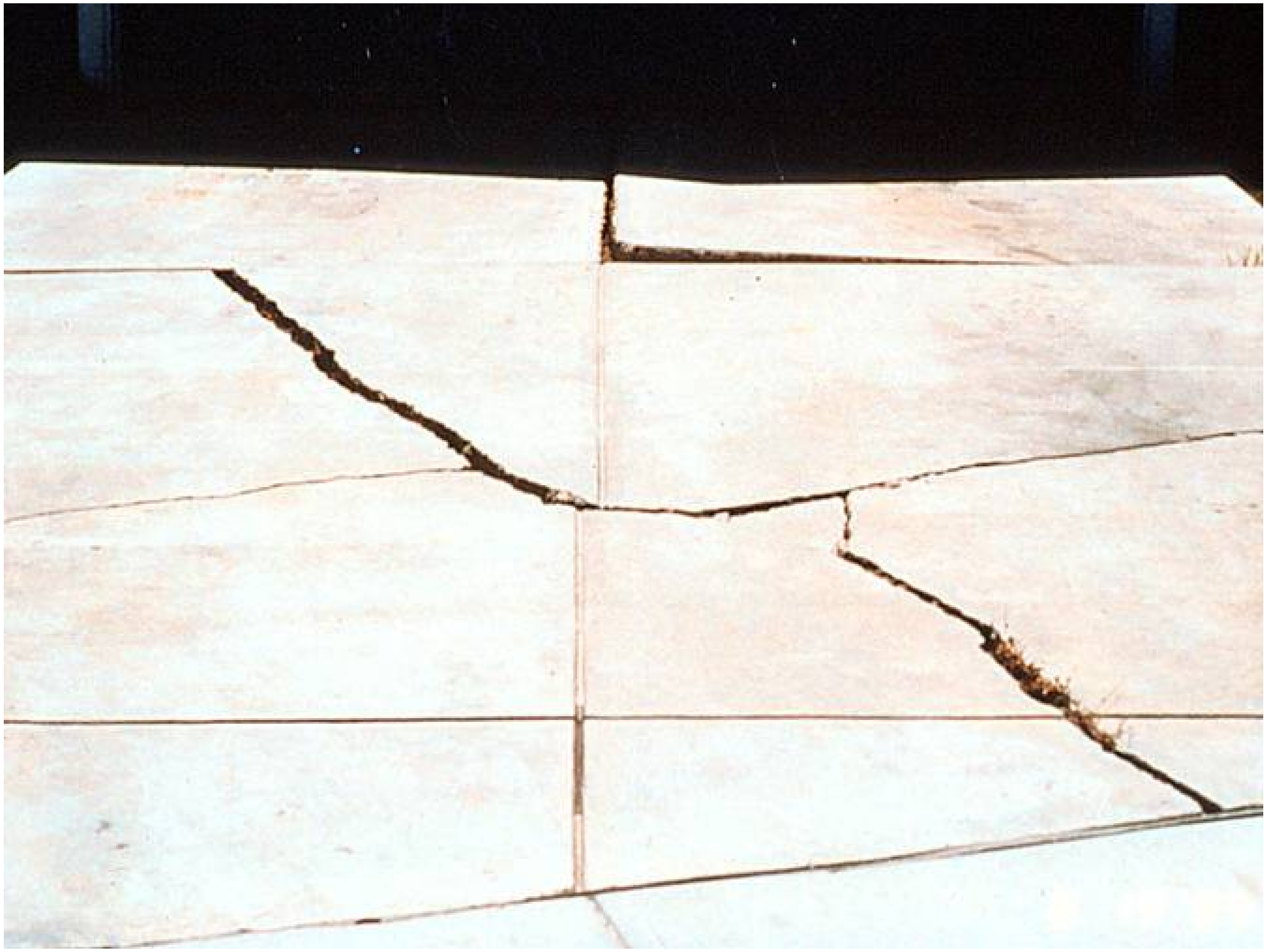
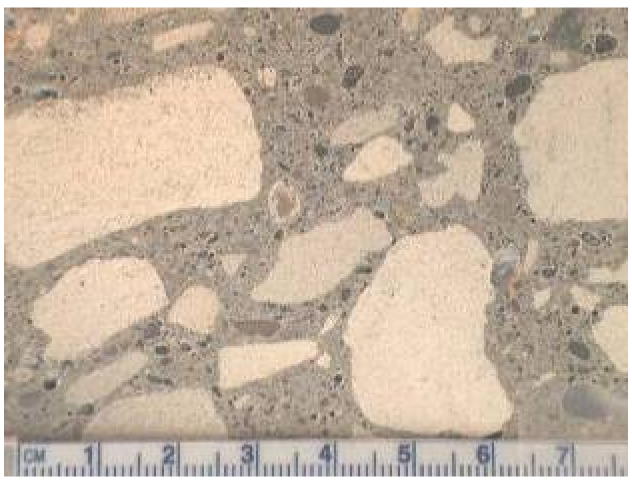
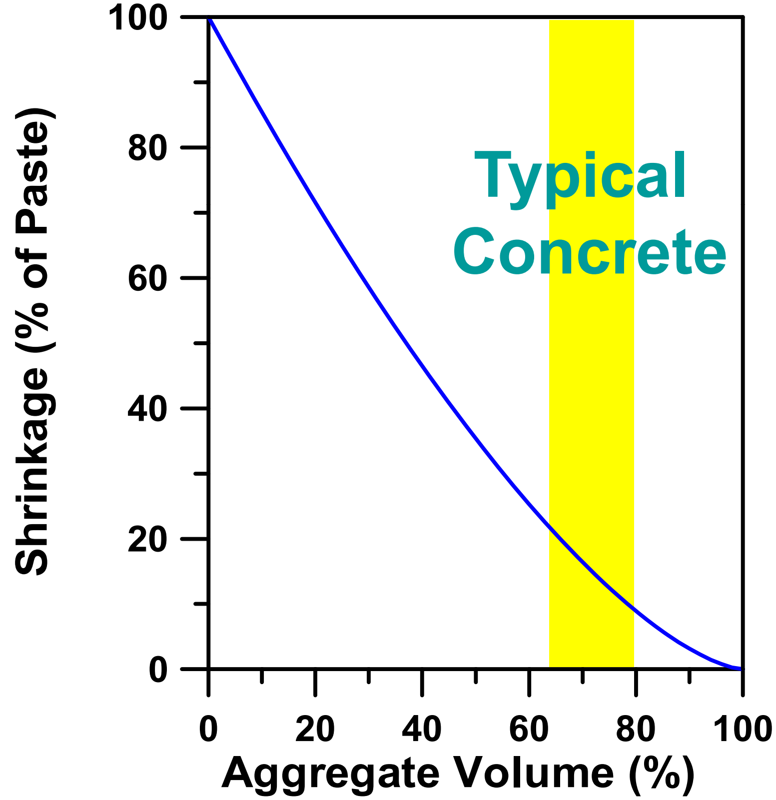
Volume Changes

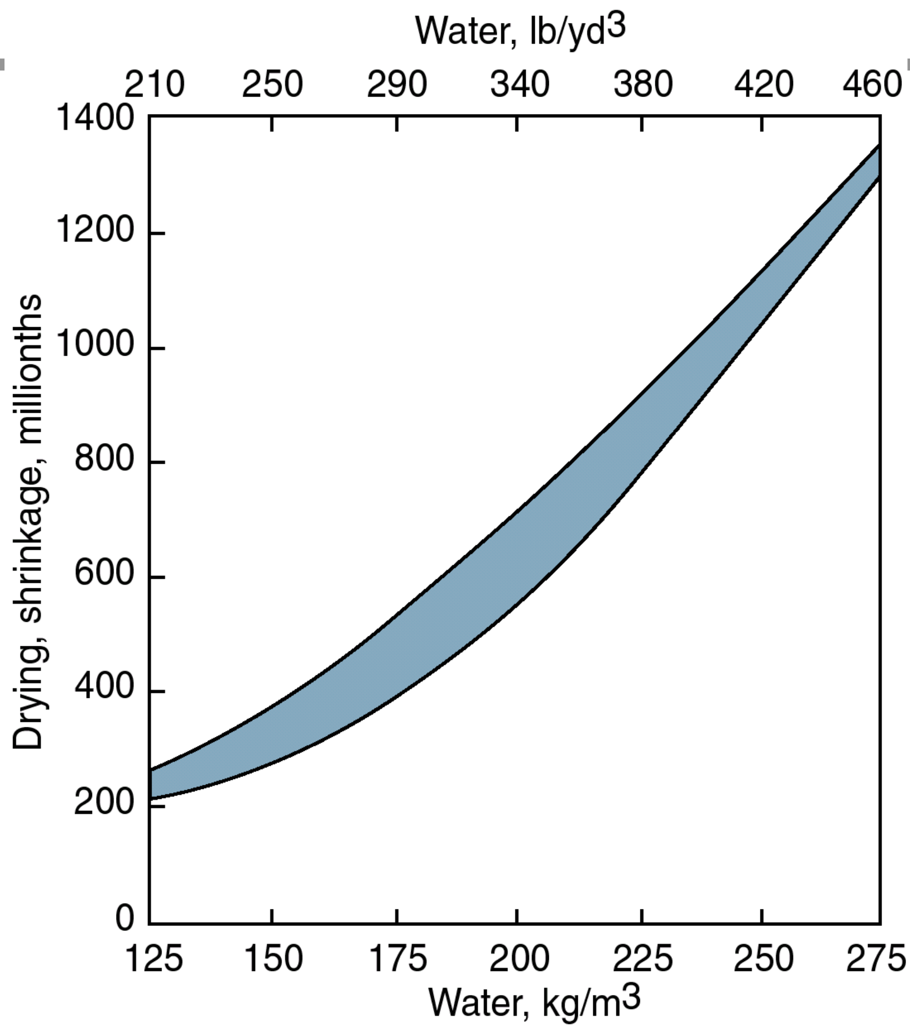


Concrete Shrinkage is Driven by Cement Paste





Concrete Shrinkage



- Concrete mixtures influence:
  - Low water content
  - High aggregate content
  - Max aggregate size

Thermal Dilation

- Coefficient of Thermal Expansion (dilation)
  - For concrete, it is about $10 \times 10^{-6}/°C$
  - For fresh concrete, it is about $70 \times 10^{-6}/°C$
- Transition during “set”
  - What if the material is hot during set?
    - Stress when cooling
    - Furthermore, CTE is changing

Question

- How do drying shrinkage stresses affect the size of internal pores?
- How does external restraint influence the problem?

Experiment

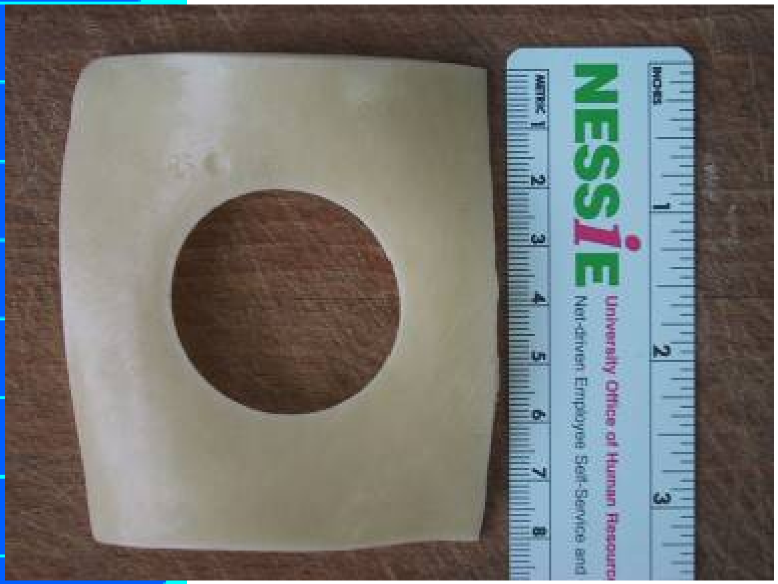
- Unrestrained and restrained conditions
- Original hole diameter = 4 cm

Drying conditions

- kitchen counter for 3 days

Results

- Unrestrained cheese
  - 11% shrinkage of cheese side dimension
  - 9% reduction in hole diameter



