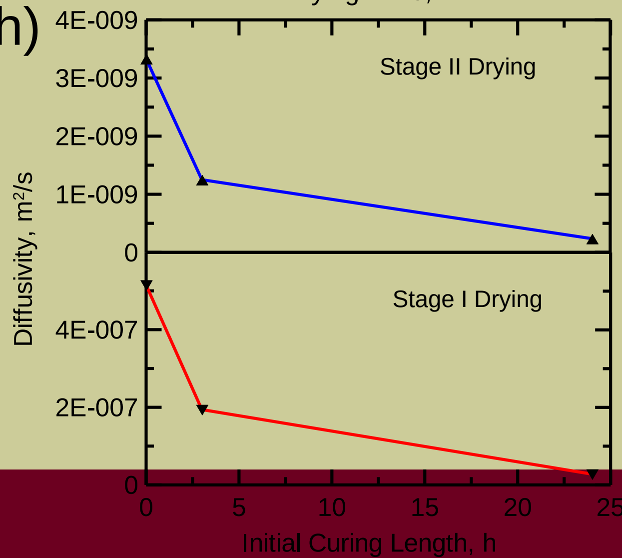
- Transition time:

  Changed from 9.7 h to 7.3 h and 3 h

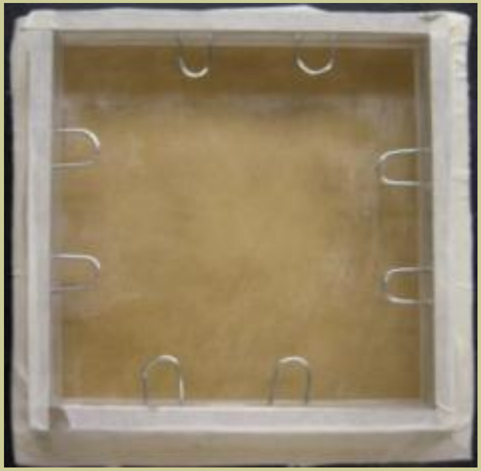
- Moisture diffusivity:

  D decreased by as much as 62% and 93%



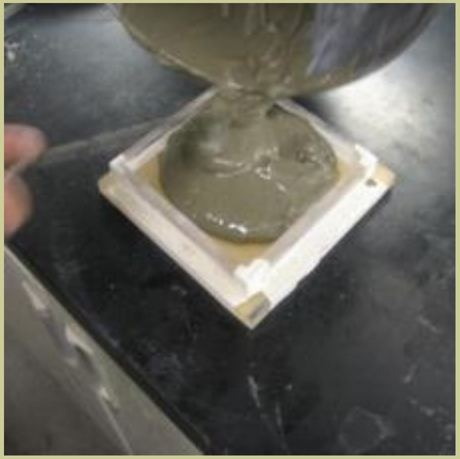


Stages of Drying Cement Paste in Vacuum Vessel



Restrained Molds
(4” × 4” × 0.5”)