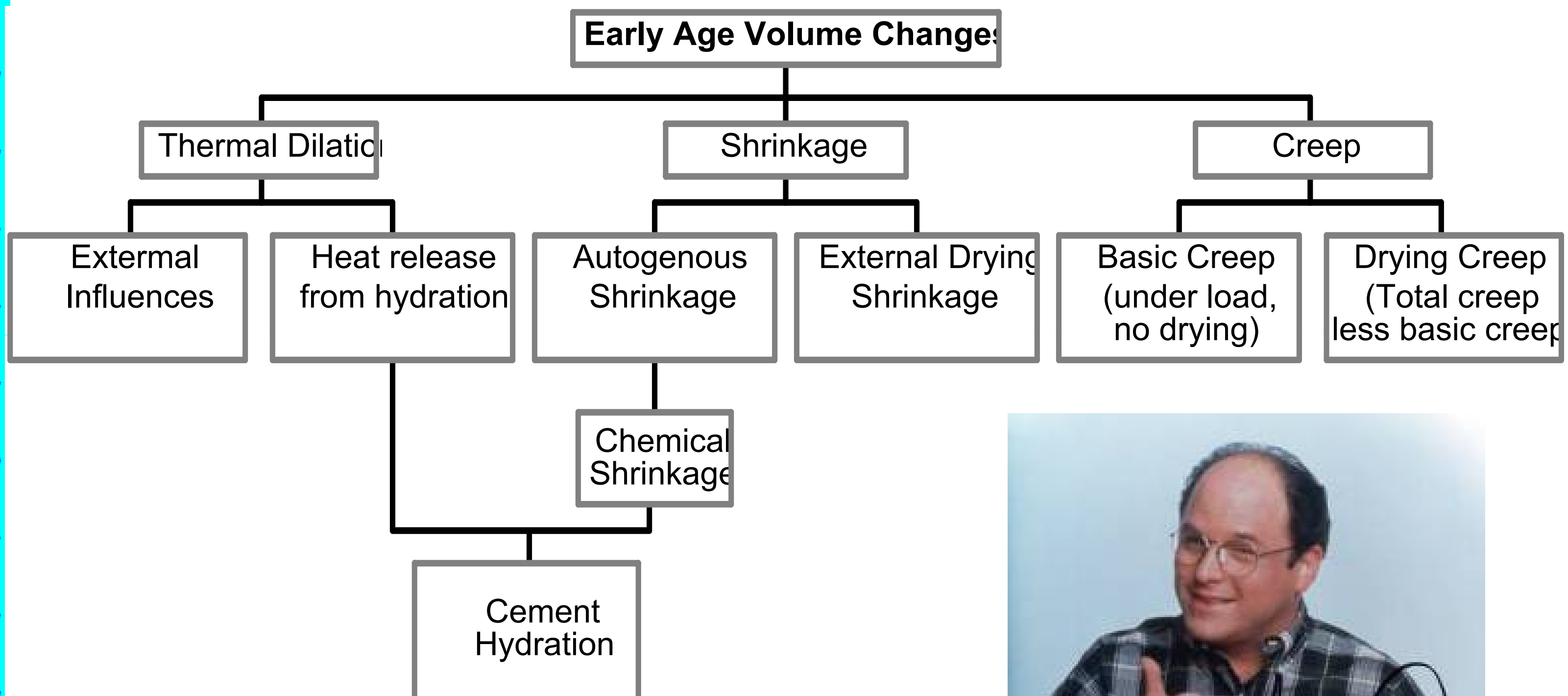
Results

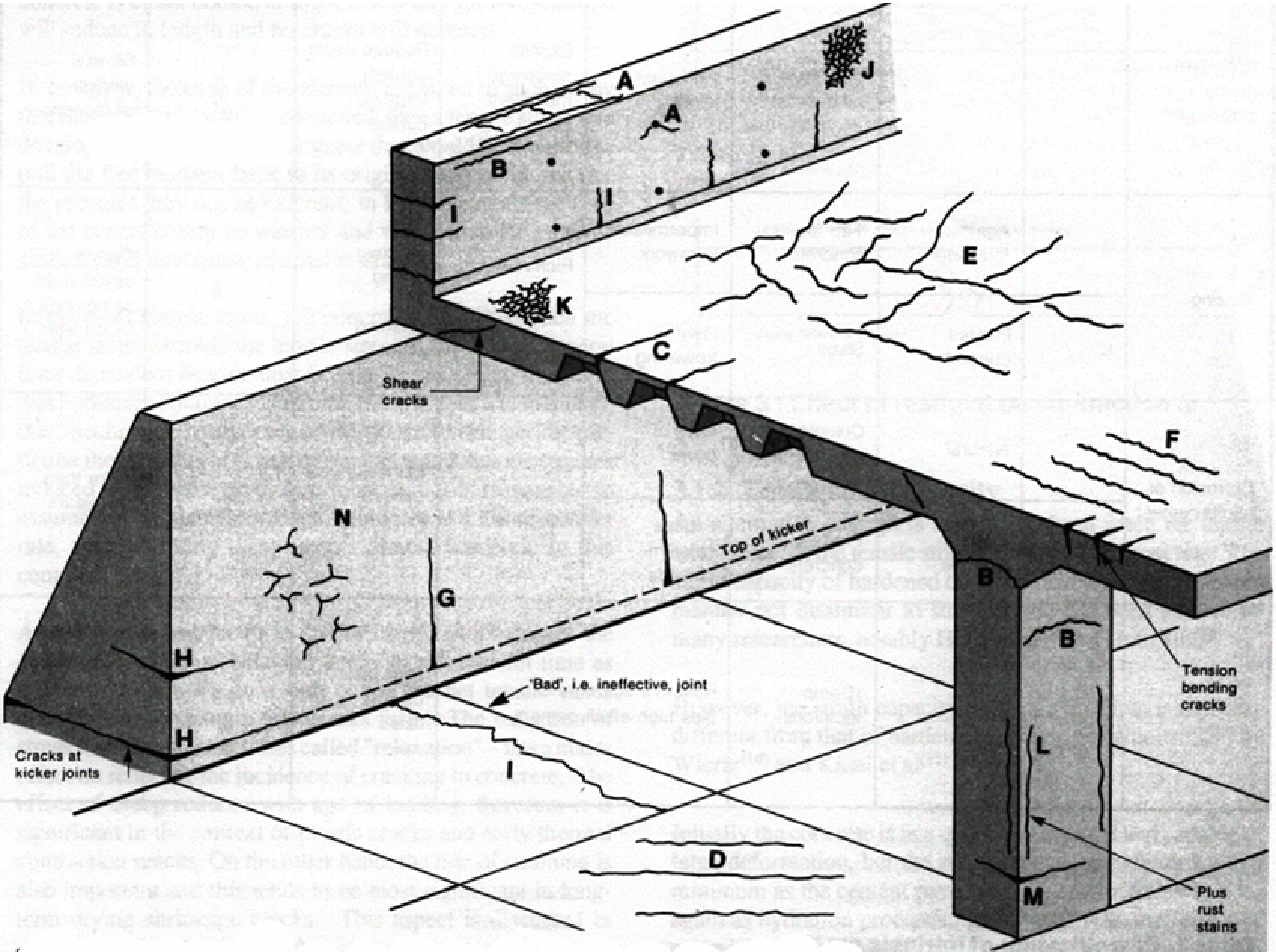
- Restrained cheese
  - ~0% shrinkage of cheese side dimension
  - 6% increase in hole diameter

Findings

- External restraint of shrinking cheese causes a dilation of internal holes
- Hoop stresses around the hole perimeter counteract tendency to dilate
- Thus, observed magnitude of dilation is lower than overall shrinkage

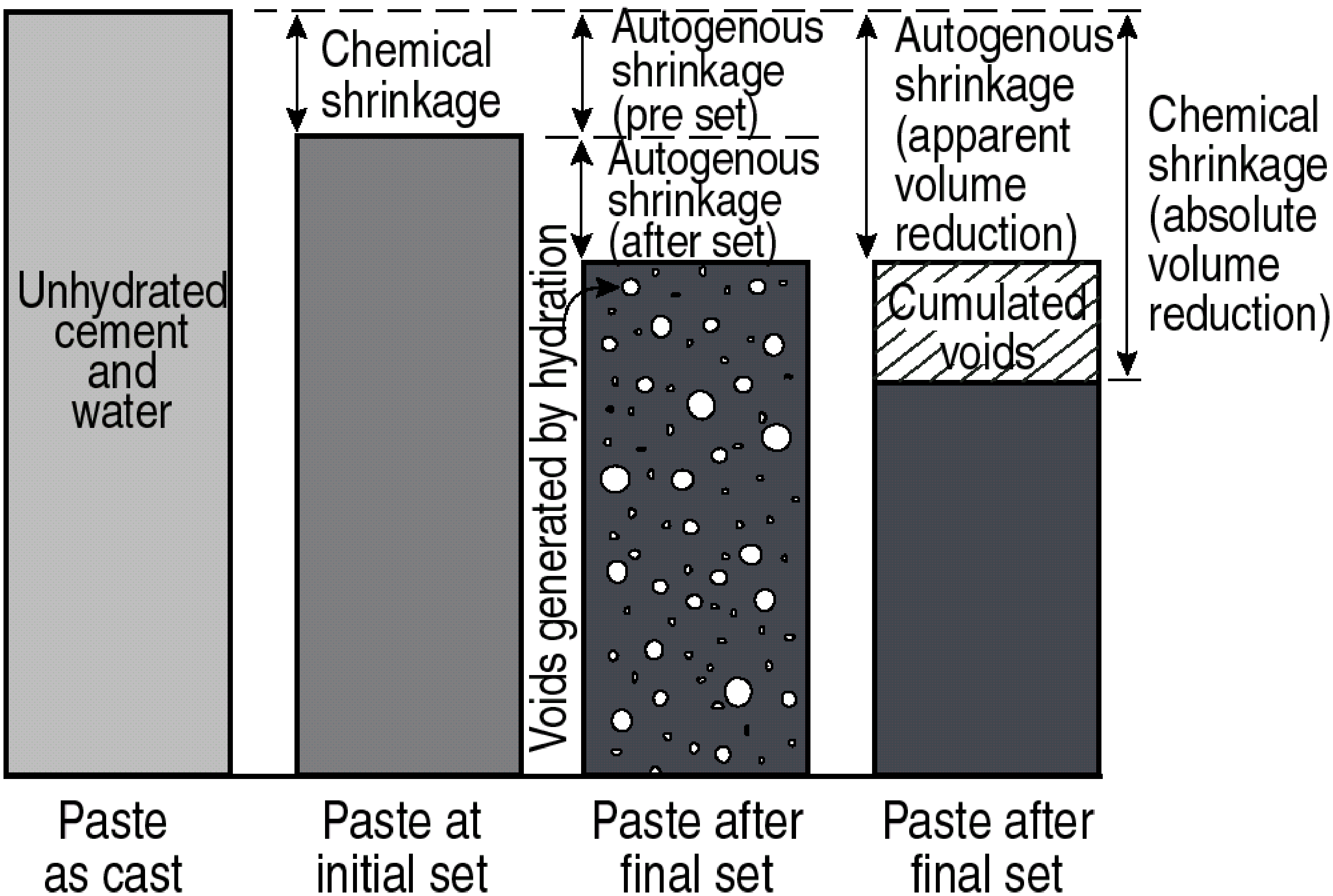
Volume Change Mechanisms Within Concrete



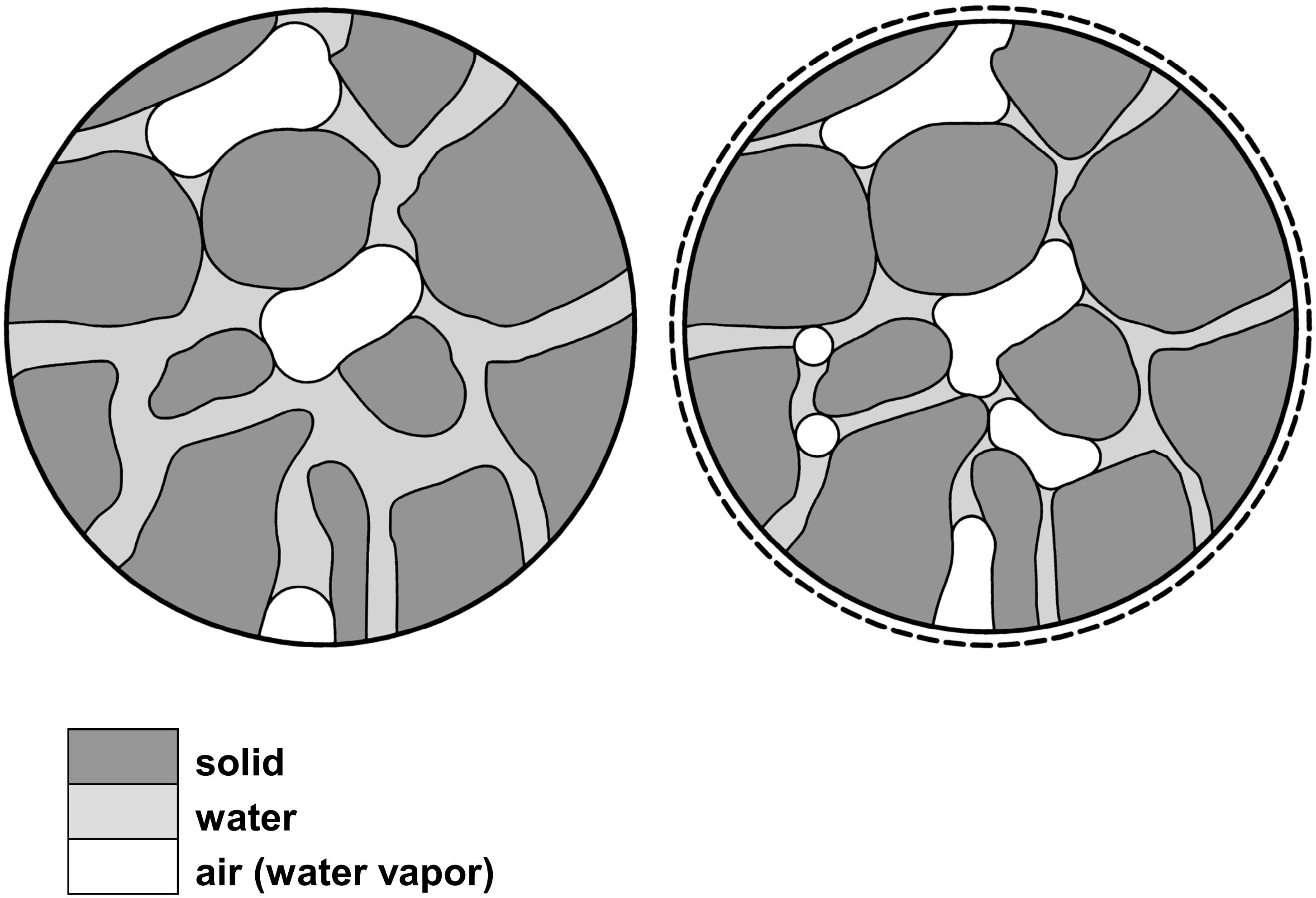

A
A
J
B
I
I
E
K
C
Shear cracks
F
N
Top of kicker
G
B
B
H
H
'Bad', i.e. ineffective, joint
Tension bending cracks
Cracks at kicker joints
I
L
D
M
Plus rust stains

Letter	Type of Cracking	Subdivision	Most Common Location	Primary Cause (excluding restraint)	Secondary Causes/Factors	Time of Appearance
A	Plastic settlement	Over reinforcement	Deep sections	Excess bleeding	Rapid early drying conditions	Ten minutes to three hours
B		Arching	Top of columns			
C		Change of depth	Trough and waffle slab			
D	Plastic shrinkage	Diagonal	Roads and slabs	Rapid early drying	Low rate of bleeding	Thirty minutes to six hours
E		Random	Reinforced concrete slabs			
F		Over reinforcement	Reinforced concrete slabs	Ditto plus steel near surface		
G	Early thermal contraction	External restraint	Thick walls	Excess heat generation	Rapid cooling	One day or two or three weeks
H		Internal restraint	Thick slabs	Excess temperature gradients		
I	Long-term drying shrinkage		Thin slabs (and walls)	Inefficient joints	Excessive shrinkage inefficient curing	Several weeks or months
J	Crazing	Against formwork	"Fair faced" concrete	Impermeable formwork	Rich mixes	One to seven days, sometimes much later
K		Floated concrete	Slabs	Over troweling	Poor curing	
L	Corrosion of reinforce-ment	Natural	Columns and beams	Lack of cover	Poor quality concrete	More than two years
M		Calcium chloride	Precast concrete	Excess calcium chloride		
I	Alkali-aggregate reaction		(Damp locations)	Reactive aggregate plus high-alkali cement		More than five years

Chemical and Autogenous Shrinkage

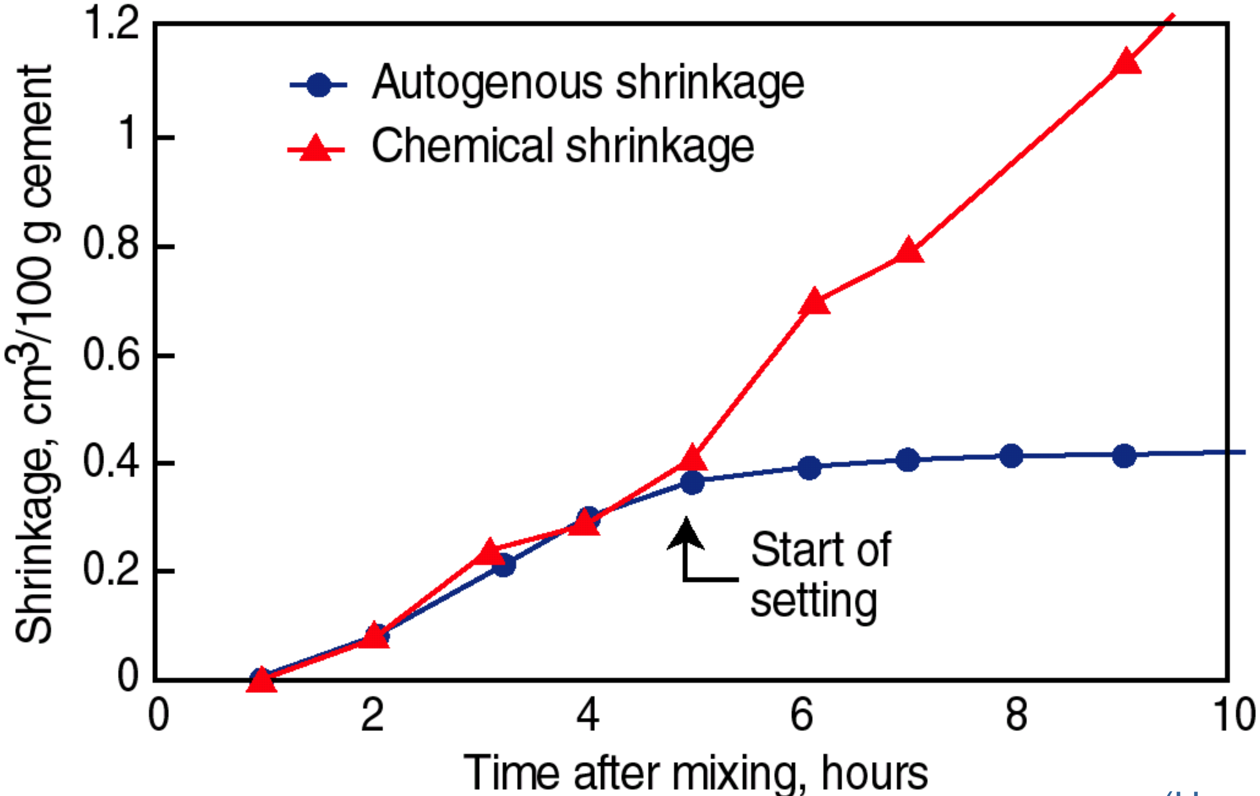


Self-desiccation



Jensen & Hansen, 2001

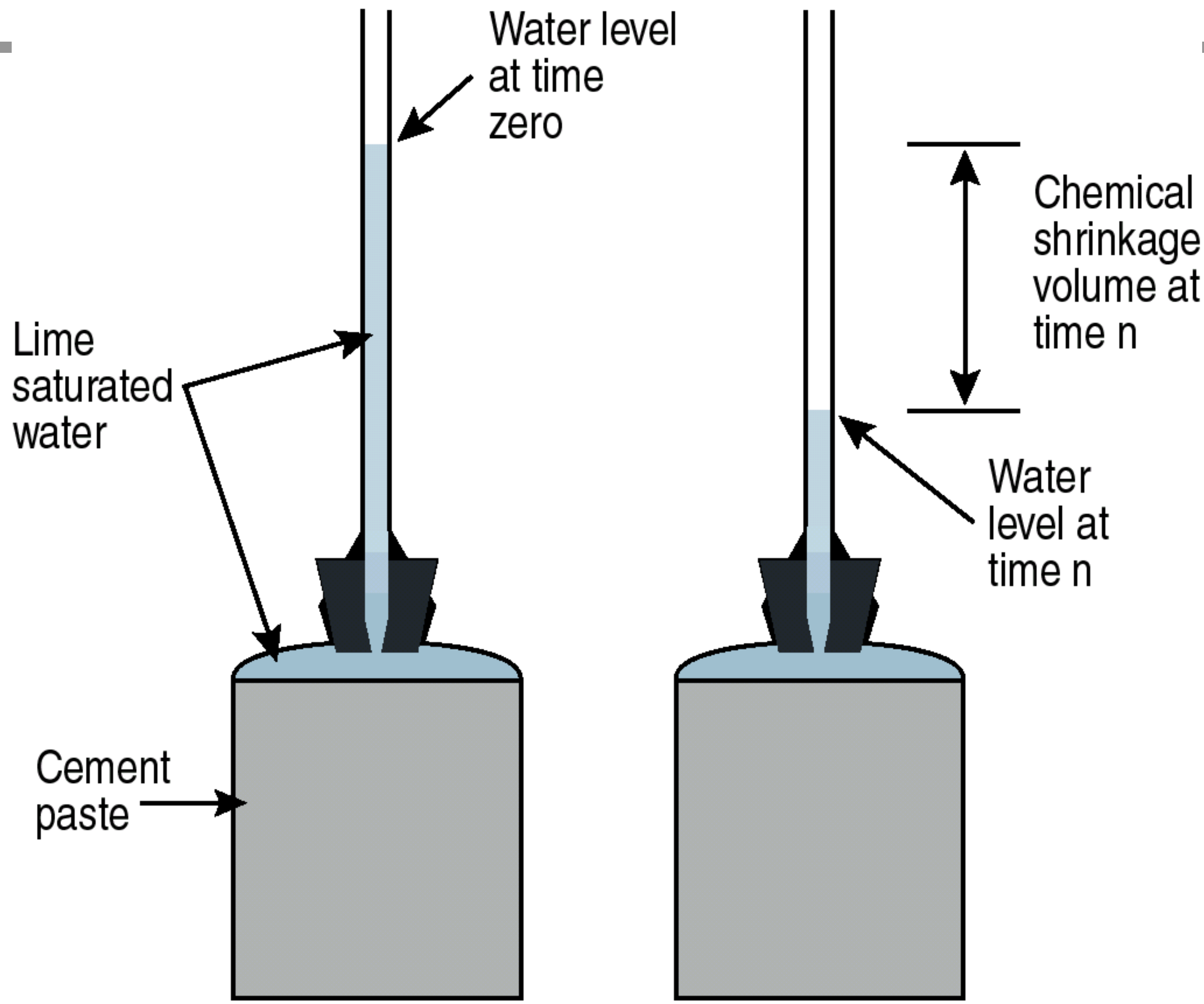
Autogenous Shrinkage vs. Chemical Shrinkage



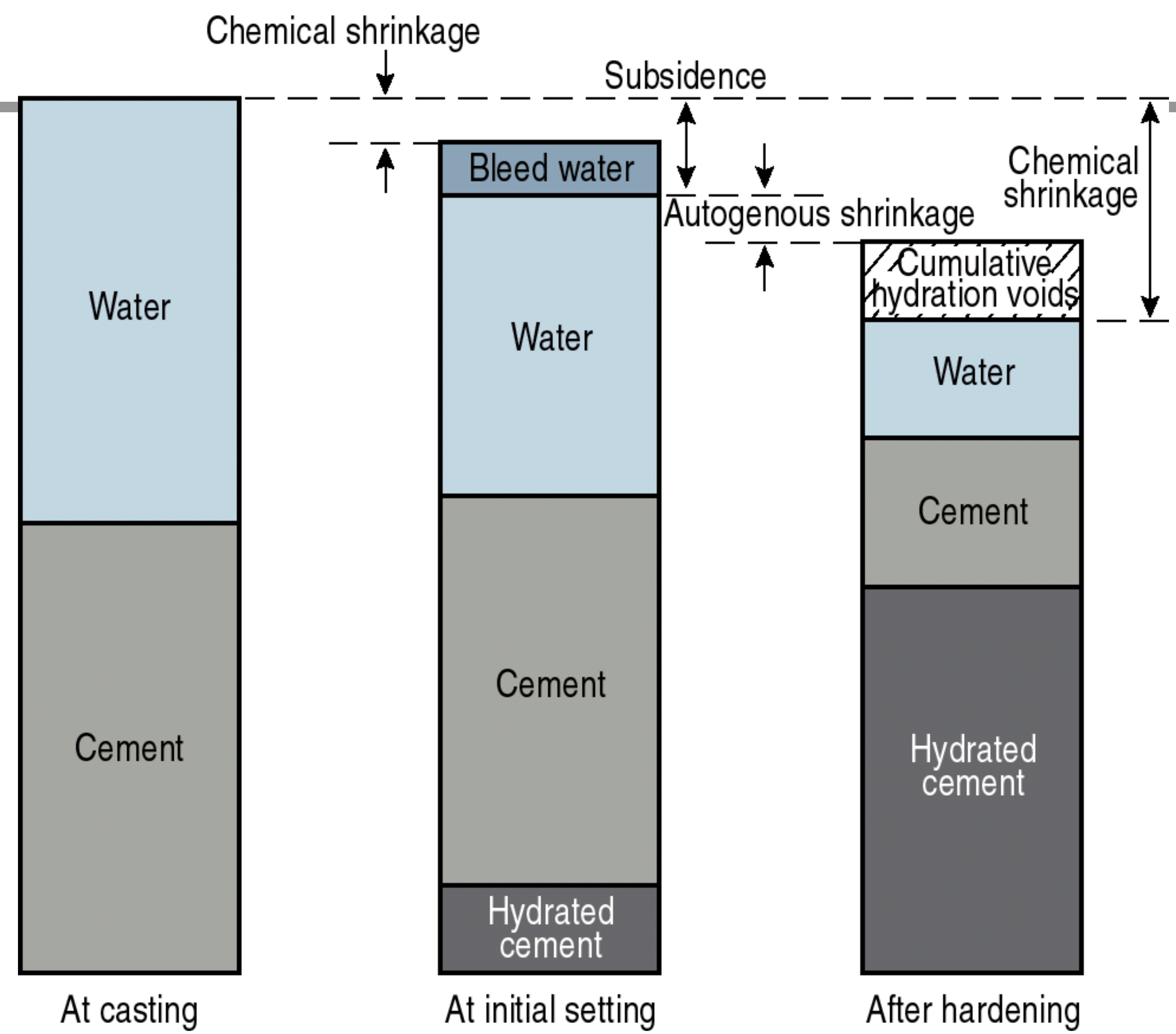
(Hammer 1999)

The diversion of chemical and autogenous shrinkage has been proposed to define "set"

Test for Chemical Shrinkage

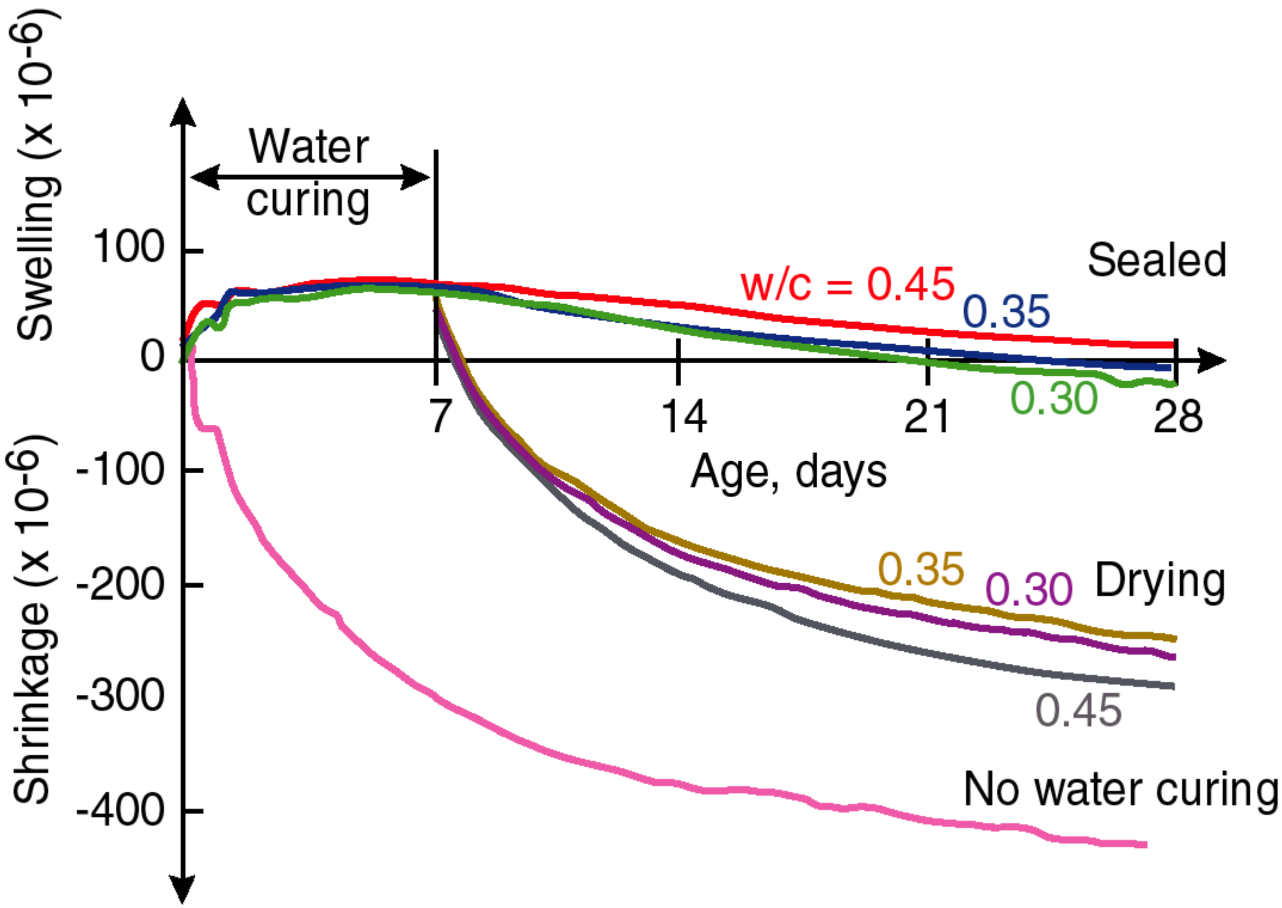


Volumetric Relationship



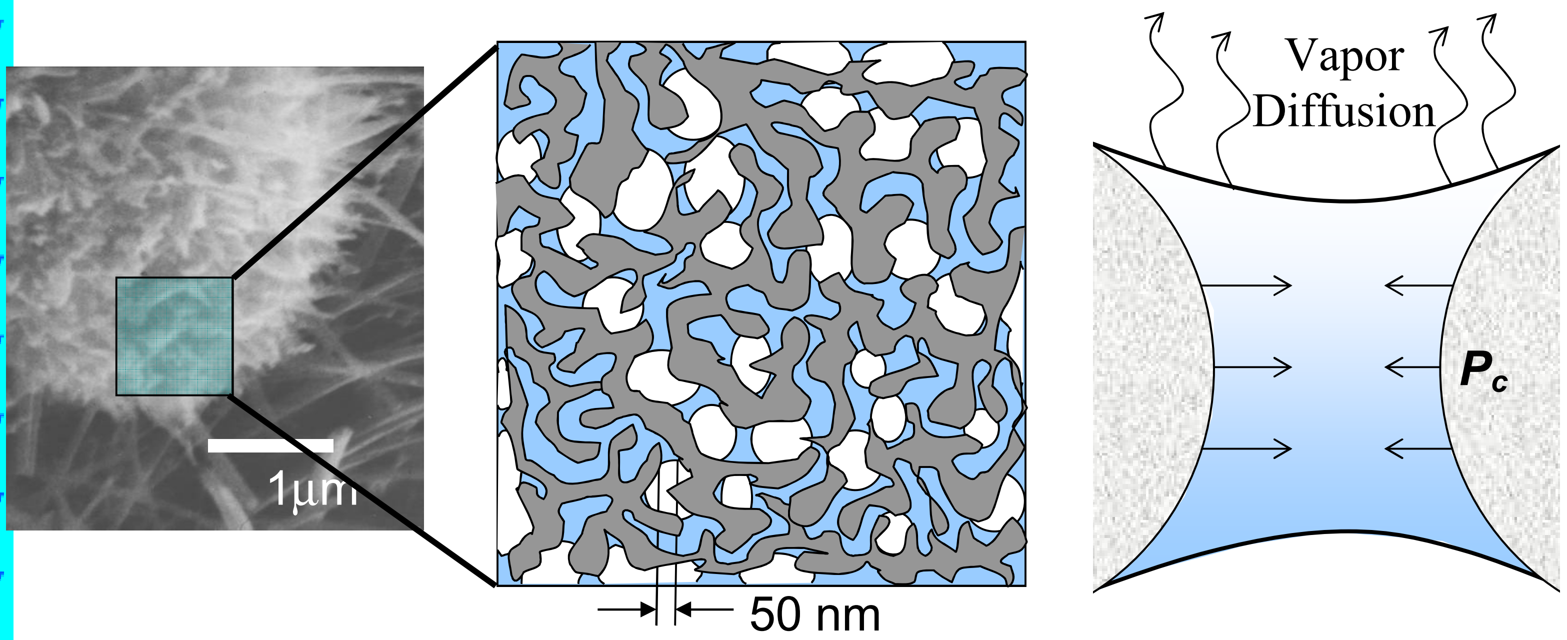
Plastic Shrinkage

Influence of Curing on Swelling and Shrinkage

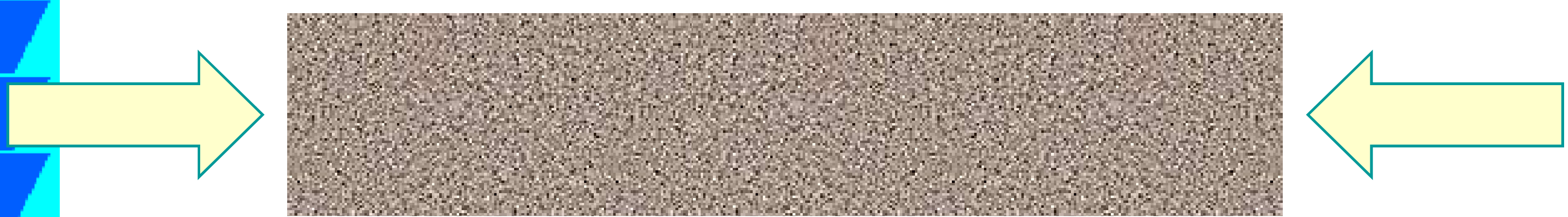


Drying Shrinkage

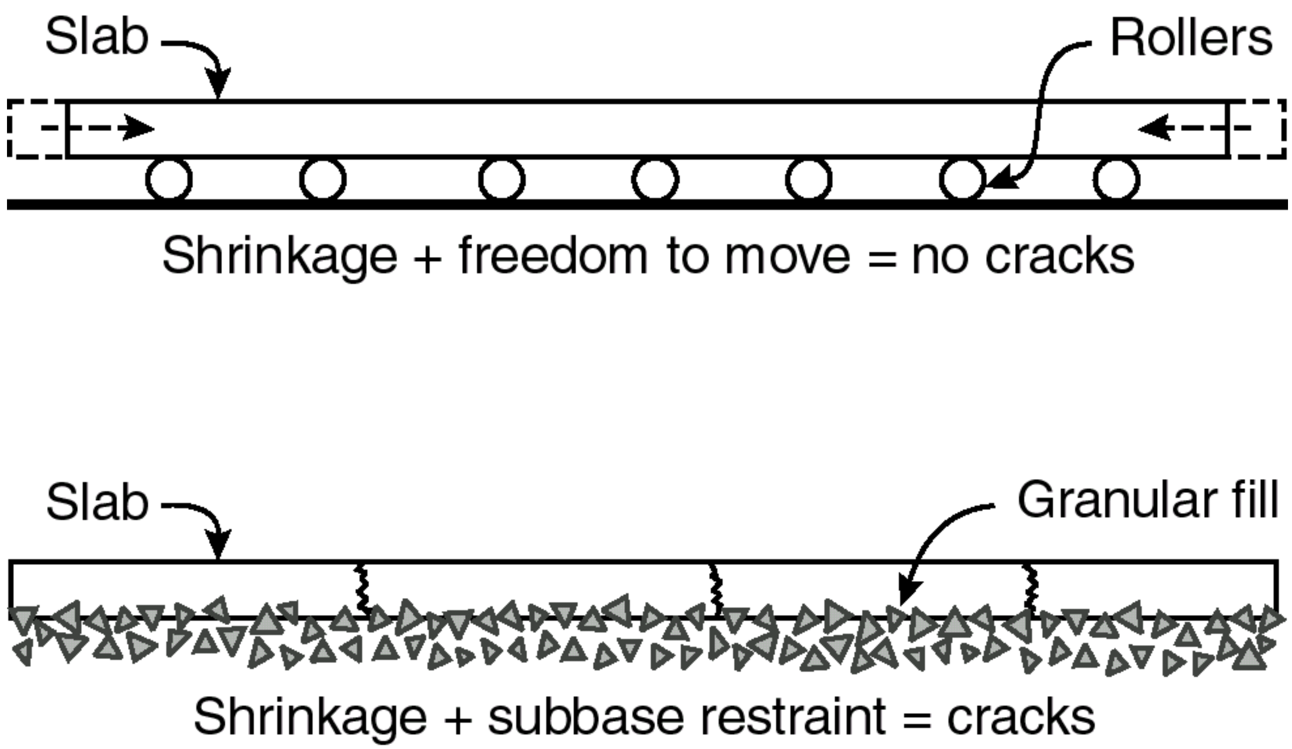
Capillary stress mechanism for shrinkage