casting



Pouring cement paste

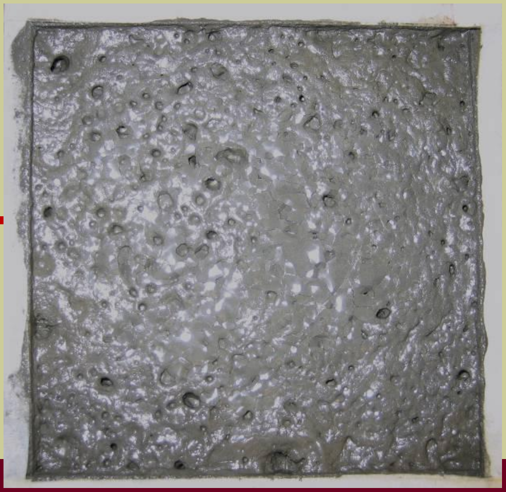
t = 30 min

A film of water on surface

t = 1 hr

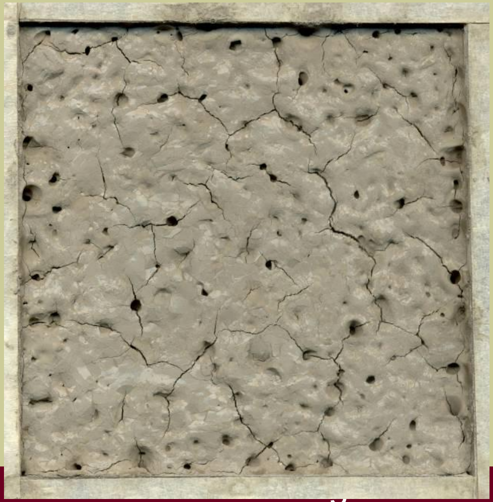
No layer of water on surface

t = 2 hr



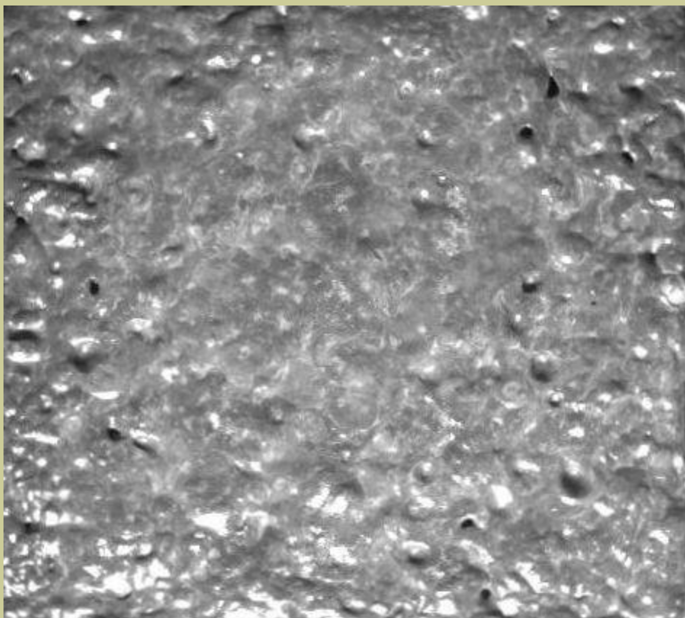
Formation of voids on paste surface

t = 4 hr

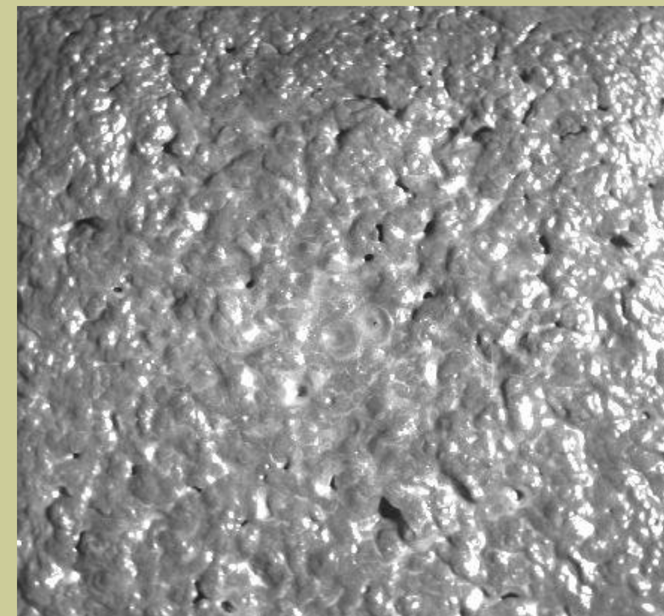


ing
cracking on paste surface

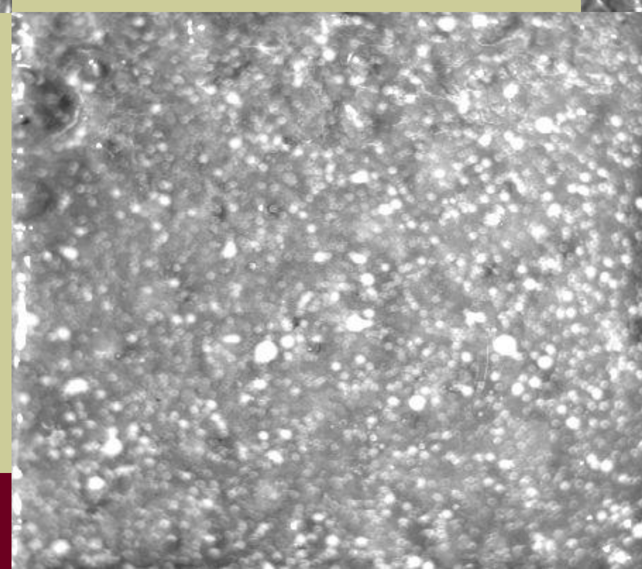
Time-Lapse Photography (Effect of w/c ratio)



w/c = 0.45



w/c = 0.55



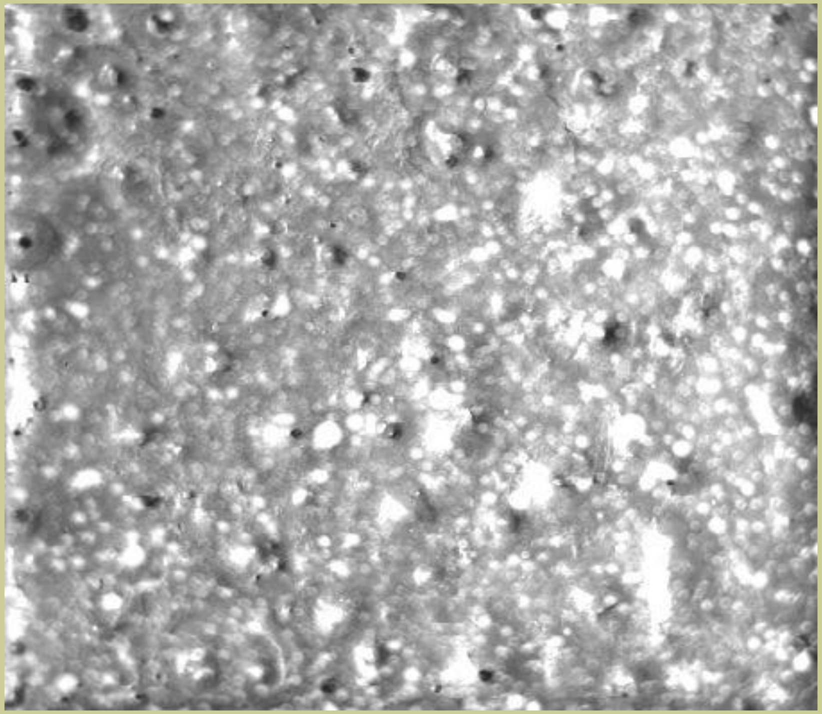
w/c = 0.65

Drying Time:

07:00

Results of Time-Lapse Photography

Paste



Fabric Reinforced Paste

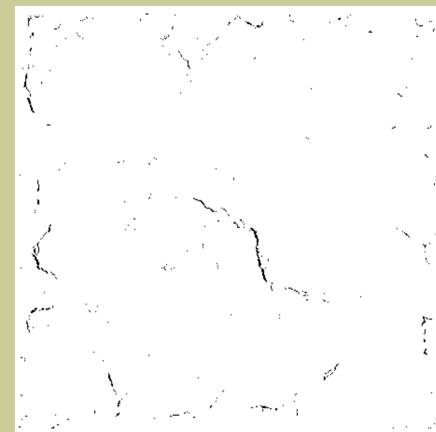
Drying Time:

07:00

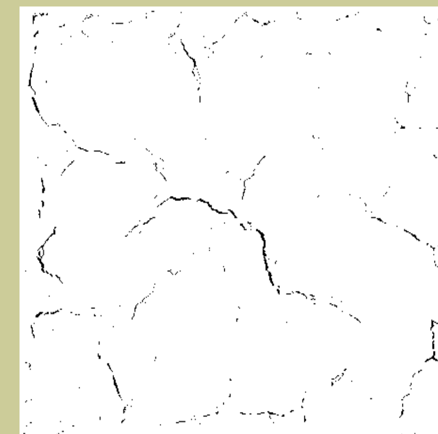
Crack Pattern Evolution

after 3.5 h

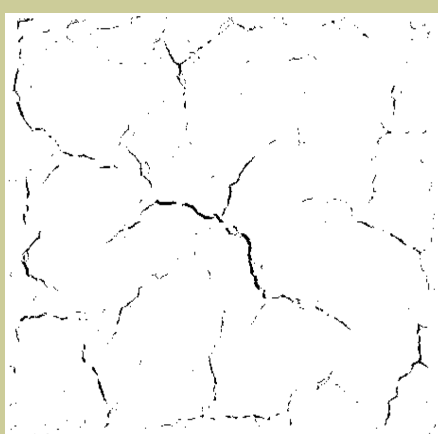
after 3.75 h



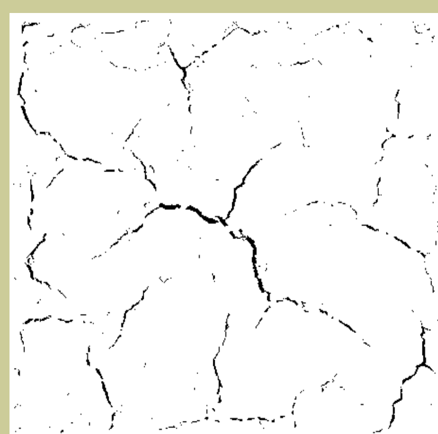
after 4 h



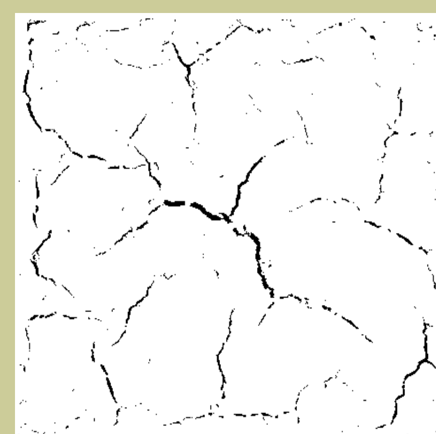
after 4.25 h



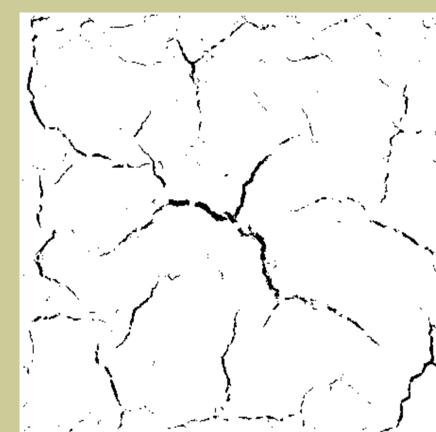
after 4.5 h



after 4.75 h

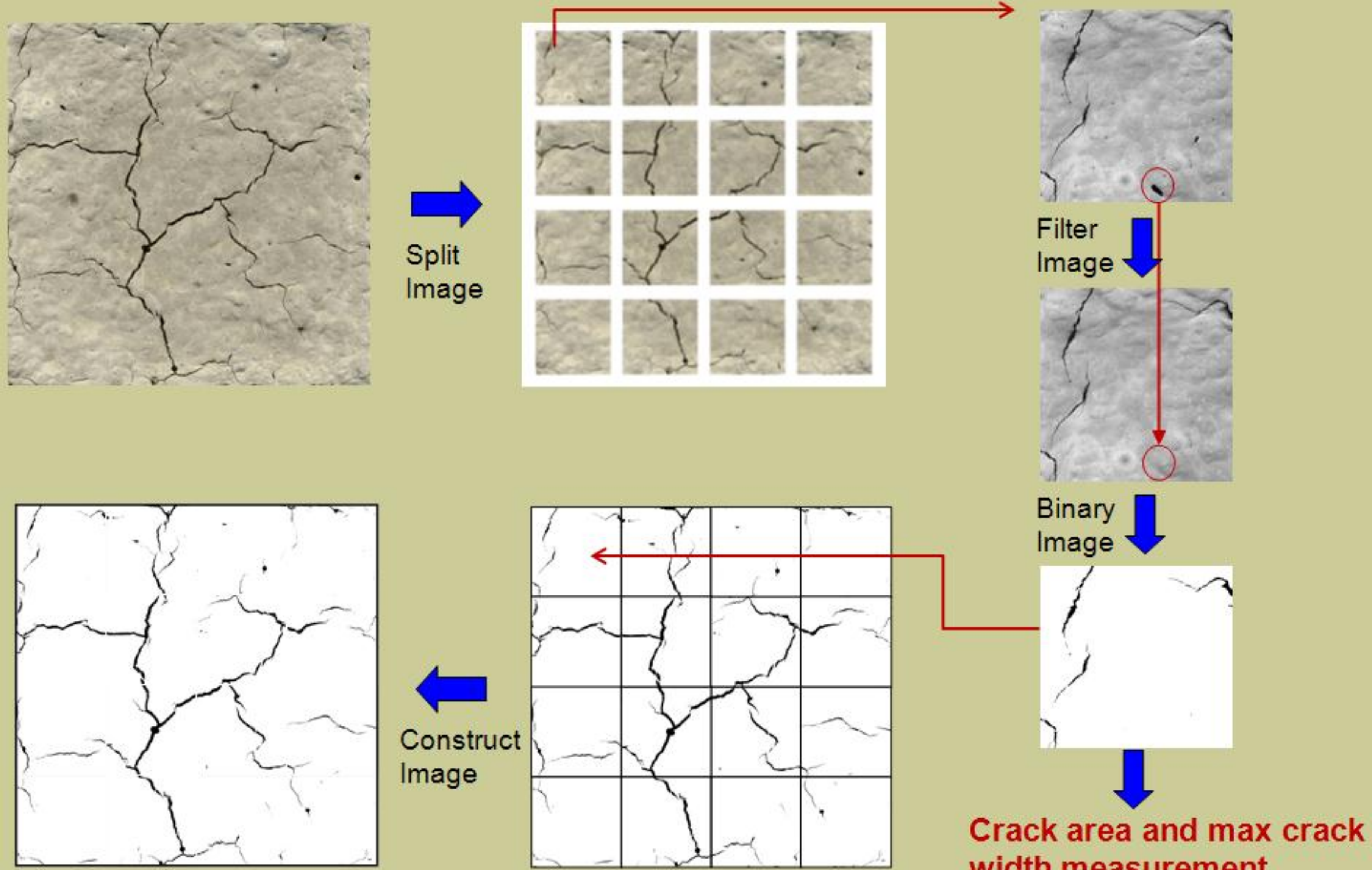


after 5 h



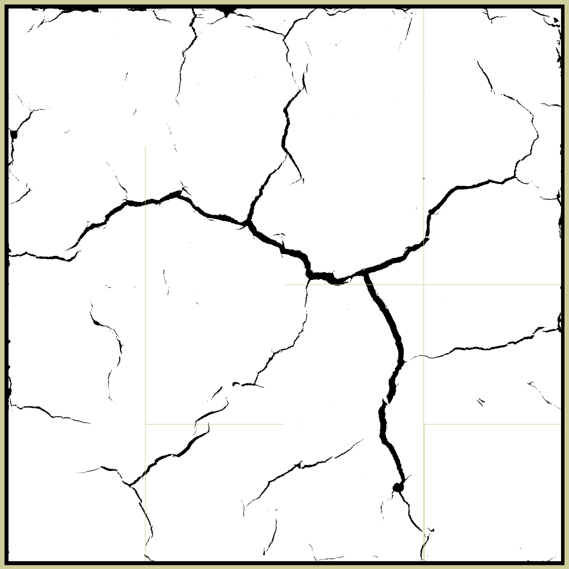
after 4.25 h

Image Analysis Process

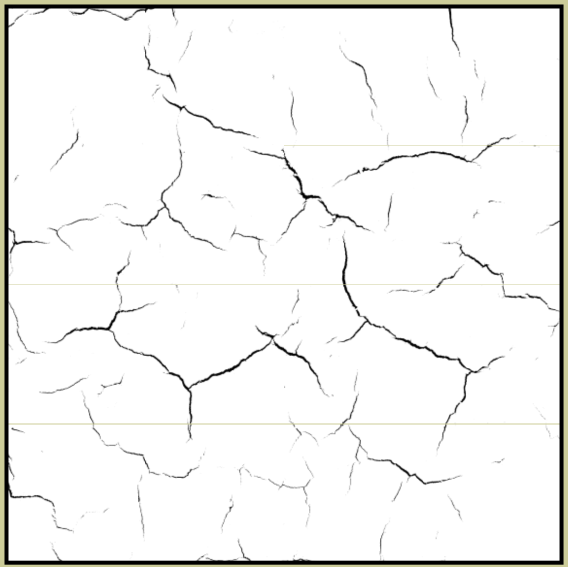


Results of image analysis on 2D cracks

Plain Concrete



Fiber content = 3 kg/m^3



Fiber content = 6 kg/m^3

Test Series	Max. Crack Width (mm)	Reduction in Max. Crack Width by Adding Fiber (%)	Areal Fraction of Cracks (mm2/mm2)	Reduction of Crack Area by Adding Fiber (%)
F0	**1.28**	-	**0.018**	-
F3	**0.68**	47%	**0.014**	25%
F6	**0.37**	134%	**0.007**	84%

Conclusions

- Shrinkage in concrete materials is a major durability concern.
- Adequate Curing, minimizing paste content, using largest aggregate size, reducing water remand, and novel admixtures are some the methods of mitigation of shrinkage cracking.
- Fibers provide internal bridging mechanisms for the closure of the cracks.
- Test methods and modeling techniques can be used to better address the performance of concrete materials

Acknowledgements

- ADOT Materials Group- Paul Sullivan
- ADOT Research Center- Christ Dimitroplos