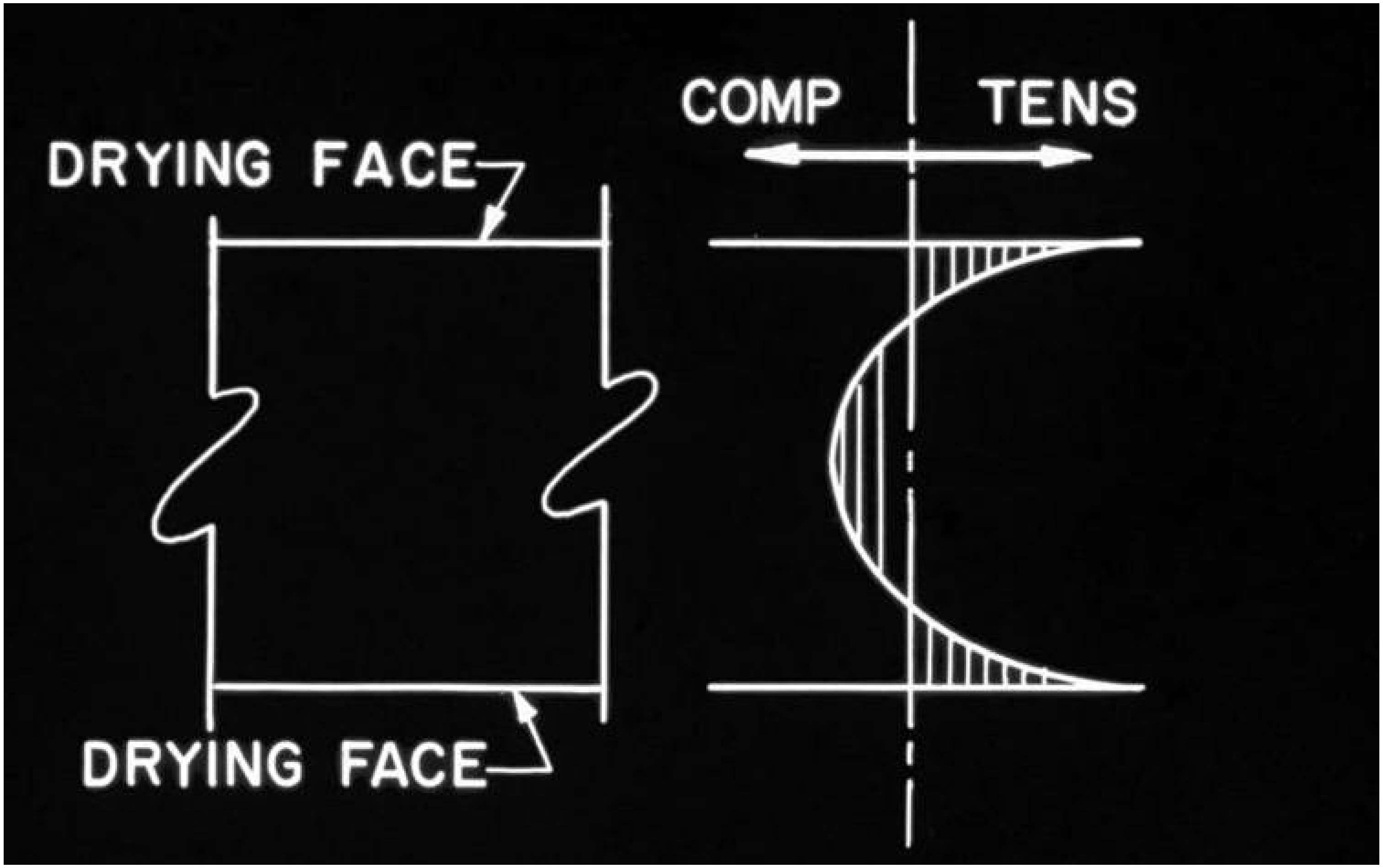
Concrete Shrinkage



Shrinkage and Cracking

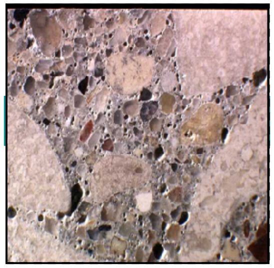


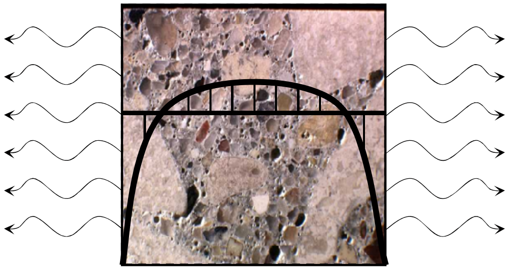
Theoretical Shrinkage Stresses

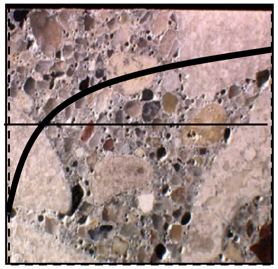


Causes for volume change

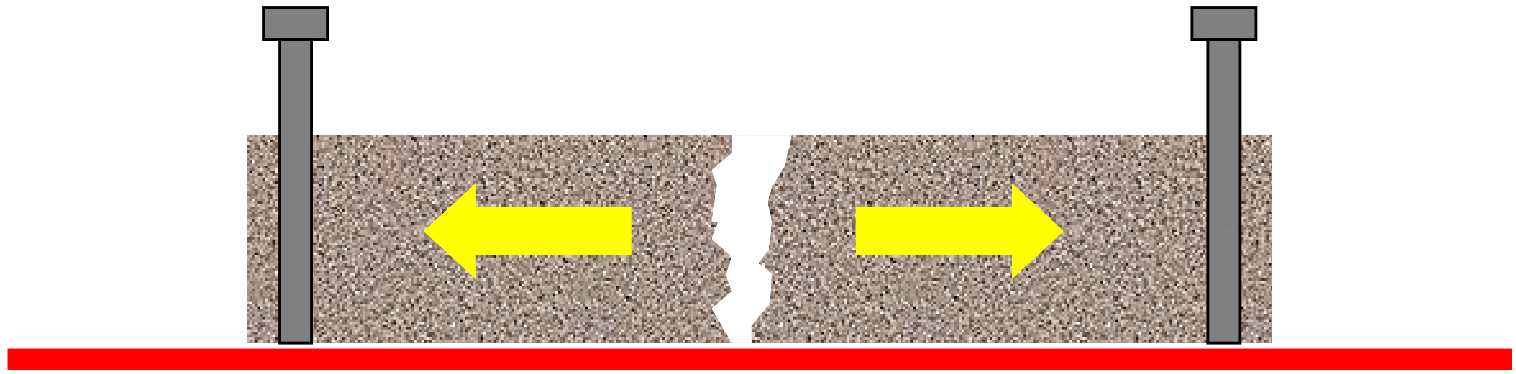
- Autogenous shrinkage
  - Self desiccation → uniform internal stress
- Drying shrinkage
  - External drying → nonlinear gradients of internal stress
- Thermal dilation
  - Differential temperature → differential stress





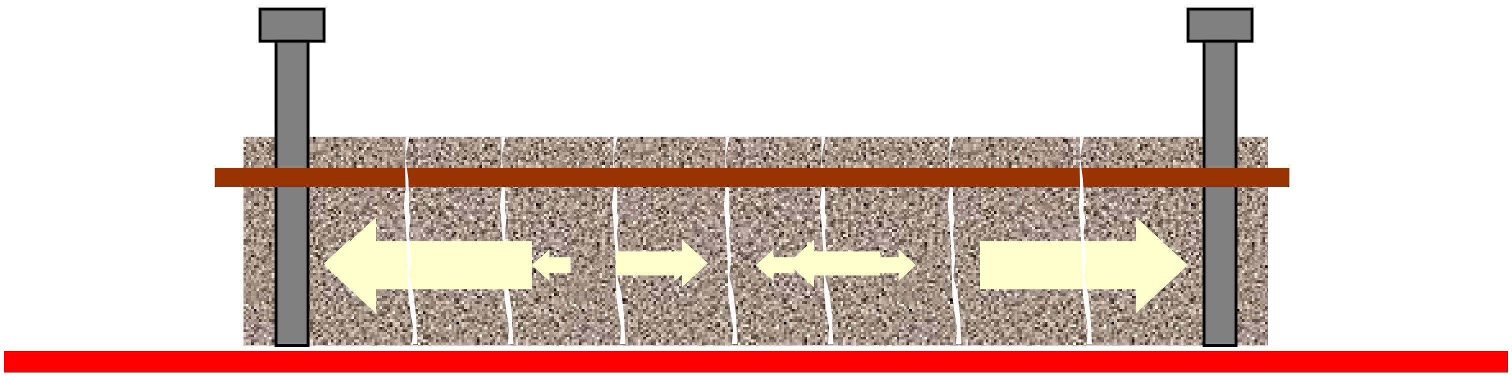


Cracks in Concrete

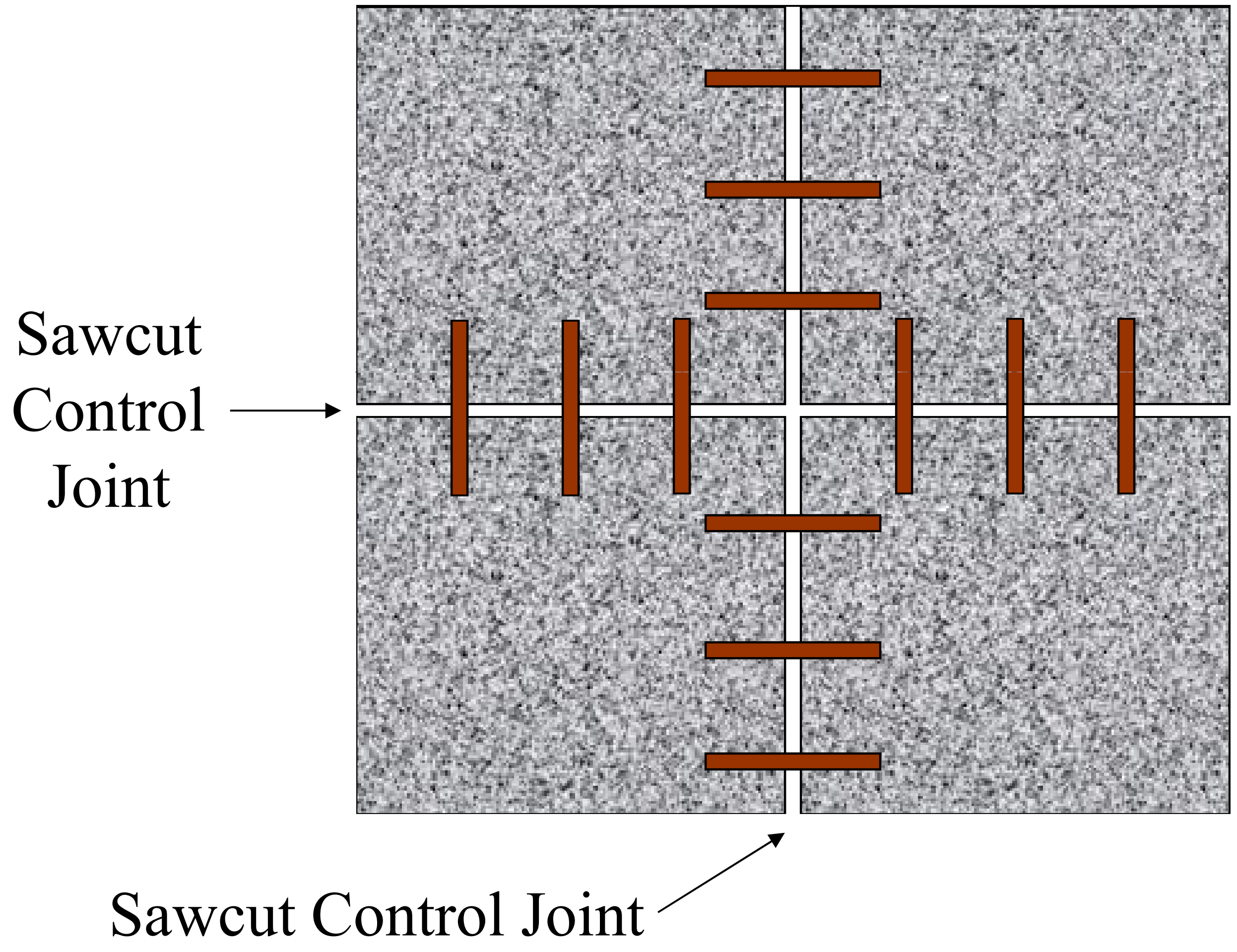


Minimize Shrinkage Cracking

Reinforcing Steel as Crack Control



Movement at Sawcut Joints w/Dowel Bars to Transfer Loads

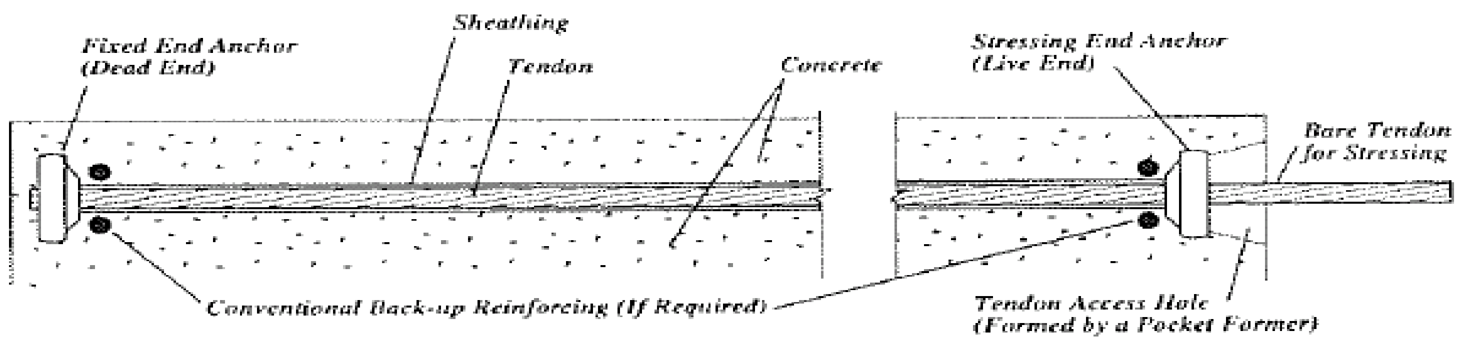


Tolerable Crack Widths for Reinforced Concrete

Exposure condition	Tolerable crack width, in.
Dry air or protective membrane	0.016
Humidity, moist air, soil	0.012
Deicing chemicals	0.007
Seawater and seawater spray; wetting and drying	0.006
Water-retaining structures	0.004

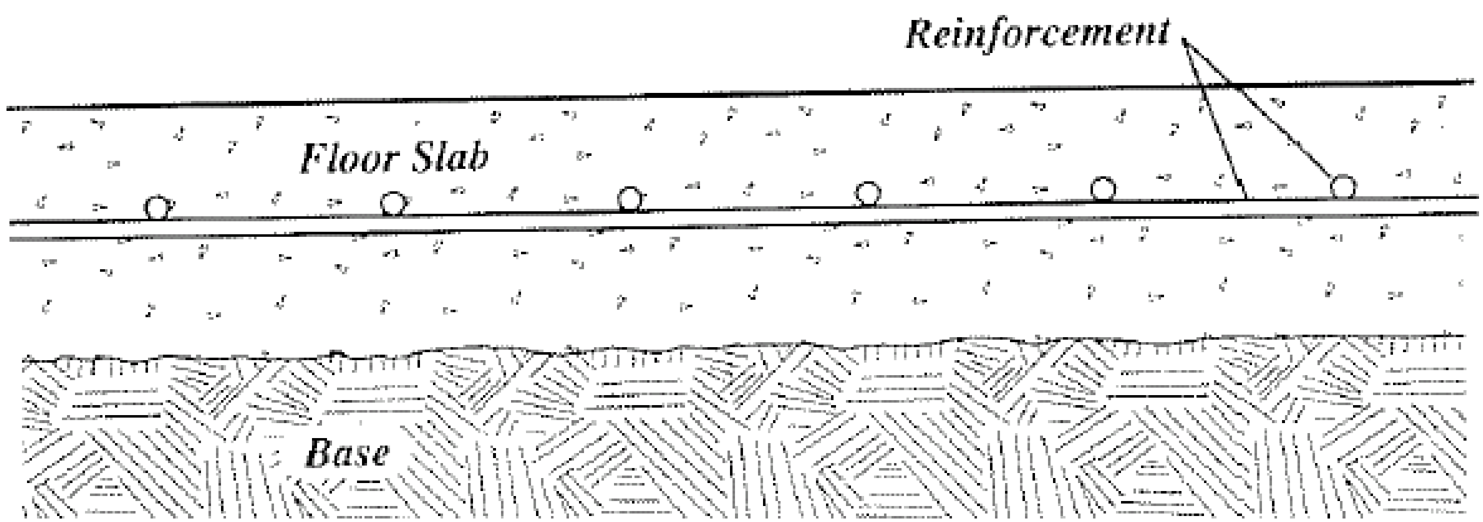
Post-Tensioned Slabs

- Tensioned tendons apply a compressive force to concrete
- Tensile stress and associated cracking reduced



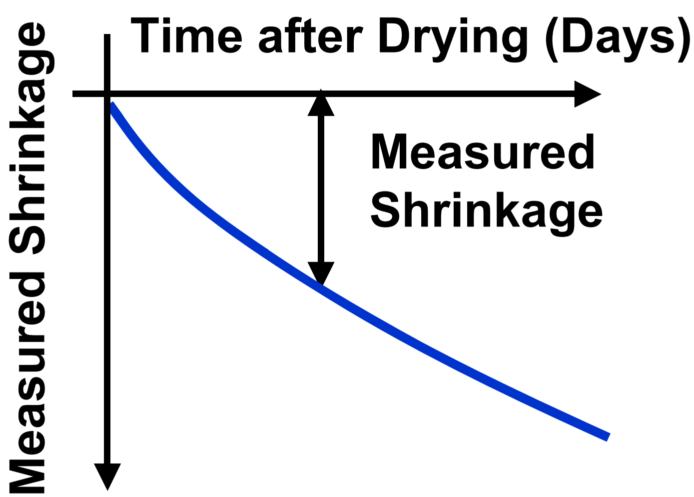
Shrinkage-Compensating Concrete

- Expansive reactions cause concrete to expand (must occur after set)
- Steel reinforcement restrains expansion
- Concrete is put into compression – no cracking



Laboratory Tests

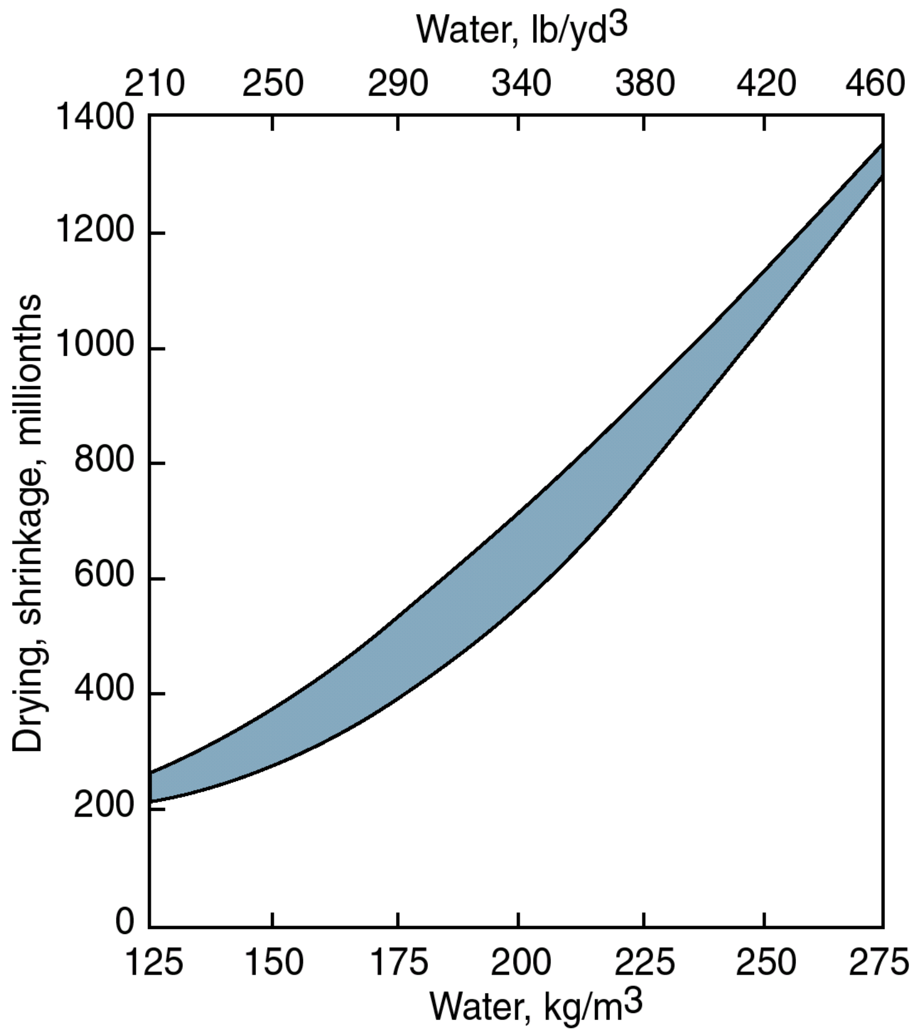
- ASTM C 157
- ASTM C 341
- ASTM C 490



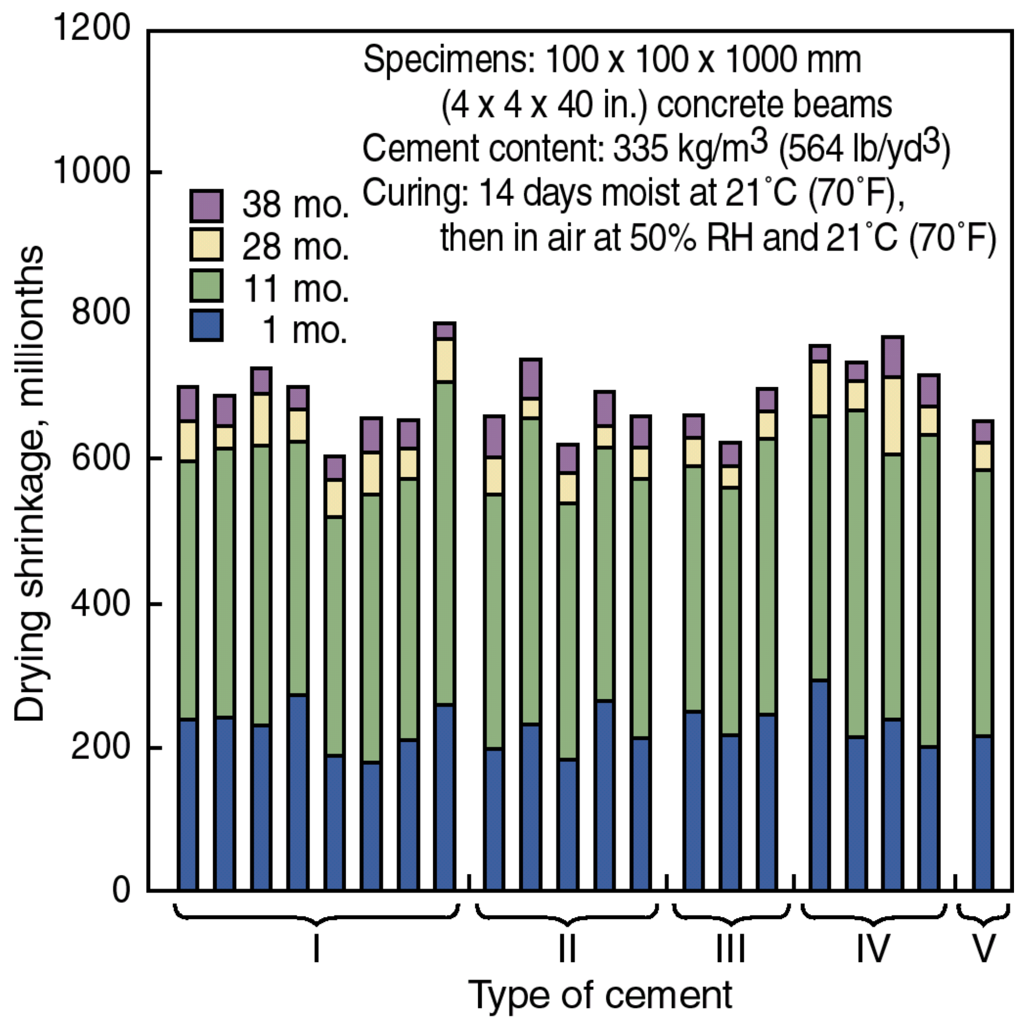
$$\varepsilon = \frac{\Delta l}{l_0}$$

Three Dimensional Phenomena

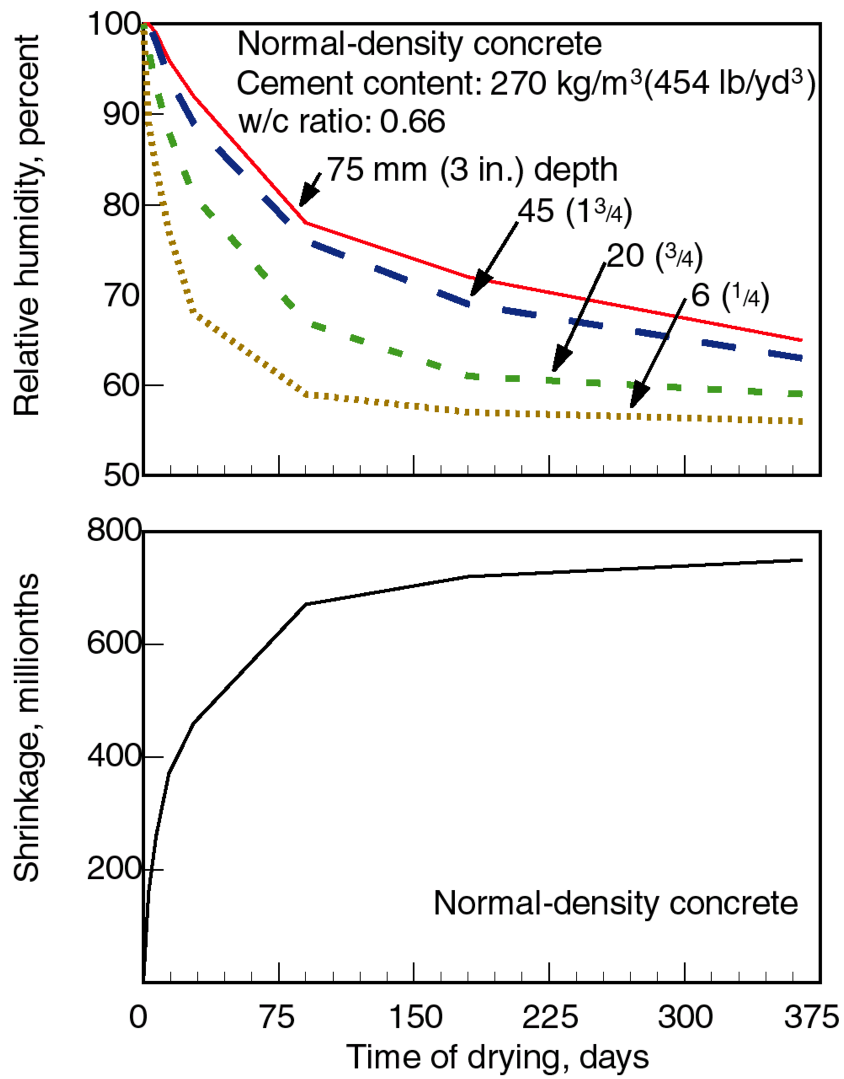
Shrinkage and Water Content



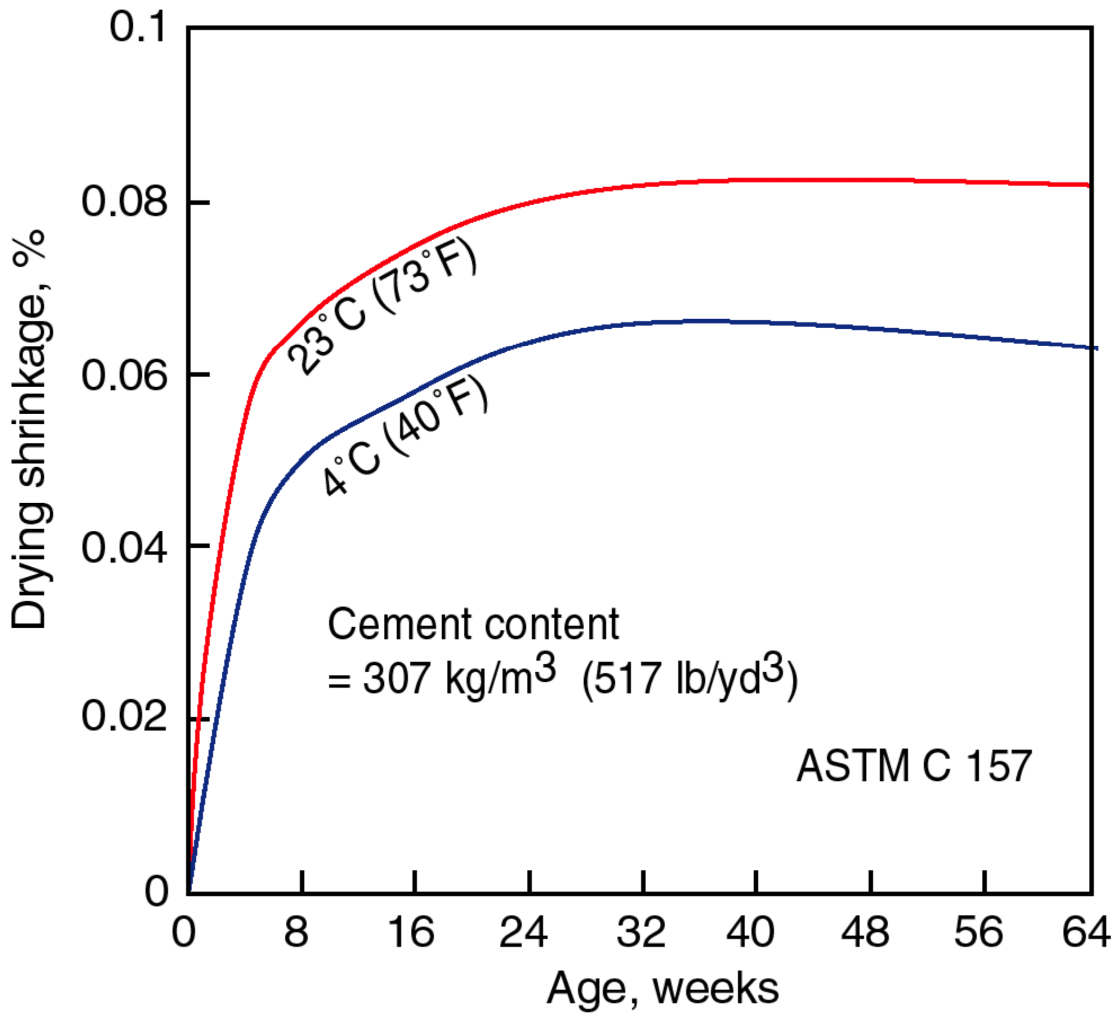
Long-Term Drying Shrinkage



Shrinkage and Drying Time

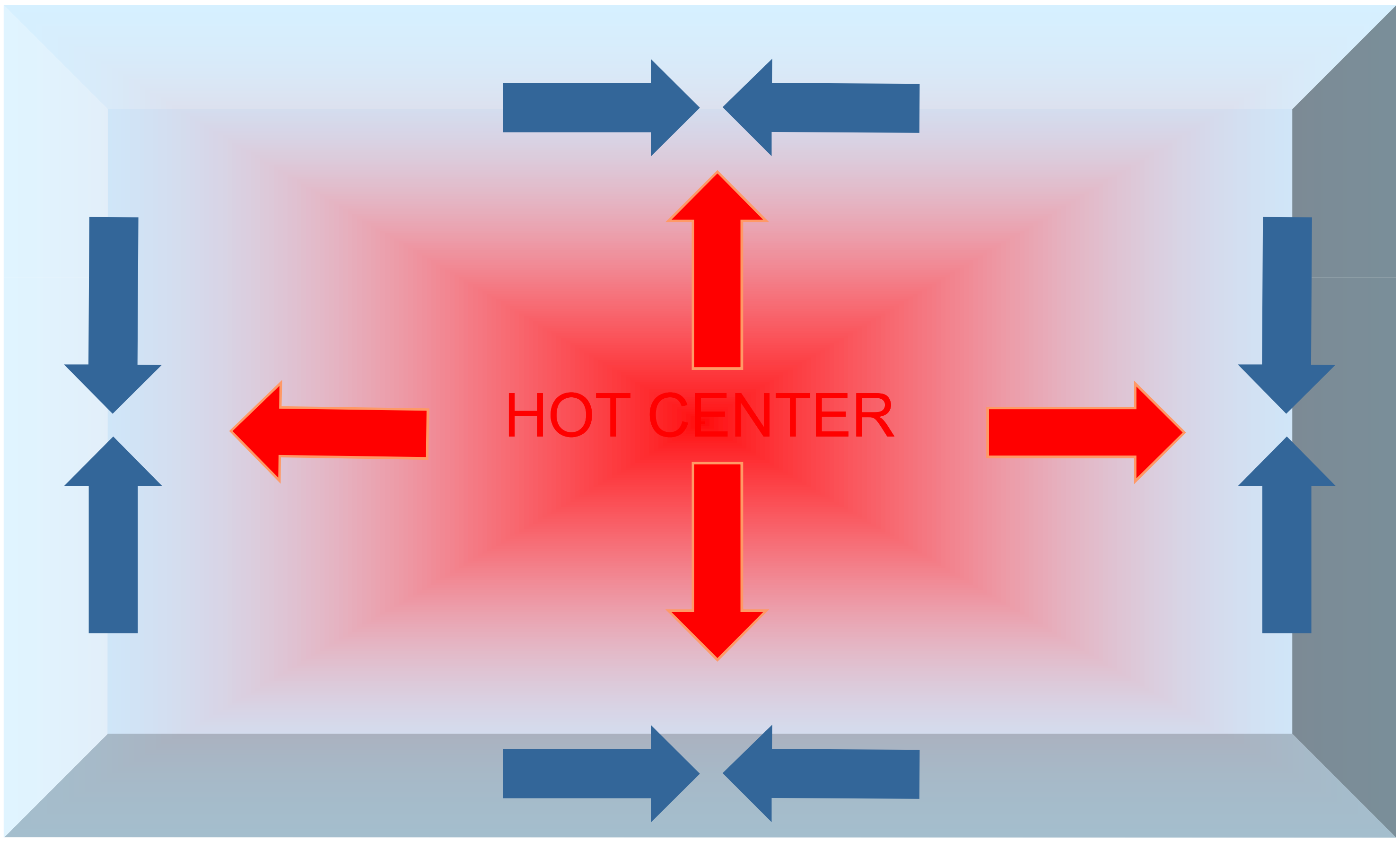


Curing and Drying Shrinkage



Thermal Dilation

Internal Thermal Restraint



Coefficient of Expansion of Concrete

Aggregate type (from one source)	Coefficient of expansion, millionths per °C	Coefficient of expansion, millionths per °F
Quartz	11.9	6.6
Sandstone	11.7	6.5
Gravel	10.8	6.0
Granite	9.5	5.3
Basalt	8.6	4.8
Limestone	6.8	3.8

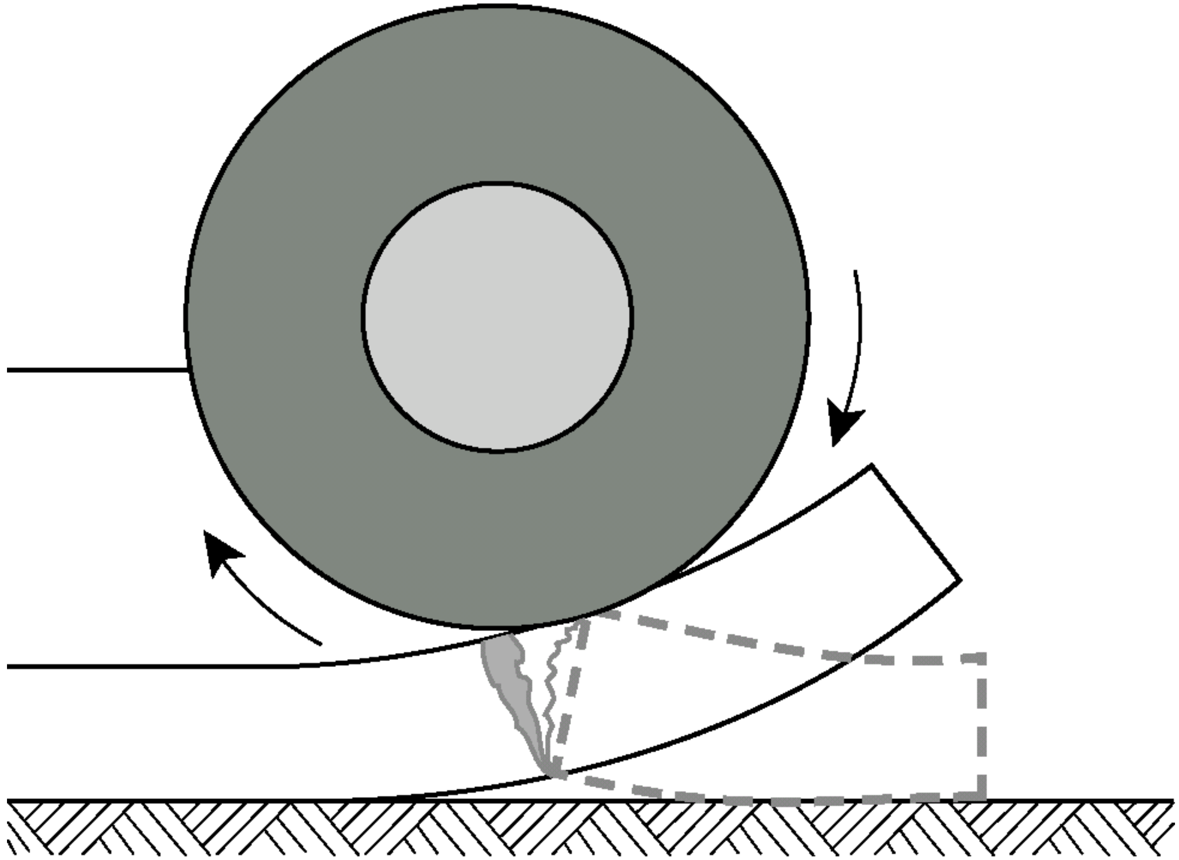
Take an example…

- Sidewalk set above pavement
- 500 ft long pavement strips
- α = 6x10^{-6} in/in/°F
- Approximately 0.7”/100’/100°F

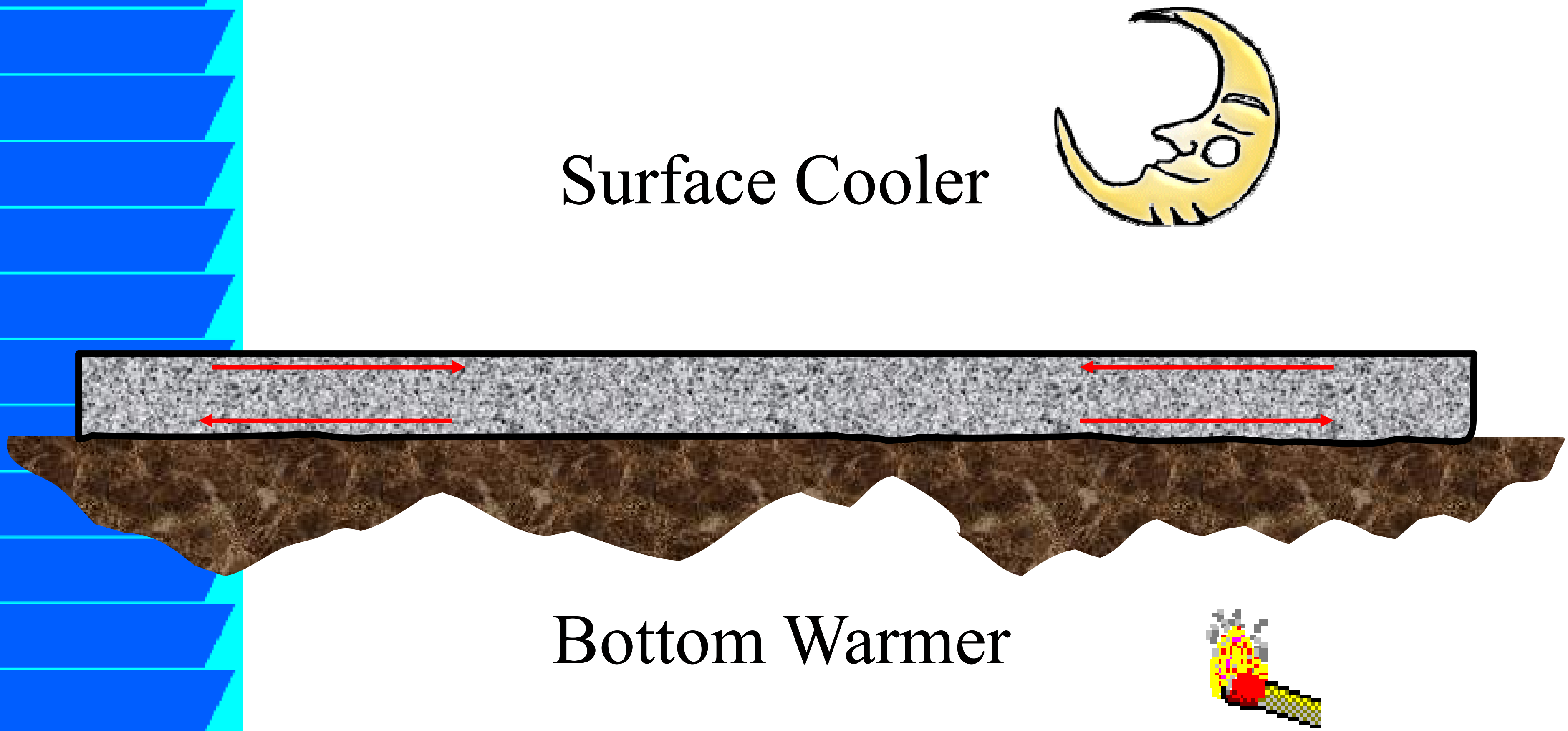
Result…

- Omission of full depth isolation /expansion joint
- Expansion of adjacent pavement results in cracking and buckling of concrete sidewalk

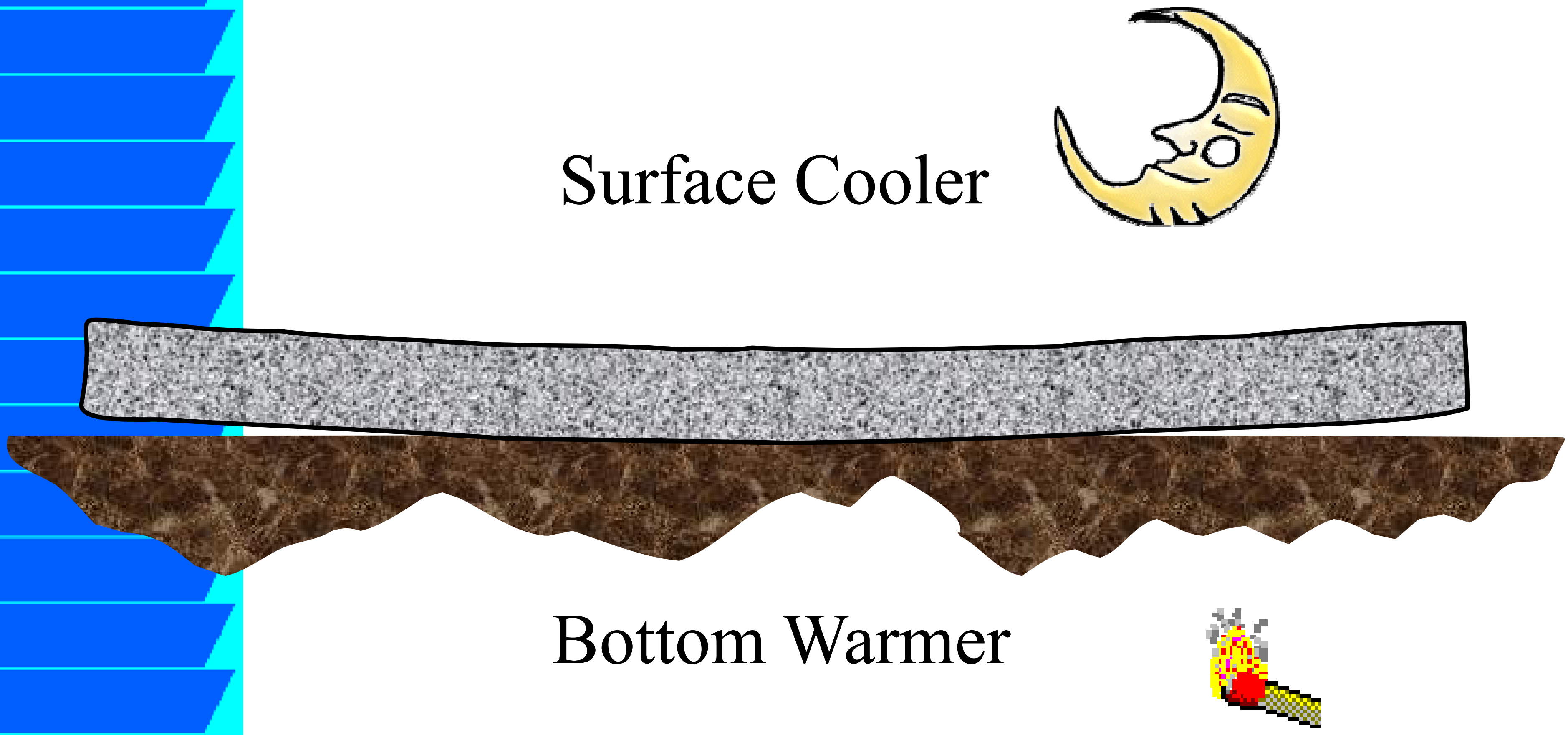
Curling (Warping)



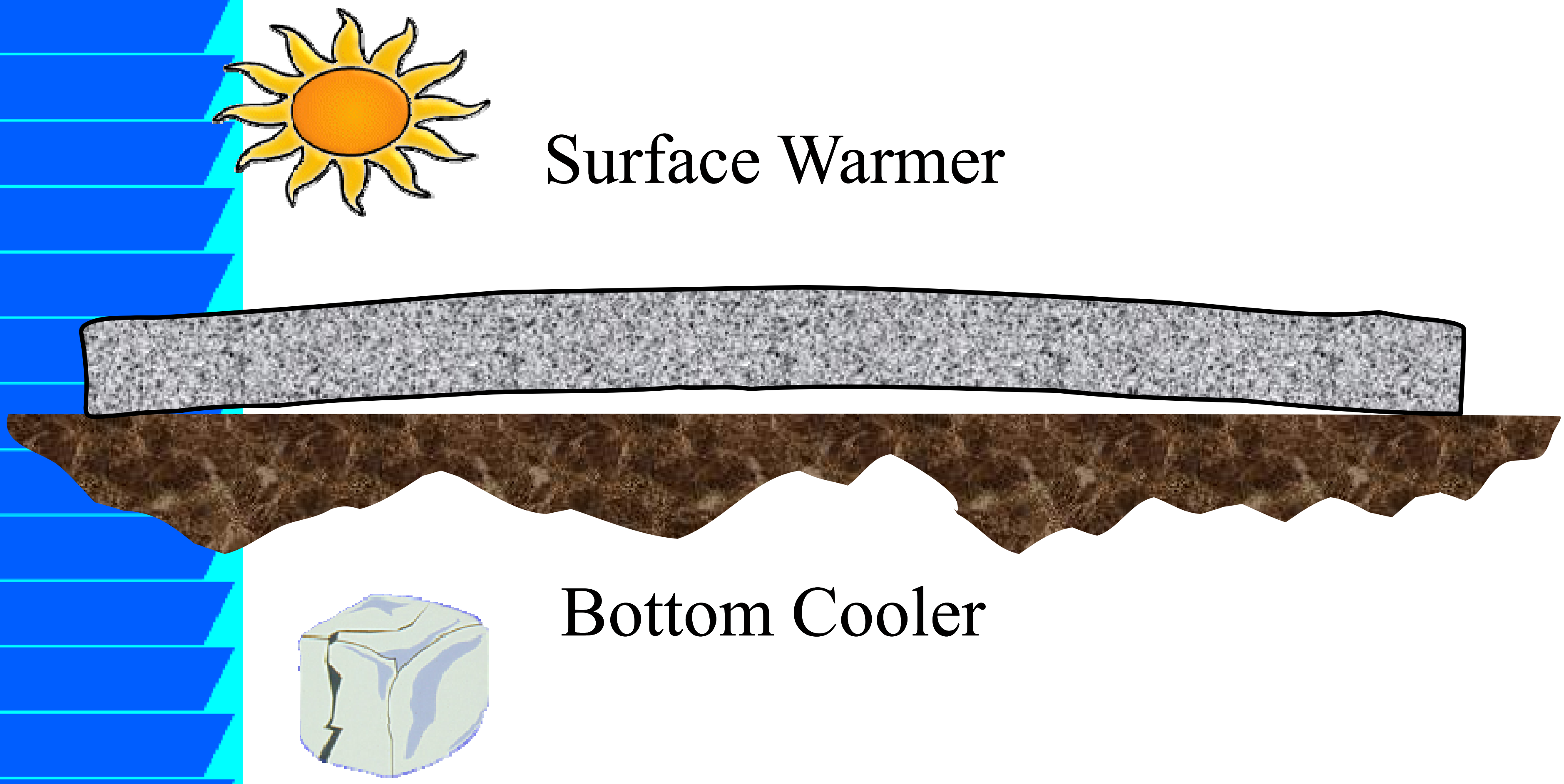
Temperature Curling



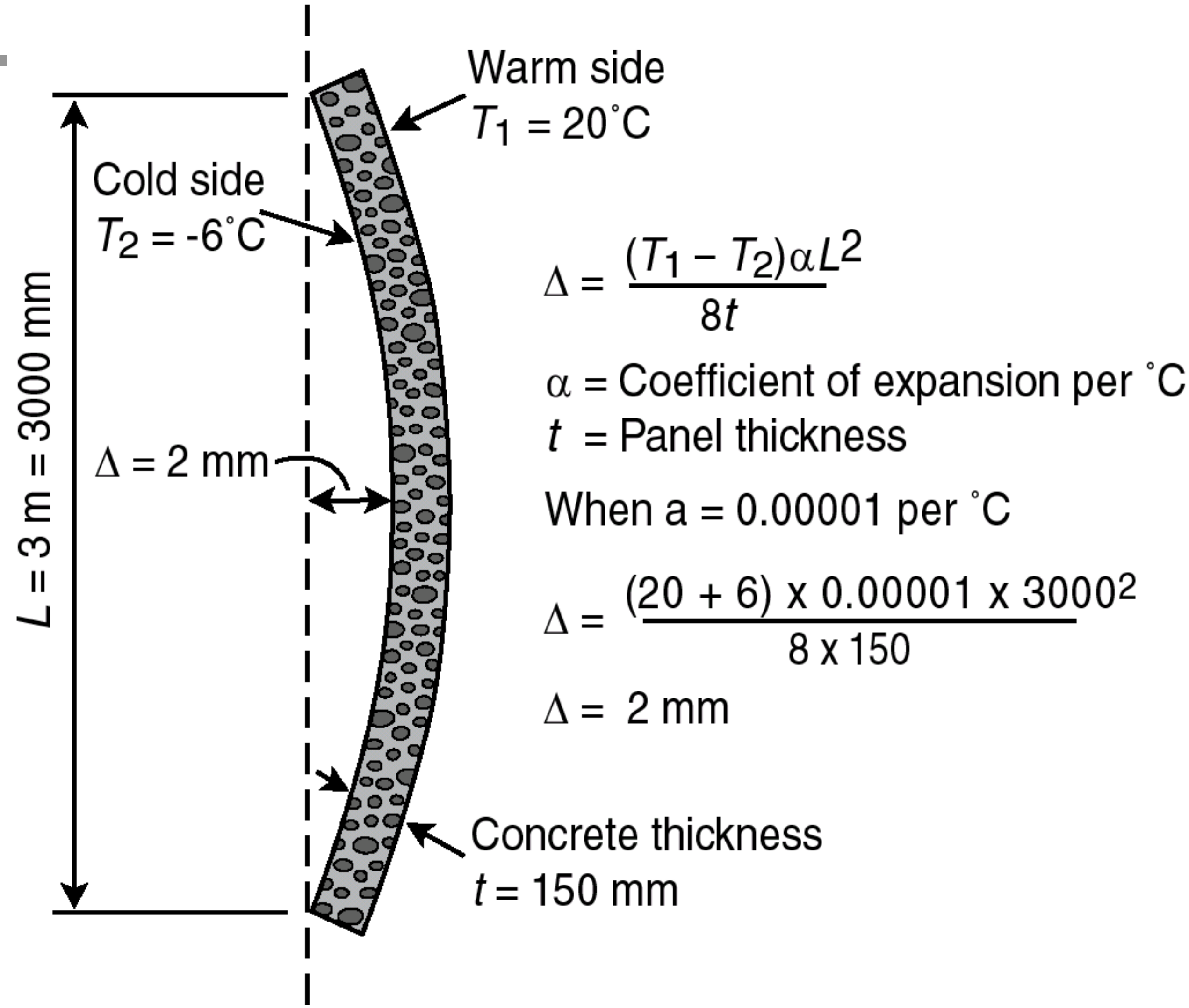
Temperature Curling



Temperature Curling

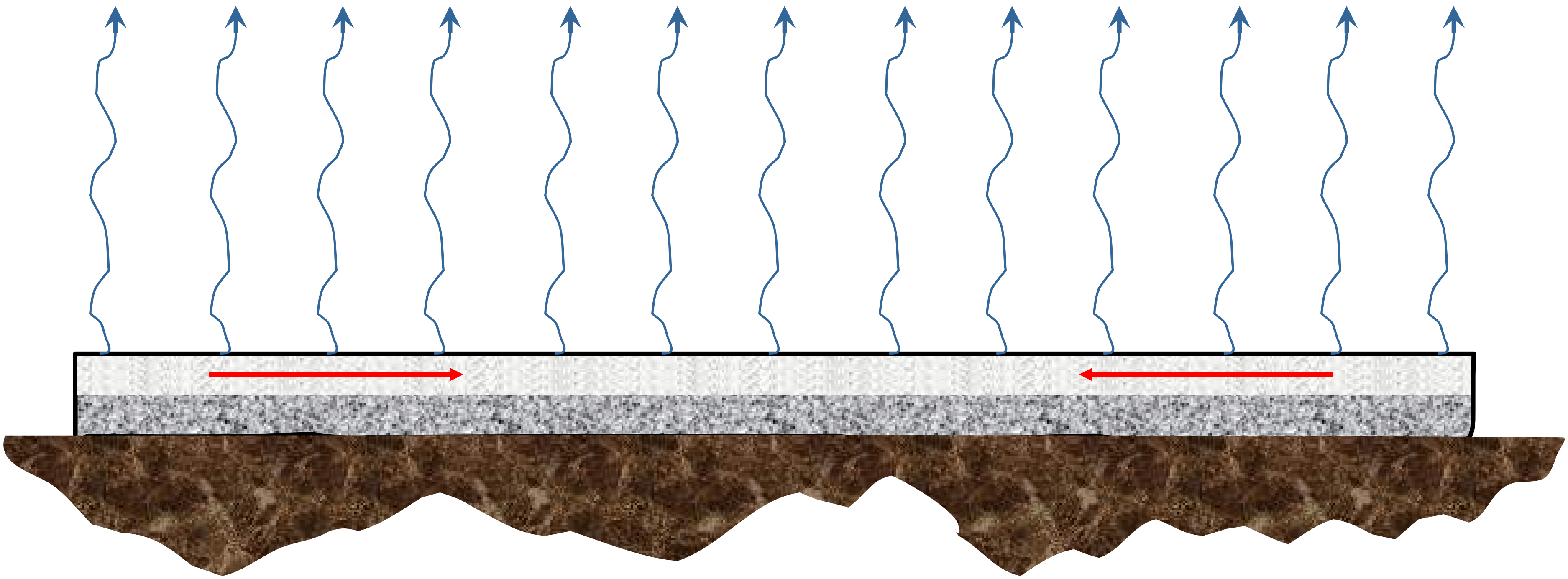


Curling of Wall Panel



Moisture Warping

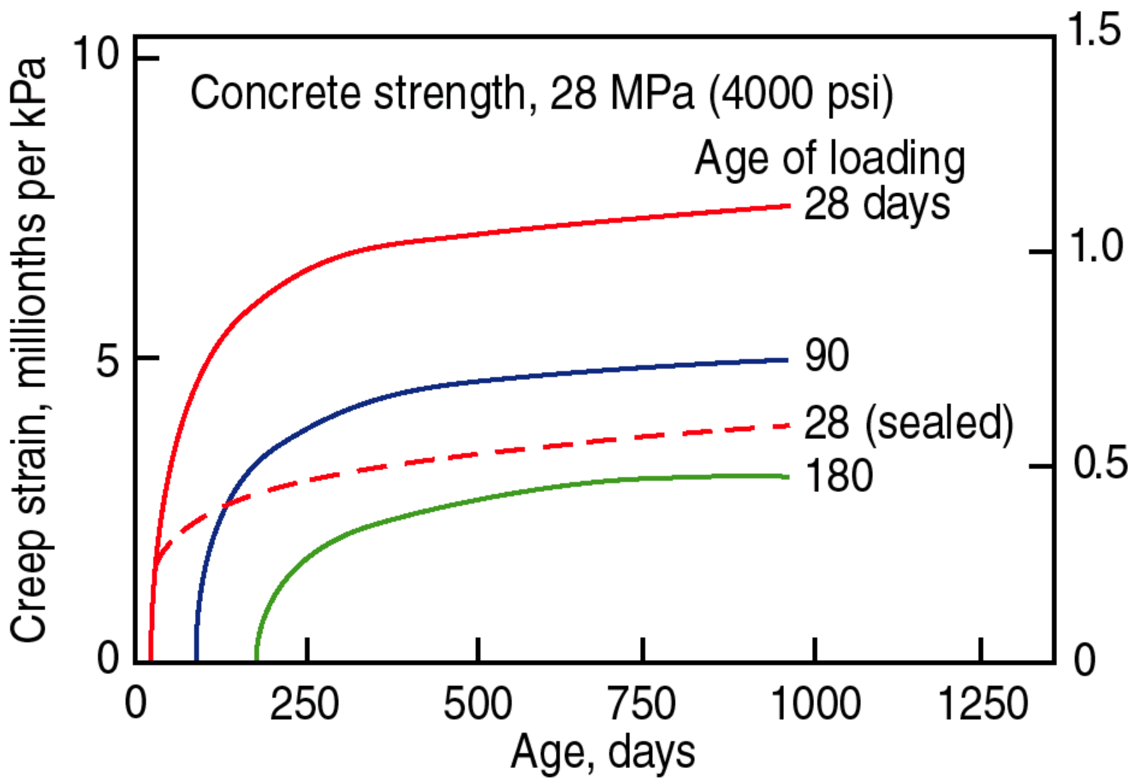
- Drying occurs from the top downward
- Dry top portion shrinks relative to the moist bottom portion



Moisture Warping

- Drying occurs from the top downward
- Dry top portion shrinks relative to the moist bottom portion
- Slab curls upward due to differential drying stresses

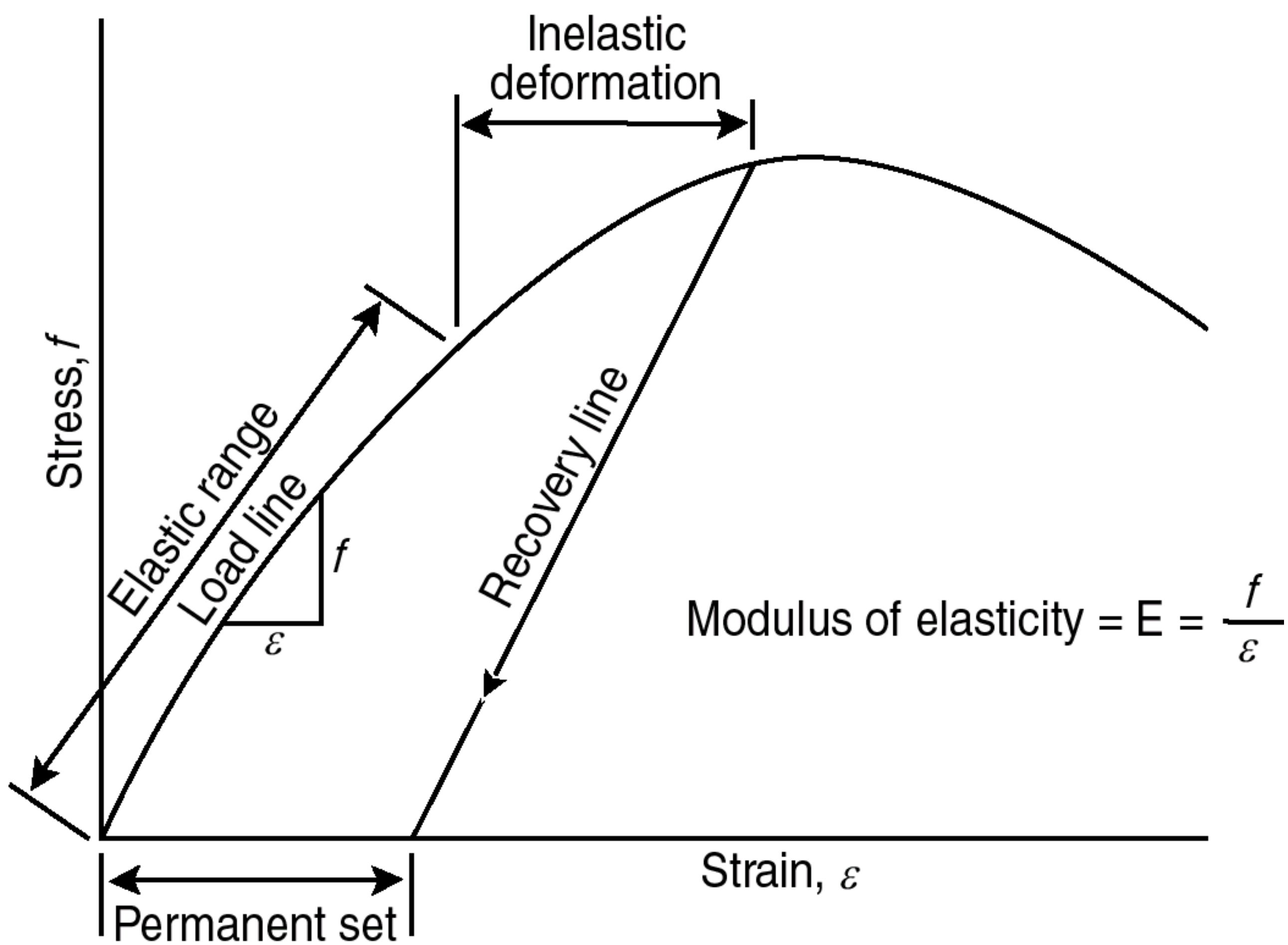
Creep



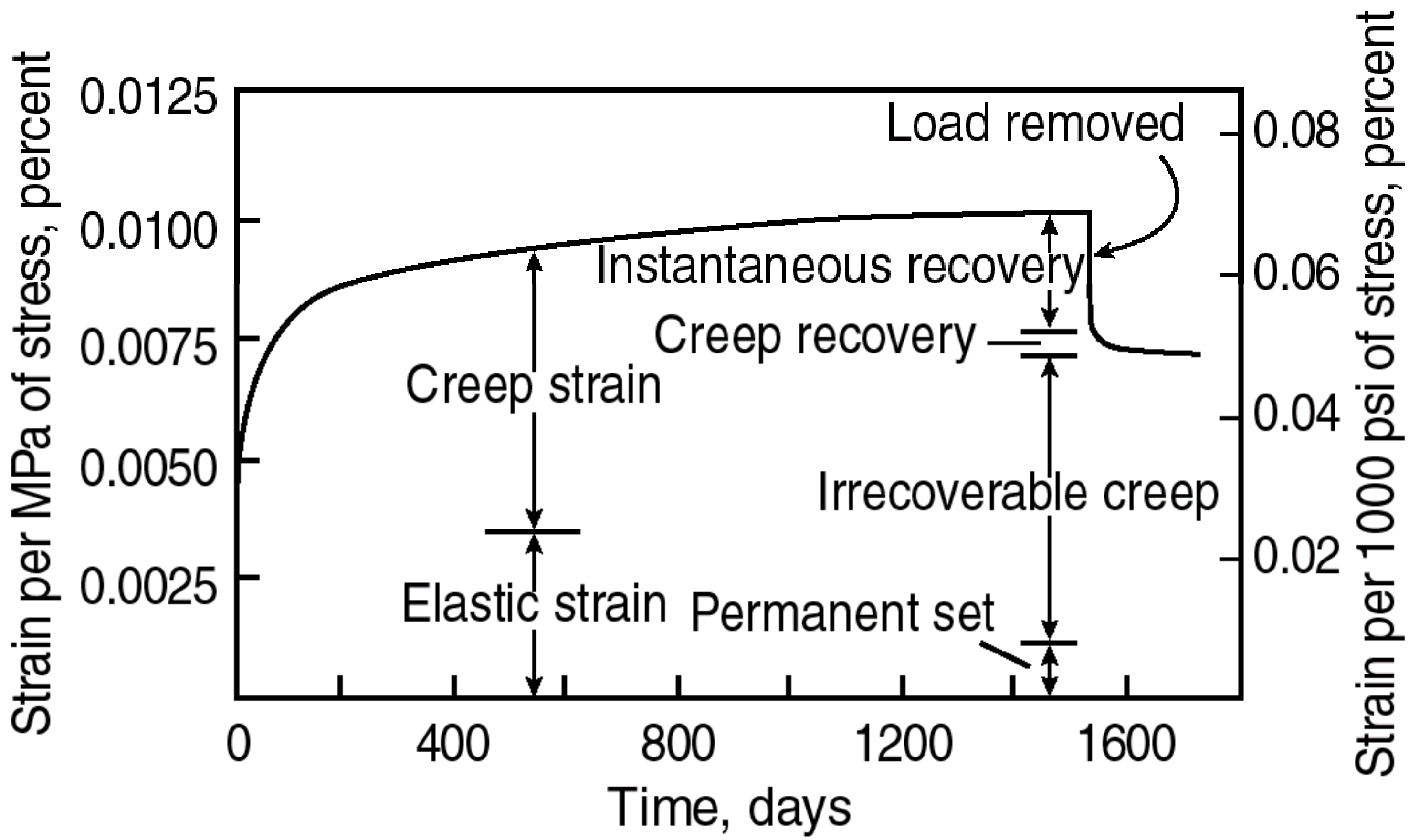
Concrete strength, 28 MPa (4000 psi)
Age of loading
28 days
90
28 (sealed)
180
Creep strain, millionths per kPa
Creep strain, millionths per psi
Age, days
0
250
500
750
1000
1250
0
5
10
0
0.5
1.0
1.5

CHARLESTON CHEW
VANILLA

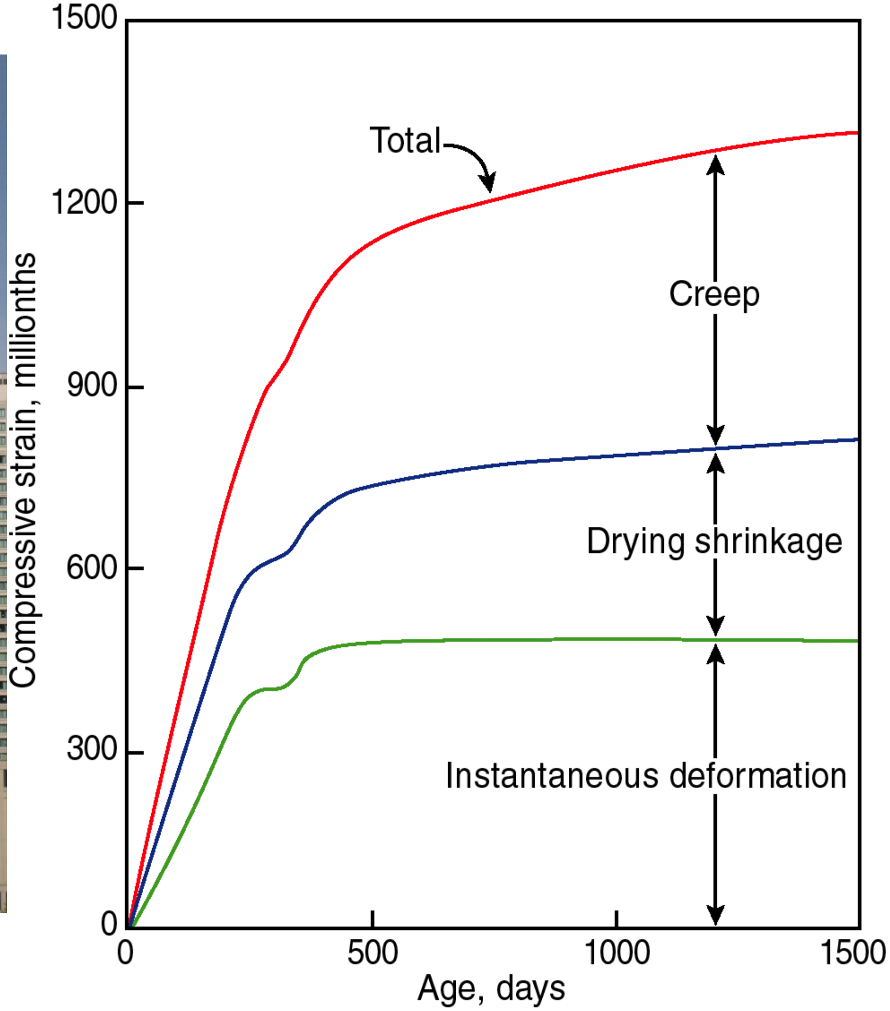
Stress-Strain Curve



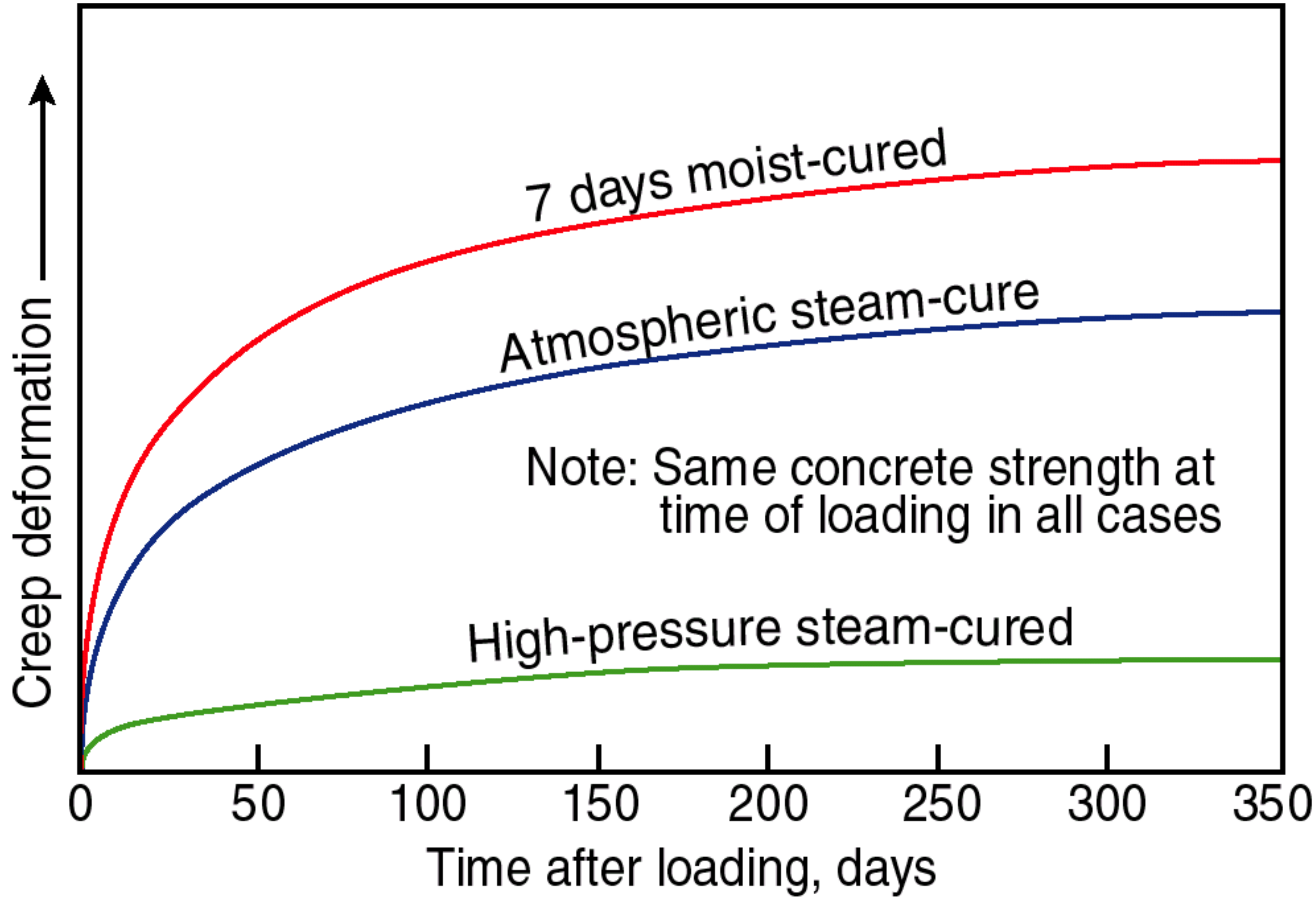
Elastic and Creep Strains



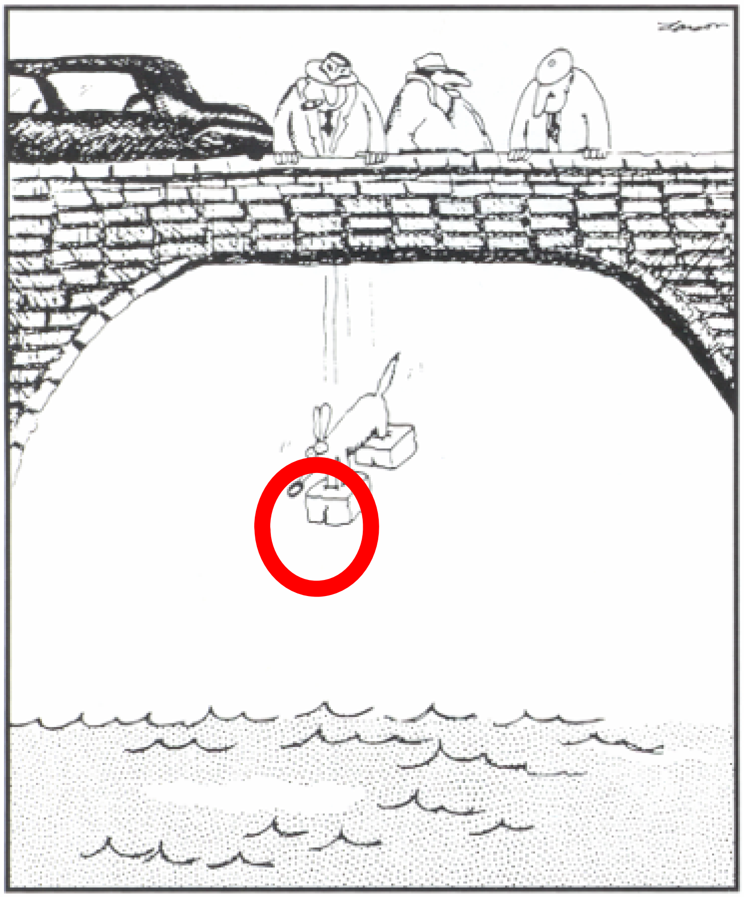
Column Shortening in a Tall Building



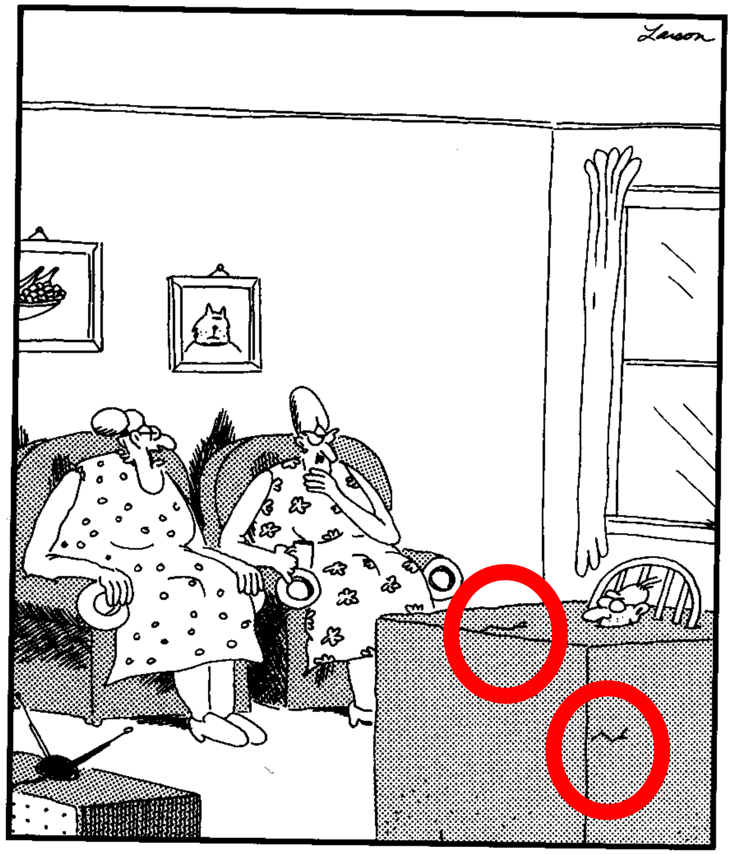
Effect of Curing on Creep



Summary



"He bit the Godfather."



"I built the forms around him just yesterday afternoon when he fell asleep, and by early evening I was able to mix and pour."

?